Quels degrés de liberté pour quels phénomènes? Part II. La coexistence de formes par les méthodes au delà du champ moyen

Michael Bender

Institut de Physique Nucléaire de Lyon, CNRS/IN2P3, Université de Lyon, Université Lyon 1
69622 Villeurbanne, France

Journées SFP–BTPN sur
les grandes questions en physique nucléaire fondamentale
Campus Michel-Ange Paris-16
21-22 Juin 2016

Université Claude Bernard Lyon 1

Which are the irreducible ingredients of a (minimal) predictive model of shape coexistence and its experimental signatures? ?

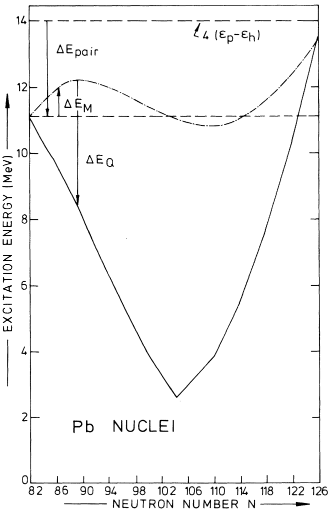
- What is there to be modeled?
  - sequence of levels and their excitation energies
  - $E0$ transition matrix elements
  - $E2$ transition matrix elements
  - (charge) radii (and isotopic shifts)
  - masses (and mass differences)
- Distinguish
  - deformation softness (states spread over a wide range of deformations)
  - shape coexistence (distinguishable states that might be directly mixed)
  - shape entanglement (distinguishable states that can only be mixed via third states) Poves, JPG 43 (2016) 020410.
- role of np-n hole excitations involving intruder / extruder states?

Which are the irreducible ingredients of a (minimal) predictive model of shape coexistence and its experimental signatures? ?

- What is there to be modeled?
  - sequence of levels and their excitation energies
  - $E0$ transition matrix elements
  - $E2$ transition matrix elements
  - (charge) radii (and isotopic shifts)
  - masses (and mass differences)
- Distinguish
  - deformation softness (states spread over a wide range of deformations)
  - shape coexistence (distinguishable states that might be directly mixed)
  - shape entanglement (distinguishable states that can only be mixed via third states) Poves, JPG 43 (2016) 020410.
- role of np-n hole excitations involving intruder / extruder states?
- Early *ad-hoc* model of shape coexistence: estimate excitation energy of 0^+ states from the difference in (spherical) single-particle energies, the change in pairing energy, a monopole correction and the quadrupole correlation energy.

Heyde *et al*, PRC44 (1991) 2216

Heyde & Woods, RMP 83 (2011) 1467



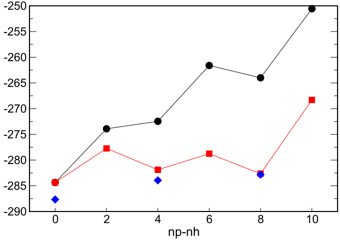
State-of-the-art modeling of shape coexistence

- Shell model: Poves, JPG 43 (2016) 020410.
  - − shape remains implicit
  - + good quantum numbers
  - + band mixing
  - − intruder states require two major shells
- Interacting boson model: Nomura *et al* JPG 43 (2016) 020408.
  - − shape remains implicit
  - + good quantum numbers
  - + band mixing
- (Self-consistent) mean field:
  - + energy surfaces with multiple minima
  - − no quantum numbers, nor slection rules
  - − non-orthogonal states
  - − no mixing of bands
- "beyond mean field" by projected GCM:
  - + projection → quantum numbers & selection rules
  - + Generator Coordinate Method → band mixing
  - − computationally intensive
- "beyond mean field" with collective Hamiltonians
  - + quantum numbers & selection rules
  - + band mixing

State-of-the-art modeling of shape coexistence

- Shell model: Poves, JPG 43 (2016) 020410.
  - − shape remains implicit
  - + good quantum numbers
  - + band mixing
  - − intruder states require two major shells
- Interacting boson model: Nomura *et al* JPG 43 (2016) 020408.
  - − shape remains implicit
  - + good quantum numbers
  - + band mixing
- (Self-consistent) mean field:
  - + energy surfaces with multiple minima
  - − no quantum numbers, nor slection rules
  - − non-orthogonal states
  - − no mixing of bands
- "beyond mean field" by projected GCM:
  - + projection → quantum numbers & selection rules
  - + Generator Coordinate Method → band mixing
  - − computationally intensive
- "beyond mean field" with collective Hamiltonians
  - + quantum numbers & selection rules
  - + band mixing

Poves, JPG 43 (2016) 020410.



