Role of the particle continuum and of three-nucleon forces in oxygen isotopes

Thomas Papenbrock

and Oak Ridge National Laboratory

Gaute Hagen (Oak Ridge),
Morten Hjorth-Jensen (Oslo/MSU)
Gustav Jansen (Oslo),
Ruprecht Machleidt (Moscow, Idaho)

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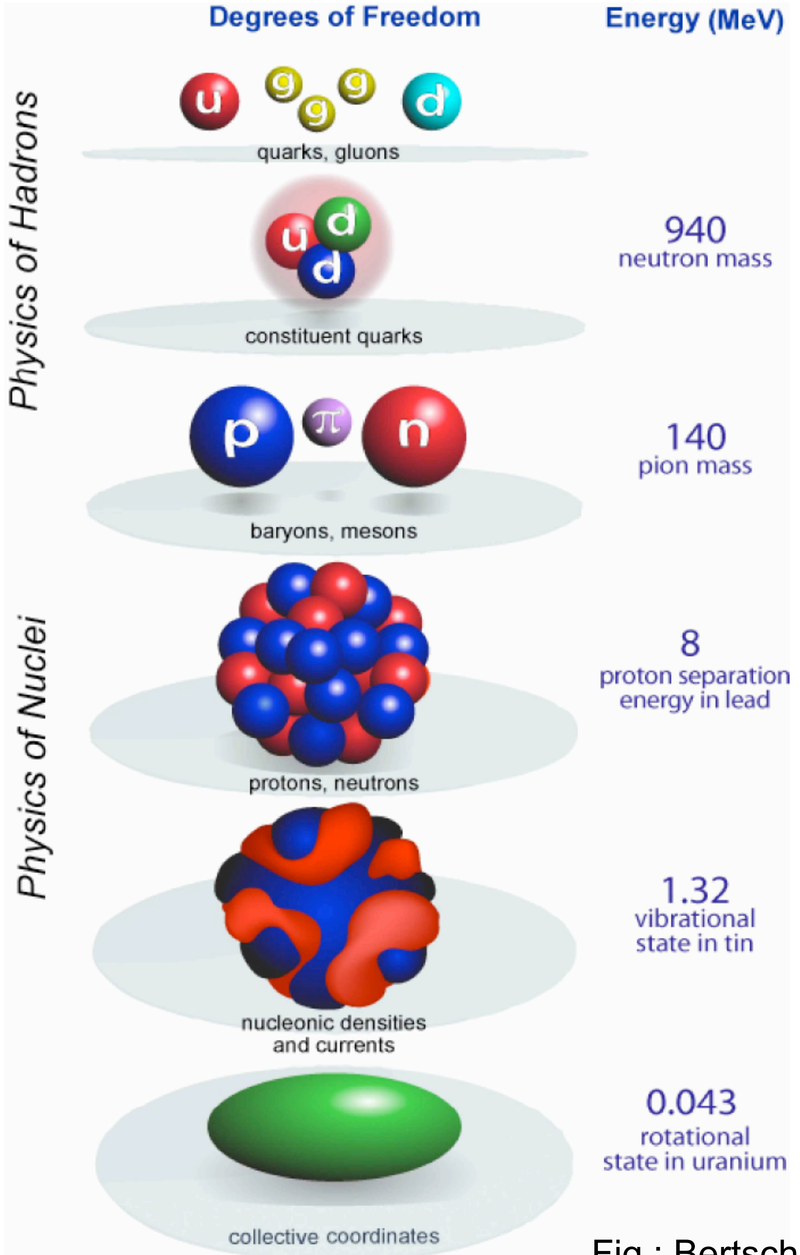
Overview

