Three-nucleon forces at neutron-rich extremes

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Shell Model as a Unified View of Nuclear Structure

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Motivation

Why perform calculation of medium-mass nuclei with nuclear forces from Chiral Effective Field Theory?

- No phenomenological fits
- Understand phenomenological adjustments necessary for realistic interactions, e.g. G-matrix
- Hope for more controlled extrapolations for neutron-rich extremes

Microscopic calculation of medium-mass nuclei

Microscopic calculation of medium-mass nuclei including 3N forces

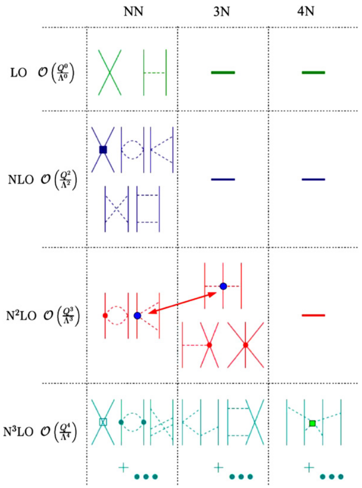
- Use Chiral Effective Field Theory (chiral EFT) interactions, includes naturally NN and 3N forces
- Perform a renormalization group evolution to $V_{low\ k}$ interaction to enhance convergence of the MBPT calculation
- Apply Many-Body Perturbation Theory (MBPT) to obtain interactions to be used in Shell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

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

⇒ 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 for nuclear forces



- NN force couplings fitted to NN, πN data
- 3N force couplings: c_i's consistent with NN; c_D,c_E fitted to few-body data: ^{3}H binding energy, ^{4}He charge radius
- Chiral EFT potentials for NN at N^{3}LO and 3N at N^{2}LO
- But: N^{3}LO 3N $\sim 1/3$ of N^{2}LO 3N

Tews et al., arXiv:1206.0025.

Shell Model interactions

- Results with NN+3N forces included to 3rd order in MBPT
- In addition to standard sd and pf shell
  - O isotopes: $sdf_{7/2}p_{3/2}$ valence space
  - Ca isotopes: $pfg_{9/2}$ valence space
- Full diagonalizations using ANTOINE

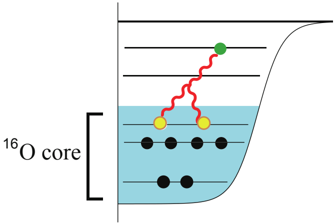
  Caurier et al., *RMP* **77** 427 (2005).

- MBPT with enlarged valence space to include as many non-perturbative orbits as possible
- Valence space beyond one major shell: center-of-mass contamination?
  - Singular value decomposition Hagen et al., *PRC* **82** 034330 (2010).,
  - Lee-Suzuki trafo to major shell,
  - In-medium SRG Tsukiyama et al., *PRC* **85** 061304 (2012).

3N forces for valence-shell theories

- Contribution to valence neutron interactions

Effective one body



$$\langle a|V_{3N,eff}|a'\rangle = \frac{1}{2}\sum_{\alpha,\beta\in core}\langle\alpha\beta a|V_{3N}|\alpha\beta a'\rangle$$

$\Rightarrow$ (Effective) single-particle energies (SPE)

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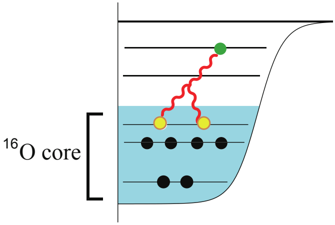

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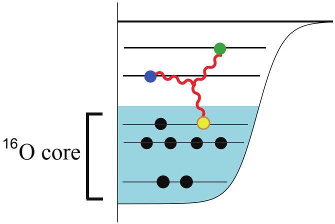
Effective two body

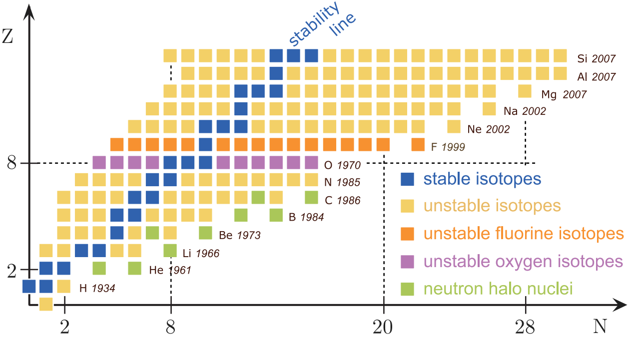


$$\langle ab|V_{3N,eff}|a'b'\rangle = \sum_{\alpha\in core}\langle\alpha ab|V_{3N}|\alpha a'b'\rangle$$

$\Rightarrow$ (Effective) two-body matrix elements (TBME)

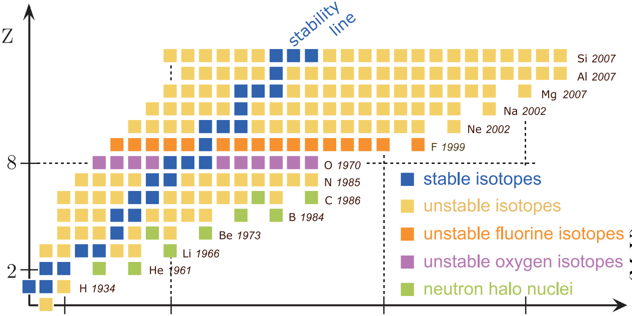
The oxygen anomaly

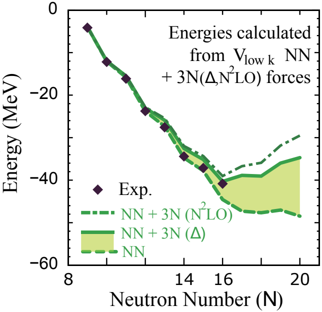
Where is the neutron dripline?



