Shape Coexistence; Monopole *vs* Multipole

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Outline

- Basic Monopole Tools
- The Quadrupole Interaction: Shapes
- Shape coexistence and the Islands of Inversion
  - ^{34}Si: The Portal to the N=20 IoI
  - ^{68}Ni: The Portal to the N=40 IoI
  - ^{78}Ni: The Portal to the N=50 IoI
- Mergers
- Conclusions

- The two basic players in the nuclear dynamics are the spherical mean field and the multipole hamiltonian: $H = \mathcal{H}_m + \mathcal{H}_M$
- Magic numbers are associated to large energy gaps in the spherical mean field. Therefore, to promote particles above the Fermi level costs a large amount of energy.
- The Multipole Hamiltonian is responsible for the very strong nuclear correlations
- It is proper to the nucleus that, quite often, certain highly correlated configurations (dubbed ”intruders”) overwhelm their loss of mean field energy with their huge gains in correlation energy.

The Spherical Mean Field (Monopole Hamiltonian)

$$\mathcal{H}_m = \sum n_i \epsilon_i + \sum \frac{1}{(1+\delta_{ij})} \overline{V}_{ij}\, n_i (n_j - \delta_{ij})$$

the coefficients $\overline{V}$ are angular averages of the two body matrix elements, or centroïds of the two body interaction:

$$\overline{V}_{ij} = \frac{\sum_J V^J_{ijij}[J]}{\sum_J [J]}$$

the sums run over Pauli allowed values.

It can be written as well as:

$$\mathcal{H}_m = \sum_i n_i \left[\epsilon_i + \sum_j \frac{1}{(1+\delta_{ij})} \overline{V}_{ij} \, (n_j - \delta_{ij}) \right]$$

Thus

$$\mathcal{H}_m = \sum_i n_i \;\; \hat{\epsilon}_i(\left[n_j\right])$$

We call these $\hat{\epsilon}_i(\left[n_j\right])$ effective single particle energies (ESPE). It is seen that the monopole hamiltonian determines the evolution of the underlying spherical mean field (aka, shell evolution) as we add particles in the valence space.

Item more ....

The monopole hamiltonian produces variations of the spherical mean field in a single nucleus for different np-nh configurations with respect to the normal filling (MCD; Monopole Configuration Drift,)

All in all, it provides the control parameters for the nuclear dynamics, given the universality of the nuclear correlators; in Andrés Zuker's words:

"Multipole Proposes and Monopole Disposes"

The Multipole Hamiltonian

- The multipole hamiltonian is responsible for the collective nuclear behavior. It is universal and well given by the realistic NN interactions. Its main components are:
- BCS-like isovector and isoscalar pairing. When pairing dominates, as in the case of nuclei with only neutrons (or only protons) on top of a doubly magic nucleus, it produces nuclear superfluids.
- Quadrupole-Quadrupole and Octupole-Octupole terms of very simple nature ($r^\lambda Y_\lambda \cdot r^\lambda Y_\lambda$) which tend to make the nucleus deformed. In this limit, the pairing correlations mainly show up as responsible for the moment of inertia of the nuclear rotors.

Why and When do the quadrupole correlations thrive in the nucleus?

- The fact that the spherical nuclear mean field is close to the HO has profound consequences, because the dynamical symmetry of the HO, responsible for the accidental degeneracies of its spectrum, is SU(3), among whose generators it is the quadrupole operator.
- When valence protons an neutrons occupy the degenerate orbits a major oscillator shell, and for an attractive Q·Q interaction, the many body problem has an analytical solution in which the ground state of the nucleus is maximally deformed (Elliott's model)

Why and When do the quadrupole correlations thrive in the nucleus?

