Three-nucleon forces and shell structure of neutron-rich Ca isotopes

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Outline

Theoretical Approach:
NN+3N forces in Shell Model

Neutron rich Ca isotopes:
Shell evolution $N = 32$ shell closure

Proton rich N=8 and N=20 isotopes

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Nuclear Structure approach

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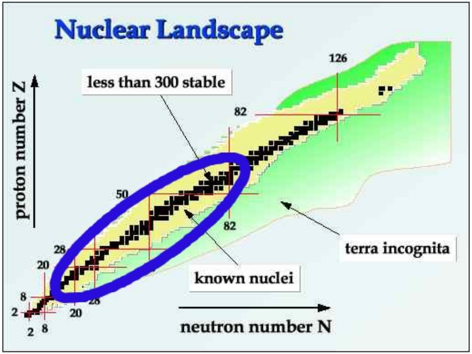


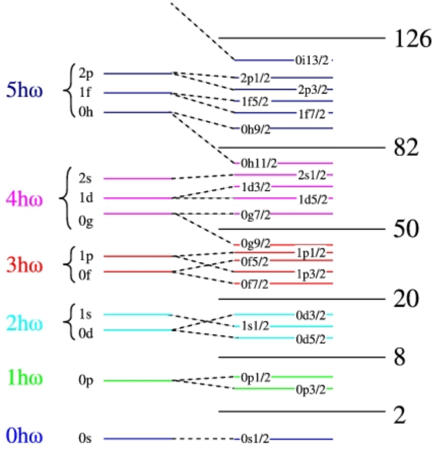
Big variety of nuclei in the nuclear chart, $A \sim 2...300$

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

Poses a hard many-body problem: design approximate methods suited for different regions

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

The Interacting Shell Model



Chose as basis states that of the 3D Harmonic Oscillator

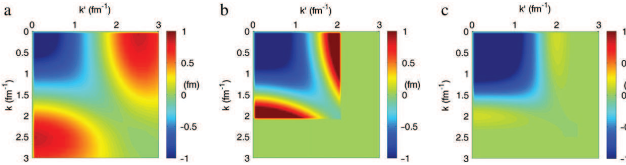
To keep the problem feasible, the configuration space is separated into

- 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

$$\mathrm{Dim} \sim \binom{(p+1)(p+2)_\nu}{N} \binom{(p+1)(p+2)_\pi}{Z}$$

Many Body Perturbation Theory

Better convergence through
V_{lowk} transformation

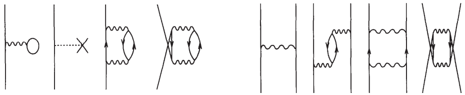


Many-body Perturbation Theory
up to third order to build
an effective Shell Model interaction
in a valence space

$H\,|\Psi\rangle = E\,|\Psi\rangle \rightarrow H_{eff}\,|\Psi\rangle_{eff} = E\,|\Psi\rangle_{eff}$

Single Particle Energies (SPEs)

Two-Body Matrix Elements (TBMEs)



Full diagonalizations using codes ANTOINE and NATHAN

Caurier et al. RMP77 427(2005) and **compare to experiment**

3N forces: Oxygen dripline

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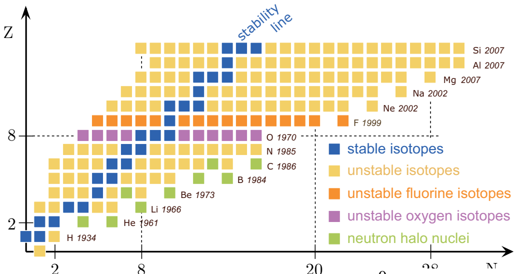


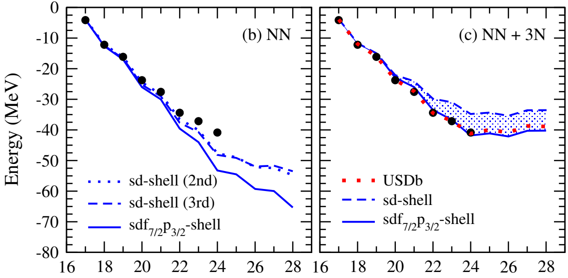
Chiral NN+3N forces to describe O dripline at ^{24}O

Otsuka et al.

