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

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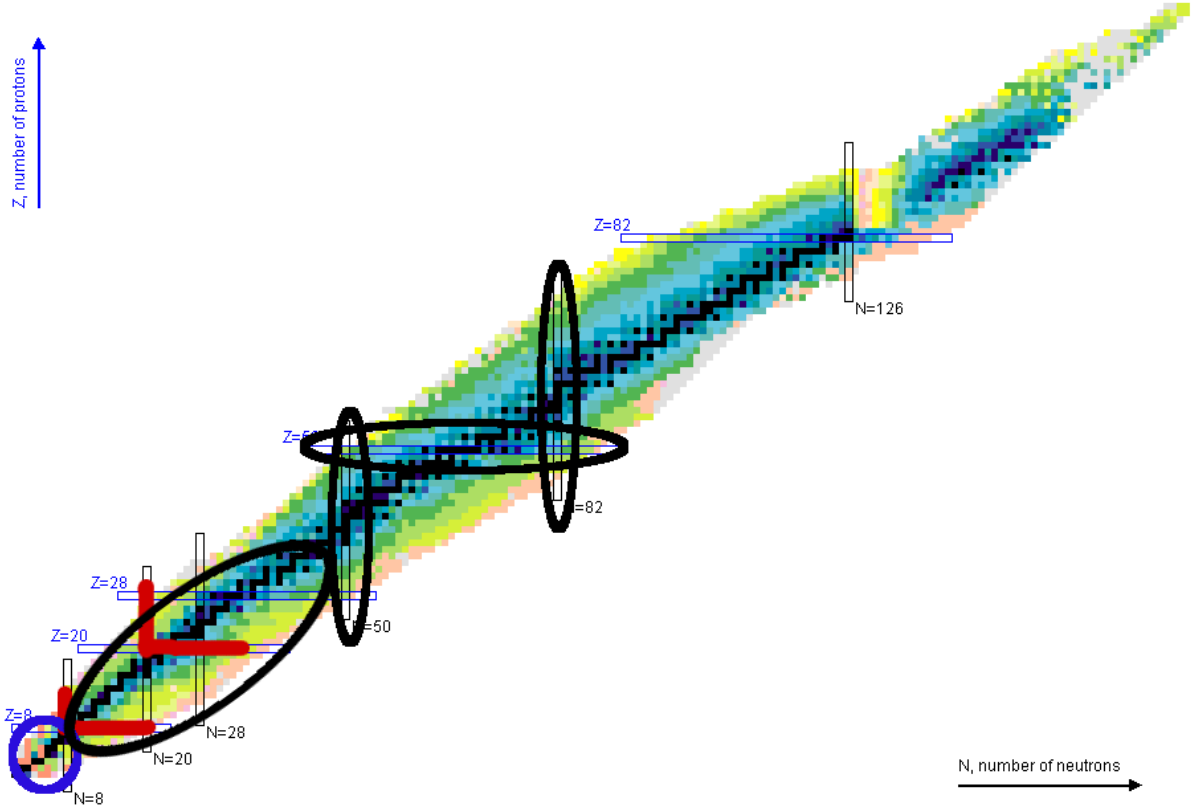
Nuclear Landscape



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

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

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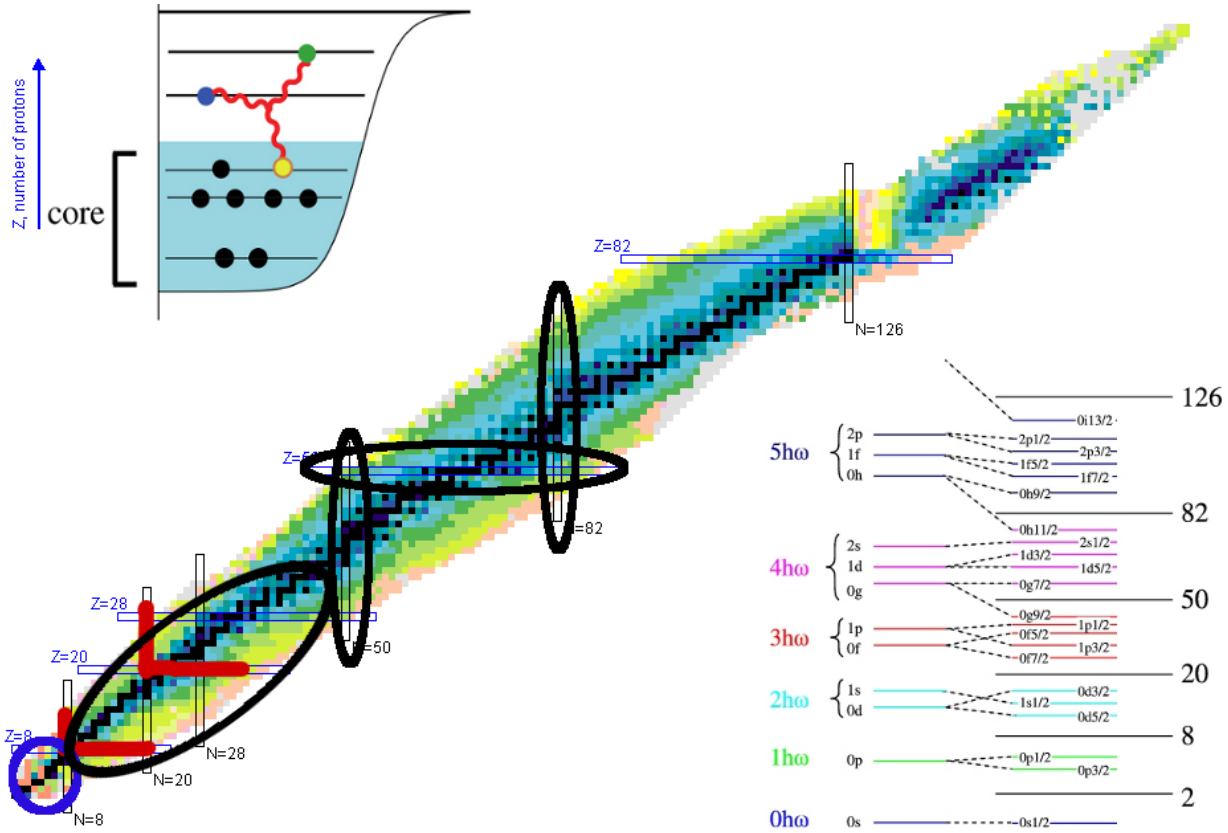

