Evolution of the nuclear structure of neutron rich calcium isotopes with microscopic two- and three-body forces

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Outline

1. Introduction
2. 3N forces in neutron rich Ca isotopes
    - Separation energies and Pairing gaps
    - 2_1^+ energies and Spectra
3. Summary and Outlook

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Medium-mass nuclei: standard approach

Standard studies of medium-mass nuclei ($A \sim 20 - 80$) are performed with theoretical approaches based on phenomenology:

- Shell Model calculations
  use fitted interactions or modified G-matrices
- Energy Density Functional interactions
  use Skyrme, Gogny or Relativistic fitted interactions

Interactions are made to reproduce experiment for stable nuclei

- When extrapolated to exotic (neutron rich) regions results differ
  $\Rightarrow$ Need to guide (ideally avoid) fits!
- Why microscopic NN interactions have to be modified?
  $\Rightarrow$ Need to include 3N forces explicitly!

Microscopic calculation of medium-mass nuclei

Microscopic calculation of medium-mass nuclei including 3N forces

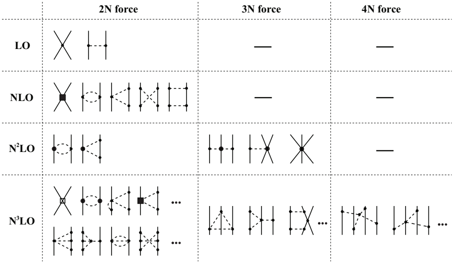
- Use Chiral Effective Field Theory (chiral EFT) interactions, includes naturally NN and 3N forces.
- Perform a renormalization group evolution to V_{lowk} interaction to enhance convergence of the MBPT calculation
- Apply Many-Body Perturbation Theory (MBPT) to 3rd order to obtain interactions to be used in Shell Model (SM) calculations

⇒ 3N forces are naturally included
Shown necessary to reproduce light nuclei spectra

⇒ All the parameters that appear in the SM hamiltonian calculated from the input of the microscopic interaction (no fits!)
Test nuclear forces for stable and exotic nuclei

NN+3N Forces in Chiral EFT

Systematic expansion: nuclear forces



NN force couplings fitted to NN data

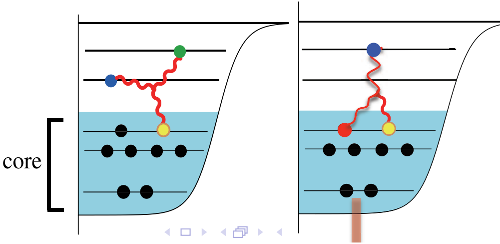
3N force couplings fitted to few body data

Chiral EFT potentials: NN at N^{3}LO
3N at N^{2}LO

normal-ordered 2B: 2 valence, 1 core particle
⇒ (effective) Two-body Matrix Elements (TBME)

normal-ordered 1B: 1 valence, 2 core particles
⇒ (effective) Single particle energies (SPE)

residual 3B:
⇒ Estimated to be suppressed by
$N_{valence}/N_{core}$



Shell Model calculations and Recent applications

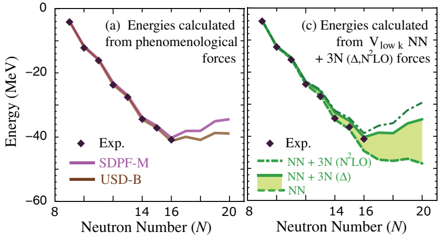
Shell Model interactions
Ca isotopes: *pf* shell and $pfg_{9/2}$ valence space
Full diagonalizations using code ANTOINE Caurier et al. RMP77 427(2005)

Recent applications within this framework, using chiral NN+3N forces:

O dripline at ^{24}O
Otsuka et al. PRL105 032501 (2010) ⇒

$N = 28$ closed shell at ^{48}Ca
Holt et al. arXiv:1009.5984v2

O spectra
Holt, JM, Schwenk arXiv:1108.2680v2



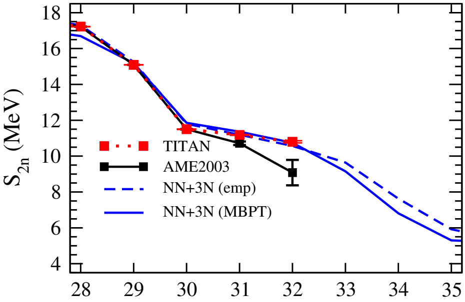
Outline

Ca isotopes: Two-neutron separation energies

Ca isotopes: $N = 20, 28, 32, 34?$ closed shells: extremely interesting

Compare S_{2n} theoretical calculations with experimental results

$$S_{2n} = -[B(N, Z) - B(N-2, Z)]$$



A. T. Gallant et al. arXiv 1204.1987

New precision measurements change previous slope from AME 2003
$\sim$ 2 MeV change in ^{52}Ca!