Shell-model analysis of 0^+ levels in ^{40}Ca

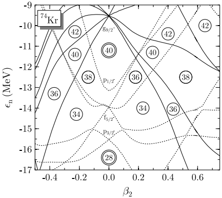
black: lowest Slater determinant in given *n*p-*n*h subspace

red: lowest mixed state in given *n*p-*n*h subspace

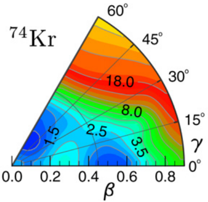
blue: full shell model calculation

Which model ingredients are really relevant?

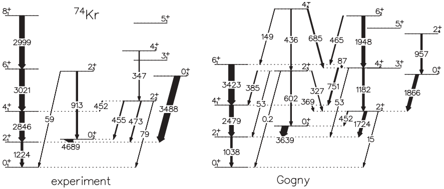
M. B.*et al*, PRC74 (2006) 024312.



Girod *et al*, PLB676 (2009) 39.



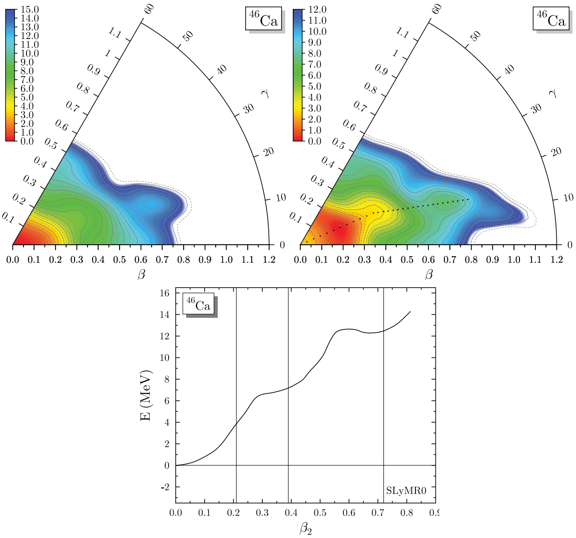
Clément *et al*, PRC75 (2007) 054313.

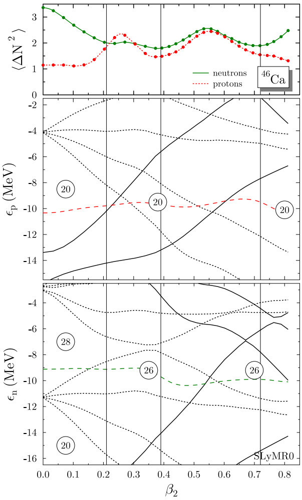


- Which are the irreducible ingredients of a (minimal) predictive microscopic model of shape coexistence and its experimental signatures?
  - quantum mechanics
  - shell structure and distinguishable configurations (that have different shape or that can be associated with different shapes)
  - different mean fields (RPA-type methods fail for shape coexistence)
  - collectivity
  - configuration mixing (orthogonality, band mixing, . . .)
  - good quantum numbers (for selection rules of transitions).
- Is there an *effective field theory* of shape coexistence?

For recent work toward an effective field theory of collectively rotating and/or vibrating deformed nuclei see Papenbrock *et al*, NPA852 (2011) 36; Zhang *et al*, PRC87 (2013) 034323; Coello-Pérez *et al*,PRC92 (2015) 014323

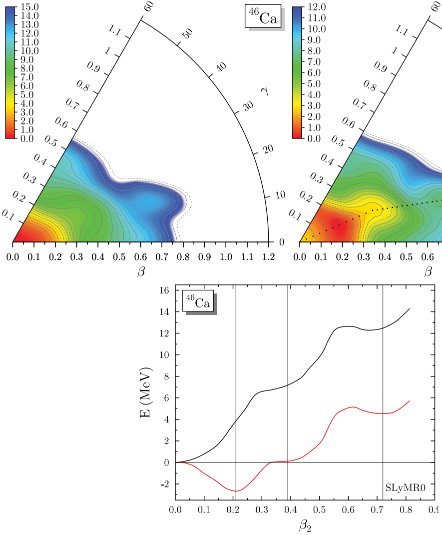
Shell-model interpretation of beyond-mean-field states and vice versa

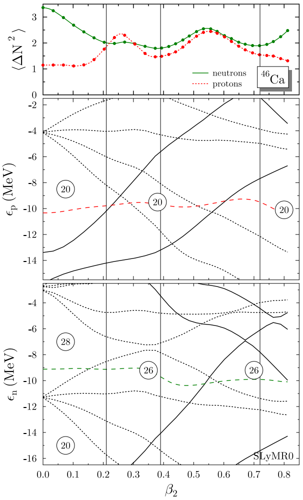




M. B., B. Bally, P.-H. Heenen, unpublished

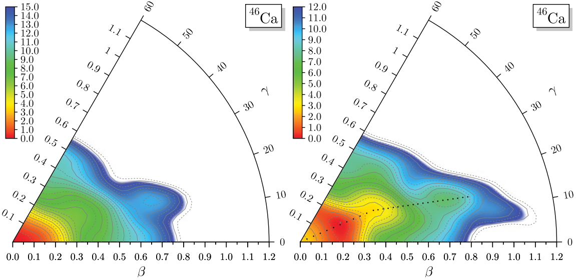
Shell-model interpretation of beyond-mean-field states and vice versa

