Three-nucleon forces and exotic nuclei

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Outline

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Theoretical Approach: NN+3N forces in Shell Model

- The nuclear interaction: need of 3N forces
- Shell Model interactions with microscopic chiral NN+3N forces

Results for exotic nuclei

- Neutron rich O isotopes
- Neutron rich Ca isotopes
- Proton rich N=8 and N=20 isotopes

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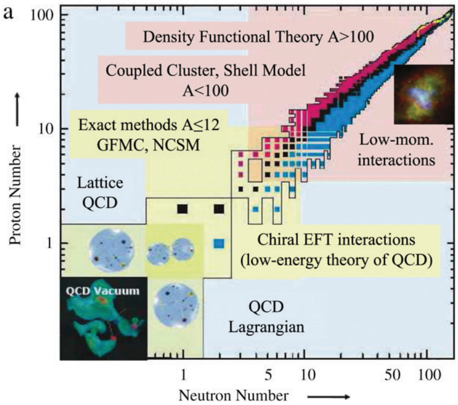
The Nuclear interaction

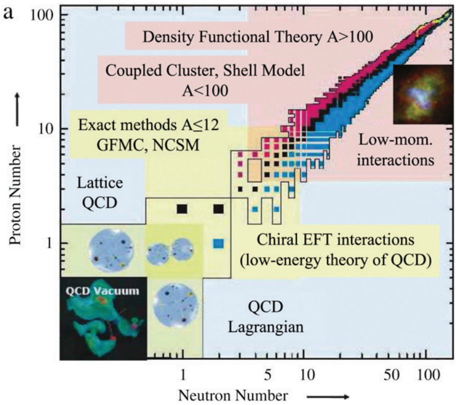


Ideally, QCD interaction
(Latice QCD)
⇒ Hard problem:
QCD non-perturbative at low energy

Alternatively, bare NN potential
(spirit of Shell Model)
⇒ Drawback:
manipulate the interaction to solve the many-body nuclear problem

Finally, use selected nuclei
(Energy Density Functionals)
⇒ Drawback:
loss of predictive power

The Nuclear interaction



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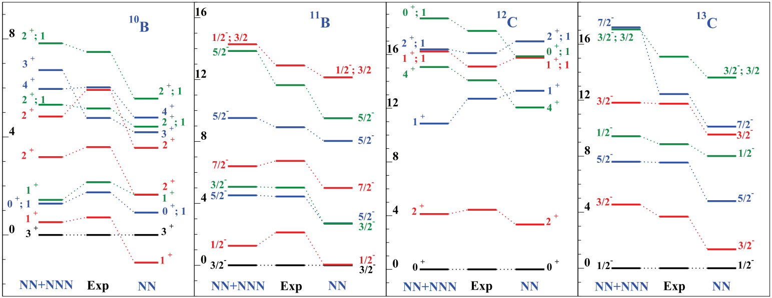
Limitation of NN potentials

Ab initio calculations (No Core Shell Model) with perfect NN potentials (AV18) fail to reproduce light nuclei spectra



Navratil et al. PRL99 042501(2007)

⇒ Confirms experience of Shell Model (monopole adjustments)

Need of 3N forces

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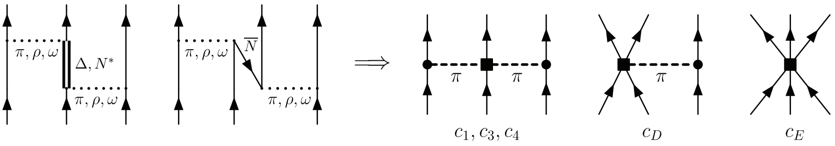
Need 3N forces!

Zuker PRL90 042502 (2003)

3N forces originate in the elimination of degrees of freedom
(N-body forces appear in any effective theory)

Bogner, Schwenk, Furnstahl PPNP65 94 (2010)



But few NNN scattering data available!