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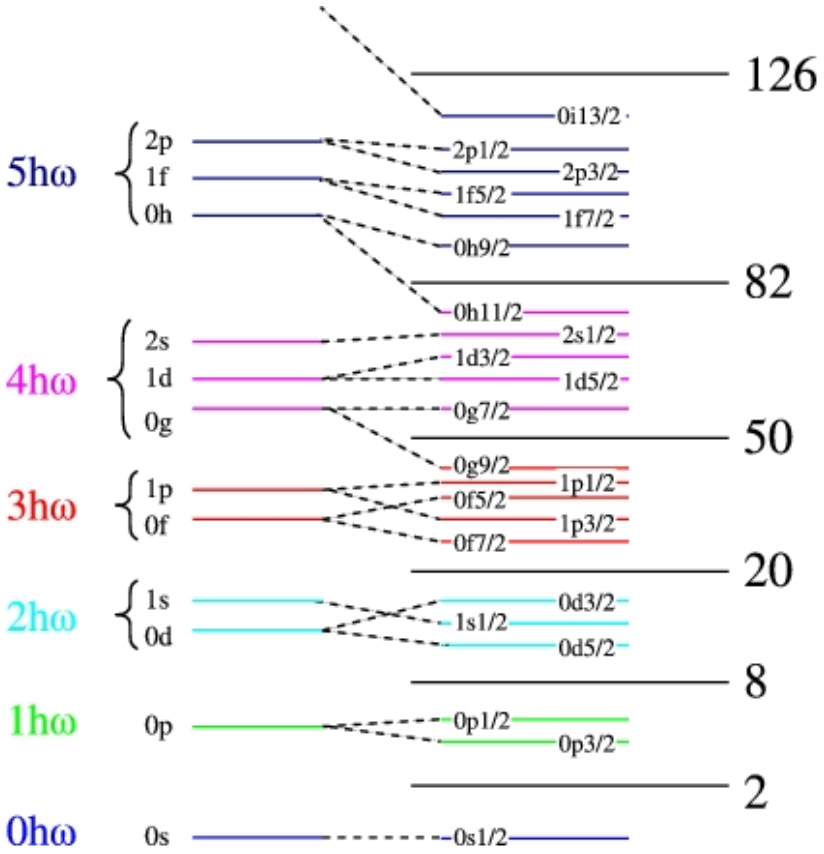
The Interacting Shell Model



Basis states 3D Harmonic Oscillator

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

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

Full diagonalization code ANTOINE Caurier et al. RMP77 427(2005)

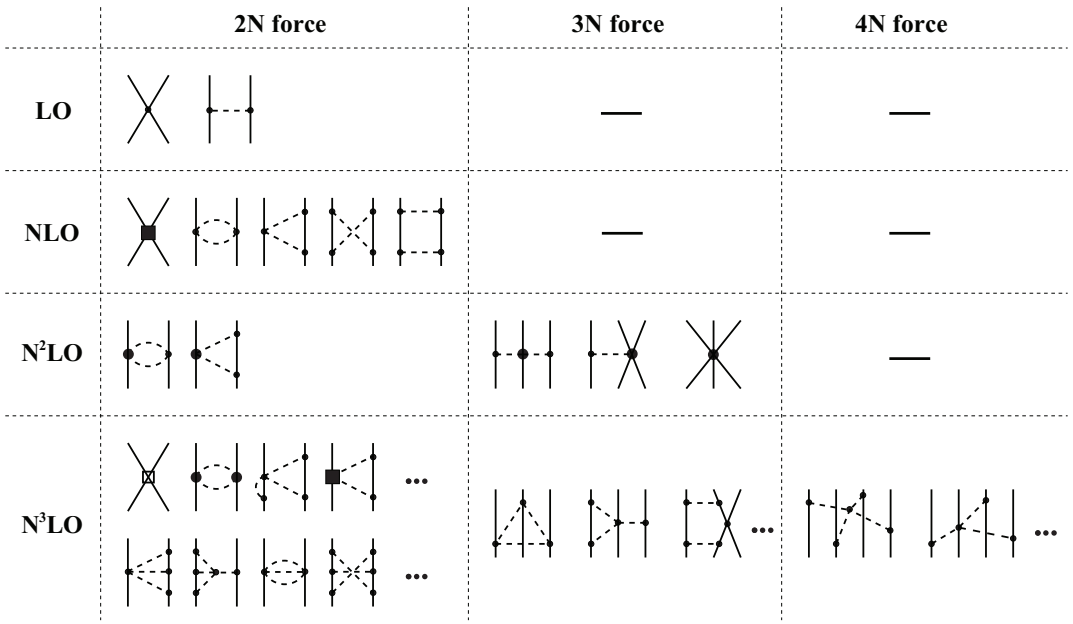
Forces and Currents in Chiral EFT

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 of nuclear forces



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

NN forces up to N^3LO

3N forces up to N^2LO

NN fitted to:

- NN scattering
- π-N scattering

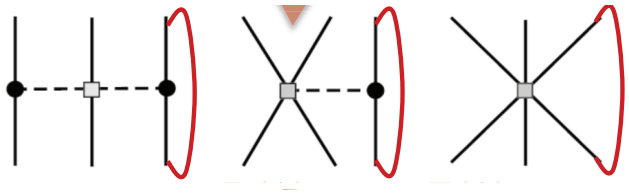
3N fitted to:

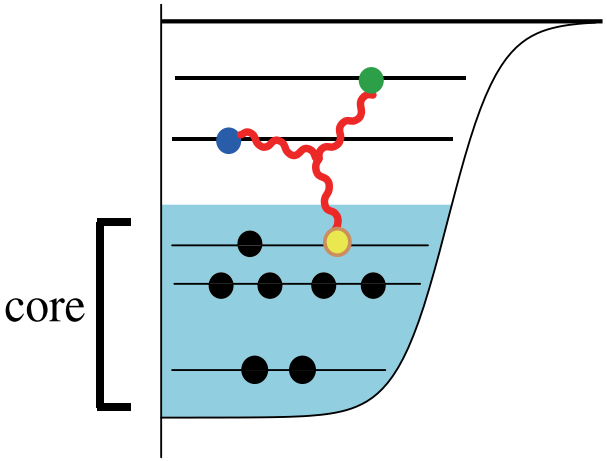
- ^{3}H Binding Energy
- ^{4}He radius

3N Forces

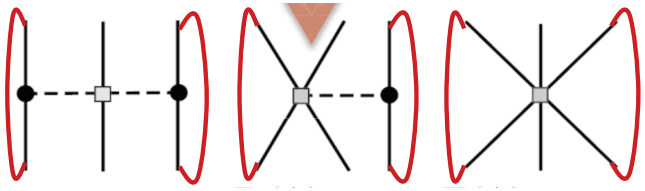
Treatment of 3N forces:

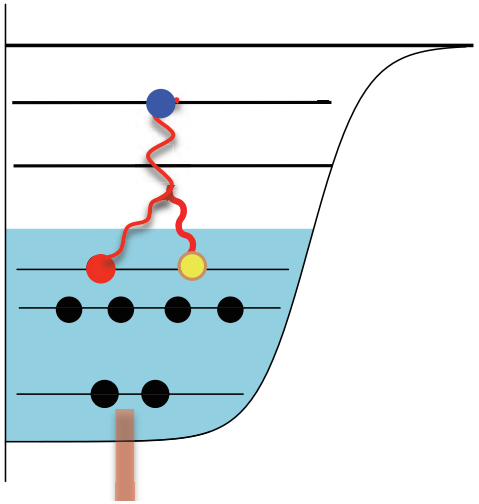
normal-ordered 2B: 2 valence, 1 core particle
⇒ (effective) Two-body Matrix Elements (TBME)





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



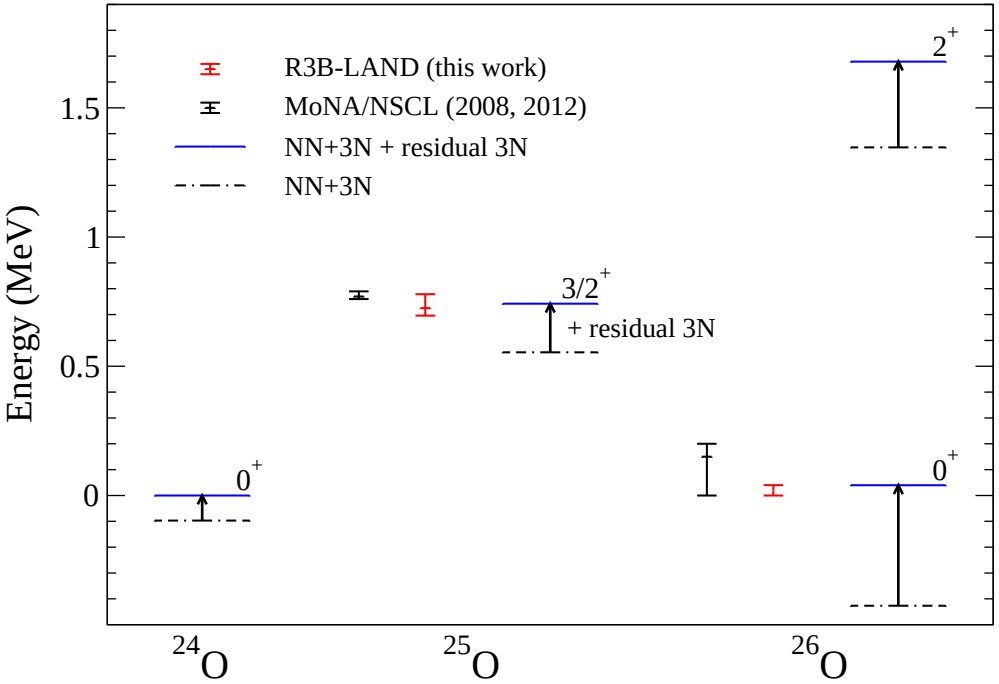


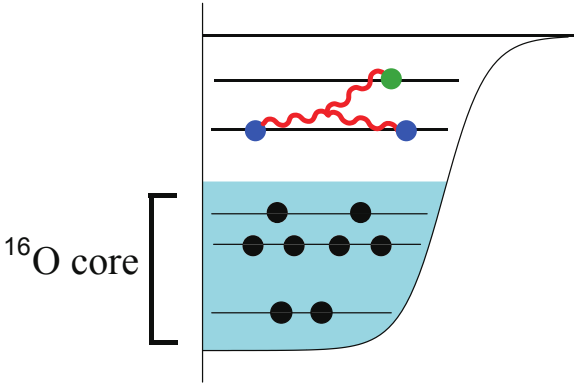
residual 3B:
⇒ Estimated to be suppressed by $N_{valence}/N_{core}$

