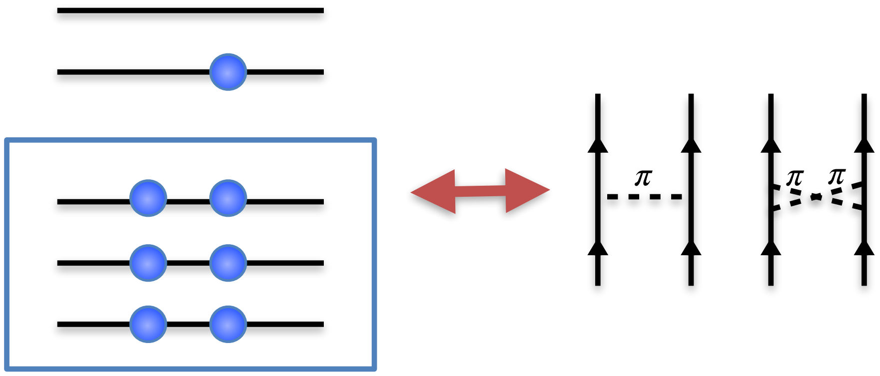
Towards a microscopic understanding of the shell model

Status and open questions

or

“Deriving the ad hoc, ab initio”

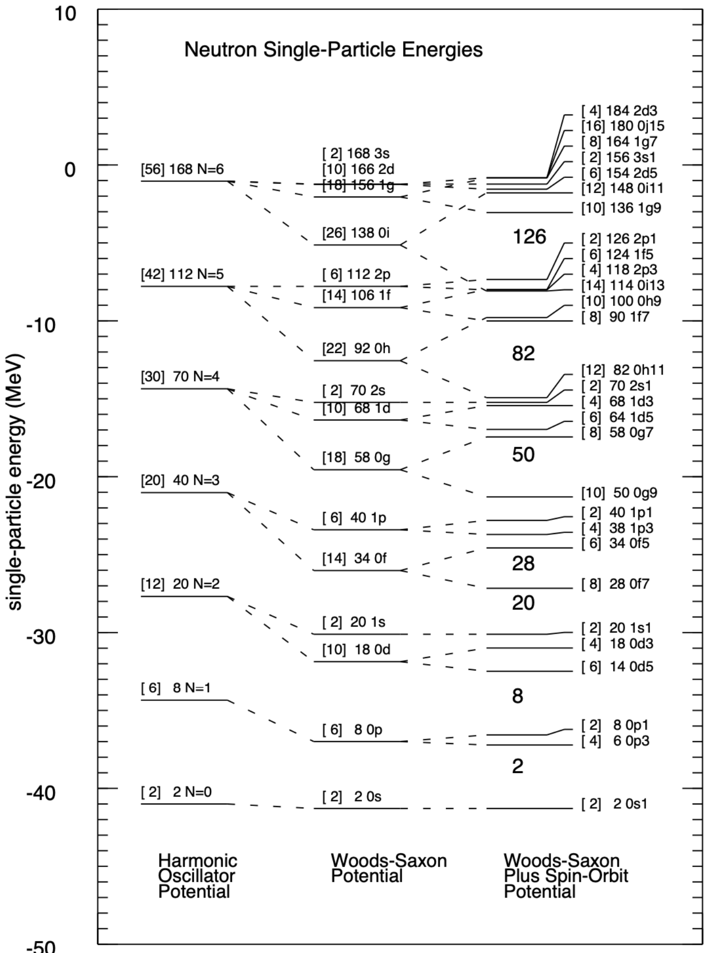


Ragnar Stroberg
University of Notre Dame

Symposium Celebrating 75 years
of The Shell Model and Maria Goeppert-Mayer
Argonne National Laboratory
July 18, 2024

Outline

- Origin of one-body spin-orbit potential
- Needed phenomenological adjustments to shell model interactions
- Effective charges for E2
- Calcium radii
- M1 moments, GT quenching



from Alex Brown's lecture notes

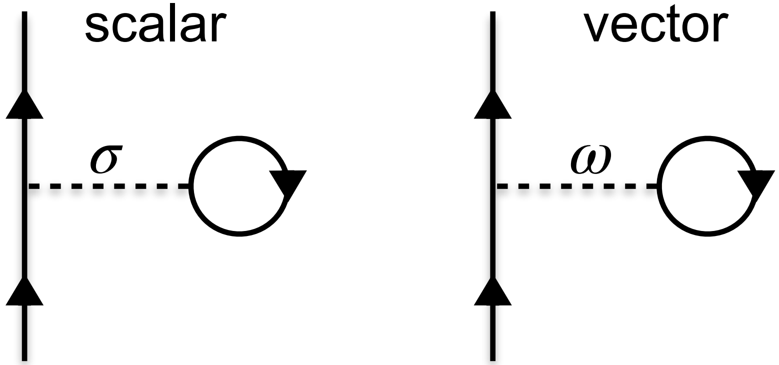
The spin-orbit potential

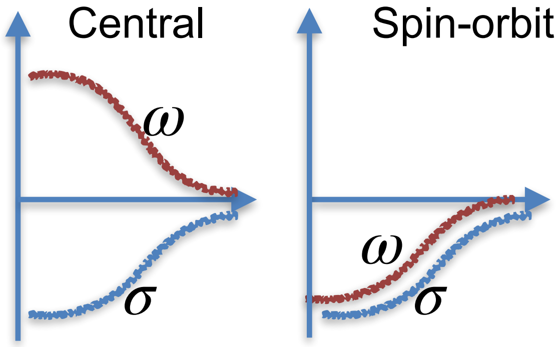
nobelprize.org

"**There is no adequate theoretical reason for the large observed value of the spin orbit coupling.** The Thomas splitting has the right sign, but is utterly inadequate in magnitude to account for the observed values. A proper type of meson potential can be made to predict splitting qualitatively similar to the Thomas splitting, and therefore qualitatively similar to the observed, but greater in magnitude than the Thomas splitting, although usually somewhat less than the observed value."

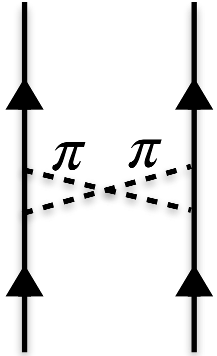
M. Goeppert Mayer, Physics. Rev. 78, 1 (1950)

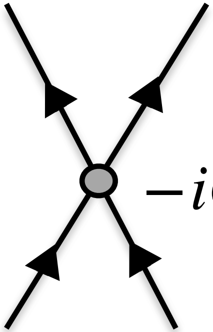
RMF:





EFT:





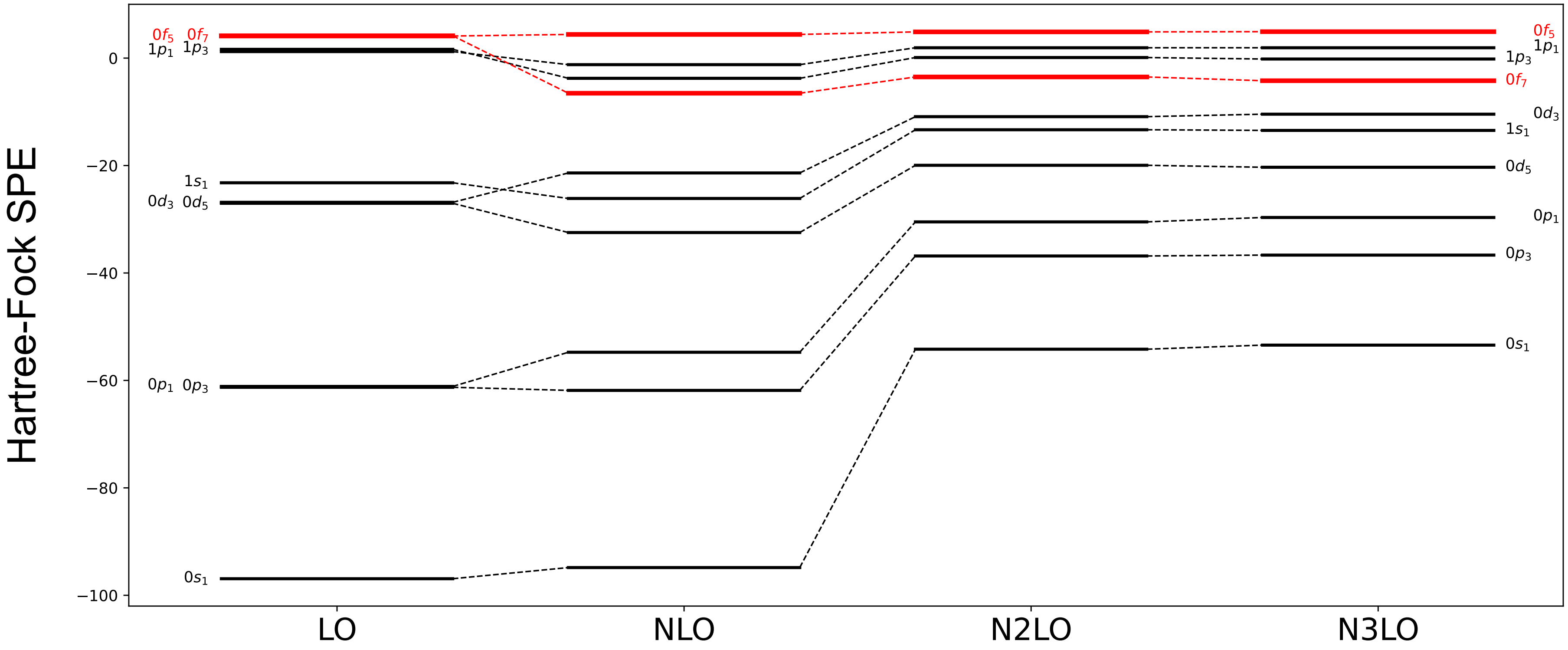
$-iC_5\vec{S}\cdot[\vec{q}\times\vec{k}]+\ldots$

