Shell evolution, spectroscopy, theoretical uncertainties in neutron-rich calcium isotopes studied with chiral three-body forces

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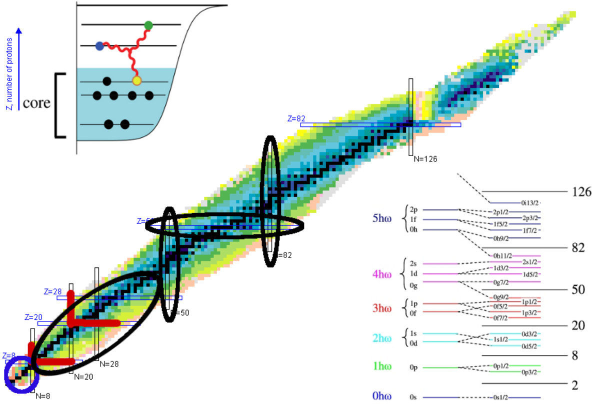
Nuclear landscape



Big variety of nuclei in the nuclear chart, $A \sim 2...300$

Systematic *ab initio* calculations only possible in the lightest nuclei

Hard many-body problem: approximate methods suited for different regions

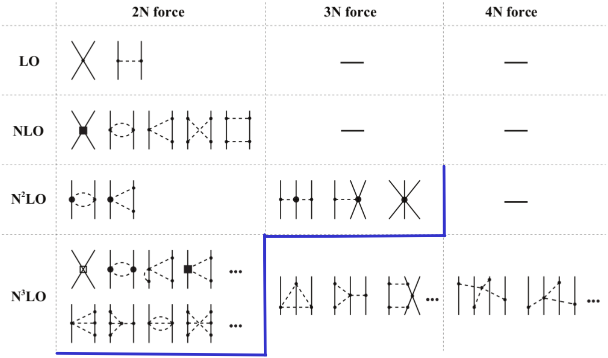
Shell Model:
Solve the problem choosing the relevant degrees of freedom
Use realistic nucleon-nucleon (NN) and three-nucleon (3N) interactions

Nuclear forces in chiral EFT

Chiral EFT: low energy approach to QCD for nuclear structure energies

Short-range couplings are fitted to experiment once

Systematic expansion of nuclear forces



Weinberg, van Kolck, Kaplan, Savage, Weise, Meißner, Epelbaum...

pion exchanges

contact terms

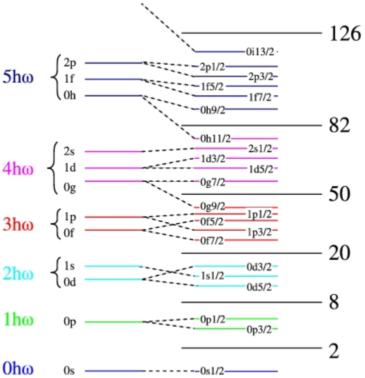
NN fitted to:

- NN scattering
- π-N scattering

3N fitted to:

- ^{3}H Binding Energy
- ^{4}He radius

Medium-mass nuclei: shell model



To keep the problem feasible, the configuration space is separated into

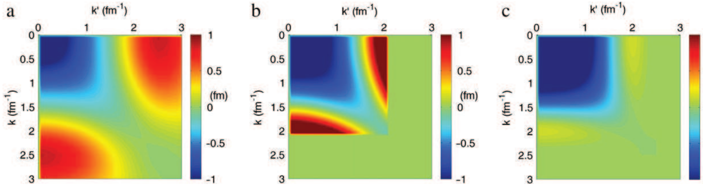
- Outer orbits:
  orbits that are always empty
- Valence space: the space in which we explicitly solve the problem
- Inner core:
  orbits that are always filled

Solve in valence space: $H|\Psi\rangle = E|\Psi\rangle \rightarrow H_{eff}|\Psi\rangle_{eff} = E|\Psi\rangle_{eff}$

H_{eff} is obtained in many-body perturbation theory (MBPT)
includes the effect of inner core and outer orbits

Renormalization group (RG) and MBPT

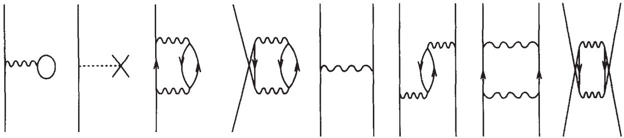
Better convergence of chiral forces after RG transformation



Many-body perturbation theory to third order: obtain effective shell model interaction in the valence space