PRL105 032501 (2010)

3N forces provide repulsion missing in NN-only forces

3N forces crucial also for reliable description of spectra



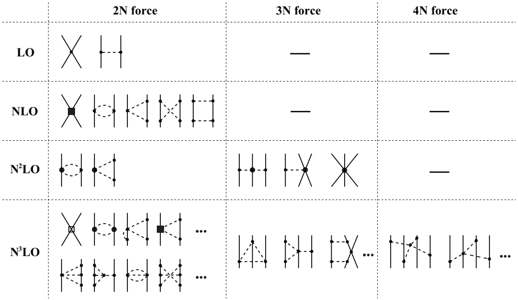
Forces and Currents in Chiral EFT

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

Approximate chiral symmetry of QCD: pions pseudo-Goldstone bosons

Short-range couplings are fitted to experiment once

Systematic expansion: nuclear forces and electroweak currents



NN forces up to N^3LO

3N forces up to N^2LO

NN fitted to:

- NN scattering data

3N fitted to:

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

Weinberg, van Kolck, Savage, Epelbaum, Kaiser, Meißner...

3N Forces

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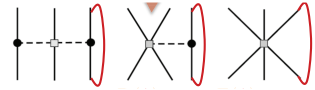
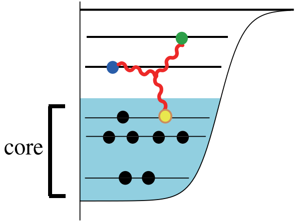
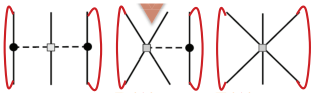
Treatment of 3N forces:

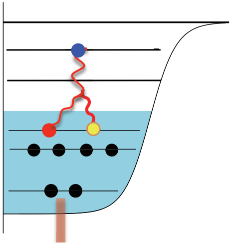
normal-ordered 2B: 2 valence, 1 core particle
$\Rightarrow$ (effective) Two-body Matrix Elements (TBME)





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

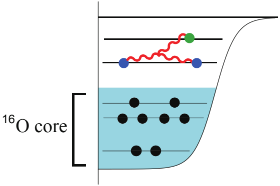


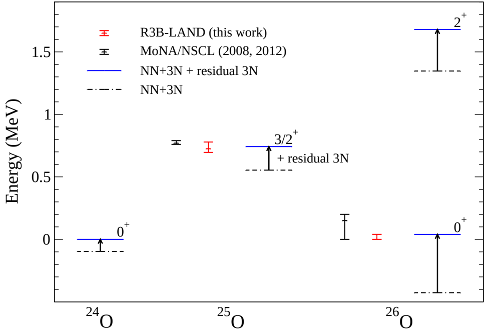


residual 3B:
$\Rightarrow$ Estimated to be suppressed by $N_{valence}/N_{core}$

Residual 3N Forces

In the most neutron-rich oxygen isotopes, 3N forces between 3 valence neutrons can give a relevant contribution





Residual 3N contributions are repulsive

They are small compared to normal-ordered 3N force, but increase with N

Very good agreement with resonances in ^{25}O and ^{26}O

Caesar, Simonis et al PRC88 034313 (2013)

Outline

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Theoretical Approach: NN+3N forces in Shell Model

Neutron rich Ca isotopes: Shell evolution $N = 32$ shell closure

Proton rich N=8 and N=20 isotopes

Ca isotopes: Masses

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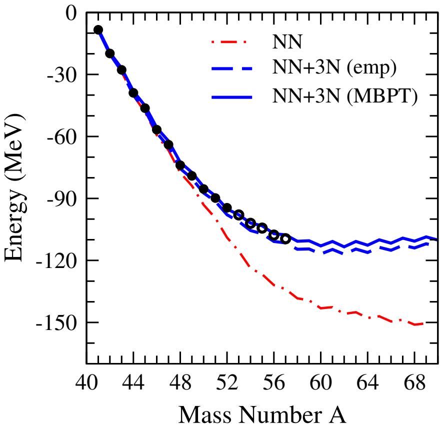
Ca isotopes: explore nuclear shell evolution $N = 20, 28, 32?, 34?$



Ca with respect to ^{40}Ca core

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

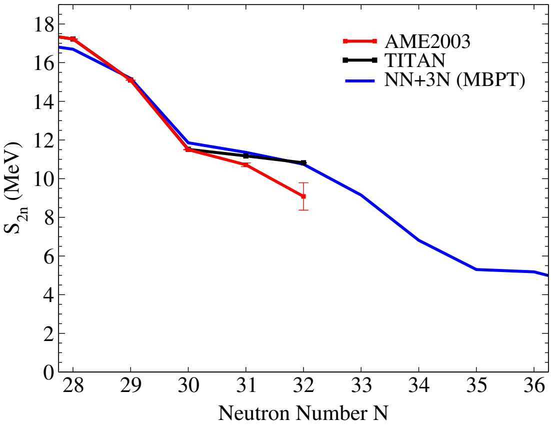
Flat behaviour towards ^{60}Ca does not allow clear prediction of the dripline