NLO

also some contributions from 3N at N2LO

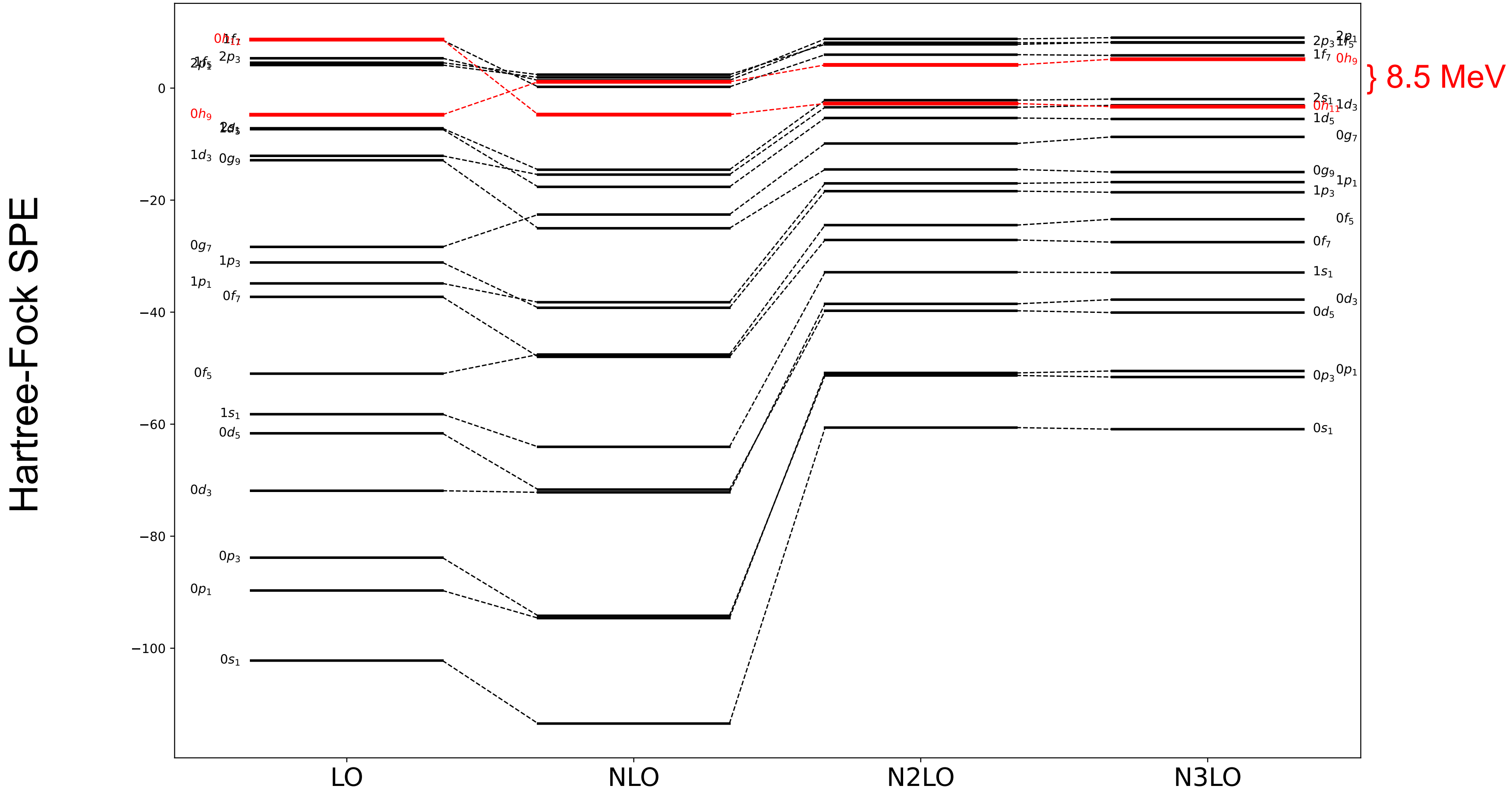
neutrons in ^{40}Ca

EMN 500 NN+3N



neutrons in ^{132}Sn

EMN 500 NN+3N



Phenomenological Adjustments to Shell Model Interactions

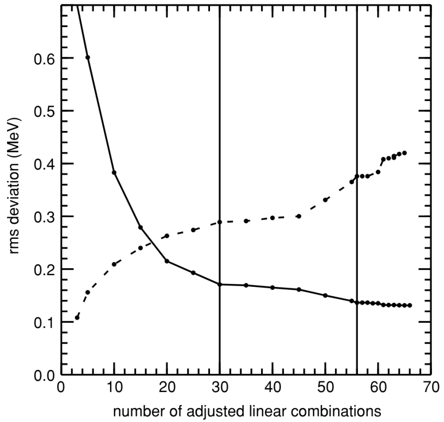
Fit single particle energies

Fit *all* TBMEs or SVD, fit most important combinations

Adjust monopoles only

$$\overline{V}_{ab} = \frac{\sum_J (2J+1) V^J_{abab}}{\sum_J (2J+1)}$$

Scale TBMEs by $A^{-1/3}$



VOLUME 90, NUMBER 4 PHYSICAL REVIEW LETTERS week ending 31 JANUARY 2003

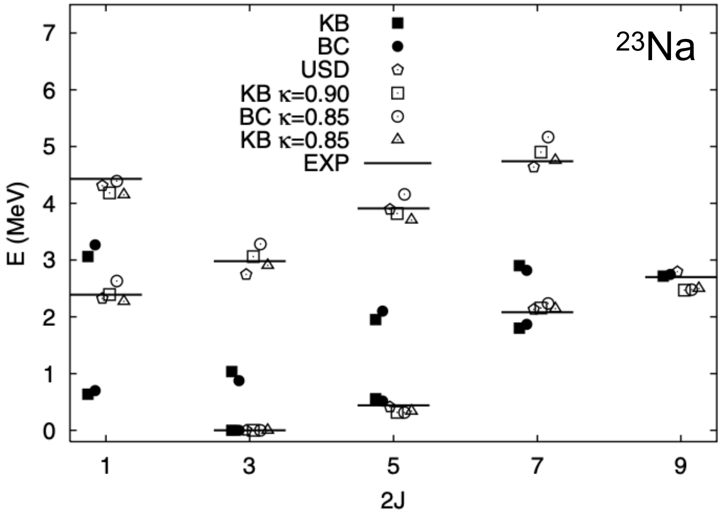
Three-Body Monopole Corrections to Realistic Interactions

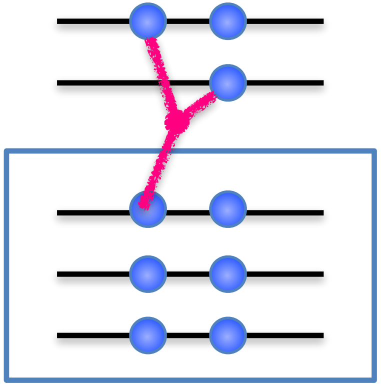
A. P. Zuker

IReS, Bâtiment 27, IN2P3-CNRS/Université Louis Pasteur, BP 28, F-67037 Strasbourg Cedex 2, France

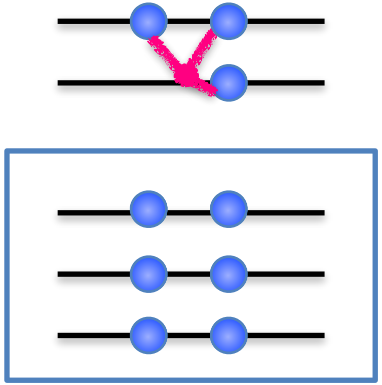
(Received 23 September 2002; published 30 January 2003)

It is shown that a very simple three-body monopole term can solve practically all the spectroscopic problems—in the *p*, *sd*, and *pf* shells—that were hitherto assumed to need drastic revisions of the realistic potentials.



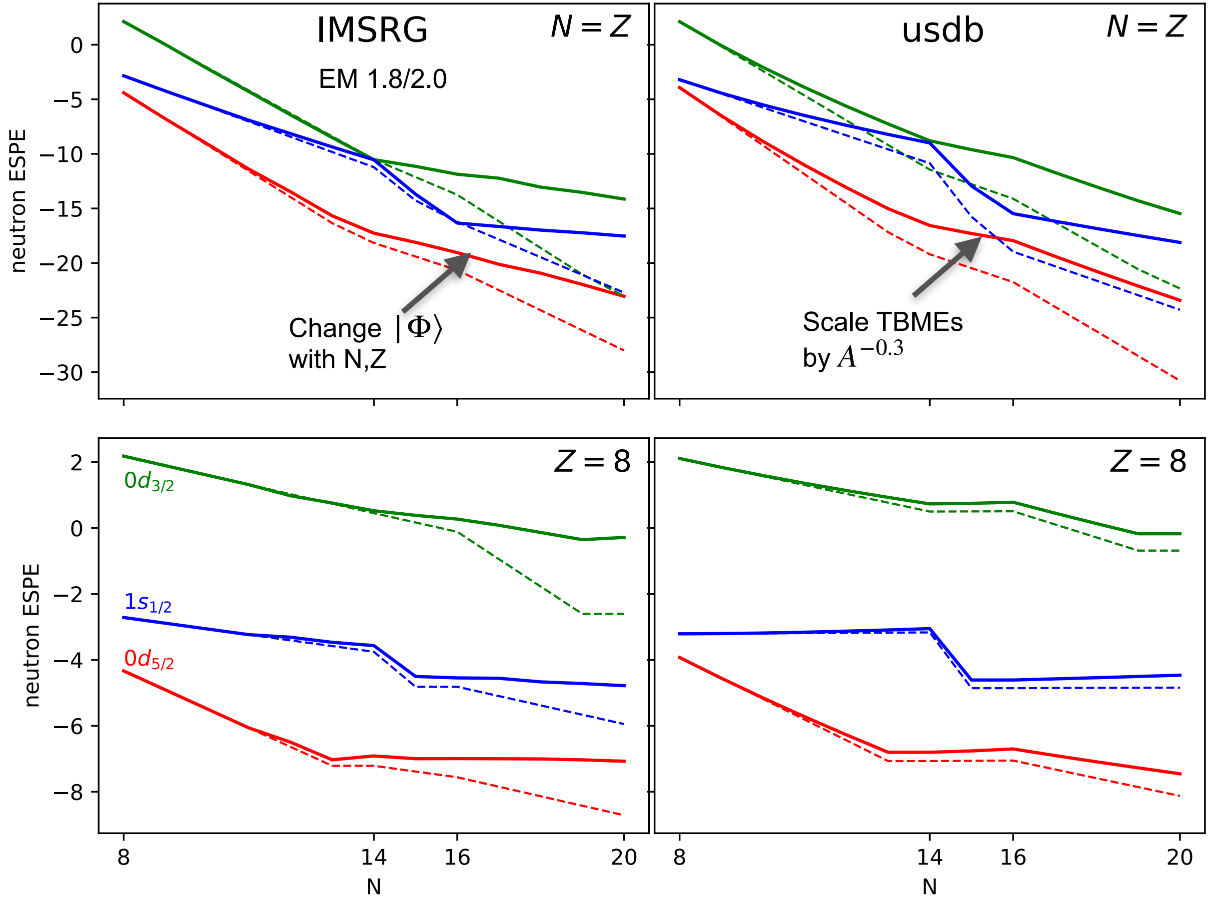


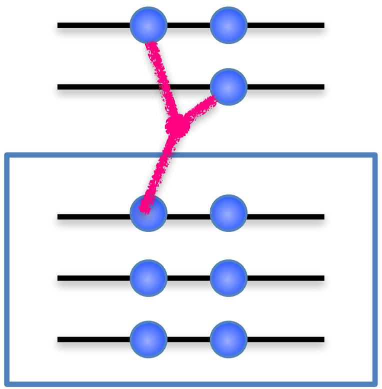
(normal-ordered 2-body)

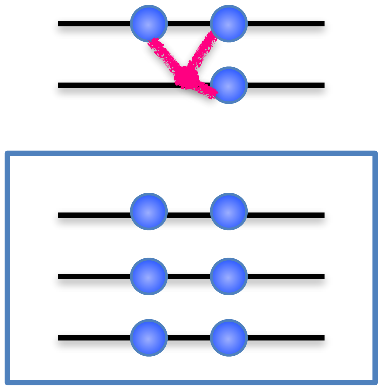


(residual 3-body)