Single Particle Energies

Two-Body Matrix Elements



Solve many-body problem with shell model code ANTOINE

Diagonalize up to 10^{10} Slater determinants Caurier *et al.* RMP 77 (2005)

$$|\phi_\alpha\rangle = a^+_{i1} a^+_{i2} ... a^+_{iA} |0\rangle \qquad |\Psi\rangle_{eff} = \sum_\alpha c_\alpha |\phi_\alpha\rangle$$

Ca isotopes: masses

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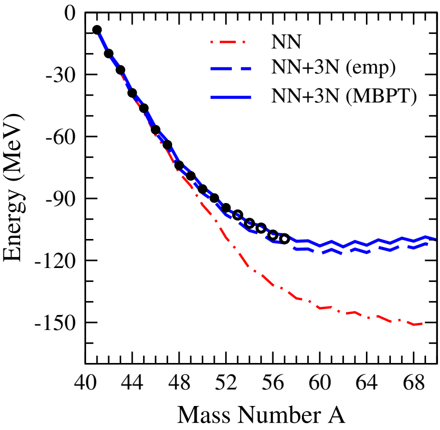
Ca isotopes: explore nuclear shell evolution $N = 20, 28, 32?, 34?$



Ca measured from ^{40}Ca core

3N forces repulsive contribution, chiral NN-only forces too attractive

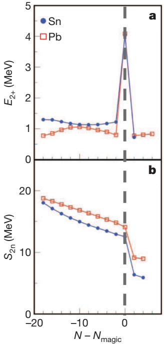
Probe shell evolution:

Mass-differences

2_1^+ energies

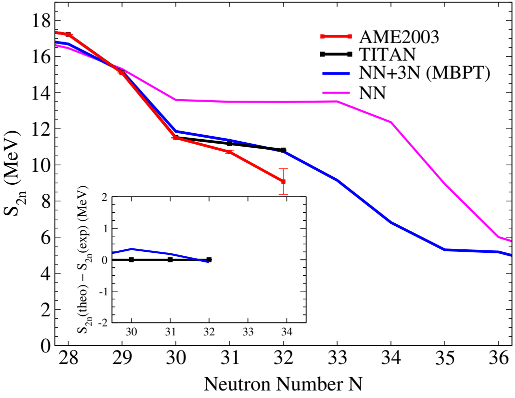
Jones et al.

Nature 465 454 (2010)



Two-neutron separation energies

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



S_{2n} in ^{52}Ca predicted in disagreement with old measurements

Precision measurements with TITAN changed AME 2003 $\sim$ 1.74 MeV in ^{52}Ca

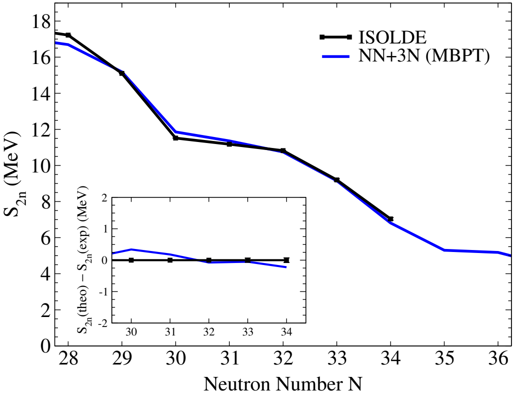
More flat behavior in ^{50}Ca–^{52}Ca

3N forces needed

Gallant et al.
PRL 109 032506 (2012)

^{54}Ca mass and $N = 32$ shell closure

Recent measurement of ^{53,54}Ca at ISOLDE



Excellent agreement with theoretical prediction

S_{2n} evolution:
^{52}Ca–^{54}Ca decrease similar to ^{48}Ca–^{50}Ca unambiguously establishes $N = 32$ shell closure

LETTER

Masses of exotic calcium isotopes pin down nuclear forces

F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfur
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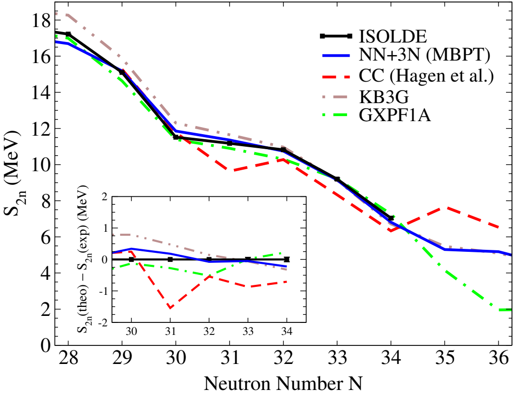
A. Schwenk[7,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

Two-neutron separation energies

Compare to other theoretical calculations



Phenomenology
good agreement
masses/gaps as input

Coupled-Cluster calculations
good agreement
phenomenological 3N forces
Hagen et al. PRL109 032502 (2012)