$\Rightarrow$ Need a framework that, in a natural manner, describes
3N forces consistent with NN forces

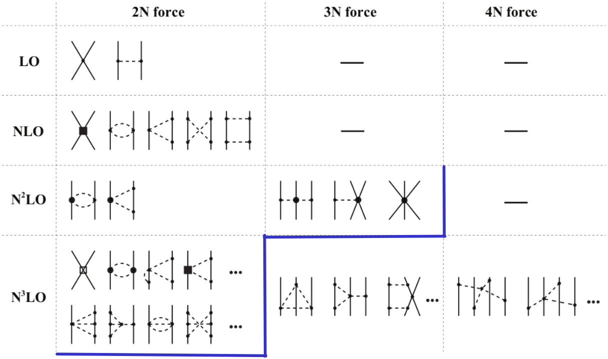
Chiral EFT

- Chiral EFT is a low energy approach to QCD
  valid for nuclear structure energies
- Exploits approximate chiral symmetry of QCD:
  pions are special particles (pseudo-Goldstone bosons)
- Nucleons interact via pion exchanges and contact interactions
  (physics non-resolved at nuclear structure energies)
- Enables a systematic basis for strong interactions,
  expansion in powers of Q/Λ_b
  $Q \sim m_\pi$, typical momentum scale
  $\Lambda_b \sim 500$ MeV, breakdown scale
- Systematic expansion naturally includes NN, 3N, 4N... forces
  (at different orders)
- Short-range couplings are fitted to experiment once

Chiral EFT NN+3N forces

Systematic expansion: state-of-the-art chiral EFT forces

- NN forces included up to N^{3}LO
- 3N forces included up to N^{2}LO



NN fitted to:

- NN scattering data

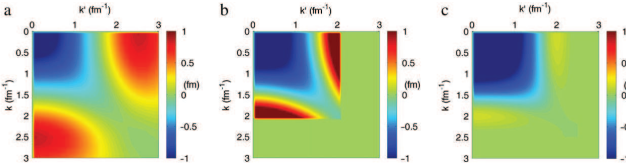
3N fitted to:

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

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

Many Body Perturbation Theory

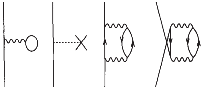
Better convergence through
V_{lowk} transformation

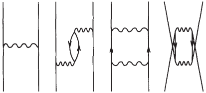


Single Particle Energies (SPEs)

Two-Body Matrix Elements (TBMEs)

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





Full diagonalizations using codes ANTOINE and NATHAN
Caurier et al. RMP77 427(2005) and **compare to experiment**

3N Forces

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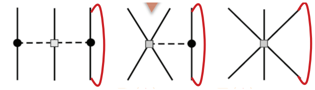
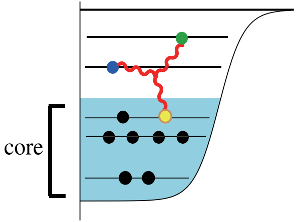
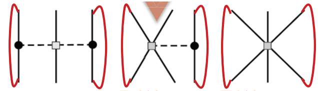
Treatment of 3N forces:

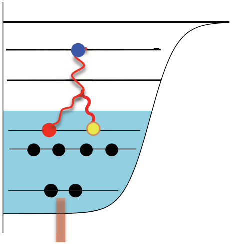
normal-ordered 2B: 2 valence, 1 core particle
⇒ (effective) Two-body Matrix Elements (TBME)





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





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

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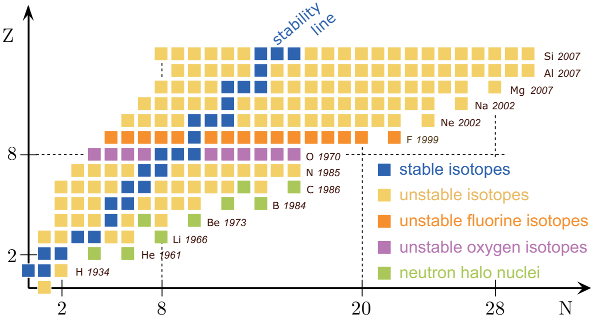
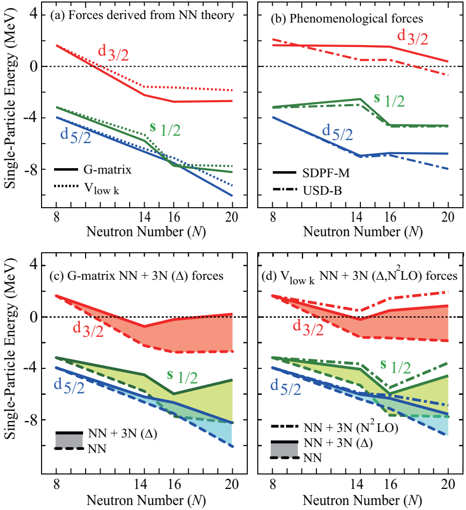
O isotopes: dripline anomaly