1. Introduction
2. Neutron-rich oxygen isotopes
3. Some comments on benchmark results
4. Summary

Energy scales and relevant degrees of freedom

Energy



Chiral effective field theory

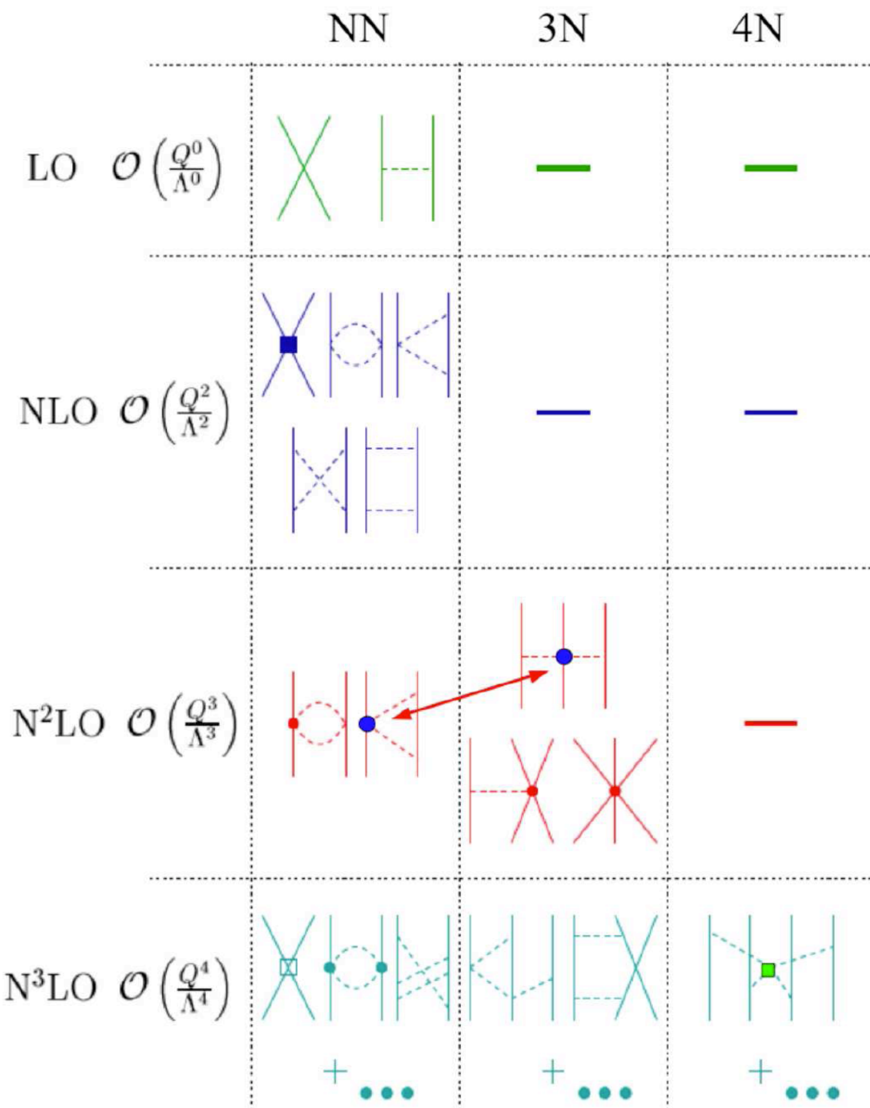
Effective theories provide us with model-independence

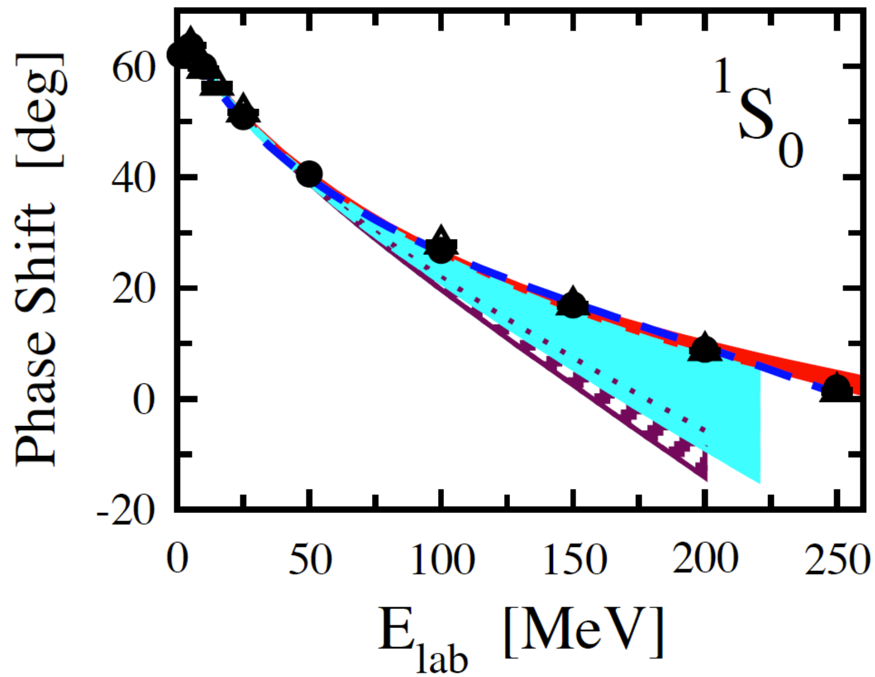
Effective theory of deformed nuclei

Fig.: Bertsch, Dean, Nazarewicz, SciDAC review (2007)

Nuclear forces from chiral effective field theory

[Weinberg; van Kolck; Epelbaum, Krebs, Meissner; Entem & Machleidt; …]





[Epelbaum, Hammer, Meissner RMP 81, 1773 (2009)]

Low energy constants from fit of NN data, A=3,4 nuclei, or light nuclei.

Is ^{28}O a bound nucleus?

Experimental situation

- "Last" stable oxygen isotope ^{24}O
- ^{25}O unstable (Hoffman et al 2008)
- ^{26}O unstable (Lunderberg et al 2012)
- ^{31}F exists (adding on proton shifts drip line by 6 neutrons!?)