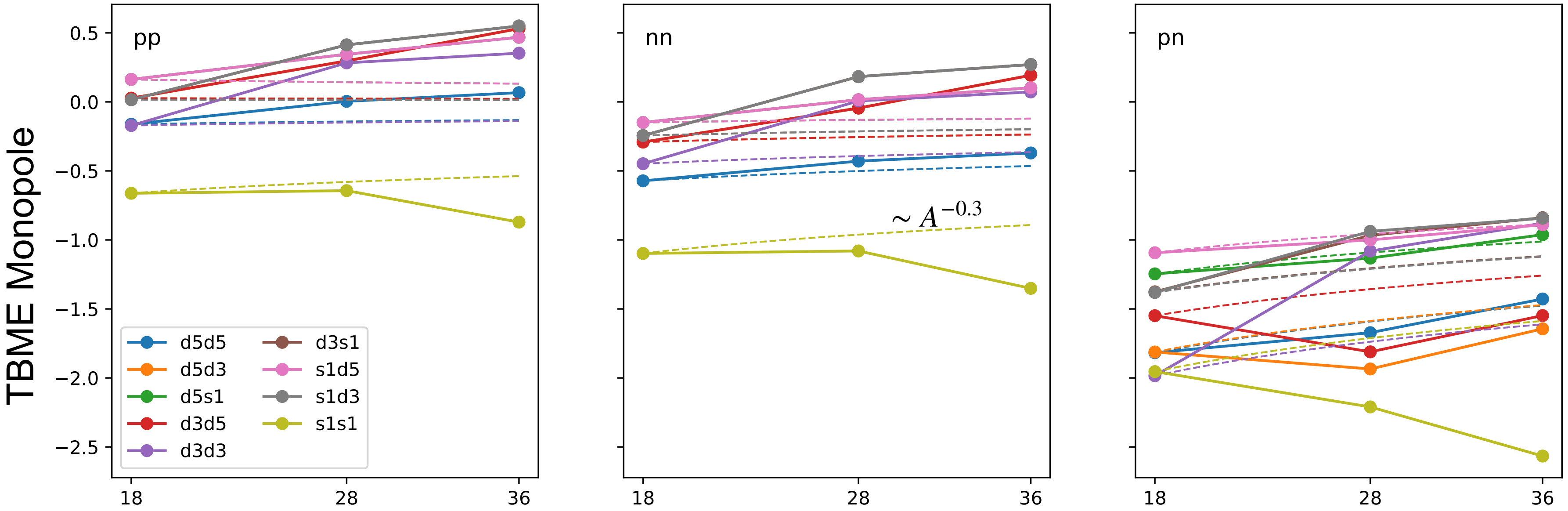
Evolution with A







Do the ab initio TBMEs follow $A^{-1/3}$ scaling?



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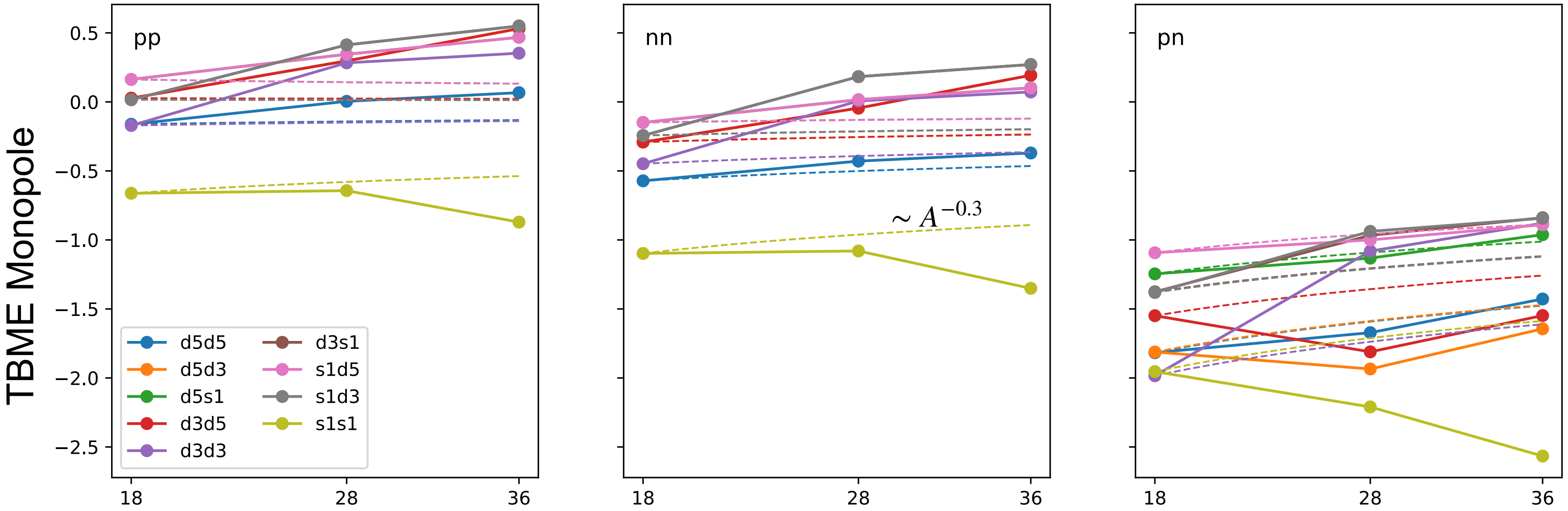
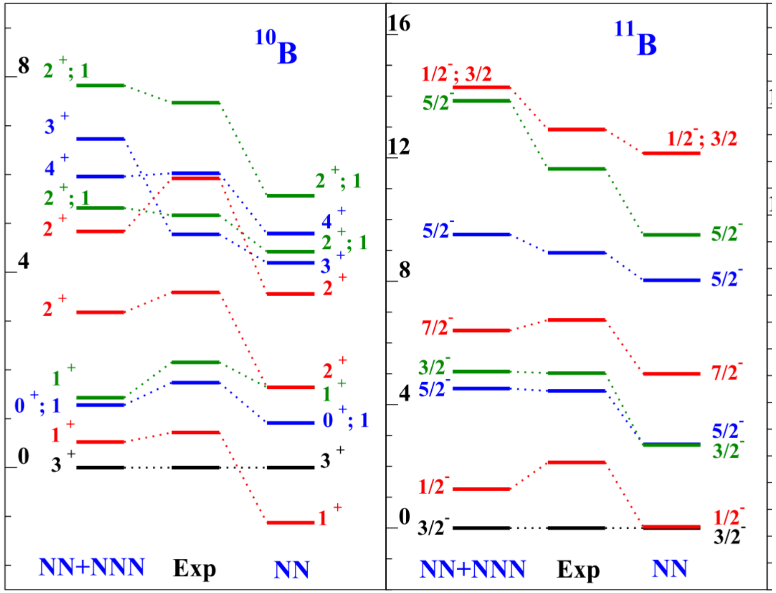
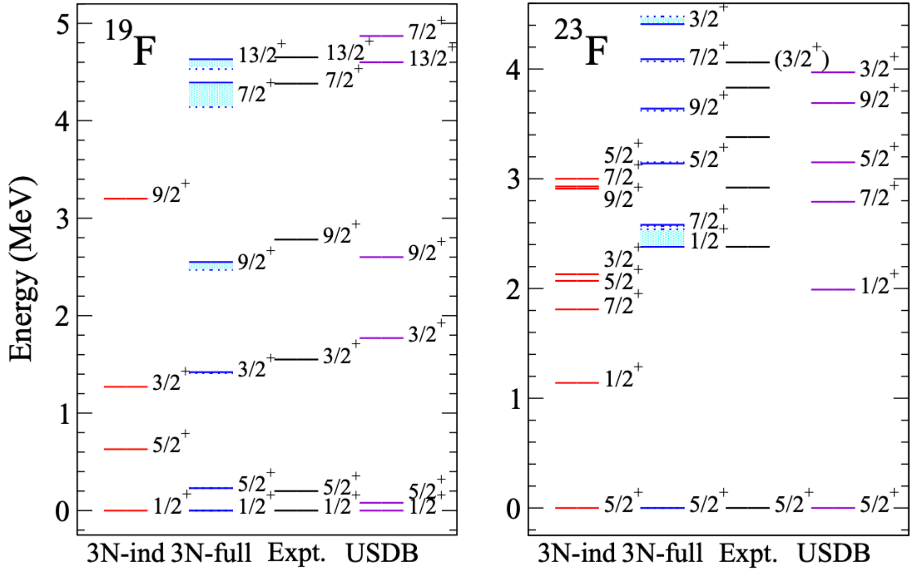