- In cases when both valence neutrons and protons occupy quasi-degenerate orbits with Δj= 2 and Δj=2, including j=p+1/2 (Quasi-SU3), or quasi-spin multiplets (Pseudo-SU3)
- For example, $0f_{7/2}$ and $1p_{3/2}$, or $0g_{9/2}$ $1d_{5/2}$ and $2s_{1/2}$ form Quasi-SU3 multiplets and $0f_{5/2}$, $1p_{3/2}$ and $1p_{1/2}$ a Pseudo-SU3 triplet

Nuclear Shapes

- The very concept of shape requires to break the rotational (and reflection) invariance, or, equivalently to define an intrinsic reference frame. Then we need to rely on semiclassical models, liquid-drop like, to define a vocabulary which describes properties akin to the concept of shape.
- The surface of a drop can be expressed in the basis of the spherical harmonics $Y_{\lambda,\mu}(\theta, \phi)$. The coefficients of the development, $\alpha_{\lambda,\mu}$, are the shape parameters. To speak about nuclear shape, we need a protocol to extract the best information about these intrinsic shape parameters from the nuclear wave functions in the laboratory frame.

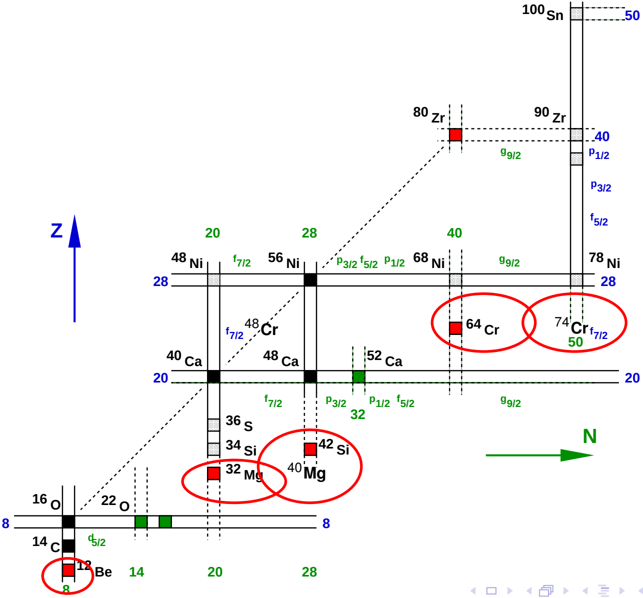
Shape Parameters; Quadrupole Deformation

- **From the values of Q_{spec}(J) and the B(E2)'s in a rotational band one can get Q_0, the intrinsic quadrupole moment using the BM formulas for the axial rotor. The deformation parameter β can be extracted using different recipes, for instance:**

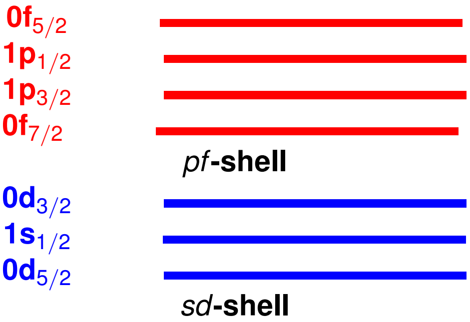
$$Q_0 = \frac{3}{\sqrt{5\pi}} R^2 \, Z \, (1 + 0.16\,\beta)\,\beta \tag{1}$$

- **If the nucleus is not axially symmetric, the situation becomes more convoluted, because now we need to recover two shape parameters, β and γ.**
- **These can be written in terms of the expectation values of scalars constructed with the quadrupole operator like $(Q_2 \times Q_2)^0$ or $(Q_2 \times Q_2 \times Q_2)^0$ (Kumar 74).**

Landscape of medium mass nuclei, featuring the Archipelago of Islands of Inversion