Theoretical description challenging (proximity of continuum, 3NFs, subtle effects)

- Continuum shell model [Volya & Zelevinsky, PRL 94, 052501 (2005)]
- Chiral NN interactions [Hagen et al., PRC 80, 021306 (2009)].
- Effects of 3NFs [Otsuka, Suzuki, Holt, Schwenk, Akaishi, PRL 105, 032501 (2010)]
- More complete calculation necessary (3NFs, continuum, large model space, minimum adjustments to interaction)

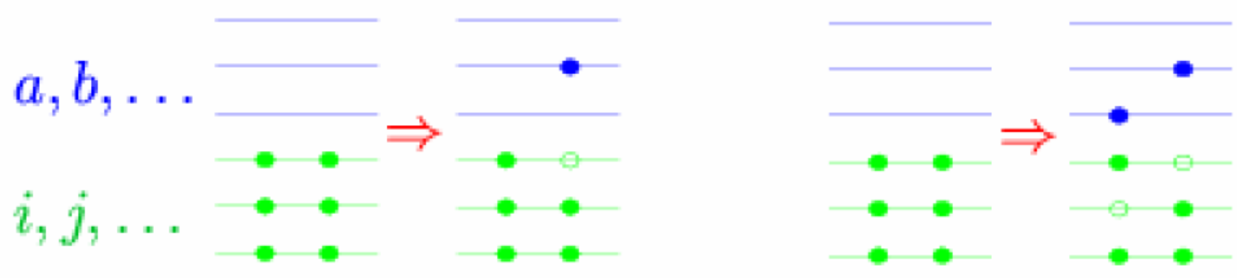
Coupled-cluster method (in CCSD approximation)

Ansatz:

$$
\begin{aligned}
|\Psi\rangle &= e^{T}|\Phi\rangle \\
T &= T_1 + T_2 + \ldots \\
T_1 &= \sum_{ia} t_i^a a_a^\dagger a_i \\
T_2 &= \sum_{ijab} t_{ij}^{ab} a_a^\dagger a_b^\dagger a_j a_i
\end{aligned}
$$

- ☺ Scales gently (polynomial) with increasing problem size o^2u^4 .
- ☺ Truncation is the only approximation.
- ☺ Size extensive (error scales with A)
- ☹ Most efficient for doubly magic nuclei

Correlations are *exponentiated* 1p-1h and 2p-2h excitations. Part of np-nh excitations included!



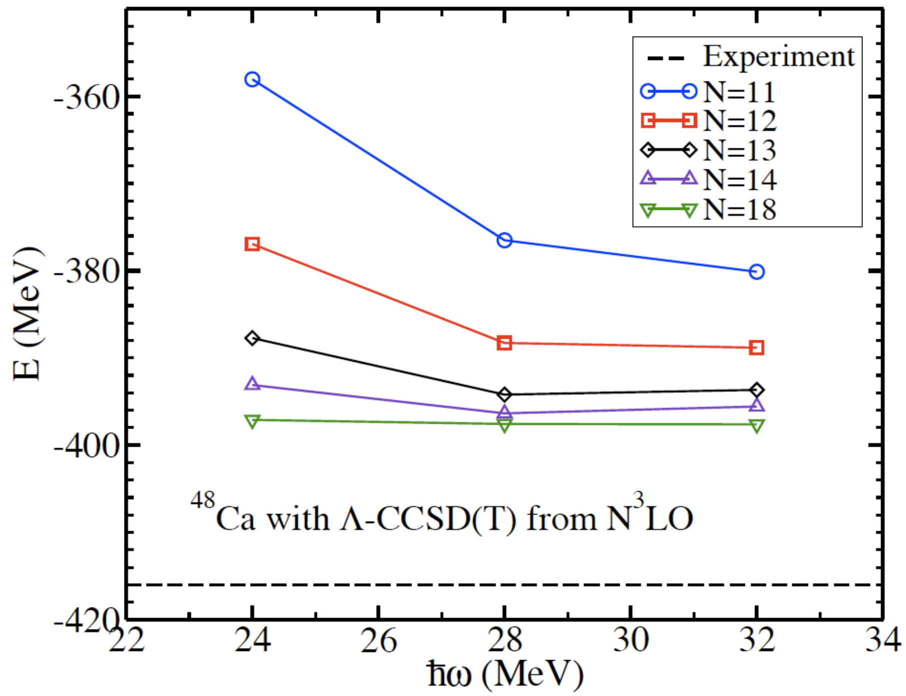
Coupled cluster equations

$$
\begin{aligned}
E &= \langle \Phi | \overline{H} | \Phi \rangle \\
0 &= \langle \Phi_i^a | \overline{H} | \Phi \rangle \\
0 &= \langle \Phi_{ij}^{ab} | \overline{H} | \Phi \rangle
\end{aligned}
$$

Alternative view: CCSD generates similarity transformed Hamiltonian with no 1p-1h and no 2p-2h excitations.

$$
\overline{H} \equiv e^{-T} H e^{T} = \left(He^{T}\right)_c = \left(H + HT_1 + HT_2 + \frac{1}{2}HT_1^2 + \ldots\right)_c
$$

Toward medium-mass nuclei
Chiral N^{3}LO (500 MeV) by Entem & Machleidt, NN only



Binding energy per nucleon

Nucleus	CCSD	Λ-CCSD(T)	Experiment
^{4}He	5.99	6.39	7.07
^{16}O	6.72	7.56	7.97
^{40}Ca	7.72	8.63	8.56
^{48}Ca	7.40	8.28	8.67

- Chiral NN forces yield saturation, lack about 0.4 MeV per nucleon in binding energy.
- Chiral three-nucleon forces expected to yield 0.4 MeV per nucleon?!