Results sensitive to SPEs, especially more neutron-rich systems,
MBPT (calculated from NN+3N forces)
Empirical (from GXPF1 interaction)
Estimate of the uncertainty

Two-Neutron separation energies

Ca isotopes (on top of ^{40}Ca core)

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



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

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

3N forces needed in theoretical calculation

$pfg_{9/2}$ valence space

Gallant et al.
PRL 109 032506 (2012)

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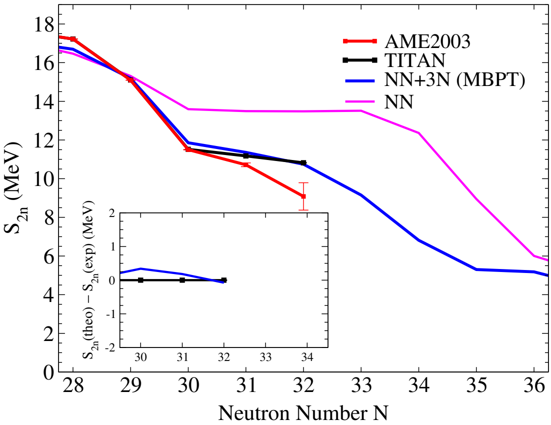

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^{54}Ca and $N = 32$ shell closure

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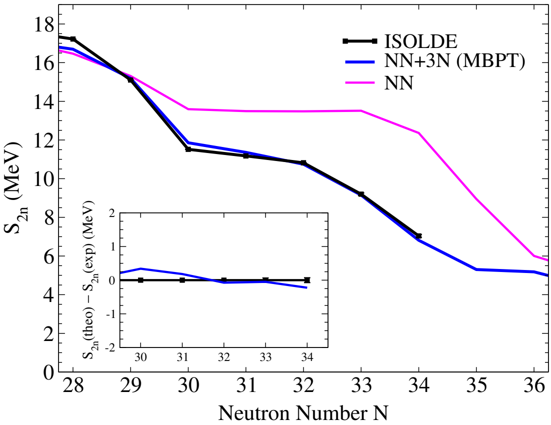

Very recently ^{53,54}Ca measured at ISOLDE

Excellent agreement between calculation and experiment

S_{2n} evolution:
^{52}Ca–^{54}Ca as ^{48}Ca–^{50}Ca:
$N = 32$ shell closure

Wienholtz et al.
Nature 498 346 (2013)

Two-neutron separation energies

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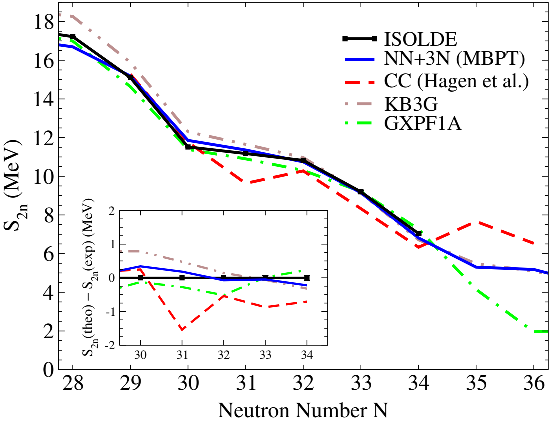
Compare $S_{2n} = -[B(N,Z) - B(N-2,Z)]$ with experiment

S_{2n} also calculated by other approaches:



Phenomenological interactions also reproduce quite well experiment (input about masses/gaps into the interactions)
Differ markedly beyond ^{54}Ca

Coupled-Cluster calculations
Hagen et al. PRL109 032502 (2012) very good agreement for even isotopes

Wienholtz et al.
Nature 498 346 (2013)

Two-neutron separation energies

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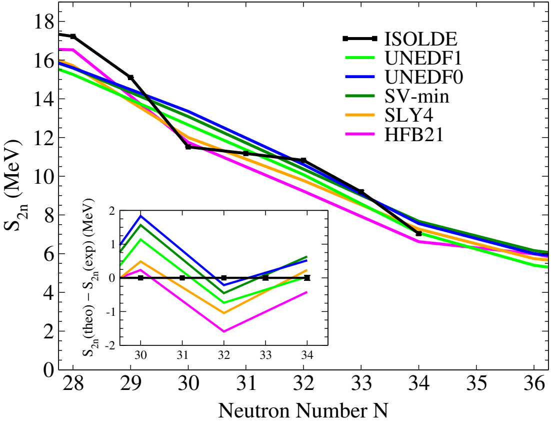