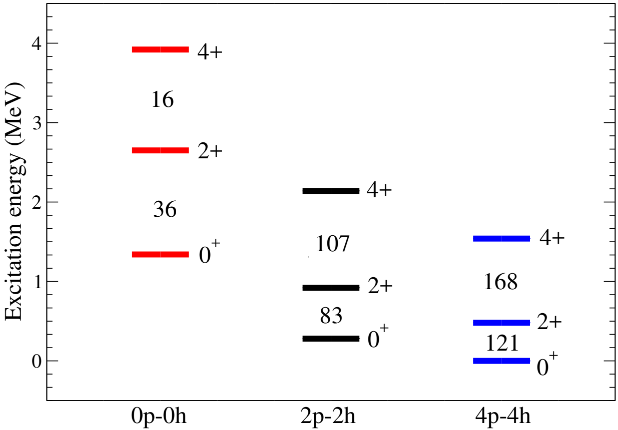


N=20 to N=28. The Valence Space; *sd*-*pf*

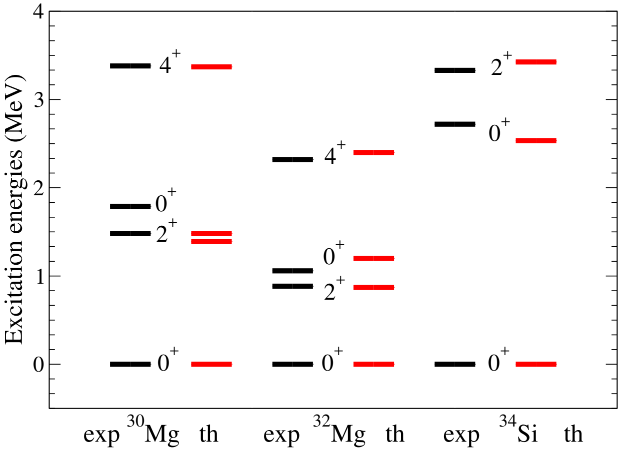


EFFECTIVE INTERACTION **SDPF-U-MIX**

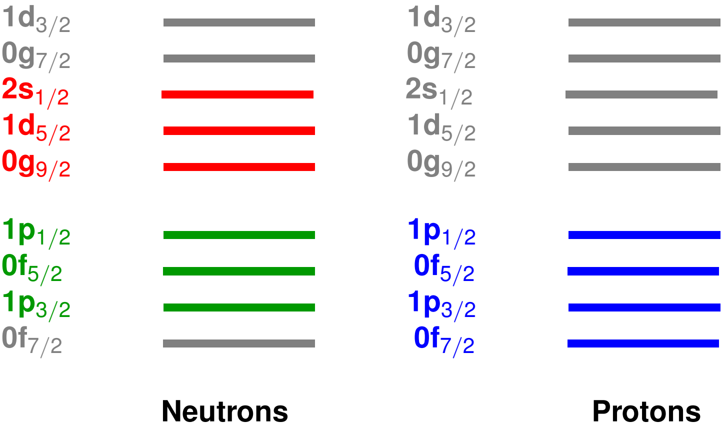
Spherical, Deformed and Superdeformed states in ^{32}Mg