No, not really…

Including 3N forces can have a big impact on spectroscopy

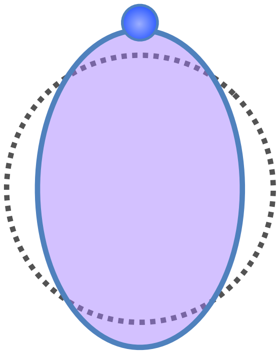


Navratil PRL 99 042501 (2007)

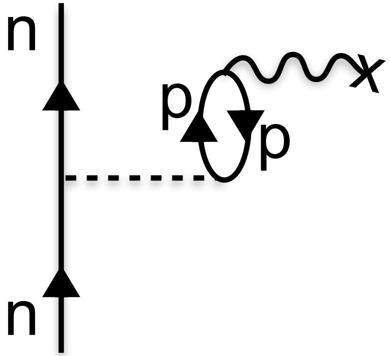


Stroberg+ PRC 93 051301(R)(2016)

Effective charges for E2 transitions/moments



$$O(E2) = \sum_i e_i r_i^2 Y_2(\hat{r}_i)$$

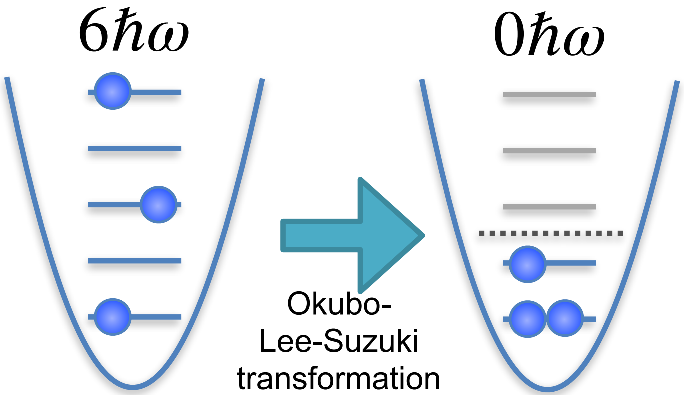


phenomenologically,
$e_p \approx 1.5$
$e_n \approx 0.5$

PHYSICAL REVIEW C VOLUME 55, NUMBER 2 FEBRUARY 1997

Microscopic origins of effective charges in the shell model

Petr Navrátil,* Michael Thoresen, and Bruce R. Barrett
Department of Physics, University of Arizona, Tucson, Arizona 85721
(Received 24 September 1996)



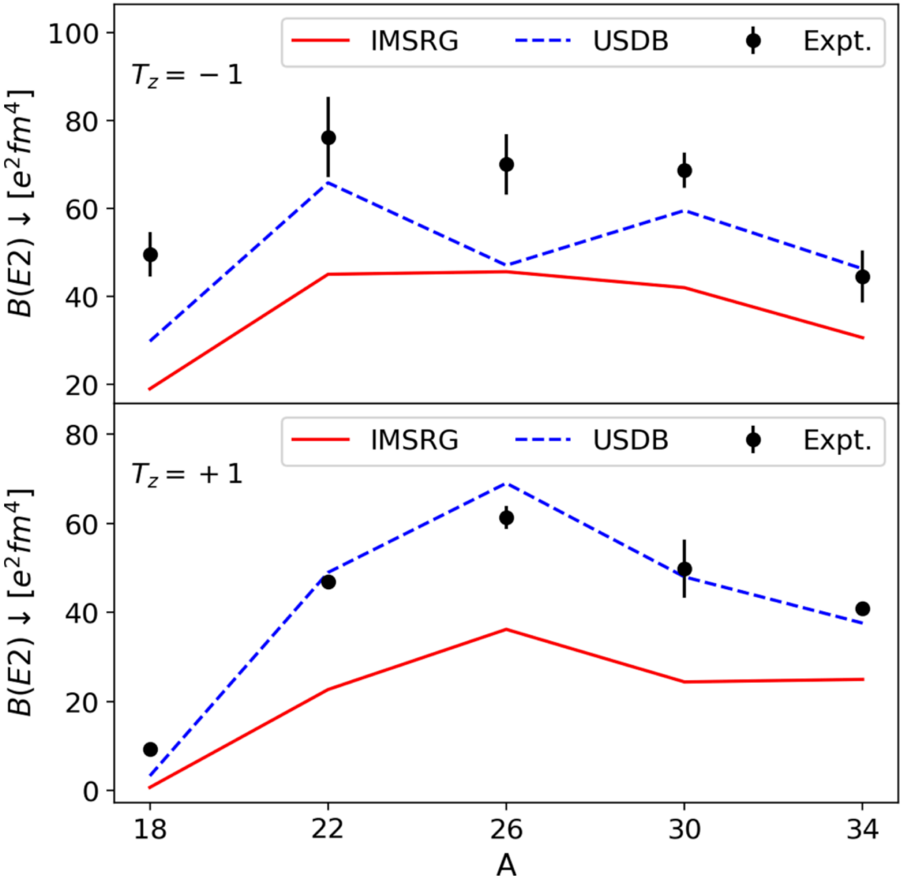
$$\bar{O}_{\text{eff}} = [1+\omega^\dagger\omega]^{-1/2}(P+P\omega^\dagger Q)\ \hat{O}\ (P+Q\omega P)[P(1+\omega^\dagger\omega)P]^{-1/2}$$

^{6}Li

	$e^{\mathrm{p}}_{\mathrm{eff}}$	$e^{\mathrm{n}}_{\mathrm{eff}}$	$e^{\mathrm{p}}_{\mathrm{eff\text{-}4}}$	$e^{\mathrm{n}}_{\mathrm{eff\text{-}4}}$
*E*2	1.527	0.364	1.302	0.244
Ml	0.907	0.085	0.931	0.063
Ms	0.937	0.001	0.953	−0.003

- Converged?
- Is the same mechanism at play for ^{6}Li as for heavier nuclei?