O isotopes: 'anomaly' in the dripline at ^{24}O, doubly magic nucleus



Theoretical calculations predict the dripline at ^{26}O or ^{28}O:
a fit to this property is needed to correctly reproduce experiment (e.g. USD interactions, EDFs)

O isotopes: effective SPE’s



Evolution of $d_{3/2}$ orbit (and to a less extent $s_{1/2}$ and $d_{5/2}$ orbits) incorrectly predicted by NN forces

Phenomenological interactions include further repulsive contributions

The effect of 3N forces is similar to phenomenological ’cures’

Otsuka et al. PRL105 032501 (2010)

O isotopes: masses and spectra

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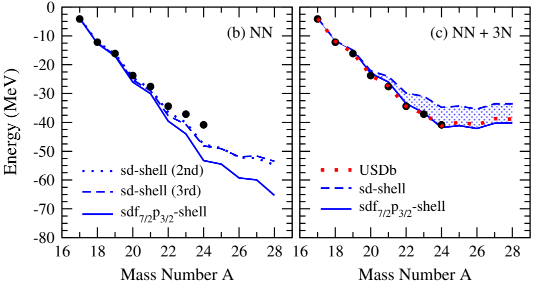
Chiral NN+3N forces give the correct picture for masses and spectra



Otsuka et al.

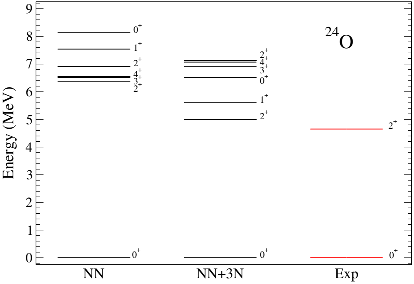
PRL105 032501 (2010)

Holt, JM, Schwenk

EPJA in press (2013)

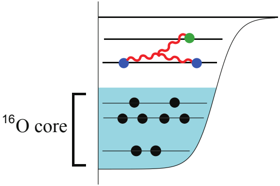
3N forces provide repulsion missing in NN-only forces

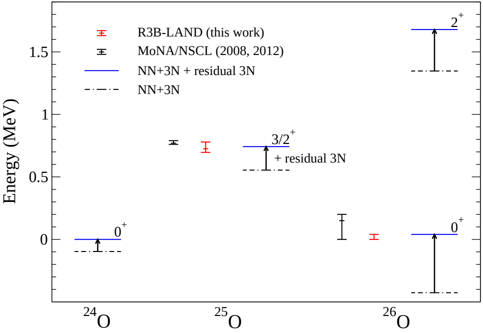
3N forces crucial also for reliable description of spectra



Residual 3N Forces

In the most neutron-rich oxygen isotopes,
3N forces between 3 valence neutrons
(remember, suppressed by $N_{valence}/N_{core}$)
can give a relevant contribution





Residual 3N contributions are repulsive

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

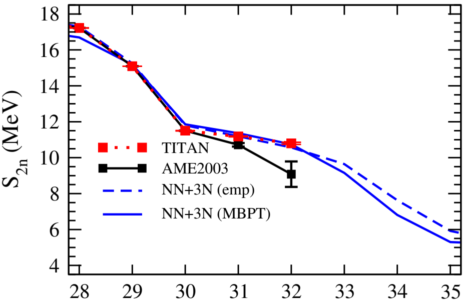
Very good agreement with resonances in ^{25}O and ^{26}O

Caesar, Simonis et al, arXiv:1209.0156

Ca isotopes: 2n separation energies

Compare S_{2n} theoretical calculations with experimental results

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



Gallant et al. PRL109 032506 (2012)

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

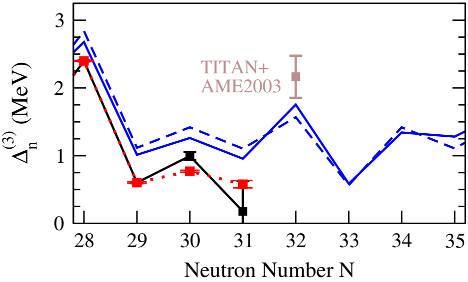
Very good agreement between calculation and experimental trend (Similar level as phenomenological interactions)

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

Nuclear Pairing Gaps

Compare also to experimental three-point mass differences:

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



Gallant et al. PRL109 032506 (2012)

