Exotic calcium isotopes and three-nucleon forces

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Outline

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Theoretical approach

Shell evolution in neutron-rich calcium

Detailed spectroscopy:
excitation spectra, electromagnetic moments and transitions

Summary

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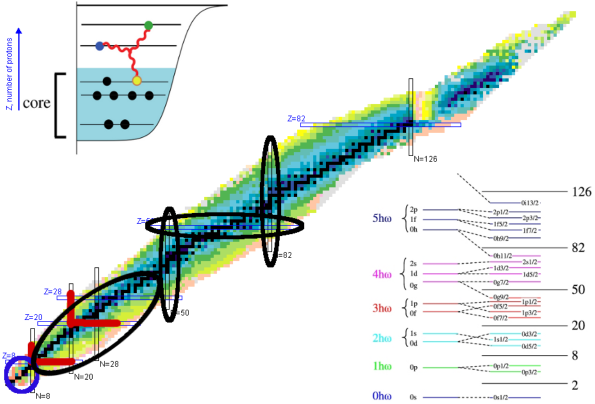
Nuclear landscape



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

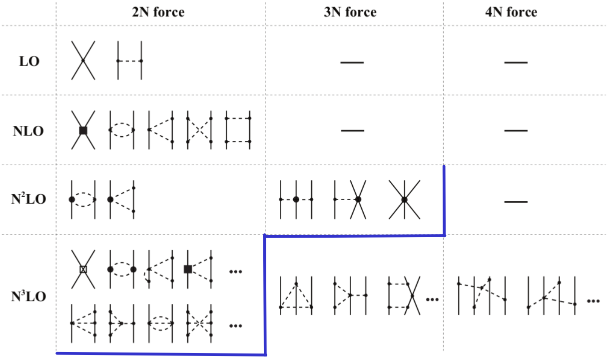
Shell Model:
Solve the problem choosing the relevant degrees of freedom
Use realistic nucleon-nucleon (NN) and three-nucleon (3N) interactions

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



pion exchanges

contact terms

NN fitted to:

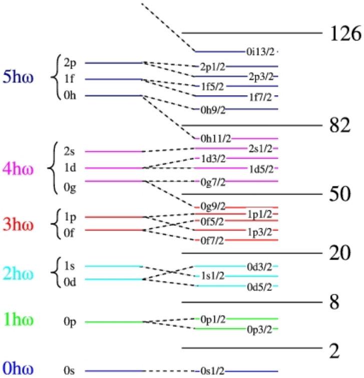
- NN scattering
- π-N scattering

3N fitted to:

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

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

Medium-mass nuclei: shell model



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

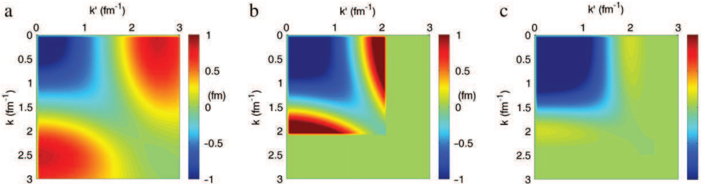
- Outer orbits:
  orbits that are always empty
- Valence space: the space in which we explicitly solve the problem
- Inner core:
  orbits that are always filled

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

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

Renormalization group (RG) and MBPT

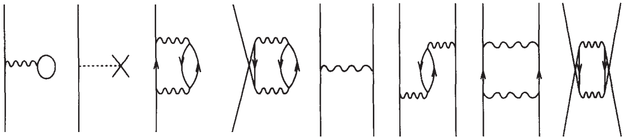
Better convergence of chiral forces after RG transformation



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

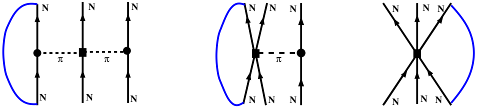
Diagonalize up to 10^{10} Slater determinants Caurier *et al.* RMP 77 (2005)

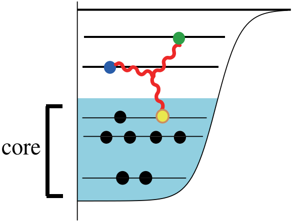
$$|\phi_\alpha\rangle = a^+_{i1} a^+_{i2} ... a^+_{iA} |0\rangle \qquad |\Psi\rangle_{eff} = \sum_\alpha c_\alpha |\phi_\alpha\rangle$$