Shape Coexistence in ^{30}Mg and ^{34}Si
The Portal to the N=20 IoI

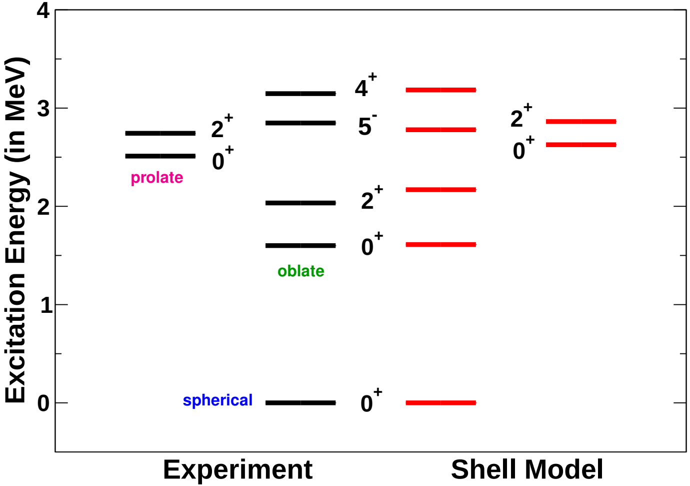


The LNPS valence space; N=40

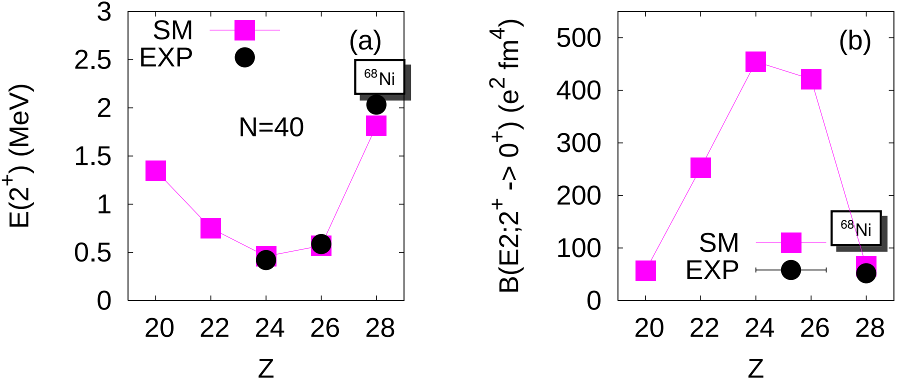


gray orbits are blocked

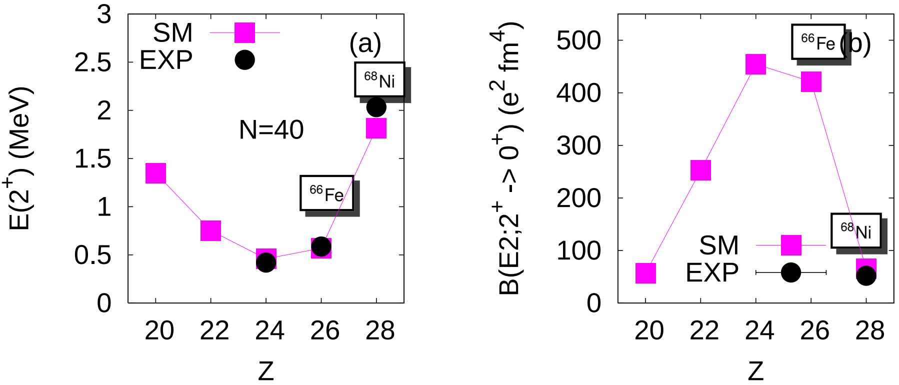
The Portal to the N=40 IoI; ^{68}Ni



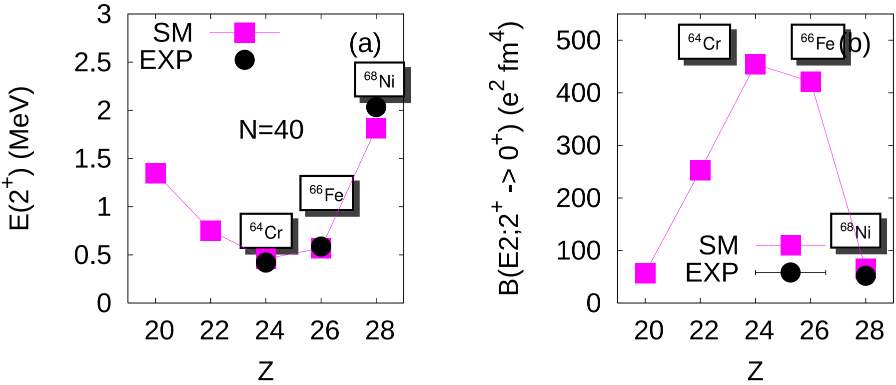
Shape transition at N=40



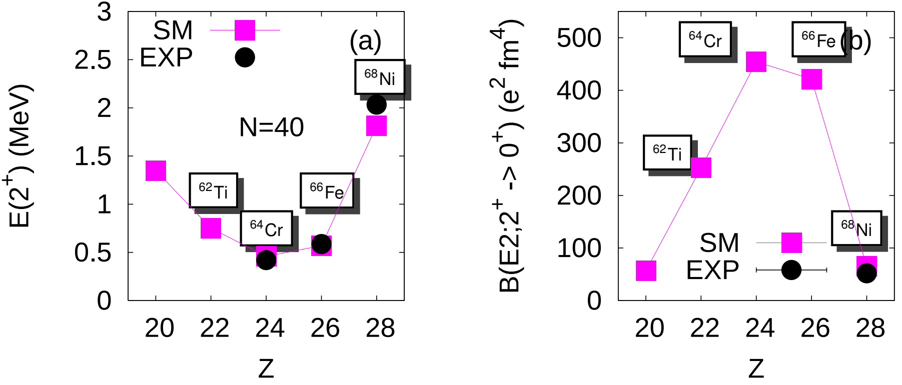
Shape transition at N=40



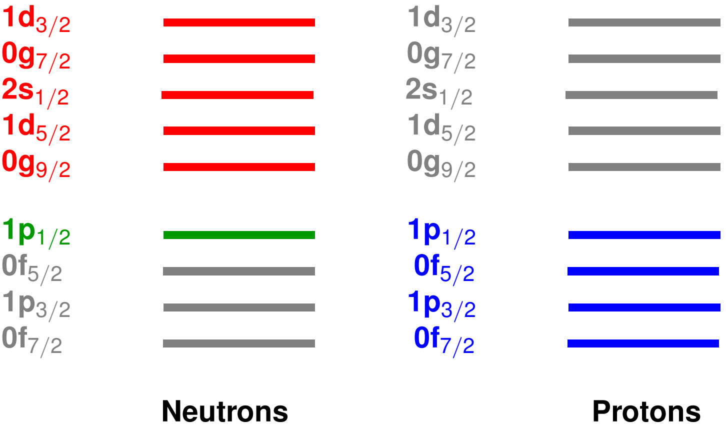
Shape transition at N=40



Shape transition at N=40

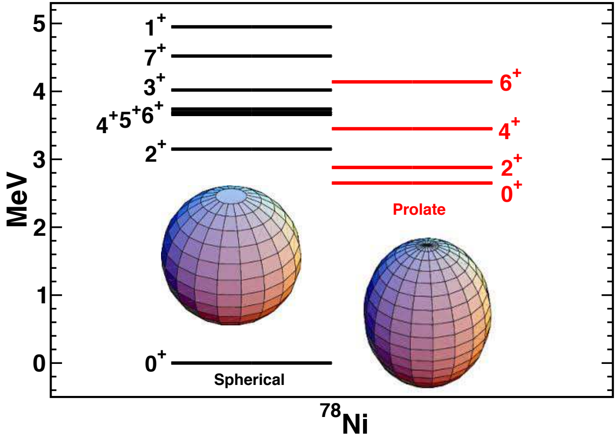


The pf-sdg valence space at N=50