Residual 3N Forces

Results with normal-ordered two-body part of 3N forces

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





Repulsive residual 3N contributions

Small compared to normal-ordered 3N force, but increase with N

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

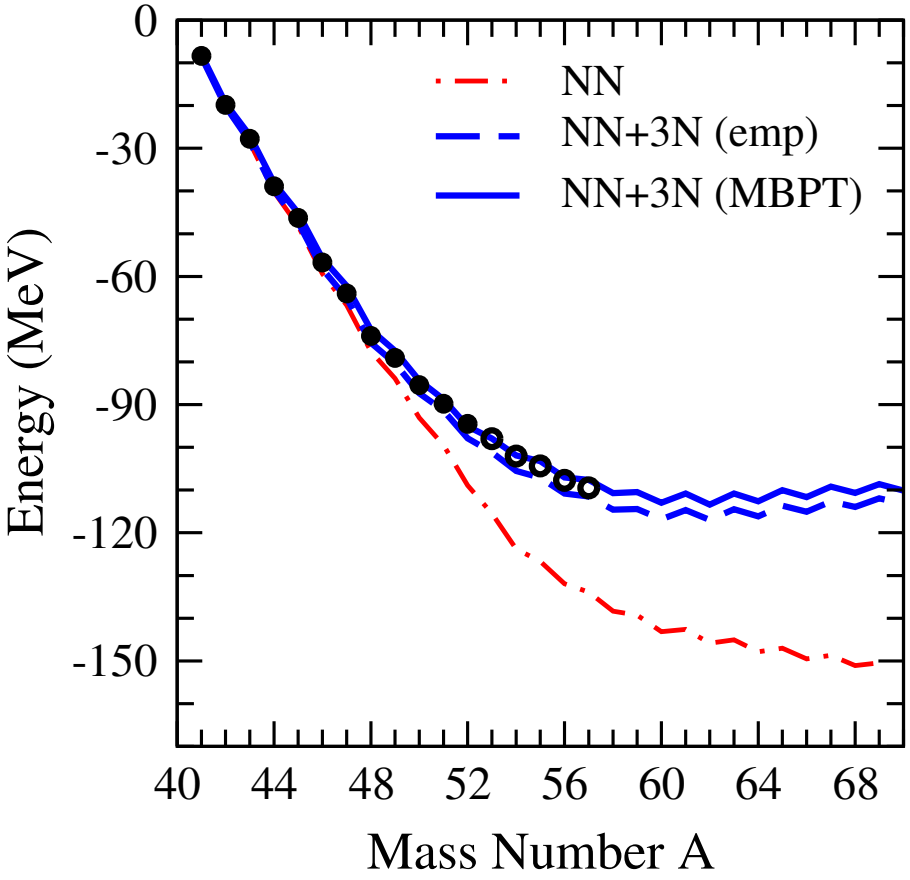
Caesar, Simonis et al

PRC88 034313 (2013)

Challenge: include continuum

Ca isotopes: Masses

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



Ca measured from ^{40}Ca core

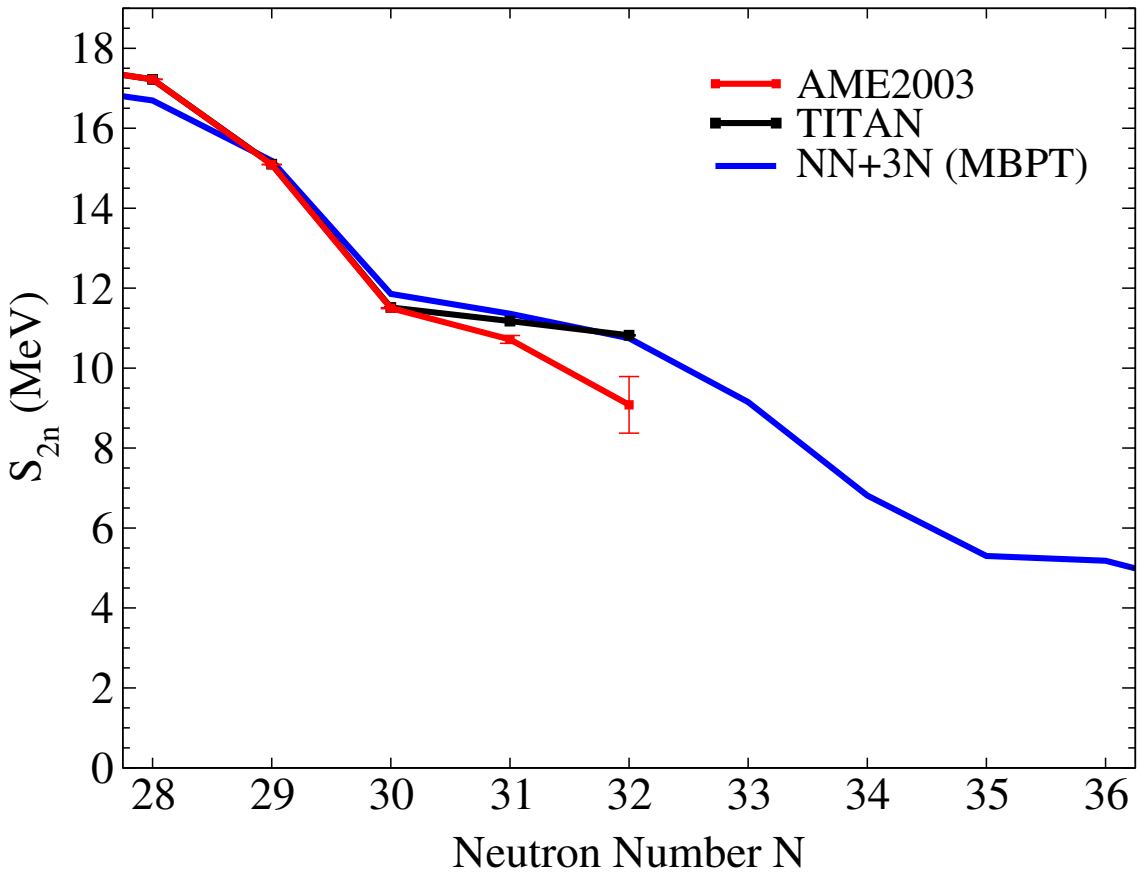
3N forces repulsive contribution, chiral NN-only forces too attractive