LETTER

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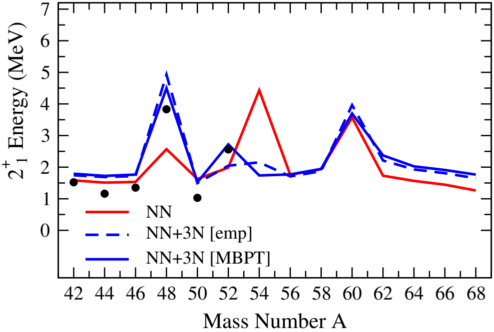
Shell closures and 2_1^+ energies

2_1^+ energies characterize shell closures

Correct closure at $N = 28$ when 3N forces are included

Holt et al. JPG39 085111(2012)

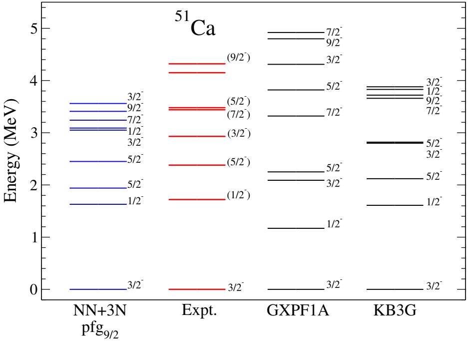
Holt, JM, Schwenk, JPG40 075105 (2013)

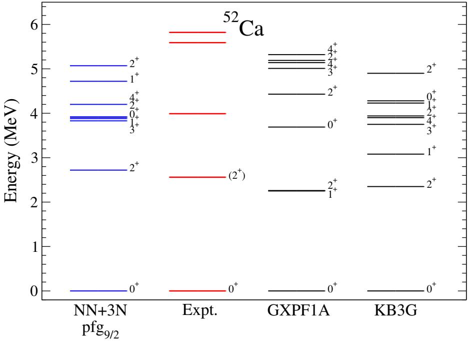


- 3N forces enhance closure at $N = 32$
- 3N forces reduce strong closure at $N = 34$
  Expt: suggest $N = 34$ shell closure
  $E(2_1^+)$=2.04 MeV Steppenbeck et al. Nature 502 207(2013)

Excitation spectra

Spectra for neutron-rich calcium isotopes





Good agreement with experiment when available,
comparable to phenomenological interactions

Predictions in very neutron-rich nuclei, test in upcoming experiments

Electromagnetic transitions

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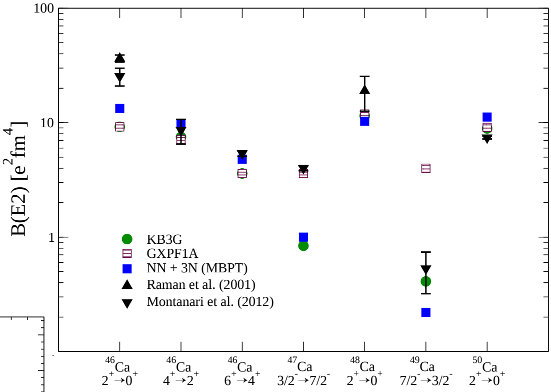
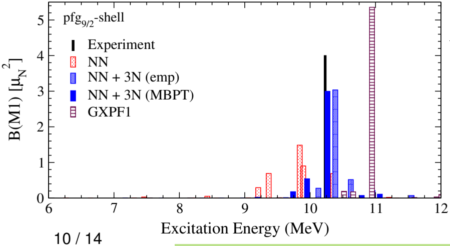
B(E2)s in reasonable agreement with experiment span three orders of magnitude

Similar quality as phenomenological interactions





B(M1) strength in ^{48}Ca NN+3N good agreement experiment strength and energy

Towards theoretical uncertainties

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Estimate theoretical uncertainties
allows meaningful comparison to experiment
and better predictions of properties of non-accessible isotopes

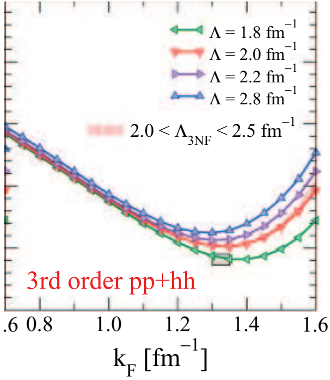
- Theoretical uncertainties associated to nuclear force:

  Explore sensitivity of results with respect to cutoff of RG evolution of unevolved chiral Hamiltonian

  Impose correct nuclear matter saturation

  Consider different unevolved chiral Hamiltonians (outlook)