E2 transitions with VS-IMSRG

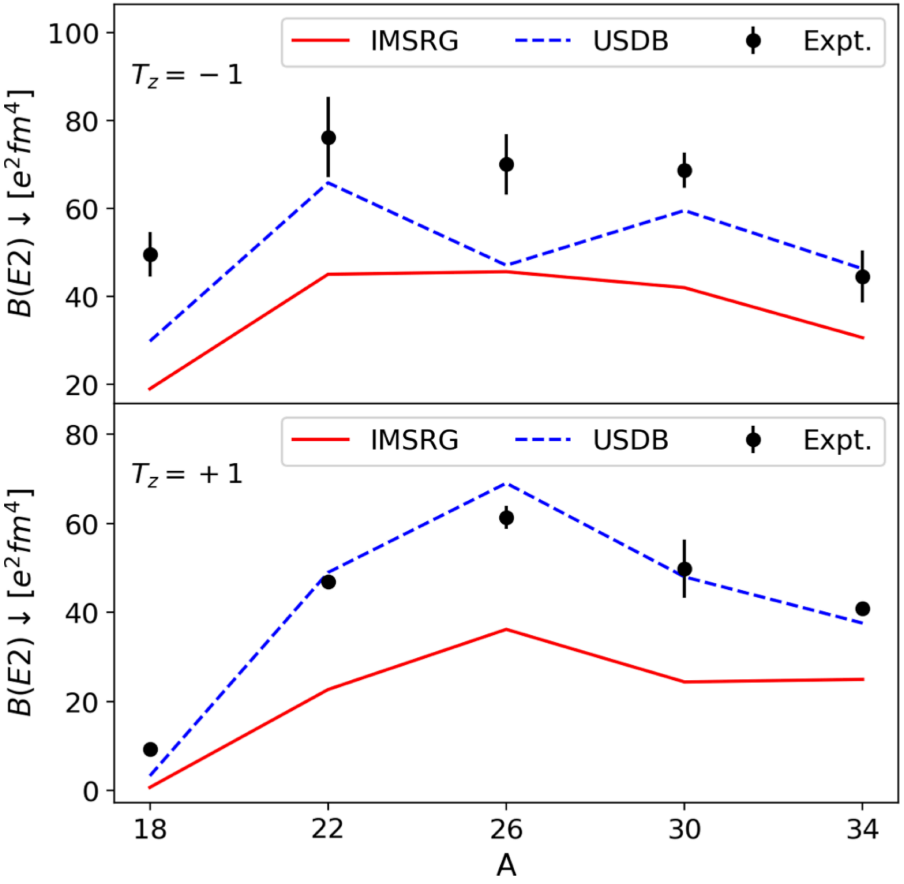


Stroberg+ PRC 105, 034333 (2022)

$$\mathcal{O}_{\text{eff}} = e^{\Omega}\mathcal{O}e^{-\Omega}$$

$$= \mathcal{O} + [\Omega, \mathcal{O}] + \frac{1}{2!}[\Omega, [\Omega, \mathcal{O}]] + \ldots$$

E2 transitions with VS-IMSRG



Stroberg+ PRC 105, 034333 (2022)

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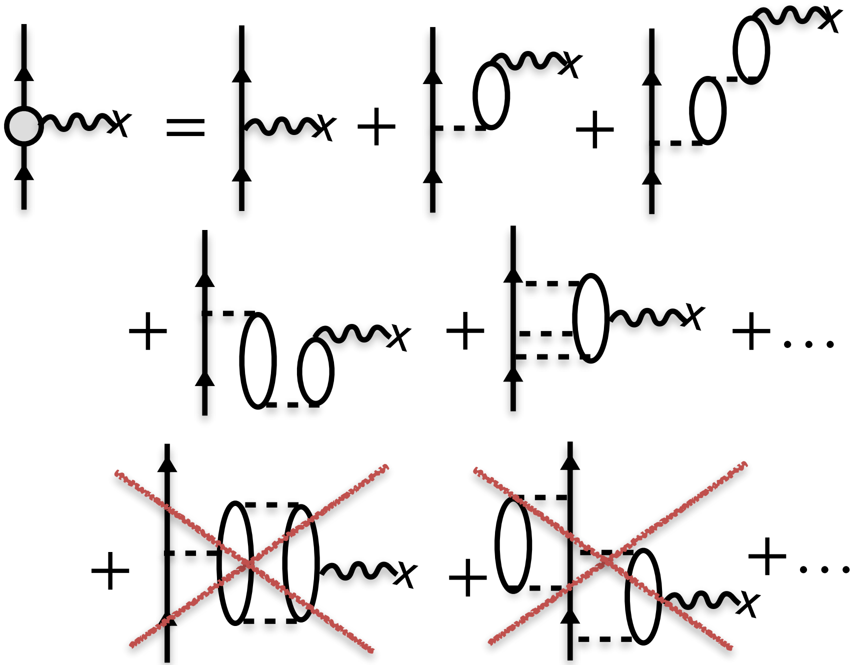
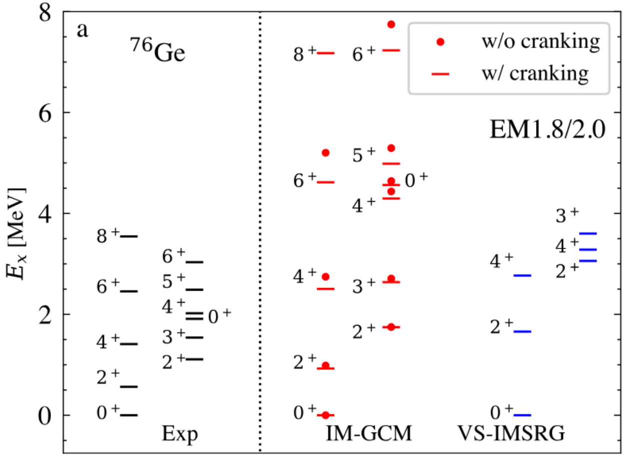
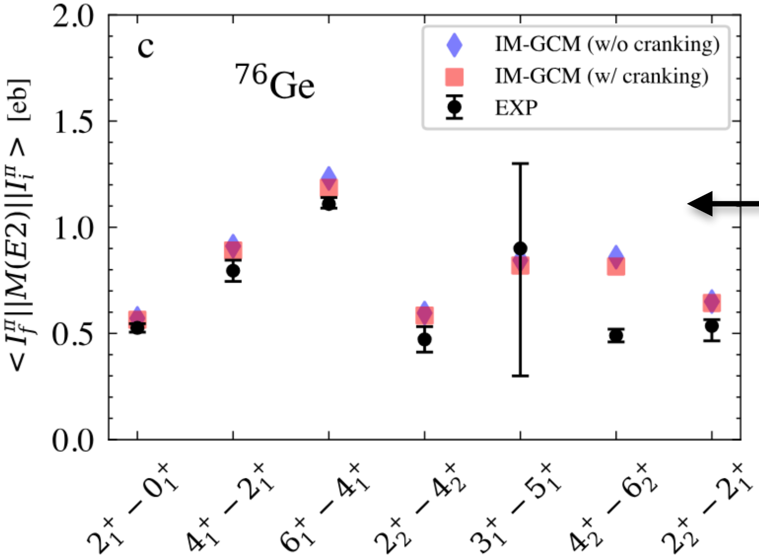


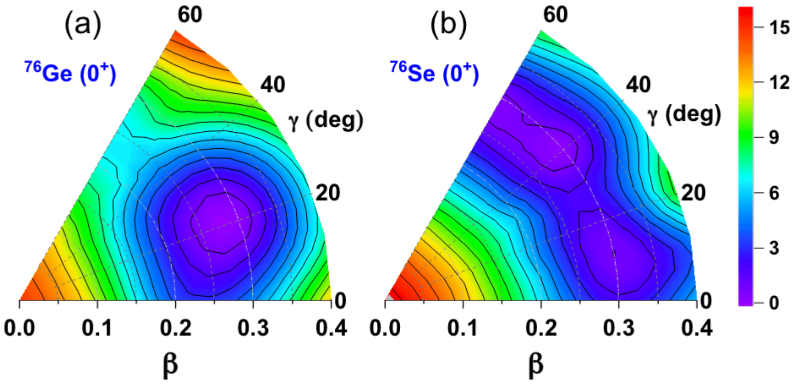
Don't blame the forces!