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

Sensitivity to SPEs
MBPT (calculated from NN+3N forces)
Empirical (from GXPF1 interaction)
Estimate of the uncertainty

Two-Neutron separation energies

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 behavior in ^{50}Ca–^{52}Ca

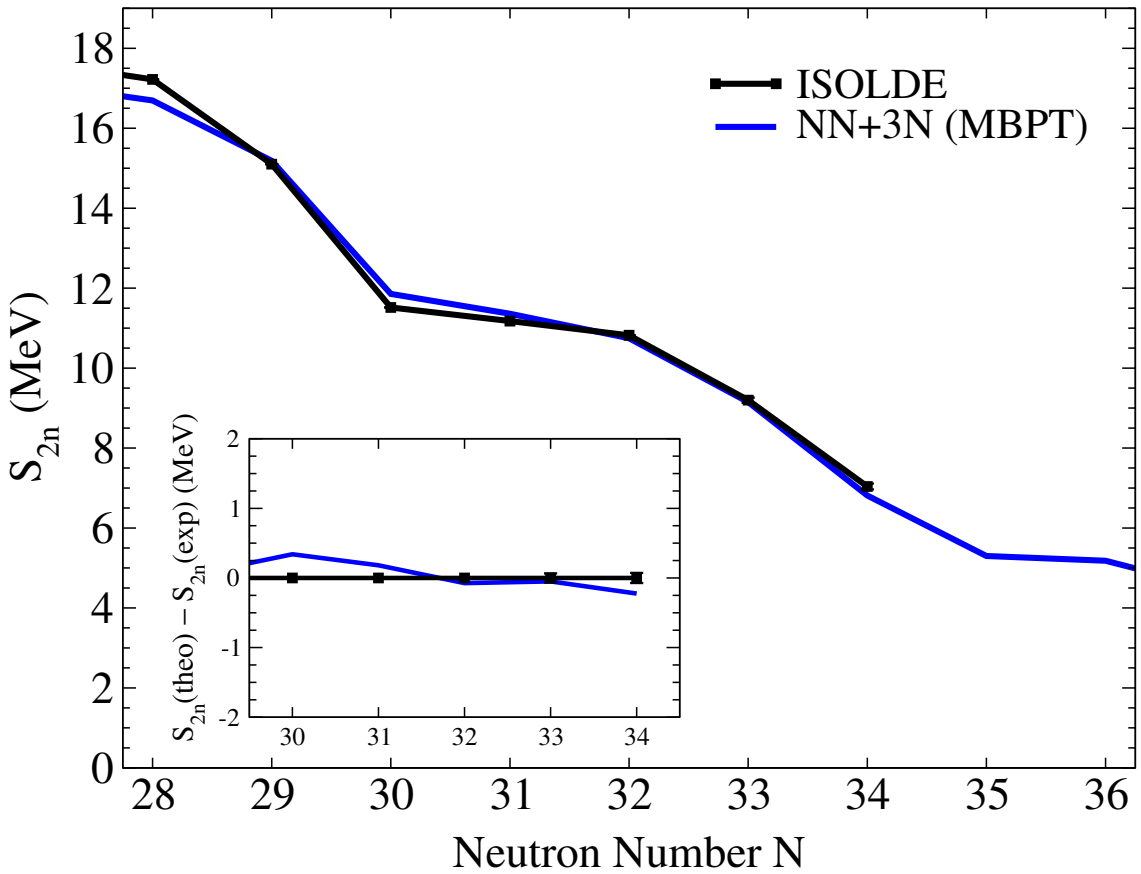
3N forces needed in theoretical calculation

Gallant et al.

PRL 109 032506 (2012)

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

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



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

Excellent agreement with theoretical prediction

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

Wienholtz et al.
Nature 498 346 (2013)

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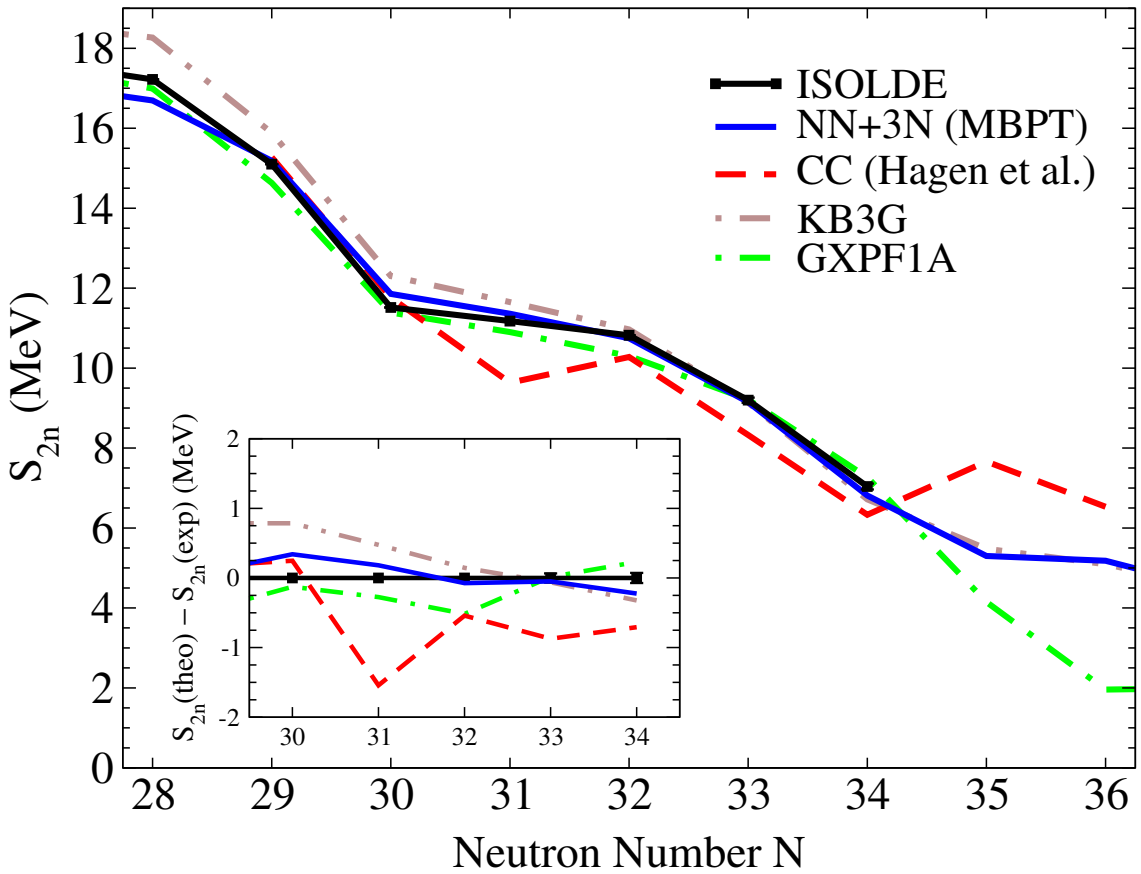