Our CC results for ^{16}O are confirmed by UMOA [Fujii et al., PRL 103, 182501 (2009)] and by IT-NCSM [R. Roth et al., PRL 107, 072501 (2011)]

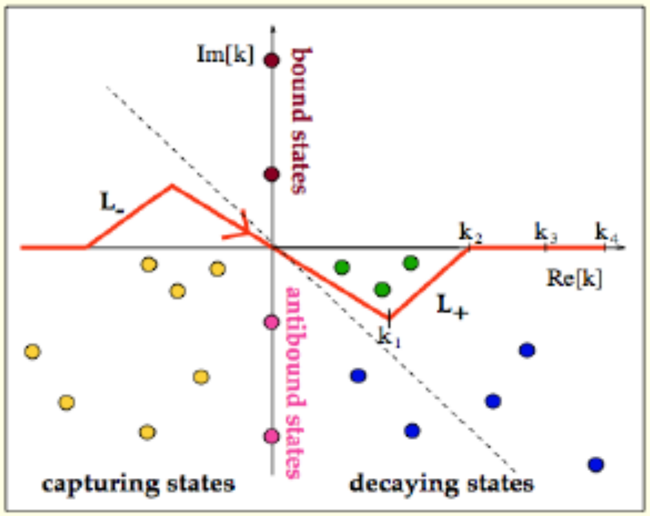
	CCM	(IT)-NCSM	UMOA
	E/A	E/A	E/A
^{4}He	-6.39(5)	-6.35	
^{16}O	-7.56(8)	-7.48(4)	-7.47

[Hagen, TP, Dean, Hjorth-Jensen, PRL 101, 092502 (2008)]

Gamow shell model

Gamow states and completeness relations

T. Berggren, Nucl. Phys. A109, 265 (1968); Nucl. Phys. A389, 261 (1982)
T. Lind, Phys. Rev. C47, 1903 (1993)

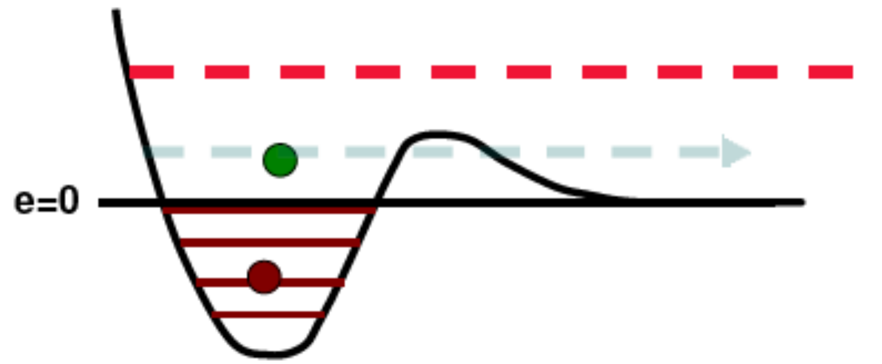


$$\sum_{n=b,r} |u_n\rangle\langle\tilde{u}_n| + \frac{1}{\pi}\int_{L_+} |u(k)\rangle\langle u(k^*)|\, dk = 1$$

particular case: Newton completeness relation

$$\sum_{n=b} |u_n\rangle\langle\tilde{u}_n| + \frac{1}{\pi}\int_{R} |u(k)\rangle\langle u(k^*)|\, dk = 1$$

(N. Michel *et al*, PRL 89 (2002) 042502)



complex-symmetric eigenvalue problem for hermitian hamiltonian

Review: Michel et al, J. Phys. G 36, 013101 (2009)

How to economically include the effects of 3NFs?