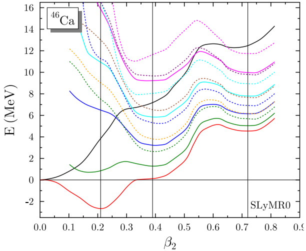


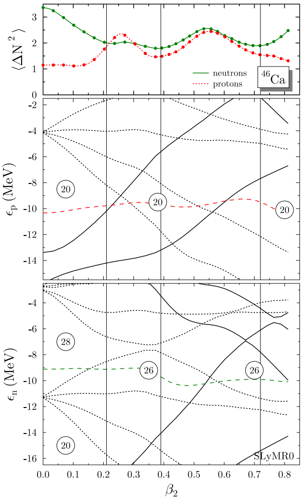


M. B., B. Bally, P.-H. Heenen, unpublished

Shell-model interpretation of beyond-mean-field states and vice versa



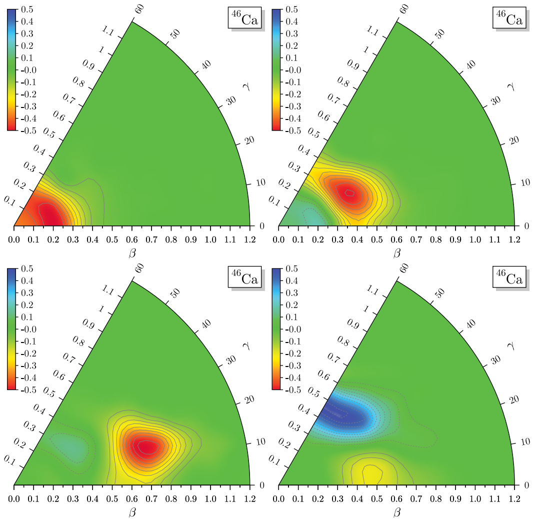


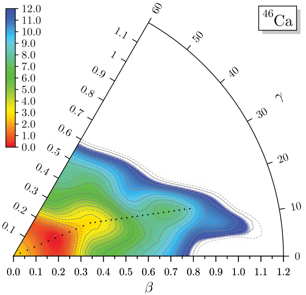


M. B., B. Bally, P.-H. Heenen, unpublished

Shell-model interpretation of beyond-mean-field states and vice versa

collective wave function of the four lowest 0^+ states

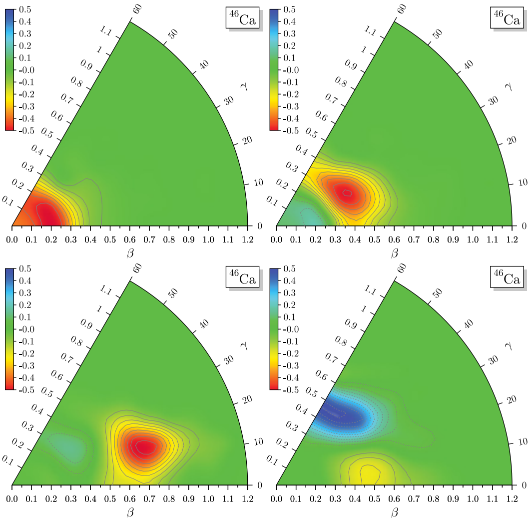


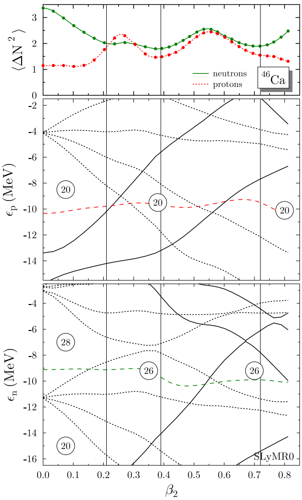


M. B., B. Bally, P.-H. Heenen, unpublished

Shell-model interpretation of beyond-mean-field states and vice versa

collective wave function of the four lowest 0^+ states



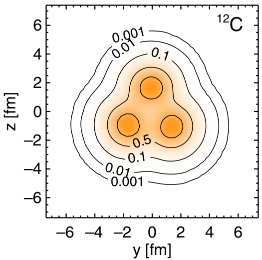


M. B., B. Bally, P.-H. Heenen, unpublished

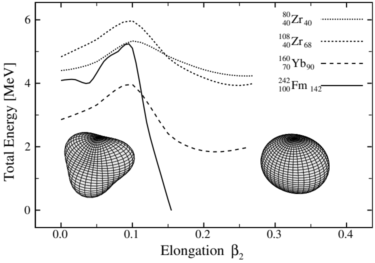
Exotic coexistences

- All examples shown so far concern the coexistence of shapes with different quadrupole moment.
- Are there coexistences driven by other shape degrees of freedom?
  - clustering.
  - octupole?
  - hexadecapole?
  - tetrahedral or octahedral shapes?
- Are they also driven by *n*p-*n*h excitations or something else?