The experimental trend is very well reproduced by theory

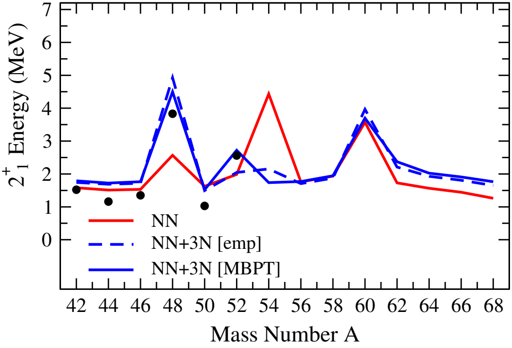
Theoretical results systematically 0.5 MeV higher than experiment

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

Shell closures in Ca isotopes

2_1^+ energies
characterize shell closures
of Ca isotopes

Closure at $N = 28$
with 3N forces in ($pfg_{9/2}$)
Holt et al. JPG39 085111(2012)



Holt, JM, Schwenk, to be submitted

3N forces enhance closure at $N = 32$ (more moderate than $N = 28$)

3N forces reduce strong closure at $N = 34$ (no apparent closure)

Predicted shell closure at $N = 60$, unaffected by 3N forces
(but continuum missing in our calculations!)

Proton dripline at $N = 8$

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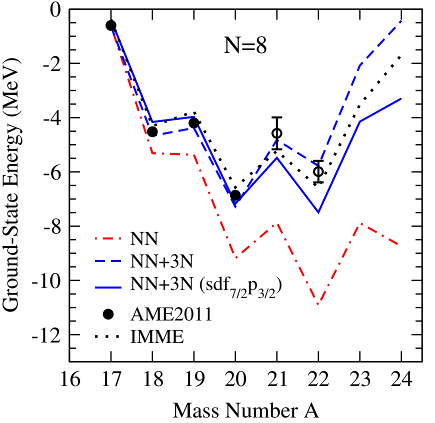


Holt, JM, Schwenk PRL110 022502 (2013)

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

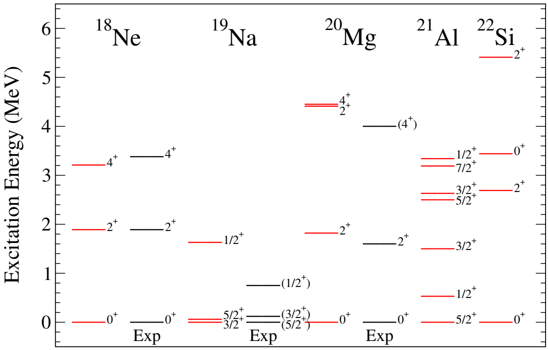
$E(A, T, T_z) = E(A, T, -T_z) + 2b(A, T)T_z$

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

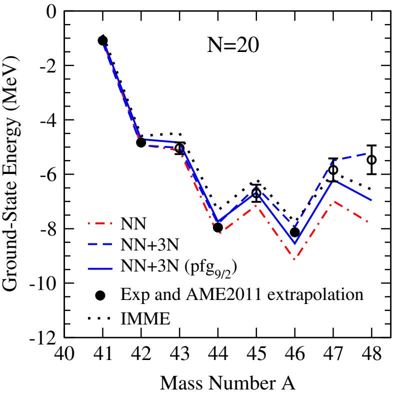
Prediction of 2^+,4^+ doublet close to previously unpublished 4^+ state in ^{20}Mg (I. Mukha)

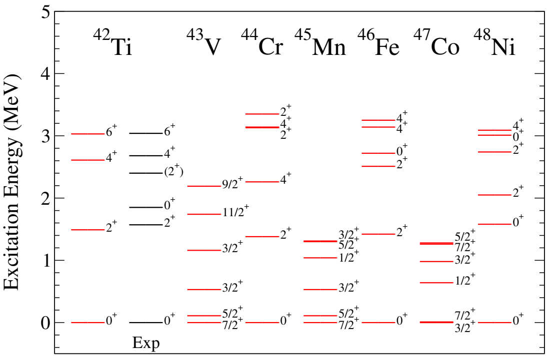
Prediction of ^{21}Al and ^{22}Si spectra

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

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:

- Neutron rich O masses and spectra reproduced with NN+3N forces
- Residual 3N forces needed for very neutron-rich ^{25,26}O
- Predicted neutron rich Ca S_{2n}'s agree with recent measurements
- Ca pairing gaps and spectra (shell closures) including NN+3N forces
- Dripline and spectra of proton-rich $N = 8, 20$ isotones predicted

Outlook:

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

Explore uncertainties in the theoretical calculation