Brisure et restauration de symétries

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Symmetries of the nuclear Hamiltonian

- Rotational $\Rightarrow$ angular momentum
- Space inversion $\Rightarrow$ parity
- Global gauge space $\Rightarrow$ proton and neutron number
- Translational & Galilean invariance $\Rightarrow$ separation of center-of-mass and internal motion
- Time translation $\Rightarrow$ energy conservation
- Time reversal

Approximate symmetry of the nuclear Hamiltonian

- Rotation in isospin space $\Rightarrow$ isospin

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Approximate symmetry of the nuclear Hamiltonian

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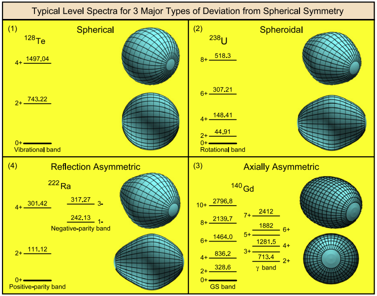
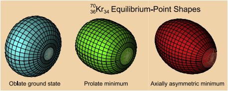
Consequences of symmetries

- Quantum numbers of states
- Selection rules for electromagnetic/weak/strong transitions between states
- Correlations (nucleons do not move independently)

But many nuclear phenomena are interpreted as if symmetries are broke



Möller, Sierk, Bengtsson, Sagawa, Ichikawa, ADNDT98 (2012) 149



- deformation (collective rotational bands!)
- shape coexistence

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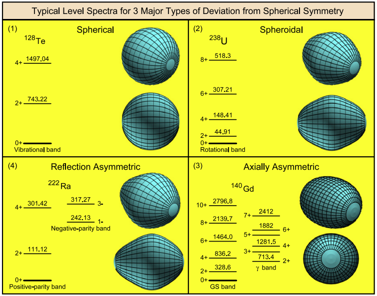

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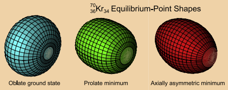
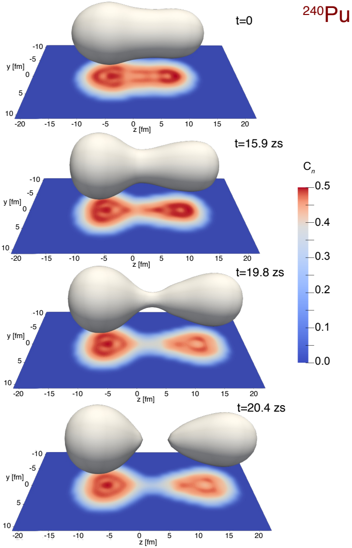


- deformation (collective rotational bands!)
- shape coexistence
- fission
- clusterisation
- pairing (nuclear superfluidity)



Scamps & Simenel, Nature 564 (2018) 382

Symmetry-conserving approaches

- conventional shell-model
- (most) conventional ab-initio approaches
- ...

Symmetry-breaking approaches

- Self-consistent mean-field models (either EDF-based or valence space with schematic interactions)
- Cluster models
- ...

Symmetry-breaking & restoration

- Projected symmetry-breaking states
- Monte-Carlo shell model
- ...

Technically, "projection" means inserting a numerical discretization of an operator that extracts the targeted components when calculating matrix elements.

"Special case" of a Generator Coordinate Method (non-orthogonal CI)

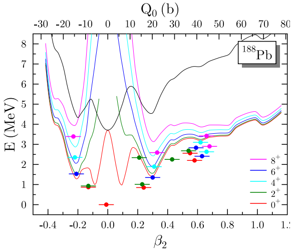
Typical situations:

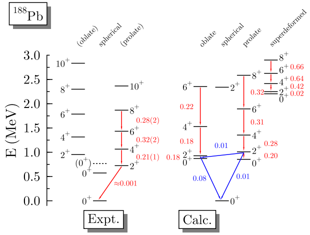
- localised finite system (broken translational symmetry)
- axial deformation (partially broken rotational symmetry)
- non-axial deformation (broken rotational symmetry)
- states with finite angular momentum (broken time-reversal)
- octupole deformation (broken parity + broken rotational symmetry)
- HFB-type pairing (broken global gauge symmetry)

Some rarely addressed situations

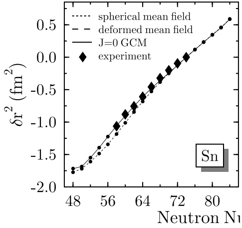
- absence of more than one plane symmetry
- broken signature (angular momentum not in the direction of a major axis)
- proton-neutron mixing (broken "axiality" in isospin)