Monopole shifts of shell-model interactions from 3NF as density-dependent NN force. [A.Zuker, PRL 90, 42502 (2003)]

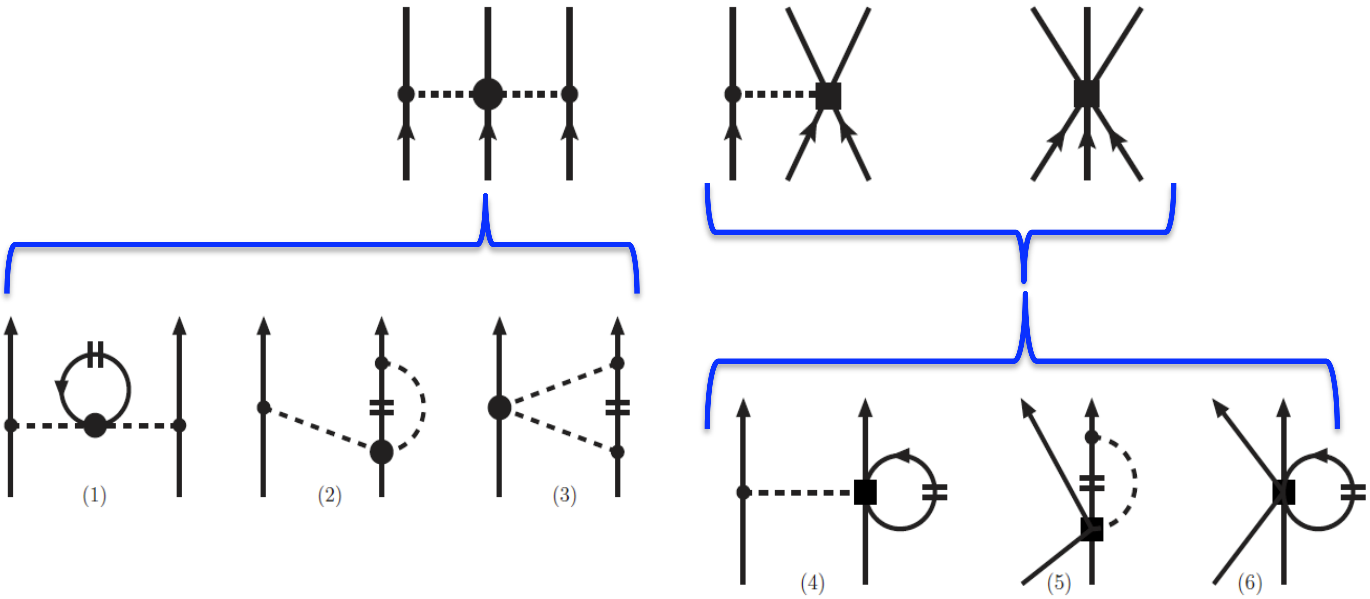
3NFs included as normal-ordered contributions [Hagen, TP, Dean, Schwenk, Nogga, Wloch, Piecuch, PRC 76, 034302 (2007); Hebeler & Schwenk PRC 82, 014314 (2010); J.W. Holt, Kaiser, Weise PRC, 024002 (2010); Otsuka, Suzuki, J. D. Holt, Schwenk, Akaishi, PRL 105 032501 (2010)]

In-medium modifications of NN interactions (Brown-Rho scaling) [J. W. Holt, Brown, Kuo, J. D. Holt, Machleidt, PRL 100, 062501 (2008)]

Our approach: In-medium modifications of NN forces, inspired by EFT

Including the effects of 3NFs

[J.W. Holt, Kaiser, Weise, PRC 81, 024002 (2010); Hebeler & Schwenk, PRC 82, 014314 (2010)]



3NFs as in-medium effective two-nucleon forces

Parameters: k_F=1.0 fm^{-1}, c_E=0.7, c_D = -0.2 from binding energies of $^{16,22}O$

Rationale: The integration over symmetric nuclear matter is an approximation for finite nuclei and for nonzero isospin. Tuning of parameters generates corrections and takes into account higher-order effects.

Can one do this?

Q1: Should one not keep the low-energy coefficients c_E, c_D as determined in light systems?

A1: The summation over symmetric nuclear matter is an approximation for finite nuclei, and adjustments in c_E aim to correct for this approximation.

Q2: What about the combinatorial factors [Hebeler & Schwenk 2010]?