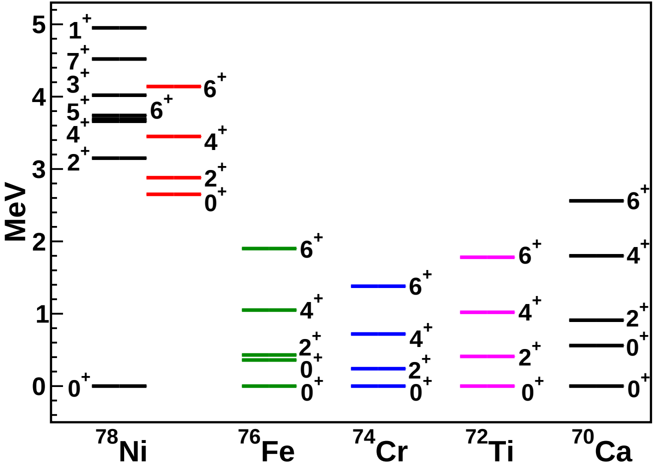
PFSDG-U interaction

Shape Coexistence, the Portal to the 5th IoI

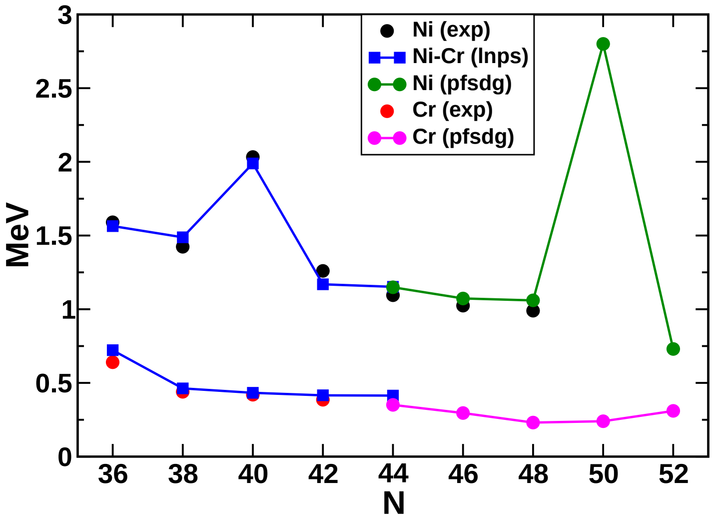


^{78}Ni is doubly magic in its ground state

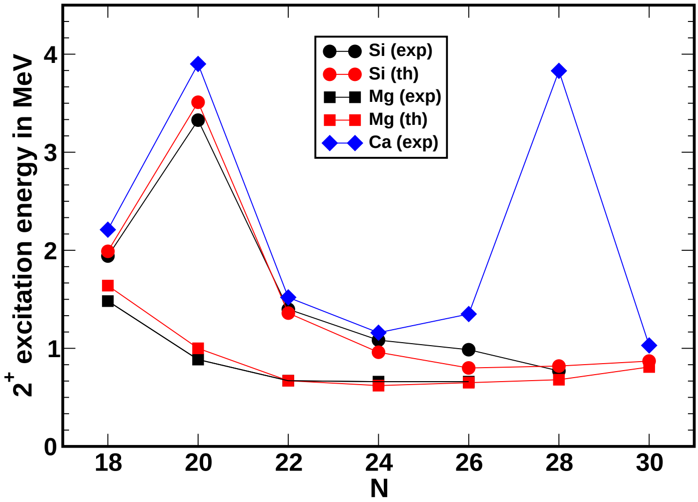
The IoI surrounding ^{74}Cr



The N=40 and N=50 IoI's Merge

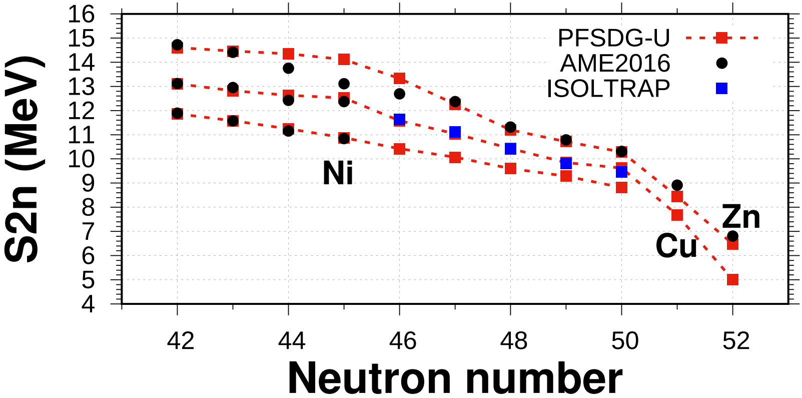


Like the N=20 and N=28 IoI's did



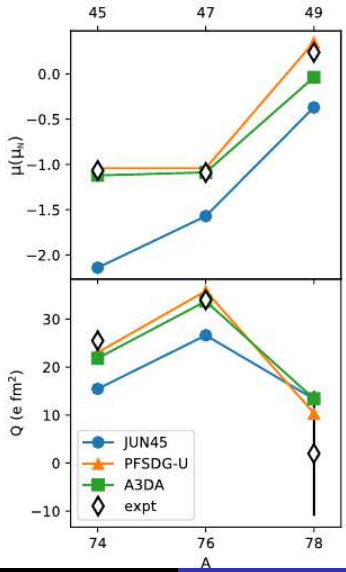
Other observables: S_{2N}

A. Welker et al. PRL 119 192502 (2017)



Copper Magnetic and Quadrupole moments

RP de Groote et al. PRC 96 041302(R) (2017)



Conclusions

- The physics around magic or semi-magic closures depends of subtle balances between the spherical mean field and the (very large) correlation energies of the open shell configurations at play
- There is a common mechanism explaining the appearance of ”islands of inversion/deformation” (IoI’s) in nuclei with large neutron excess, and shape coexistence usually shows up at their portals
- The IoI’s at N=20 and N=28 merge in the Magnesium isotopes.
- ^{68}Ni is a case of triple coexistence, precursor of the N=40 IoI
- Shape coexistence in ^{78}Ni is the portal to a new IoI at N=50
- The IoI’s at N=40 and N=50 merge in the Chromium isotopes.