Normal-ordered 3N Forces

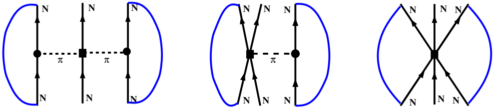
Treatment of 3N forces:

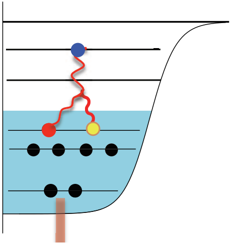
normal-ordered 2B: 2 valence, 1 core particle
⇒ Two-body Matrix Elements





normal-ordered 1B: 1 valence, 2 core particles
⇒ Single particle energies





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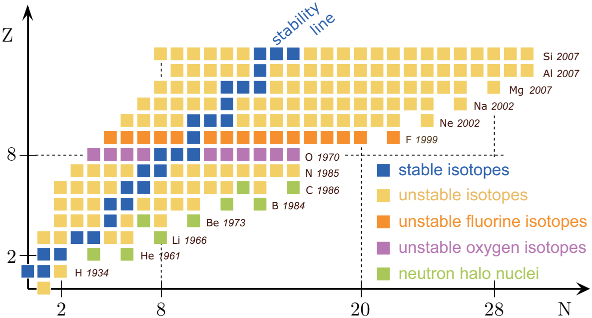
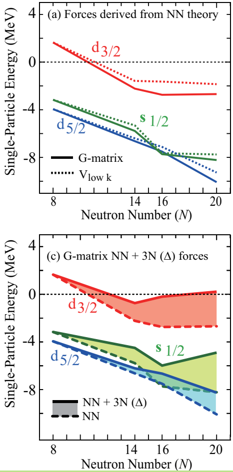
Oxygen dripline anomaly and 3N forces

O isotopes: 'anomaly' in the dripline at ^{24}O, doubly magic nucleus
Chiral NN+3N forces provided repulsion needed to predict dripline





Based on many-body perturbation theory

Otsuka et al. PRL105 032501 (2010)

Ab-initio oxygen dripline

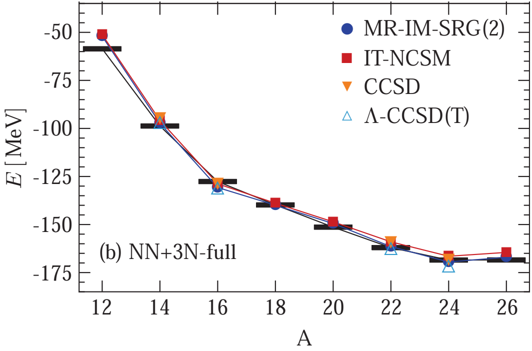
Oxygen dripline benchmarked with few ab-initio approaches:

No-core shell model (truncated)

In-medium SRG

Coupled-cluster

Self-consistent Green's function



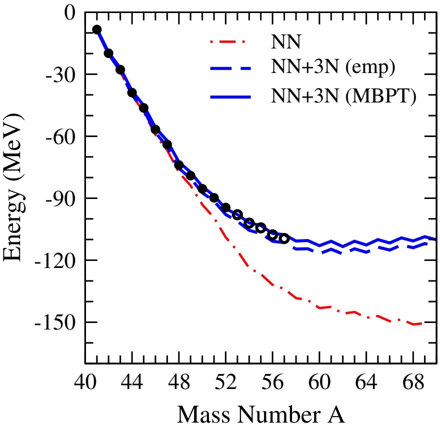
Hergert et al. PRL110 242501 (2013)

Sensitivity to the chiral interaction used, to be explored

Simonis et al. in preparation

Ca isotopes: masses

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



Ca measured from ^{40}Ca core in $pfg_{9/2}$ valence space

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

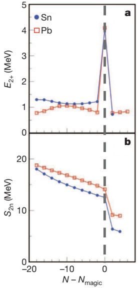
Probe shell evolution:

