On-going theoretical developments for mid- and heavy-mass nuclei

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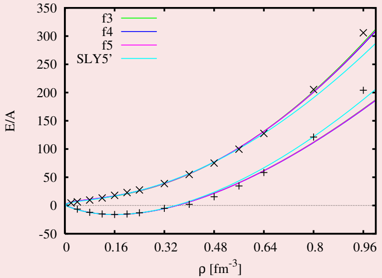
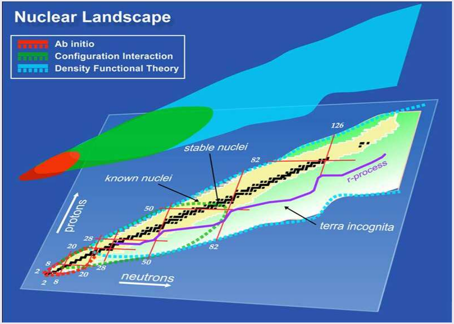
Towards a unified description of nucleonic matter

Extended matter $\rho \in [0, \text{few}\,\rho_{\text{sat}}]$



[T. Lesinski *et al.*, PRC74 (2006) 044315]

Finite nuclei $Z \in [0, 118+]$



Goals of low-energy nuclear theory

1. QCD-rooted model of interactions between 2, 3... nucleons (baryons)
2. Properties of nuclei and their limits of existence
3. States of baryonic matter in astrophysical environments

State-of-the art theoretical many-body methods

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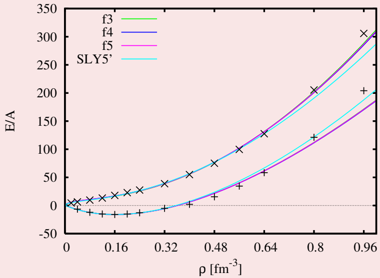

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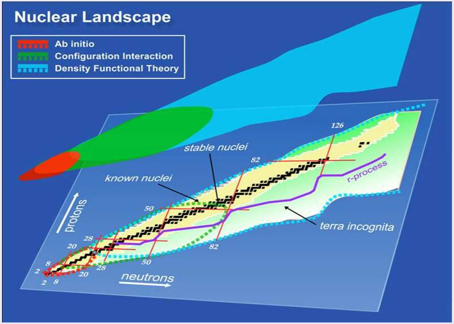


Theoretical methods

1. "Exact" (VMC, . . .)
2. Ab-initio (SCGF, BHF, . . .)
3. Effective (EDF)

Theoretical methods

1. "Exact" (GFMC, NCSM, LEFT, . . .)
2. Ab-initio (CC, SCGF, IMSRG)
3. Effective (SM, EDF)

Selection of recent theoretical achievements

Elementary AN interactions

- Link to QCD via χ-EFT
- 3N at N^{3}LO and N^{4}LO
- RG-evolved 2N and 3N forces

Collective spectroscopy

- MR-EDF for even nuclei
- Deformed QRPA
- MR-EDF for odd nuclei

Limits of existence

- Microscopic SM with 3NF
- SM/CC with continuum coupl.

Fission

- Static paths with SR-EDF
- Fragm. prop. with TD MR-EDF

Ab-initio A-body methods

- LEFT (e.g. Hoyle state in ^{12}C)
- CC/SCGF in CS±1 with $A \lesssim 50$
- Breakthrough into mid-mass open-shell

Reaction theory

- Near-barrier fusion with TD SR-EDF
- Ab-initio rad. capt./scatt./fus. ($A \lesssim 8$)
- OP from SCGF for n/p-CS ($A \lesssim 50$)

Astrophysics

- Improved ab-initio EOS (finite T, 3NF, $\Lambda, \Sigma \ldots$)
- r-process abundances vs correlations, fission...
- Quantal calculations of neutron-star crust

Outline

1. Ab-initio approaches to mid-mass nuclei
2. Spectroscopy of complex (odd) nuclei
3. Non-observability of the shell structure

Outline

Ab-initio approach to closed-shell mid-mass nuclei

Ab-initio calculations

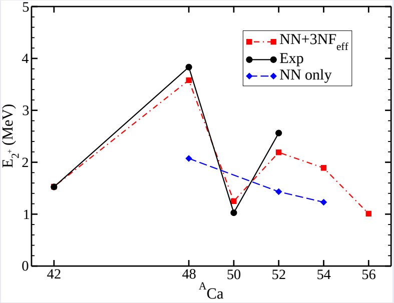
1. Many-body solved from vacuum ANF
2. Based on a controlled expansion
3. CC, Dyson-SCGF, IMSRG