Modern Energy Density Functionals reproduce correctly overall trends and neutron/proton driplines have more dificulties in describing shell closures

Erler et al. Nature486 509(2012)

Wienholtz et al.
Nature 498 346 (2013)

Shell closures and 2_1^+ energies

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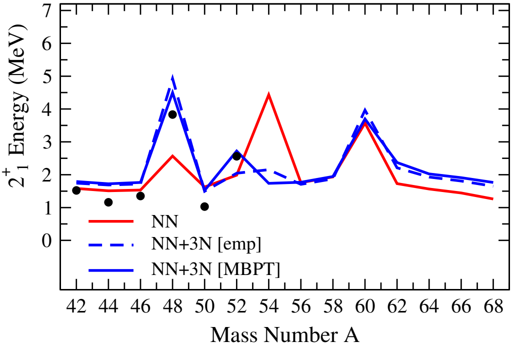
2_1^+ energies characterise shell closures of the neutron rich calcium isotopes

Holt, JM, Schwenk, JPG40 075105 (2013)



- Correct closure at $N = 28$ when 3N forces are included
  Holt et al. JPG39 085111(2012)
- 3N forces enhance closure at $N = 32$
- 3N forces reduce strong closure at $N = 34$ (1.7-2.2 MeV)
  Measured at 2.1 MeV   Steppenbeck et al. Nature, in press

^{48}Ca spectrum

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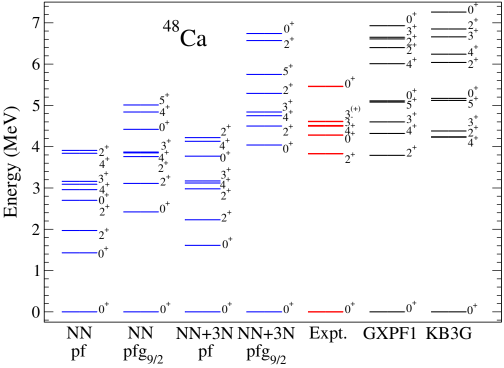
Challenge: Doubly-closed nucleus ^{48}Ca



Spectra too compressed with NN forces only or *pf* space

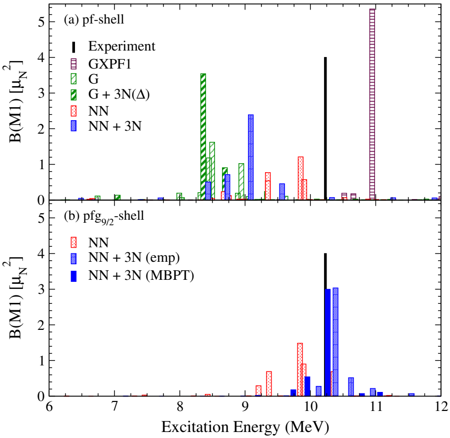
2_1^+ state only $\sim$appropriate energy in $pfg_{9/2}$ NN+3N calculation

0_1^+ state too low (1st excited state) especially compared to phenomenological interactions

Importance of 3N forces

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

B(M1) Transition in ^{48}Ca



B(M1) strength in ^{48}Ca too fragmented in *pf* space
Phenomenological calculations reproduce experimental concentration

In the extended $pfg_{9/2}$ space NN forces also fragmented strength

NN+3N calculation in $pfg_{9/2}$ very good agreement with experiment

B(E2) Transition Strengths

Isotope	Transition	KB3G	GXPF1A	MBPT	EXP.
^{46}Ca	$2^+ \to 0^+$	9.2	9.2	13.3	25.4±4.5
					36.4±2.6
^{46}Ca	$6^+ \to 4^+$	3.6	3.6	4.8	5.38±0.29
^{47}Ca	$3/2^- \to 7/2^-$	0.84	3.6	1.0	4.0±0.2
^{48}Ca	$2^+ \to 0^+$	11.5	11.9	10.3	19±6.4
^{49}Ca	$7/2^- \to 3/2^-$	0.41	4.0	0.22	0.53±0.21
^{50}Ca	$2^+ \to 0^+$	8.9	9.1	11.2	7.4±0.2

B(E2)s in reasonable agreement with experiment
(order of magnitude)

Similar quality as phenomenological interactions (very close to KB3G)