Mass-differences

2_1^+ energies

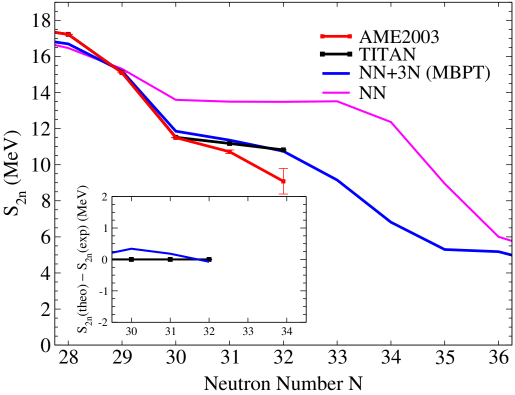
Jones et al.

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

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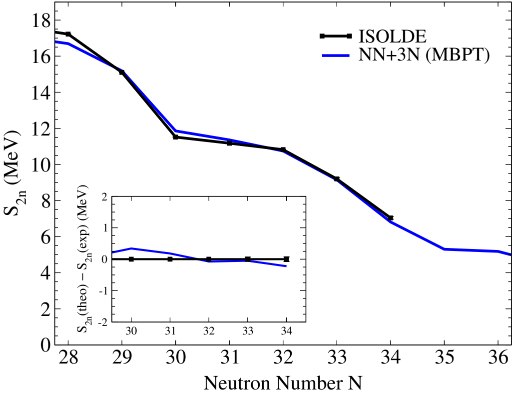
Recent measurement of ^{53,54}Ca at ISOLDE



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

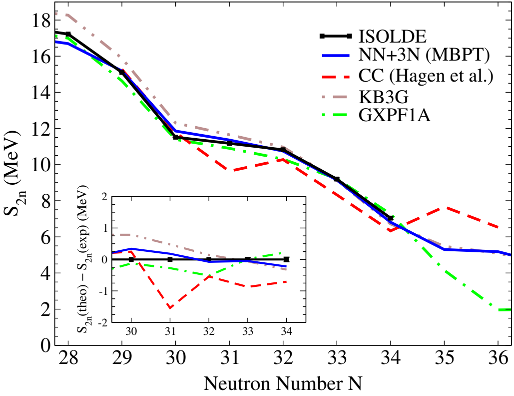
LETTER

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
M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schw
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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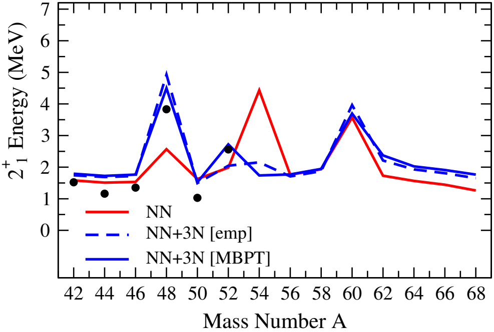
Shell closures and 2_1^+ energies

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)

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Excitation spectra

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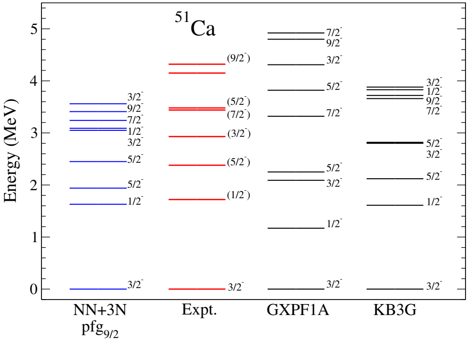
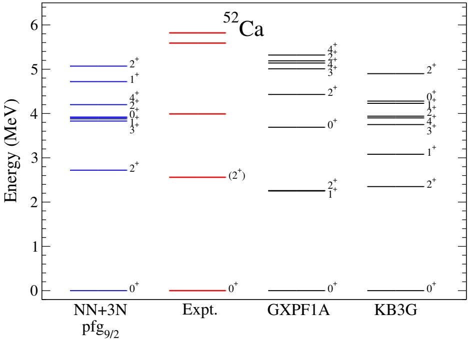
Spectra for neutron-rich calcium isotopes





Good agreement with experiment when available,
comparable to standard phenomenological interactions