The oxygen anomaly

Where is the neutron dripline?





- NN forces too attractive
- Inclusion of 3N force leads to repulsion
  ⇒Correct prediction of dripline

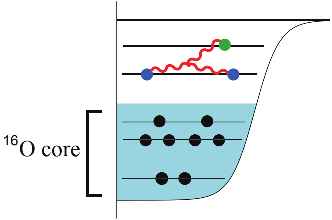
Otsuka et al., *PRL* **105** 032501 (2010).

3N forces for valence-shell theories

When going to neutron-rich extremes must include

- Residual three body — Friman, Schwenk, arXiv:1101.4858.
  - Estimated to be suppressed N_v/N_c

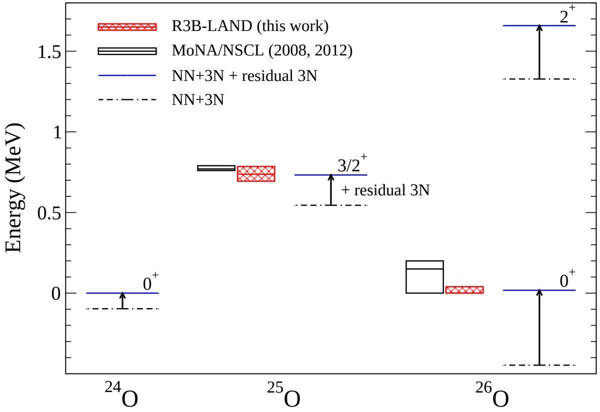
$$\Delta E \sim \frac{N_v}{N_c} E_{2-body}^{normal-ordered}$$



  - Becomes important for most neutron-rich isotopes
  - Included perturbatively using wave function from ANTOINE

$$\Delta E = \langle \Psi | V_{3N} | \Psi \rangle$$

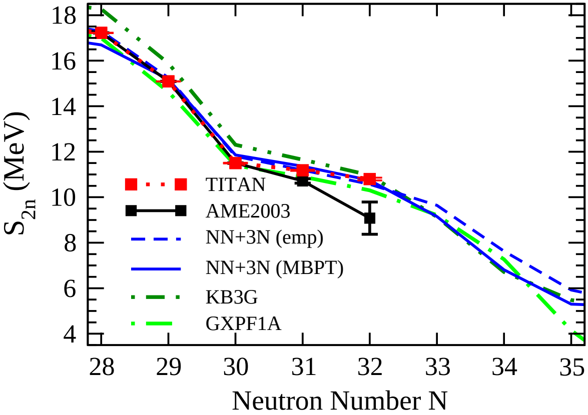
Theory vs. experiment - arXiv:1209.0156.



- Residual three-body contribution is repulsive, small compared to normal-ordered 3N
- Increases with neutron number as expected
- Very good agreement with resonances in $^{25,26}O$

Hoffman et al., *PRL* **100** 152502 (2008).; Lunderberg et al., *PRL* **108** 142503 (2012).

Two-neutron separation energies of Ca isotopes



- New mass measurement at TITAN for ^{51,52}Ca
- 1.74 MeV deviation for ^{52}Ca from AME2003
- KB3G/GXPF1A in good agreement
- Effect of residual three body? smaller than in O as expected from N_v/N_c

Gallant et al., *PRL* **109** 032506 (2012).

Summary and Outlook

Microscopic calculation based on chiral EFT (NN+3N forces) with inclusion of residual three-body contribution for the first time

Contribution of residual three body small, but increases with neutron number in the shell model up to 0.4 MeV in ^{26}O

Very good agreement with experiment for neutron-rich oxygen isotopes

Outlook:

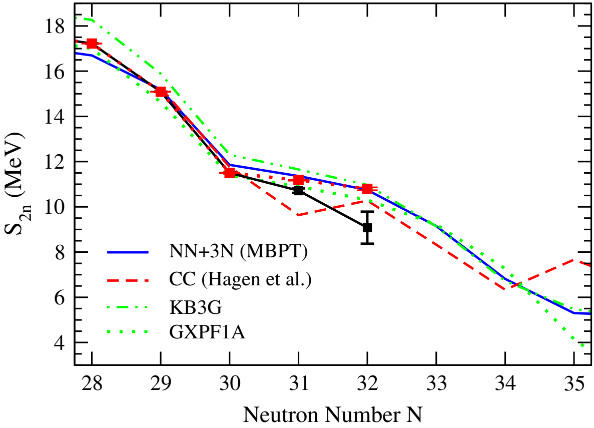
Explore effect of residual three body in Ca and other chains

Error estimate by cutoff- and c_i-variation

Inclusion of N^3LO 3N forces

Thank you for your attention!

Two-neutron separation energies of Ca isotopes



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