Phenomenology
masses/gaps as input, differ markedly beyond ^{54}Ca

Coupled-Cluster calculations
good agreement with adjusted 3N forces

Wienholtz et al.
Nature 498 346 (2013)

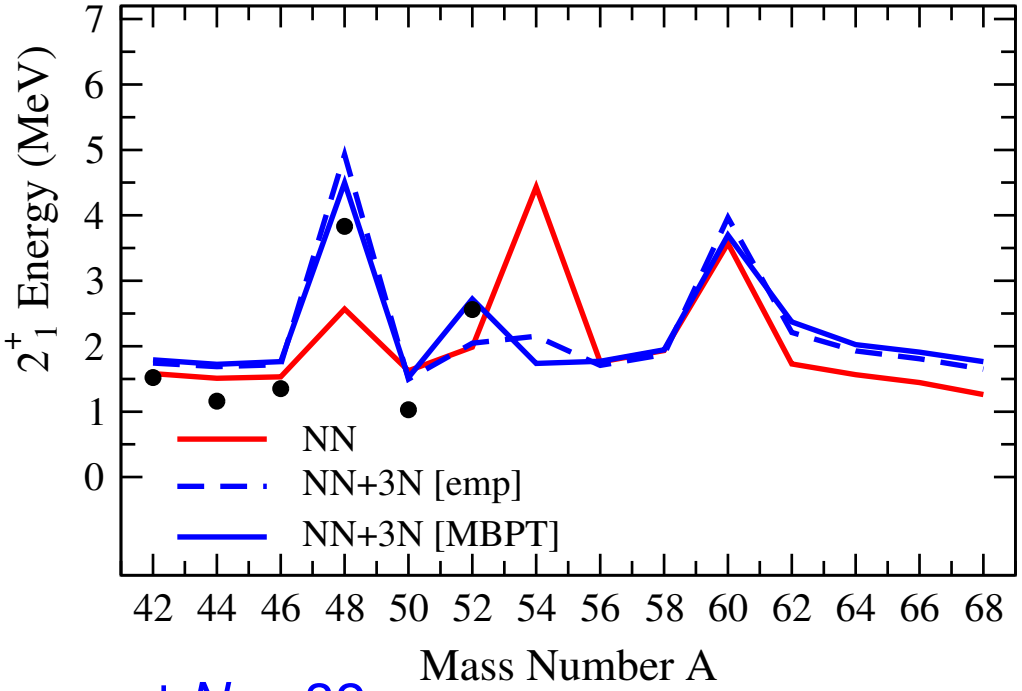
Shell closures and 2_1^+ energies

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)