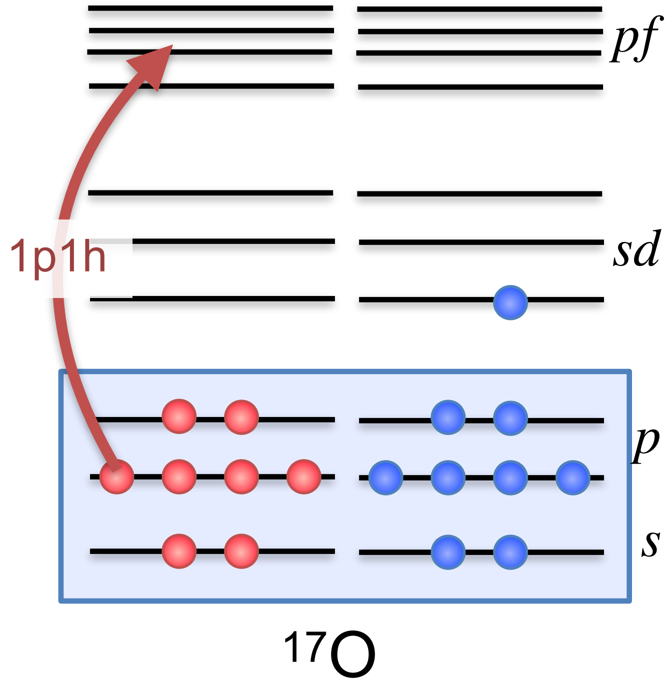


IM-GCM with same interaction beautifully reproduces E2s.

Belley+ PRL 132, 182502 (2024)

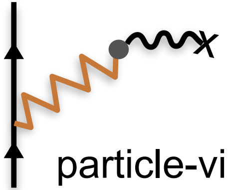


VS-IMSRG spectrum is improved by incorporating intermediate 3-body operators. Will that also fix the E2s? (Probably not completely).



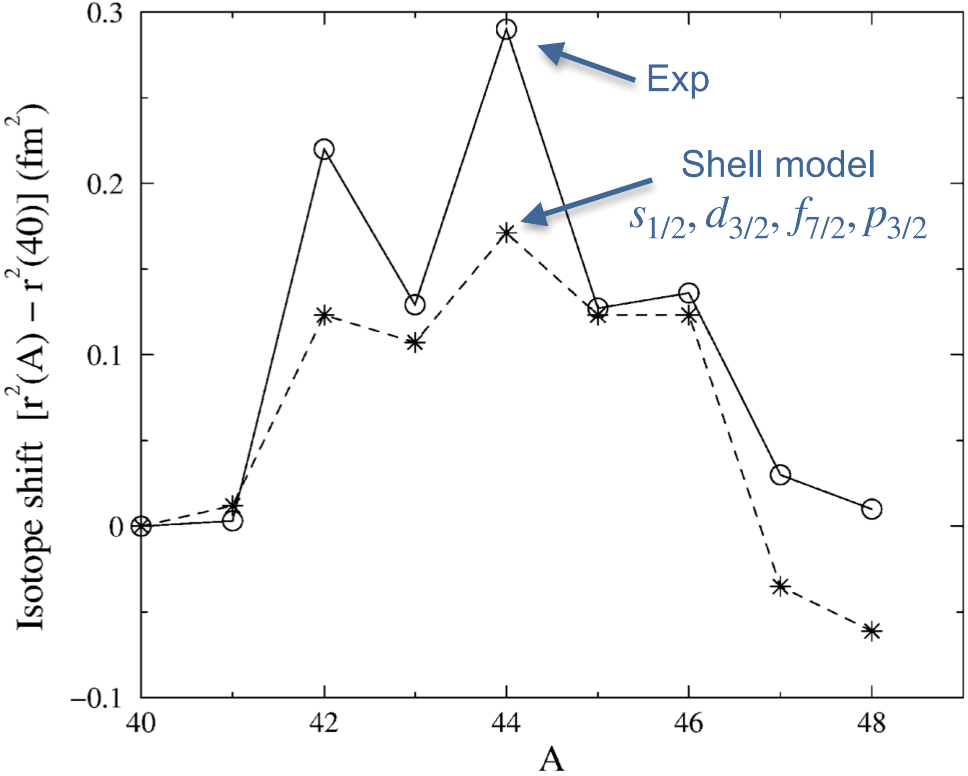
int.		CP	TDA	RPA	VS-IMSRG	CI $N_{\max}$ 2	CI $N_{\max}$ 4	CI $N_{\max}$ 6
$Q \cdot Q$	e_n	0.23	0.29	0.42	0.43	0.26	0.32	0.41
	e_p	1.25	1.31	1.44	1.49	1.30	1.37	1.46
NN only	e_n	0.16	0.17	0.17	0.17	0.14	0.17	0.19
	e_p	1.05	1.09	1.10	1.04	1.04	1.05	1.05
NN $+3N$	e_n	0.24	0.31	0.33	0.26	0.20	0.23	0.29
	e_p	1.07	1.16	1.19	1.02	1.04	1.05	1.05

Stroberg+ PRC 105, 034333 (2022)