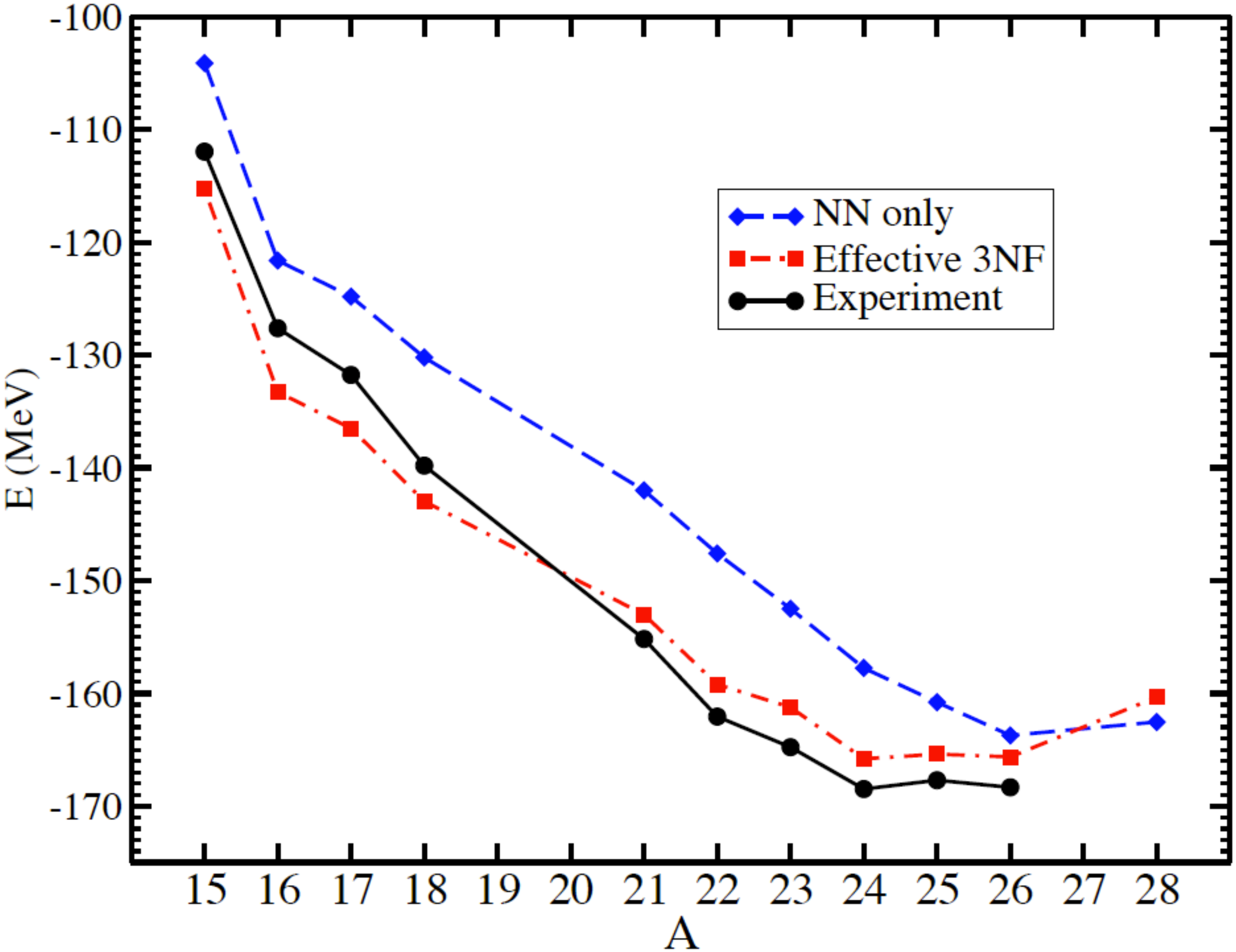
A2: A1

Q3: Will this work in ^{4}He?

A3: This approximation is probably limited to heavier nuclei.

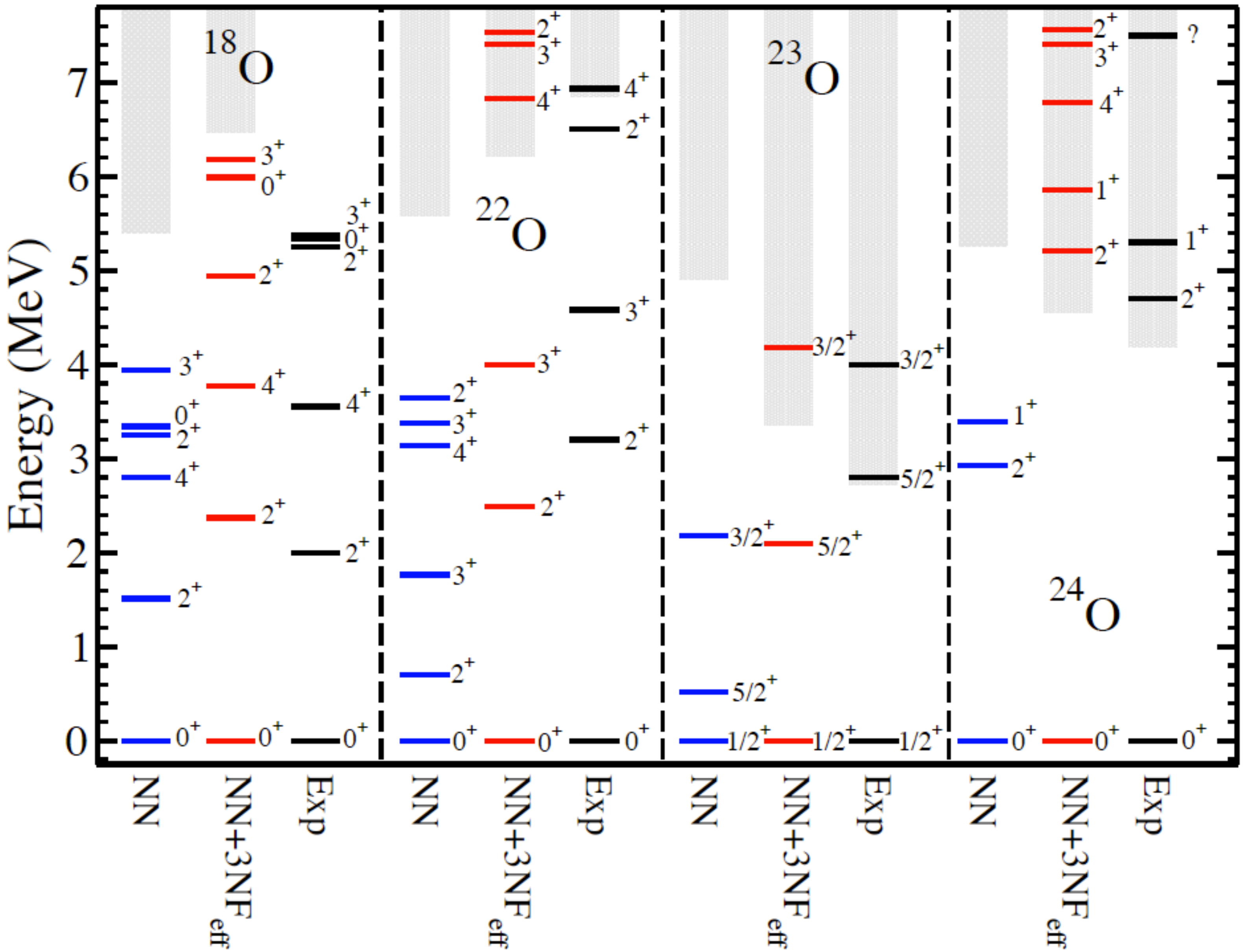
Let's see, to what extent this works in practice.