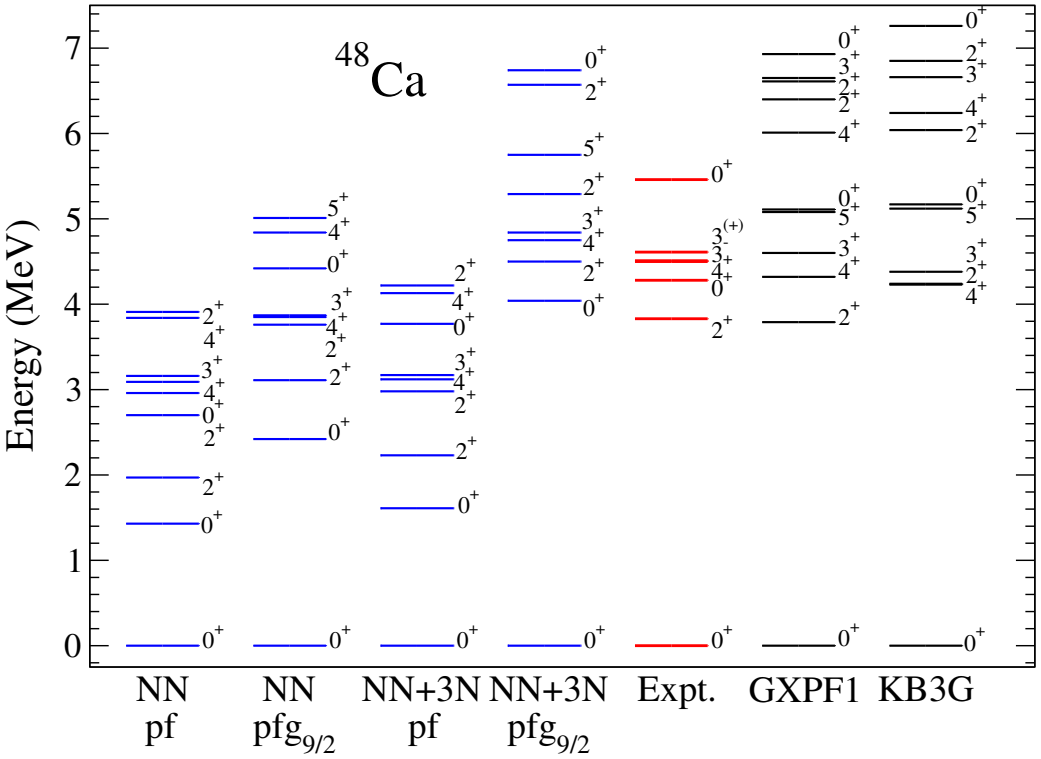


- 3N forces enhance closure at $N = 32$
- 3N forces reduce strong closure at $N = 34$ (1.7-2.2 MeV)
  Measured at 2.04 MeV, suggest $N = 34$ shell closure
  Steppenbeck et al. Nature 502 207(2013)

2_1^+ energy in ^{54}Ca complemented with mass measurements in ^{55,56}Ca confirm magic number $N = 34$ and test theoretical calculations

^{48}Ca spectrum

Challenge: doubly-magic nucleus ^{48}Ca,
$N = 28$ shell closure not reproduced with NN forces

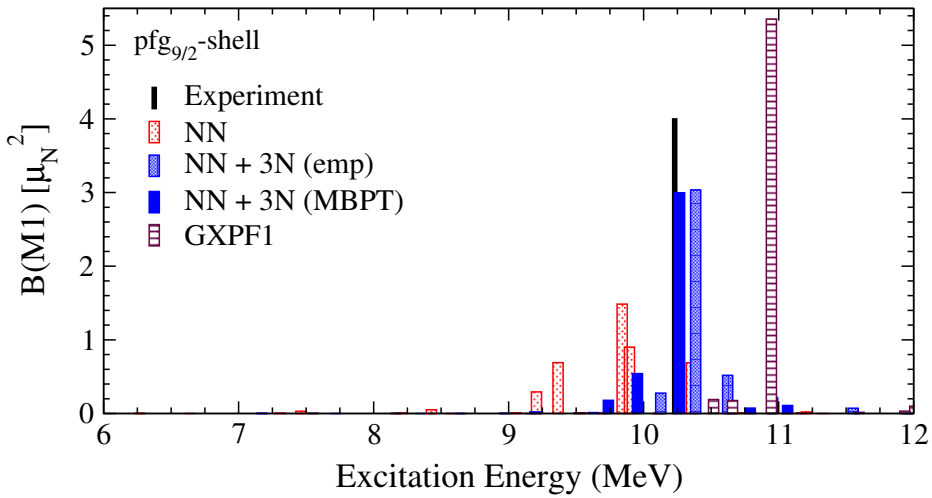


Spectra in reasonable overall agreement with experiment

2_1^+ state well reproduced, energy slightly too high

0_1^+ state too low especially compared to phenomenological interactions

B(M1) and B(E2) Transitions



B(M1) strength in ^{48}Ca too fragmented with NN forces

NN+3N good agreement with experiment strength and energy

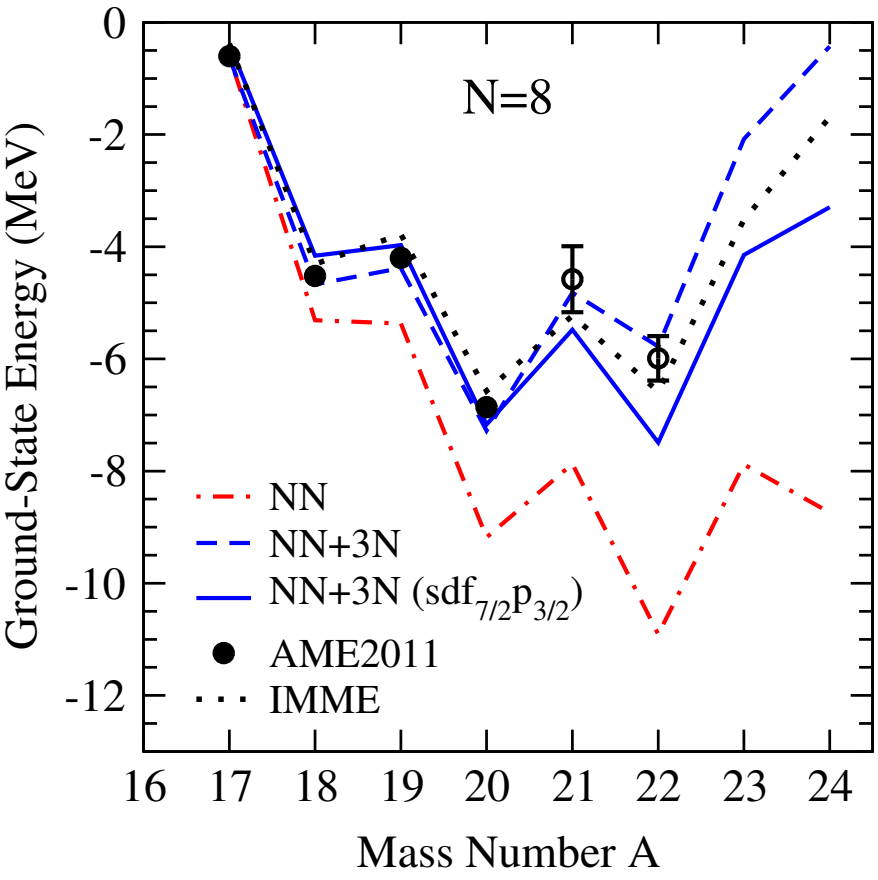
Comparable to phenomenology

B(E2)s in reasonable agreement with experiment

Similar quality as phenomenological interactions

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

Proton dripline at $N = 8$



Holt, JM, Schwenk PRL110 022502 (2013)