Neff, EPJST156 (2008) 69

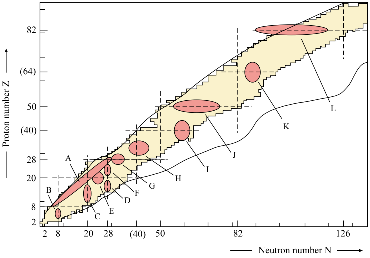


Dudek *et al*, PRL88 (2002) 252502



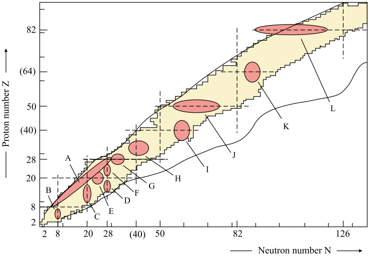
Coexistence in normal nuclei, exotic nuclei, and elsewhere

Heyde & Woods, RMP 83 (2011) 1467

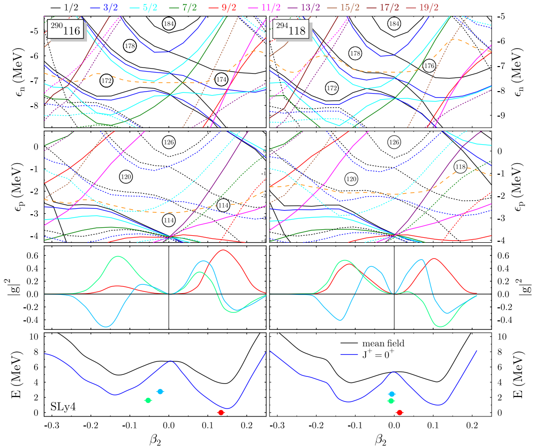


Coexistence in normal nuclei, exotic nuclei, and elsewhere

Heyde & Woods, RMP 83 (2011) 1467



Heenen, M. B., Bally & Ryssens, to be published



Summary

- Profiting from high-performance computing, over the last few years the range of applicability of the shell model and of beyond-mean-field methods has been enlarged such that both methods begin to cover the physics relevant for shape coexistence (intruder states, good quantum numbers, configuration mixing, . . .).
- Shape coexistence emerges in both methods in similar situations: np-nh excitations involving intruder states.
- In the context of the shell these states are usually interpreted "vertically" in terms of occupations of spherical shells ("islands of inversion").
- In the context of self-consistent mean-field models "and beyond" these states are usually interpreted "horizontally" in terms of gaps in the Nilsson diagram.

Summary

- Profiting from high-performance computing, over the last few years the range of applicability of the shell model and of beyond-mean-field methods has been enlarged such that both methods begin to cover the physics relevant for shape coexistence (intruder states, good quantum numbers, configuration mixing, ...).
- Shape coexistence emerges in both methods in similar situations: np-nh excitations involving intruder states.
- In the context of the shell these states are usually interpreted "vertically" in terms of occupations of spherical shells ("islands of inversion").
- In the context of self-consistent mean-field models "and beyond" these states are usually interpreted "horizontally" in terms of gaps in the Nilsson diagram.

The difference in interpretation appears to be more "cultural" than physical.

What is Shape Coexistence?

"Shape coexistence is a very peculiar nuclear phenomenon consisting in the presence in the same nuclei, at low excitation energy, and within a very narrow energy range, of two or more states (or bands of states) which: (a) have well defined and distinct properties, and, (b) which can be interpreted in terms of different intrinsic shapes."

A. Poves, foreword to the 2015 special issue of JPG on "Shape coexistence in nuclei"

- Shape coexistence is a generic feature of atomic nuclei that in one way or the other is exhibited by the majority of nuclei. It can come in many flavours:
  - coexisting structures in regions of transitional nuclei (evolution with shapes with filling of shells)
  - island(s) of inversion
  - rotational bands of "spherical nuclei" including doubly-magic ones (^{16}O, ^{40}Ca, ^{56}Ni, ...)
  - fission isomers / superdeformation / hyperdeformation
  - clustering
- Shape coexistence imprints its presence on (the systematics of) virtually all spectroscopic properties of nuclei at low excitation energy.