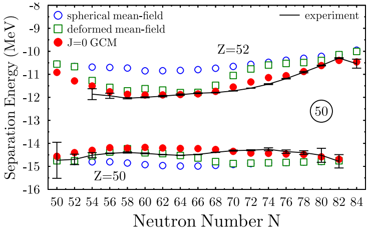
- lowest projected state usually has more broken symmetries than mean-field minimum
- additional correlation energy varies quickly for transitional nuclei





Bender, Bonche, Duguet, Heenen, PRC 69 (2004) 064303

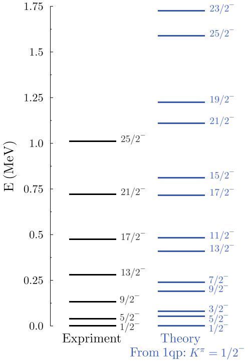




Bender, Bertsch, Heenen, PRCC 73 (2006) 034322; PRC 78 (2008) 054312

Coupling of collective and single-particle degrees of freedom

^{251}Md



J	rrmsp (fm)	rrmsn (fm)	mu (mu_N)	Q_s e fm^2
7/2	5.8769	6.0193	1.4540	596.84
9/2	5.8769	6.0194	1.8407	232.67
11/2	5.8769	6.0194	2.2308	14.27
13/2	5.8769	6.0194	2.6230	-127.63
15/2	5.8770	6.0194	3.0164	-225.40
17/2	5.8770	6.0195	3.4108	-295.86
19/2	5.8771	6.0195	3.8057	-348.48
21/2	5.8771	6.0196	4.2011	-388.91
23/2	5.8772	6.0196	4.5968	-420.74
25/2	5.8773	6.0197	4.9928	-446.29

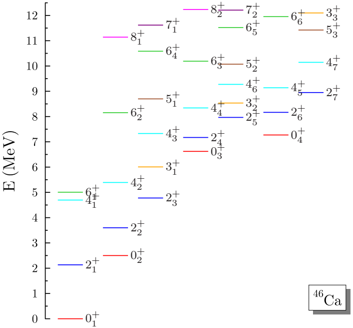
transition	B(E2) (e^2 fm^4)	M(M1) (mu_N^2)
9/2 -> 7/2	55214	2.6167 E-04
11/2 -> 7/2	11834	---
11/2 -> 9/2	55760	3.9979 E-04
13/2 -> 9/2	21953	---
13/2 -> 11/2	47809	4.8087 E-04

- In odd-*A* nuclei, bands get easily mixed.

Heenen, Bally, Bender, Ryssens, EPJ Web of Conf 131 (2016) 02001;

Bally, Bender, Heenen, to be published

seniority-2 states in ^{46}Ca

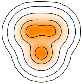


- Characteristic pattern emerges when 2qp states are mixed in
- Mixed with collective bands.

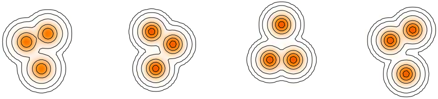
Bender, Bally, Heenen, to be published

Clustering

Dominant configuration in the ground-state of ^{12}C

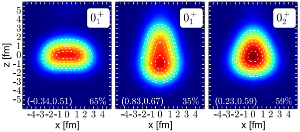


Dominant configurations in the Hoyle state



Parity, angular-momentum & center-of-mass-projected Fermionic Molecular Dynamics

Chernykh et al, PRL98 (2007) 032501; Neff, JPhys Conf Ser 403 (2012) 012028



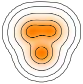
Parity & angular-momentum projected axial relativistic mean field

Marevic, Ebran, E. Khan, T. Niksic, Vretenar, PRC 99, 034317 (2019)

Non-standard deformation modes might only show up when breaking & restoring symmetries

Clustering

Dominant configuration in the ground-state of ^{12}C



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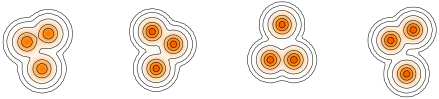

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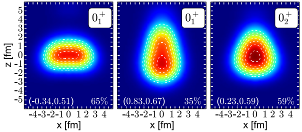

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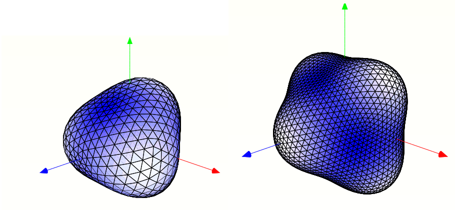
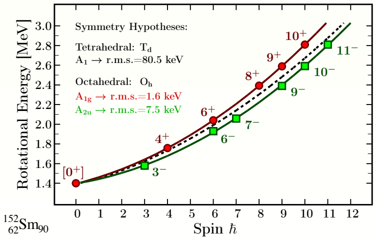
Marevic, Ebran, E. Khan, T. Niksic, Vretenar, PRC 99, 034317 (2019)