Very good agreement between calculation and experimental trend (Similar level as phenomenological interactions)

Two sets of spe's, empirical and calculated, in $pfg_{9/2}$ valence space

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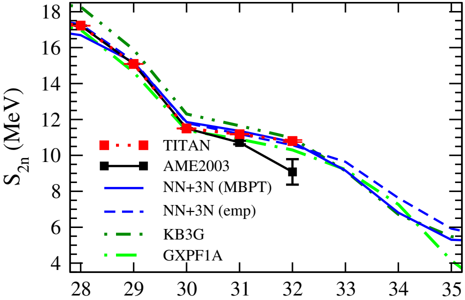

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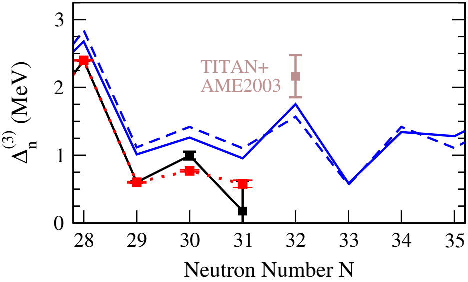
Nuclear Pairing Gaps

Compare also to experimental three-point mass differences:

$$\Delta_n^{(3)} = \frac{(-1)^N}{2}[B(N+1,Z) + B(N-1,Z) - 2B(N,Z)]$$



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The experimental trend is very well reproduced by theory

Theoretical results systematically 0.5 MeV higher than experiment

Prediction of sub-shell closure candidates $N = 32$ (moderate closure) and $N = 34$ (no apparent closure)

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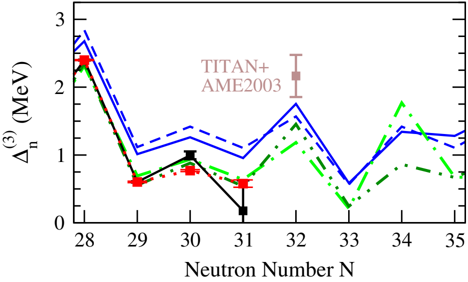

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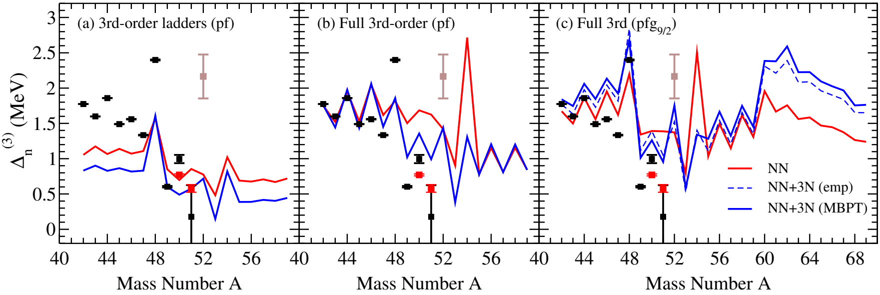
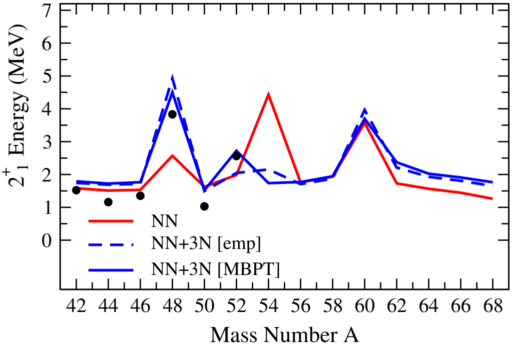
Nuclear Pairing Gaps: NN vs NN+3N



- At *pp-hh* diagram level, 3N forces reduce the pairing gaps as observed in EDF: Lesinski et al. JPhysG39 015108 (2012)
- Full third order MBPT improves agreement with experiment
  Core-polarization effects significantly enhance pairing gaps
- Very good agreement with experimental trends