Holt, JM, Simonis, Schwenk PRC90 024312 (2014)

Excitation spectra

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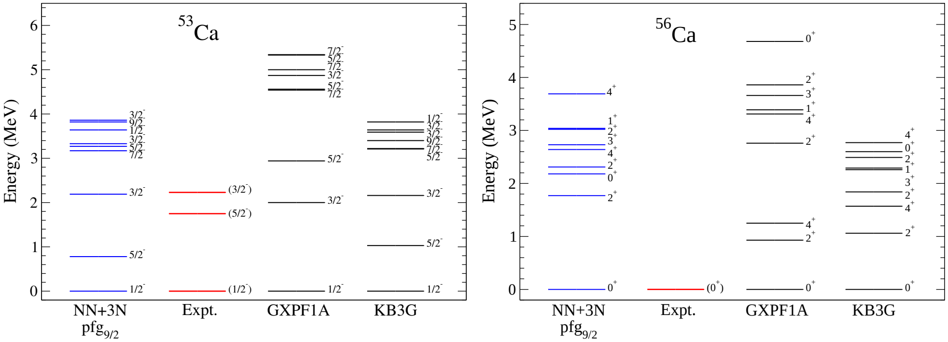
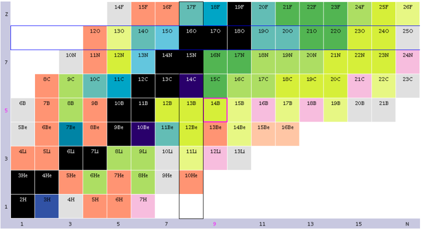
Spectra for neutron-rich calcium isotopes



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

Holt, JM, Simonis, Schwenk PRC90 024312 (2014)

Carbon electromagnetic transitions



Electromagnetic transitions can be calculated in p-shell

No need of effective charges

Still require consistent evolution of transition operator

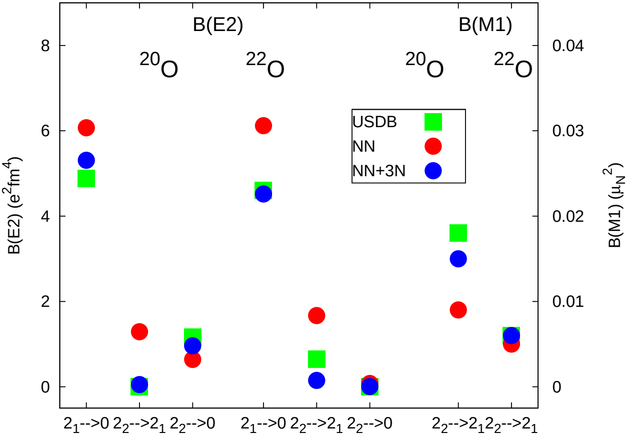
Second 2_2^+ state decay sensitive to 3N forces

Decay not seen experimentally: 3N forces favored

	Experiment	CDB2k	NN	$NN+NNN$	WBP	WBT	WBT*
$2_2^+ \to 2_1^+$	>91.2%	32.4%	21.6%	97.6%	92.2%	93.2%	97.6%
$2_2^+ \to 0_1^+$	<8.8%	67.6%	78.4%	2.4%	7.8%	6.8%	2.4%

Petri et al. PRC86 044329 (2012)

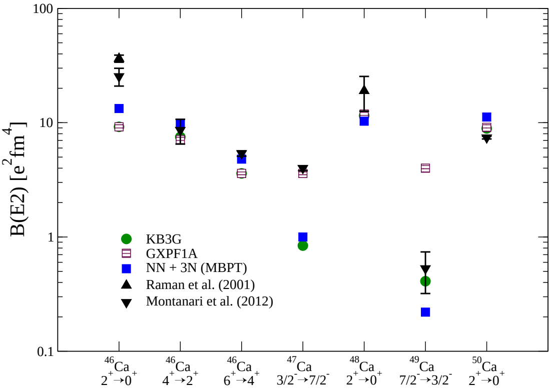
Oxygen electromagnetic transitions



Electromagnetic transitions (decay lifetimes)

B(E2) transitions in 2_2^+ states ^{20}O and ^{22}O also sensitive to 3N forces

Calcium B(E2) transition strengths



B(E2)s reasonable agreement with experiment, spread two over orders of magnitude

Similar quality as phenomenological interactions

^{46}Ca: *sd* degrees of freedom?