Exotic deformations

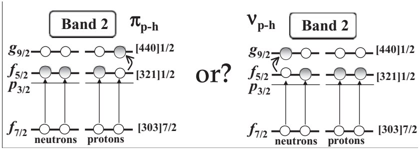




borrowed from a talk by J. Dudek @ IPNL (2017)

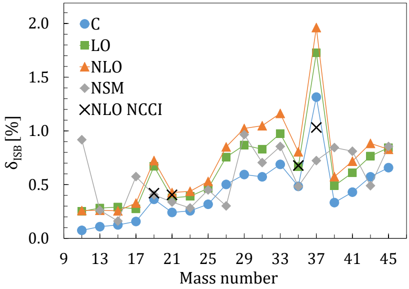
- physically broken by the Coulomb interaction, the difference of proton and neutron masses, and small contributions of the strong interaction
- spuriously broken by mean-field methods, with some severe consequences for calculated properties of nuclei close to the $N = Z$ line.
- spurious breaking can be removed by diagonalizing the symmetry-breaking Hamiltonian in a basis of isospin-projected mean-field states.
- isospin projection mixes proton and neutron single-particle states.
- controlling the physical isospin breaking has relevance for tests of the standard model through the analysis of superallowed $0^+ \to 0^+$ Fermi β decay

Example: rotational bands of ^{56}Ni



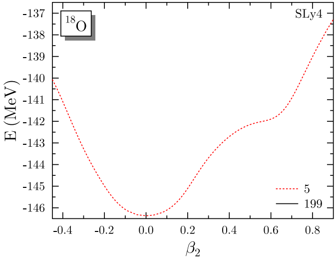
Satuła, Dobaczewski, Nazarewicz, Rafalski, PRC 81 (2010) 054310

Example: Isospin correction to Fermi decays



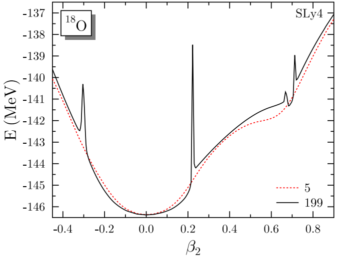
Konieczka, P. Baczyk, Satuła, arXiv:1909.09350

N & Z projecction of an HFB state of ^{18}O

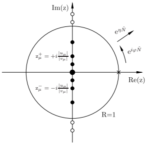


Need for specific functionals

N & Z projecction of an HFB state of ^{18}O



- energy as a function of deformation
- general EDF



Lacroix, Duguet, Bender, PRC 79 (2009) 044318

Bender, Duguet, Lacroix, PRC 79 (2009) 044319

Duguet, Bender, Bennaceur, Lacroix, Lesinski, PRC 79 (2009) 044320

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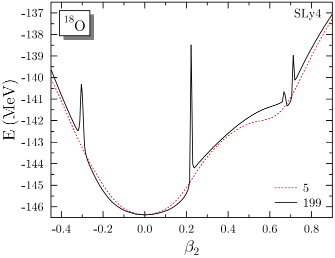

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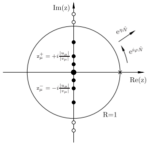
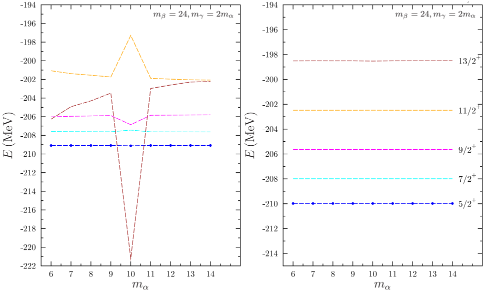


Lacroix, Duguet, Bender, PRC 79 (2009) 044318

Bender, Duguet, Lacroix, PRC 79 (2009) 044319

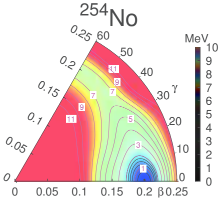
Duguet, Bender, Bennaceur, Lacroix, Lesinski, PRC 79 (2009) 044320

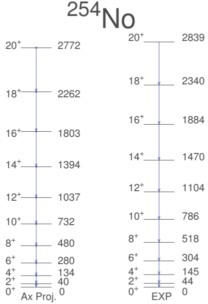
J-projetion of a HF state of ^{25}Mg



- energy decomposition of one pathological state as a function of discretisation of the projector
- Left: density-dependent EDF
- right: non-density-dependent EDF from generating operator
- predictive well-defined EDFs turn out to be difficult to construct; necessary operator structure has not yet been identified.