Compare NN+3N theory to isobaric mass-multiplet formula (IMME)

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

Isospin-symmetry breaking terms predicted by chiral EFT

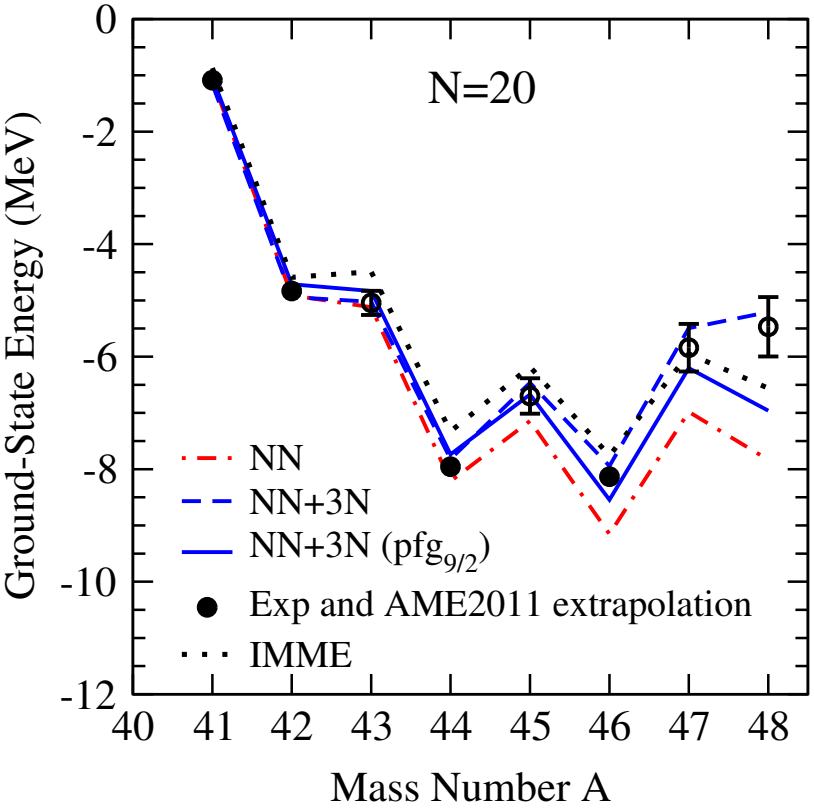
Coulomb included in calculations

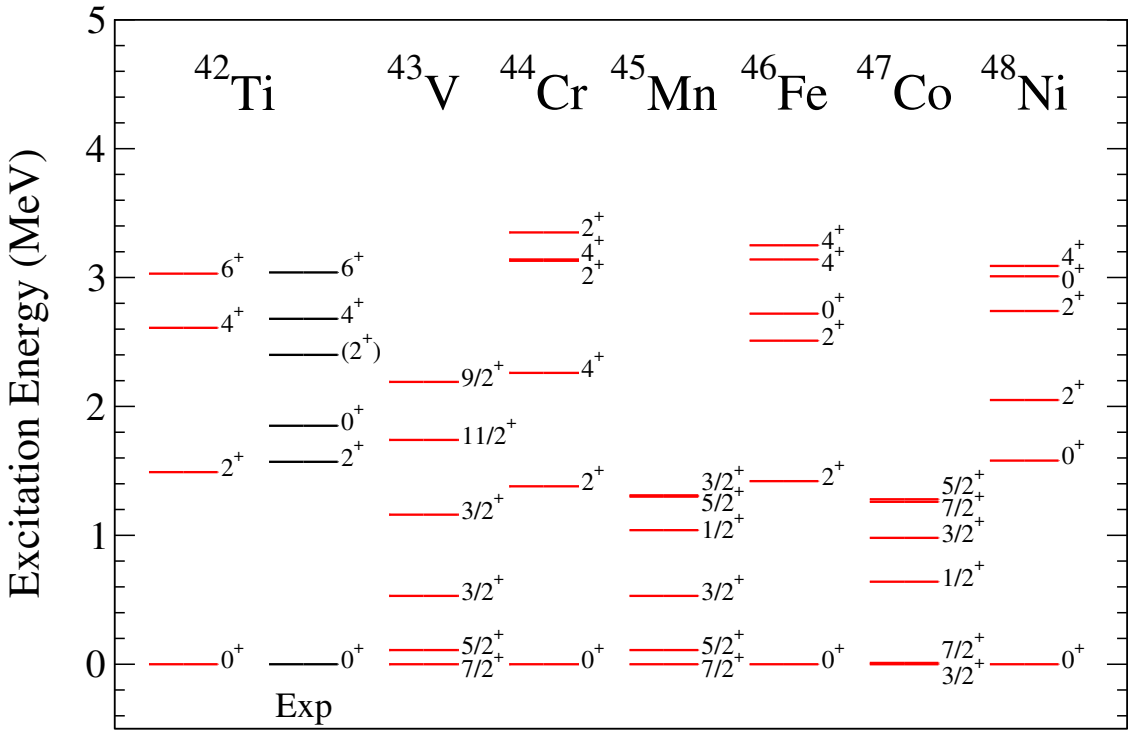
Proton dripline not certain predicted at ^{20}Mg or ^{22}Si:

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

Excitation spectra for N=8 isotones predicted: ^{20}Mg, ^{21}Al, ^{22}Si

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)

Spectra: ideal ground for spectroscopic studies

Summary and Outlook

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Shell Model based on chiral EFT (NN+3N forces)
Good agreement with experimental shell evolution and spectroscopy:

- 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) TBMEs

Explore uncertainties in the theoretical calculation

Collaborators

TECHNISCHE UNIVERSITÄT DARMSTADT

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

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

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