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

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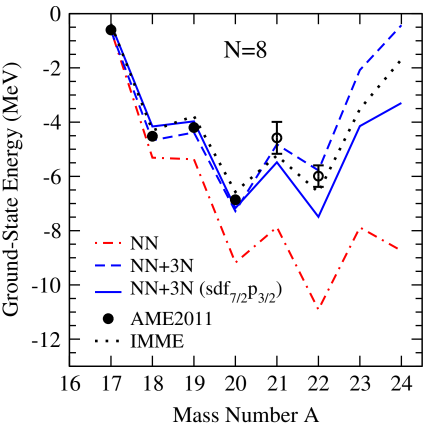
Proton dripline at $N = 8$



Holt, JM, Schwenk PRL110 022502 (2013)

Theory complements/improves mass extrapolations and isomeric mass-multiplet formula (IMME)

$E(A, T, T_z) = E(A, T, -T_z) + 2b(A, T)T_z$

NN forces oberbind

3N forces essential to describe masses and the predict the proton dripline

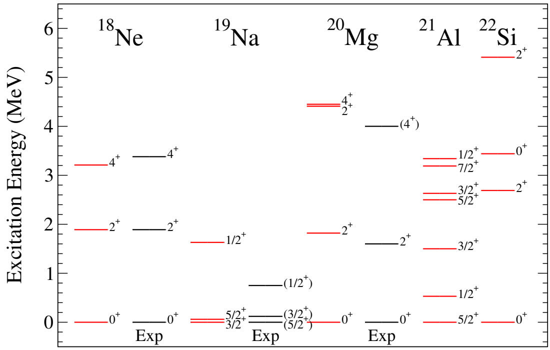
Proton dripline not certain predicted either in ^{20}Mg or ^{22}Si:

S_{2p}= -0.12 (Theory) / +0.01 (IMME)

Measurement needed!

Calculations in standard and extended spaces

Spectra of $N = 8$ isotones



Holt, JM, Schwenk PRL110 022502 (2013)

Including NN+3N forces good agreement with known spectra

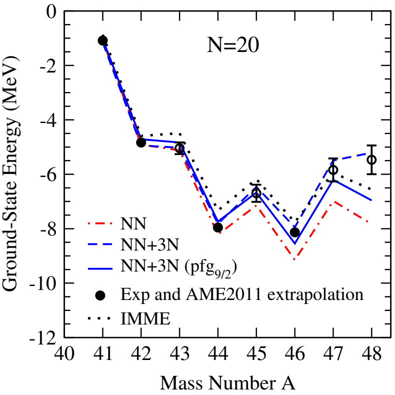
Prediction of 2^+,4^+ doublet close to previously unpublished 4^+ state in ^{20}Mg (I. Mukha)

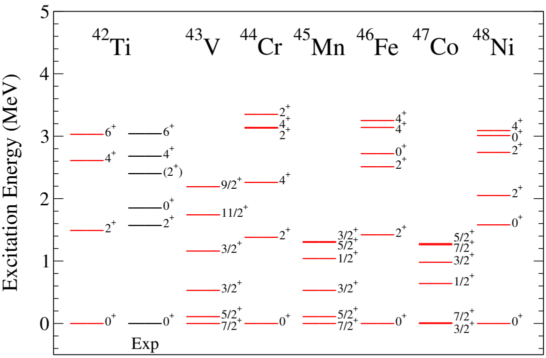
Prediction of ^{21}Al and ^{22}Si spectra

In ^{22}Si calculations point to a sub-shell closure (analogous to ^{22}O)

More experimental information greatly appreciated!

Masses and spectra of $N = 20$ isotones





Holt, JM, Schwenk PRL110 022502 (2013)

Dripline robustly predicted at ^{46}Fe

Good description of ^{48}Ni: S_{2p}= -1.02 (Th) vs -1.28(6) (Exp) Pomorski (2012)

Summary and Outlook

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Shell Model calculation based on chiral EFT (NN+3N forces) and MBPT gives good agreement with experimental masses, two-neutron separation energies, pairing gaps and excitation spectra for oxygen, calcium isotopes and proton-rich N=8,20 isotones:

- Oxygen dripline, unbound ^{25,26}O reproduced with residual 3N forces
- 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 at $N = 32$
- Ca spectroscopy: spectra, electromagnetic strengths
- Dripline and spectra of proton-rich $N = 8, 20$ isotones predicted

Outlook:

Heavier isotope and isotone chains: include T=0 (pn) TBME

Explore uncertainties in the theoretical calculation

Collaborators

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

R^{3}B Collaboration
(C. Caesar, T. Aumann...)

TITAN Collaboration
(A. Gallant, J. Dilling...)

ISOLTRAP Collaboration
(F. Wienholtz, K. Blaum...)