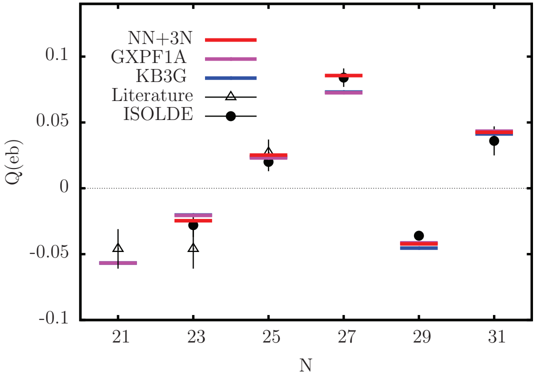
Phenomenological effective charges $q_n = 0.5e$

Holt, JM, Simonis, Schwenk PRC90 024312 (2014)

Calcium quadrupole moments

Electric quadrupole moments in ground states of calcium isotopes very recently measured by COLLAPS at ISOLDE

Good agreement to experiment, up to neutron-rich systems



Consistent description of ground-state masses and spectroscopy

Comparable to phenomenological interactions

Phenomenological effective charges $q_n = 0.5e$

Garcia Ruiz et al., to be submitted

B(M1) transition in ^{48}Ca

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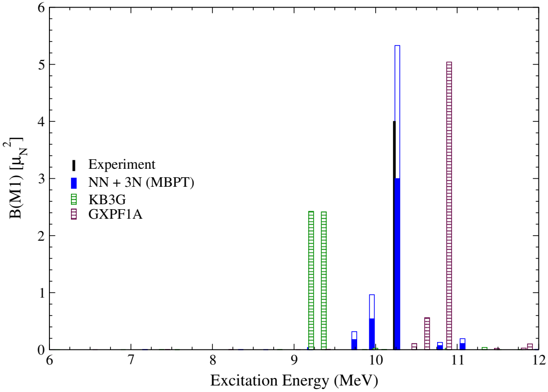
B(M1) strength in ^{48}Ca compared to experiment



NN+3N calculation good agreement with experiment

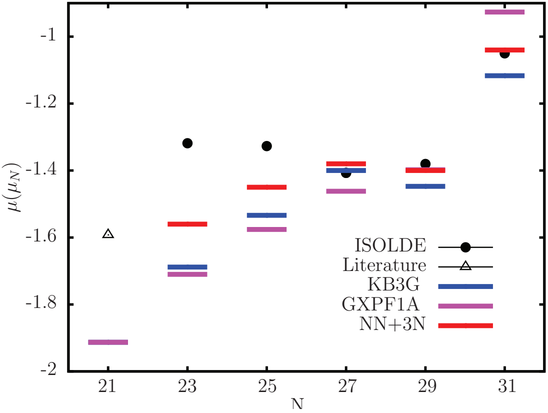
Experimental concentration of the strength very sensitive to effective interaction

NN+3N interaction associated to mildly quenched g-factors

Holt, JM, Simonis, Schwenk PRC90 024312 (2014)

Calcium magnetic moments

Predictions of magnetic moments in good agreement with very recent measurements by COLLAPS at ISOLDE



Even improve agreement of phenomenological interactions

Missing sd degrees of freedom in lighter isotopes, (sensitive to unpaired particles)

Bare g-factors!

Garcia Ruiz et al., to be submitted

Outline

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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 (ISOLDE)
- Shell structure: prominent closure established at $N = 32$
- Predicted ^{54}Ca 2_1^+ in good agreement with measurement at RIKEN
- Excitation spectra reasonable agreement to experiment, prediction of excited states in neutron-rich isotopes
- B(E2) and B(M1) transitions well described
- Quadrupole and Magnetic moments in neutron-rich isotopes very good agreement to recent ISOLDE measurements

Collaborators

K. Hebeler, A. Schwenk, J. Simonis

J. D. Holt

TITAN Collaboration

ISOLTRAP Collaboration

COLLAPS Collaboration