Ground-state energies of oxygen isotopes



Hagen, Hjorth-Jensen, Jansen, Machleidt, TP, arXiv:1202.2839

Spectra (1p-1h excitations only)

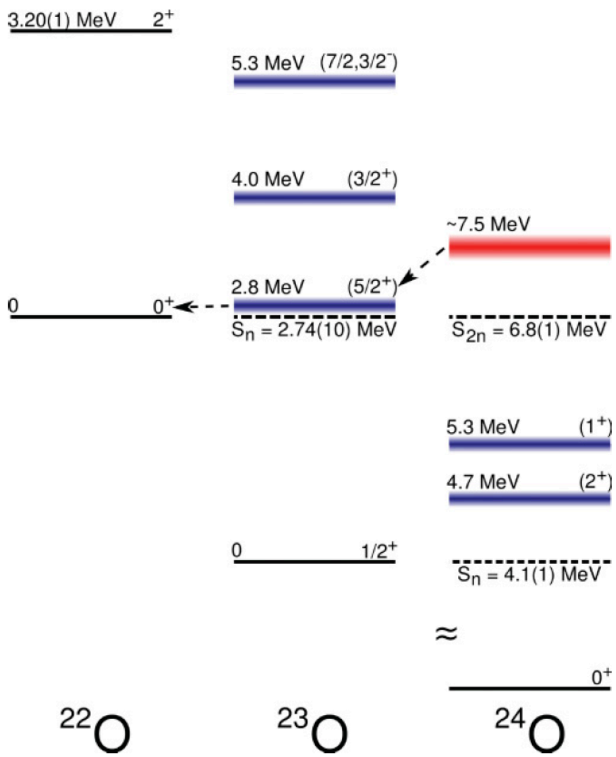


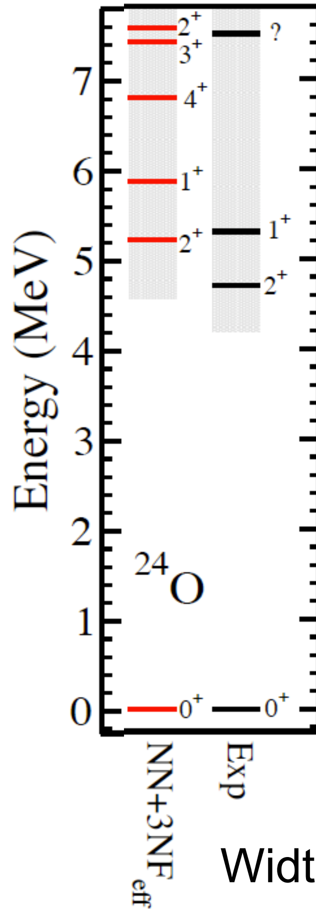
Hagen, Hjorth-Jensen, Jansen, Machleidt, TP, arXiv:1202.2839

Excited states in ^{24}O

Experiment

[Hoffman et al. PRC 83, 031303 (2011)] Unbound states in ^{24}O populated by knockout from ^{26}F. Observation of ^{22}O and two-neutron cascade. Speculation: single resonance or superposition of states with $J^\pi = 1^+$ to 4^+.