Shell closures in calcium isotopes

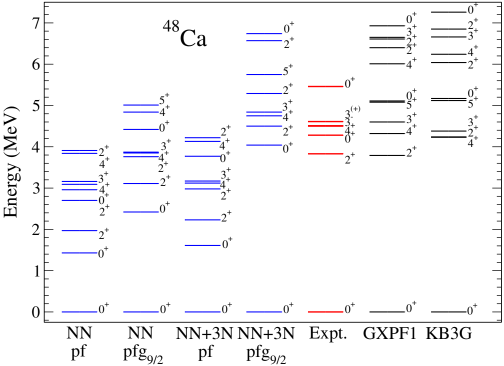
2_1^+ energies characterise shell closures of the neutron rich calcium isotopes



- Correct closure at $N = 28$ when 3N forces are included ($pfg_{9/2}$)
- 3N forces enhance closure at $N = 32$
- 3N forces reduce strong closure at $N = 34$
- Predicted shell closure at $N = 60$, unaffected by 3N forces

^{48}Ca spectra

Results in *pf*–*pfg*$_{9/2}$ spaces and based on NN–NN+3N interactions compared to standard phenomenological interactions



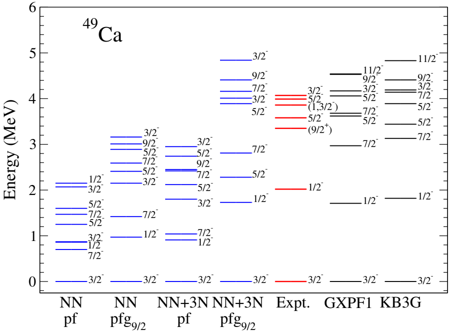
Spectra too compressed

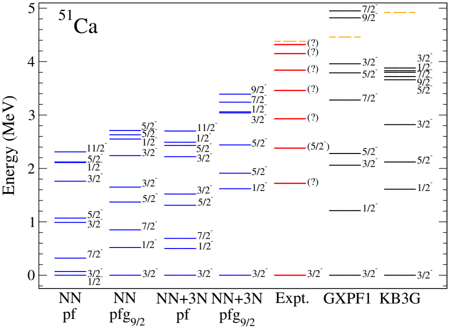
2_1^+ state only ∼appropriate energy in *pfg*$_{9/2}$ NN+3N calculation

Importance of 3N forces

Importance of including $g_{9/2}$ orbit

^{49}Ca, ^{51}Ca neutron rich spectra



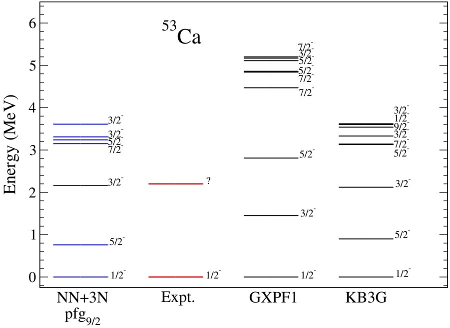


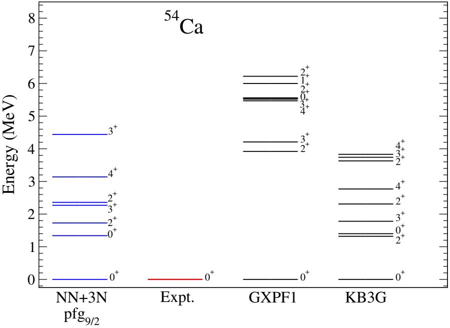
Spectrum compressed unless $pfg_{9/2}$ NN+3N

Correct $(1/2)^-$ energy, (but too low $(5/2)^-$), possibility to assign experimental spins

Similar quality comparable to phenomenological interactions

^{53}Ca, ^{54}Ca neutron rich spectra





Phenomenological interactions different results in neutron rich nuclei

MBPT: prediction

Explore sensitivity to theoretical uncertainties

More experimental information greatly appreciated!

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Summary and Outlook

Microscopic calculation based on chiral EFT (NN+3N forces) and MBPT gives good agreement with experimental two-neutron separation energies, pairing gaps and excitation spectra for calcium isotopes:

- Experimental trends in S_{2n}'s and $\Delta_n^{(3)}$'s nicely reproduced
- 2_1^+ energies and pairing gaps stablish shell closures
  $N = 28$ appears, $N = 32/34$ enhanced/reduced by 3N forces
- Predicted spectra for Ca neutron rich isotopes

Outlook:

Explore heavier isotope and isotone chains: include T=0 TBME

Explore uncertainties in the theoretical calculation

Improve MBPT: In-medium Similarity RG