Some recent accomplishments

1. Closed-shell ± 1 nuclei up to ^{56}Ni
2. CC in closed-shell ± 2 nuclei in ^{A}O
3. Effective 3NF in CC up to ^{A}Ca
4. CC with continuum basis

Ab-initio approach to closed-shell mid-mass nuclei

$E_{\mathrm{exc}}(^{A}\mathrm{Ca})$ from CC and 3NF



	^{48}Ca	^{52}Ca	^{54}Ca
E_{2^+} (CC)	3.58	2.19	1.89
E_{2^+} (Exp)	3.83	2.56	n.a.
E_{4^+}/E_{2^+} (CC)	1.17	1.80	2.36
E_{4^+}/E_{2^+} (Exp)	1.17	n.a.	n.a.
S_n (CC)	9.45	6.59	4.59
S_n (Exp)	9.95	6.0*	4.0†

[G. Hagen *et al.*, PRL 109 (2012) 032502]

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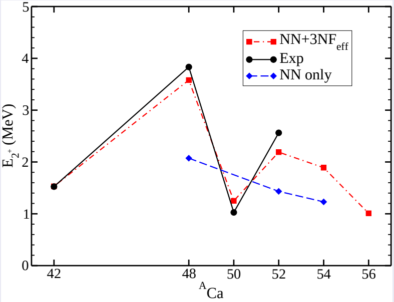

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Some upcoming challenges

1. Implement (averaged) 3NF in all available methods
2. Investigate nuclear structure of, e.g., ^{78}Ni (±1 nucleons)
3. Extend the reach to higher A up to, e.g., ^{132}Sn (±1 nucleons)
4. Implement ab-initio methods for truly open-shell mid-mass nuclei

Ab-initio approach to open-shell mid-mass nuclei

Gorkov self-consistent Green's function method

1. Extends Dyson SCGF to open-shell nuclei
2. Extends reach from $\sim 10^1$ to $\sim 10^2$ nuclei
3. Treatment of superfluidity built in

[V. Somà, T. Duguet, C. Barbieri, PRC 84 (2011) 064317]

Some specific objectives

1. Ab-initio understanding of pairing
2. Nuclear structure evolution
3. Collectivity in superfluid nuclei

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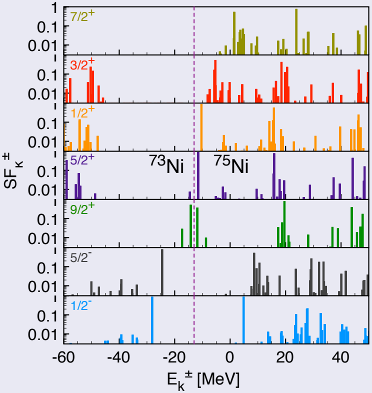
Neutron SSD in ^{74}Ni (2NF only!)



E_0 (MeV)	$\Delta_n^{(3)}$ (MeV)	$R_{\rm rms}$ (fm)
−1269.7(2)	1.17(1)	2.75

[V. Somà *et al.*, tomorrow on arXiv...]

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Upcoming challenges

1. Include (averaged) 3NF
2. Extend scheme to Faddeev-QRPA level
3. Optical potential for open-shell nuclei

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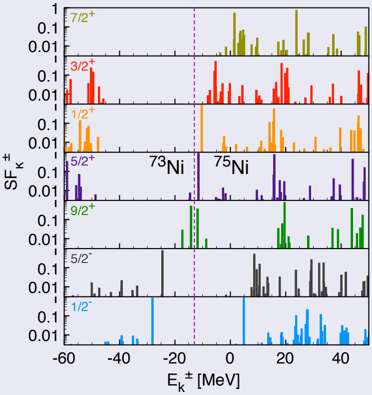

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Outline

Spectroscopy from Multi-Reference EDF method

GS rotational band in ^{49}Cr

[B. Bally *et al.*, (2012) unpublished]

Based on effective kernel $\mathcal{E}[\rho, \kappa, \kappa^*]$

1. Single-reference implementation
   - Broken symmetries (N, Z, J^2)
2. Multi-reference implementation
   - Symmetry restorations (Proj.)
   - Collective fluctuations (GCM)
   - G.S. correlations + spectro.