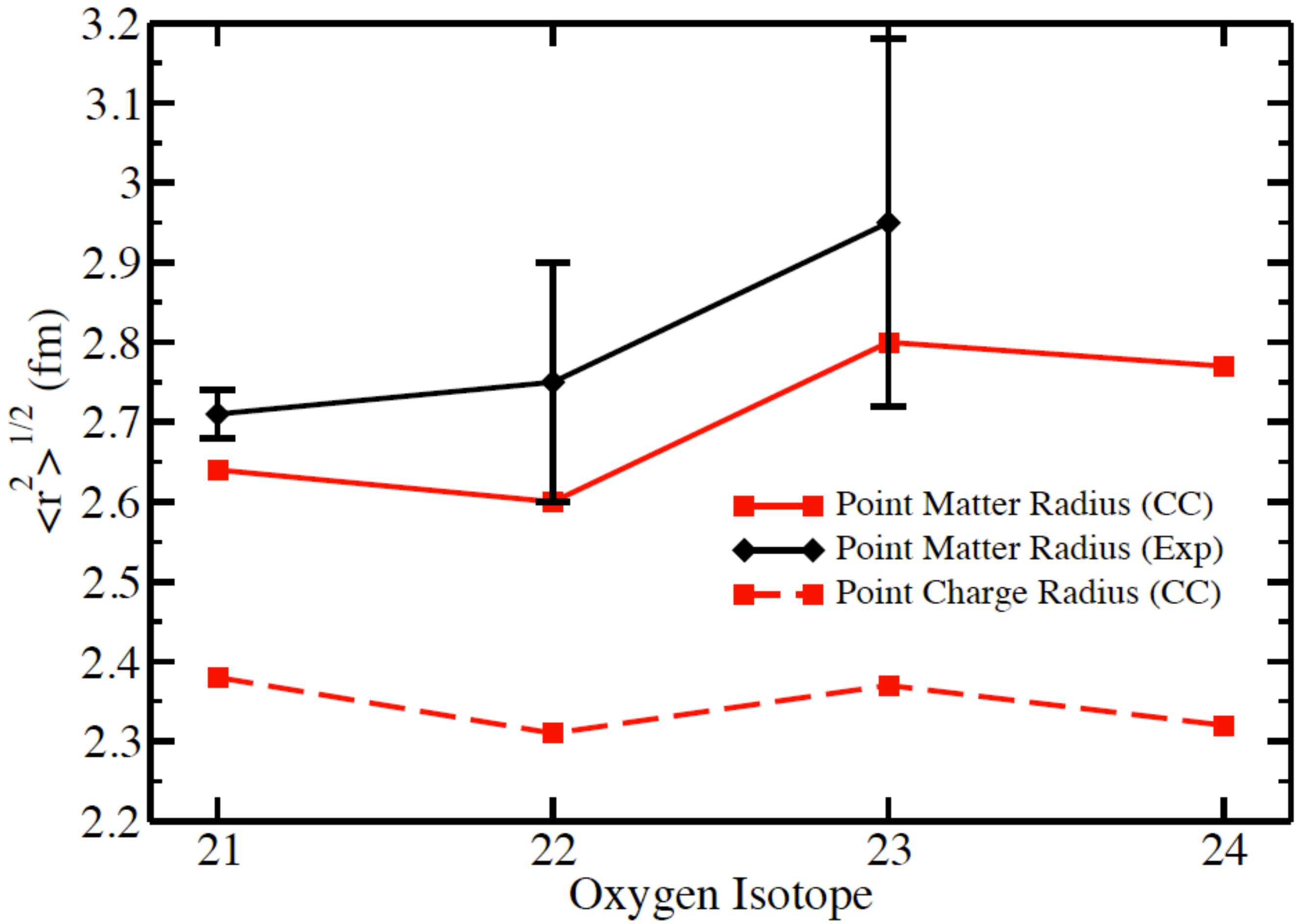
Theory

Experiment has seen superposition of states with $J^\pi = 2^+$ to 4^+.

Widths agree well with available data

J^π	2_1^+	1_1^+	4_1^+	3_1^+	2_2^+	1_2^+
E_{CC}	5.2	5.9	6.8	7.4	7.6	8.9
E_{Exp}	4.7(1)	5.33(10)				
Γ_{CC}	0.03	0.05	0.006	0.02	0.04	0.57
Γ_{Exp}	$0.05^{+0.21}_{-0.05}$	$0.03^{+0.12}_{-0.03}$				

Matter and charge radii



Data: [Ozawa et al., NPA 693, 32 (2001); Kanungo et al., PRC 84, 061304(R) (2011)]

Summary & Outlook

- Proposed and tested efficient approximation for the inclusion of 3NFs; in keeping with spirit of EFT and a sense of reality
- Much-improved binding energies, separation energies, and spectra
- ^{24}O is dripline nucleus with several long-lived resonances at ~7 MeV of excitation energy
- Continuum effects yield about 0.3 MeV of additional binding for resonances and bound states close to threshold

- Progress in computational capabilities since 2001 benchmark
- Agreement on error estimates necessary for credibility and impact