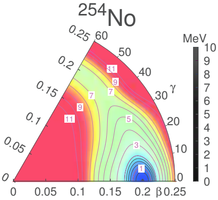
Bender, Heenen, unpublished

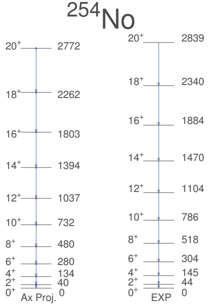




triaxial HF, axial J projection

Bounseng Bounthong, thèse, Strasbourg, 2016





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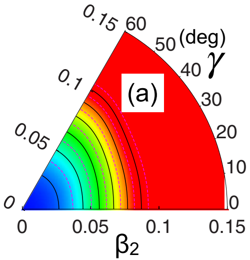
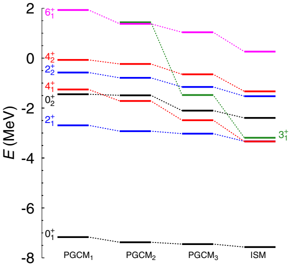
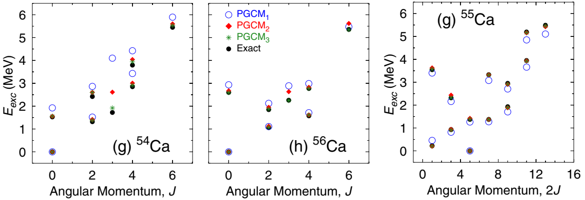


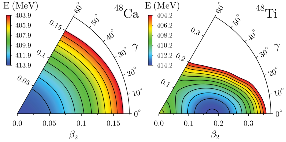


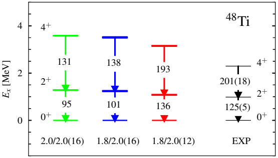


fully symmetry-breaking HFB, N+Z+J+parity projection+GCM

Bally, Sánchez-Fernández, Rodríguez, PRC 100 (2019) 044308

Multi-Reference In-Medium Similarity Renormalization Group

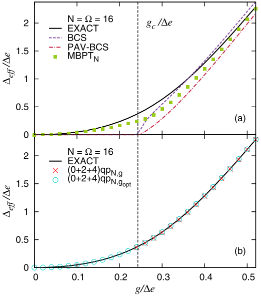




Access to $0\nu\beta\beta$ matrix element.

Yao, Engel, Wang, Jiao, Hergert, PRCC 98, 054311 (2018); Yao, Bally, Engel, Wirth, Rodríguez, Hergert, arXiv:1908.05424

Many-body perturbation theory combined with symmetry-breaking+restoration



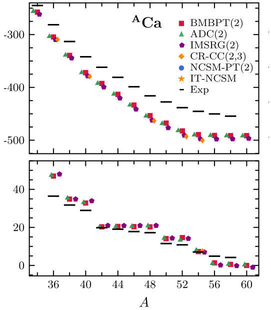
Schematic pairing Hamiltonian

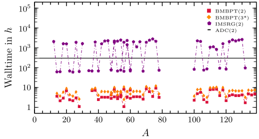
Ripoche, Lacroix, Gambacurta, Ebran, Duguet, PRC95, 014326 (2017)

Also particle-number restored Bogoliubov Coupled-Cluster,

Qiu, Henderson, Duguet, Scuseri, PRC 99 (2019) 044301

Bogoliubov MBPT





Huge reduction of CPU time!

Tichai, Arthuis .Duguet, Hergert, . Somà, Roth, PLB 786 (2018) 195

Outlook

Why breaking & restoring symmetries?

- Symmetry breaking configurations simplify the interpretation of numerous nuclear phenomena
- Breaking & restoring symmetries instead of using symmetry-conserving schemes can enormously reduce numerical cost because of much quicker convergence with the number of (much richer) configurations to be considered.

Necessary developments concerning EDF methods

- breaking additional symmetries to describe exotic shapes and/or exotic rotational phenomena
- combined restoration of many broken symmetries
- Construct EDF that is well-defined for symmetry restoration

Transfer of "breaking & restoring symmetries" to other frameworks

- valence-space symmetry-restored GCM with shell-model Hamiltonians.
- ab-initio calculations of singly- doubly-open shell nuclei (Green's functions, Coupled-Cluster, Many-Body Perturbation Theory, Multi-Reference In-Medium-Similarity- Renormalization Group, No-core shell model, . . .)
- Time-dependent approaches (EDF-based and others)

Advancing all areas will require reinforcement with young motivated scientists.