- Theoretical uncertainties associated to the many-body approach

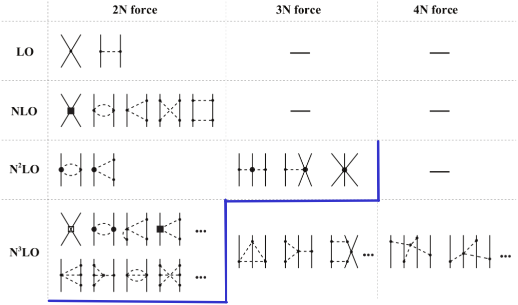


Hebeler et al. PRC 83 031301 (2011)

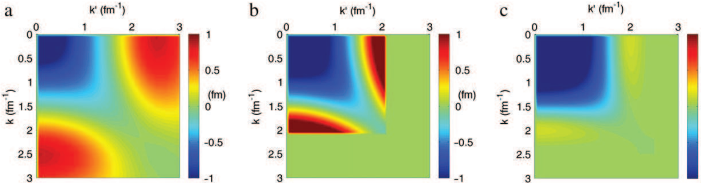
Chiral EFT and RG

Original Hamiltonian includes:

Chiral NN force up to N^3LO
Chiral 3N force up to N^2LO



Evolve through RG transformation to improve the convergence in many-body calculation



Theoretical uncertainties in *sd* nuclei

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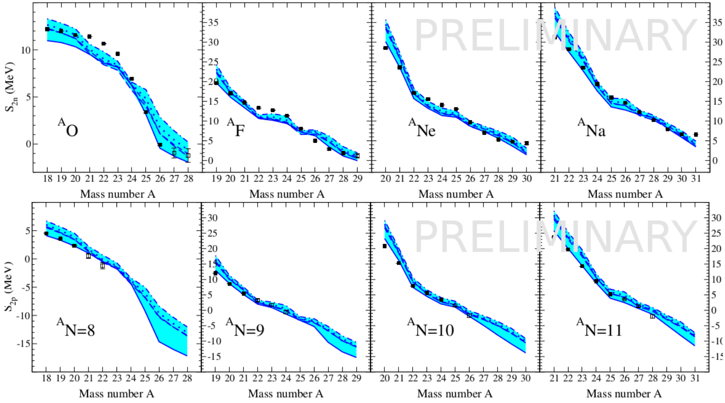
Sensitivity to resolution-scale dependence of RG-evolved nuclear forces

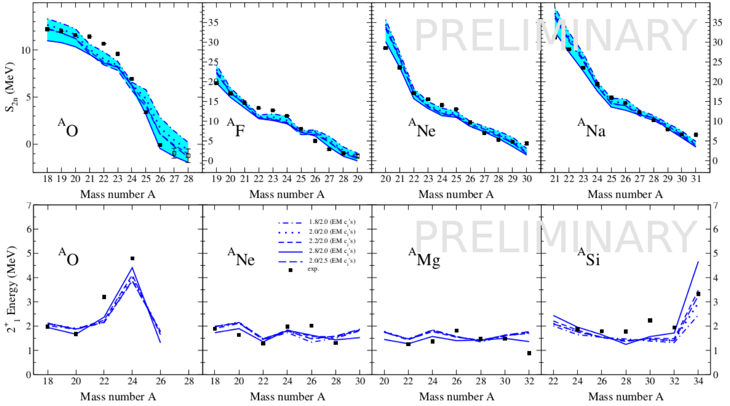


Experimental trends very well reproduced in S_{2n}'s and S_{2p}'s

Uncertainties in S_{2n}'s $\sim 1-3$ MeV, in spectra much smaller $\sim$ 500 keV

Theoretical uncertainties in *sd* nuclei

Sensitivity to resolution-scale dependence of RG-evolved nuclear forces



Experimental trends very well reproduced in S_{2n}'s and S_{2p}'s

Uncertainties in S_{2n}'s $\sim 1-3$ MeV, in spectra much smaller $\sim$ 500 keV

Summary

Shell Model calculation based on chiral effective field theory including NN+3N forces and many-body perturbation theory

- Predicted neutron rich Ca S_{2n}'s with NN+3N forces agree with recent measurements of ^{51,52}Ca (TRIUMF) and ^{53,54}Ca (ISOLTRAP)
- Shell structure: prominent closure established at $N = 32$
- Predicted ^{54}Ca 2_1^+ in good agreement with measurement at RIBF
- Shell structure: suggested shell closure at $N = 34$
  to be complemented with mass measurements at ^{55}Ca and ^{56}Ca
- Excitation spectra, B(E2) and B(M1) transitions
- Towards theoretical uncertainty quantification

Collaborators

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K. Hebeler, J. D. Holt,
A. Schwenk, J. Simonis

ISOLTRAP Collaboration

TITAN Collaboration