Some recent accomplishments

1. Fission dynamics (TKE and mass)
2. Extension to triaxial SR states
3. Impact on r-process $A \approx 195$ abund.
4. Extension to odd nuclei

Some upcoming challenges

1. Mix 0 and 2 qp configurations for 2_1^+ in semi-magic nuclei and K isomers
2. Kernel with improved analytical form, fitting protocol and microscopic basis

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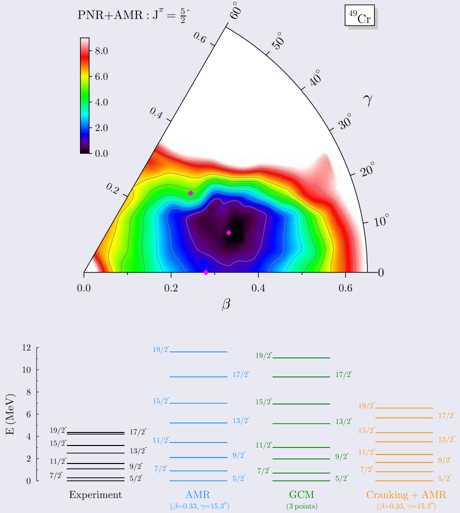

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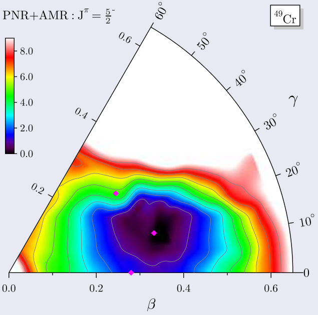

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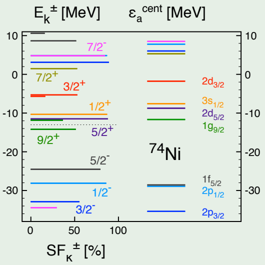
Non-observability of single-nucleon shell structure

Effective single-particle energies (ESPEs) [Baranger (1970)]

$$\varepsilon_p^{\text{cent}} \equiv \sum_{\mu \in \mathcal{H}_{A+1}} |\langle \Psi_\mu^{\text{A+1}} | a_p^\dagger | \Psi_0^{\text{A}} \rangle|^2 \, E_\mu^+ + \sum_{\nu \in \mathcal{H}_{A-1}} |\langle \Psi_\nu^{\text{A-1}} | a_p | \Psi_0^{\text{A}} \rangle|^2 \, E_\nu^-$$

ESPEs in ^{74}Ni



[V. Somà *et al.*, arXiv:]

Unitary transformation $H(2) = U^\dagger H(1) U$

Observable

- $E_k^\pm(1) = E_k^\pm(2)$
- $\sigma_k^\pm(1) = \sigma_k^\pm(2)$

Not observable

- $\varepsilon_p^{\text{cent}}(1) \neq \varepsilon_p^{\text{cent}}(2)$
- $SF_k^\pm(1) \neq SF_k^\pm(2)$

ESPEs (as SFs) are changed under U

[T. Duguet and G. Hagen, PRC 85 (2012) 034330]

Extracting *the* shell structure from $\{E_k^\pm, \sigma_k^\pm\}$ is an illusory objective

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- Requires however a *consistent* reconstruction

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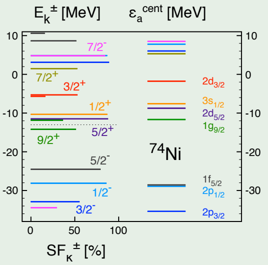

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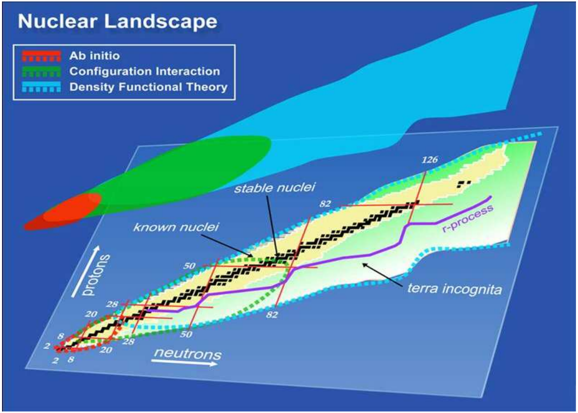
- Shell structure useful to give *one* interpretation of reality per H
- Requires however a *consistent* reconstruction
  1. Reaction and structure theories based on consistent approximations
  2. *Same* H used throughout

Looking into the future



Attacking the nuclear many-body problem in the next ten years

1. Coming RIB facilities = era of unstable neutron-rich medium-mass nuclei
2. Ab-initio and more effective methods are meant to overlap strongly
3. Structure theories are meant to be extended as reliable reaction theories

Thank you !