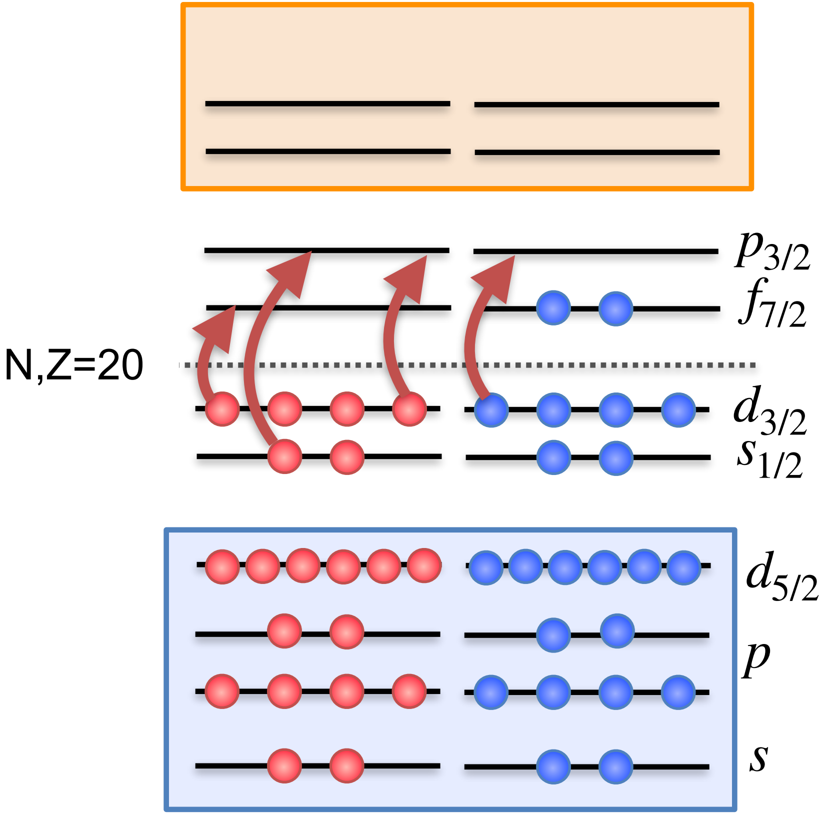


particle-vibration coupling

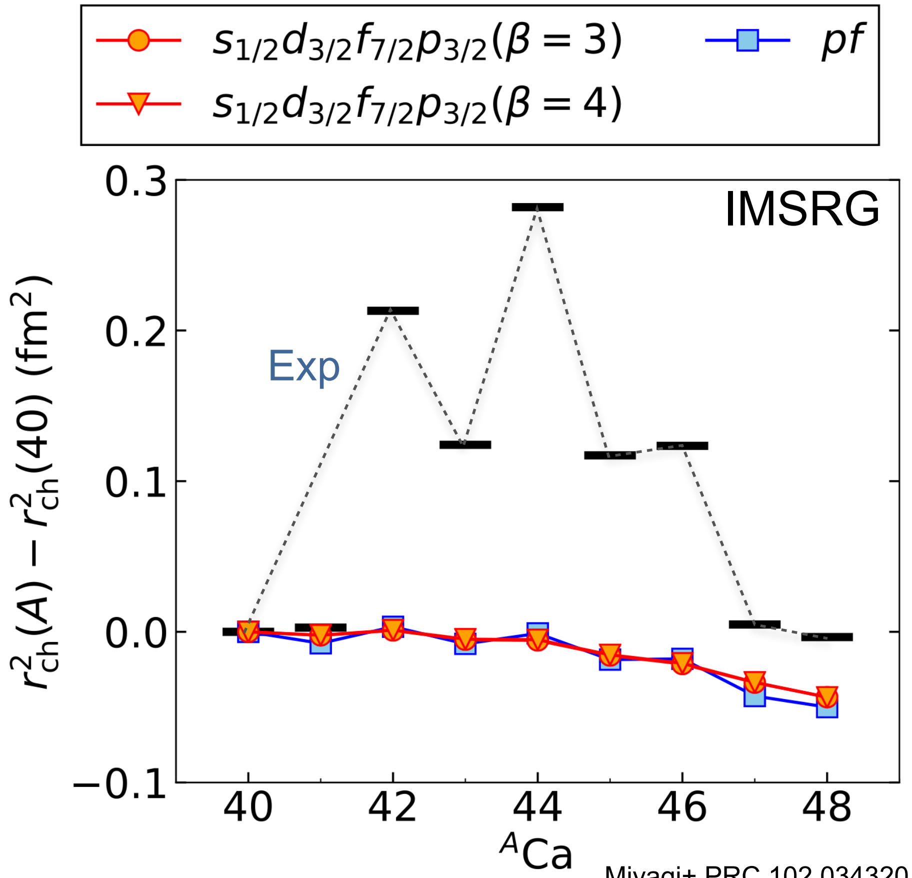
Calcium charge radii



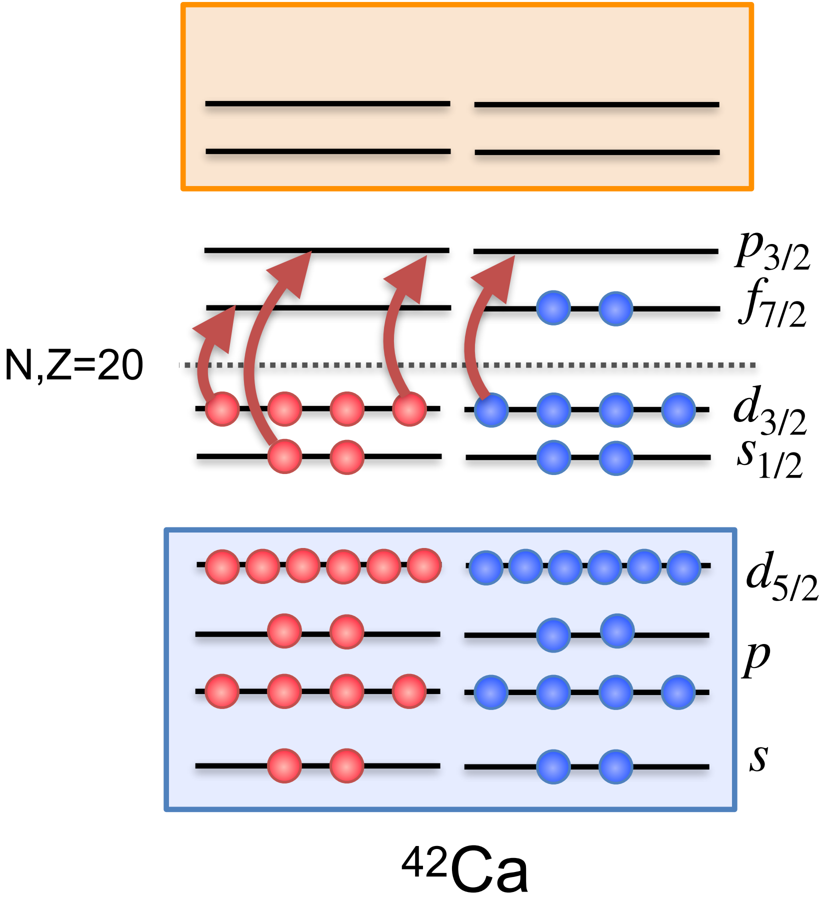
Caurier+ PLB 522 240 (2001)



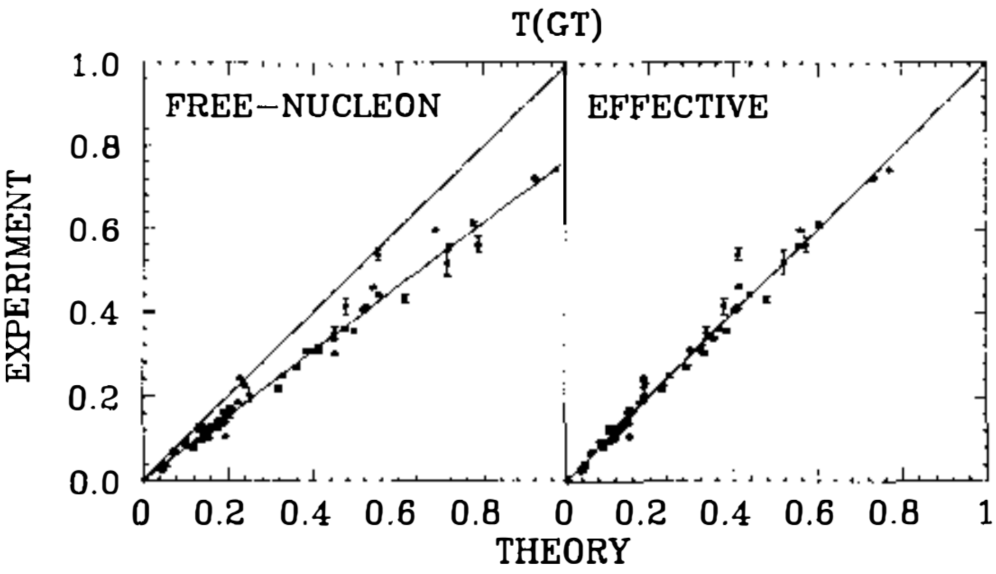
^{42}Ca



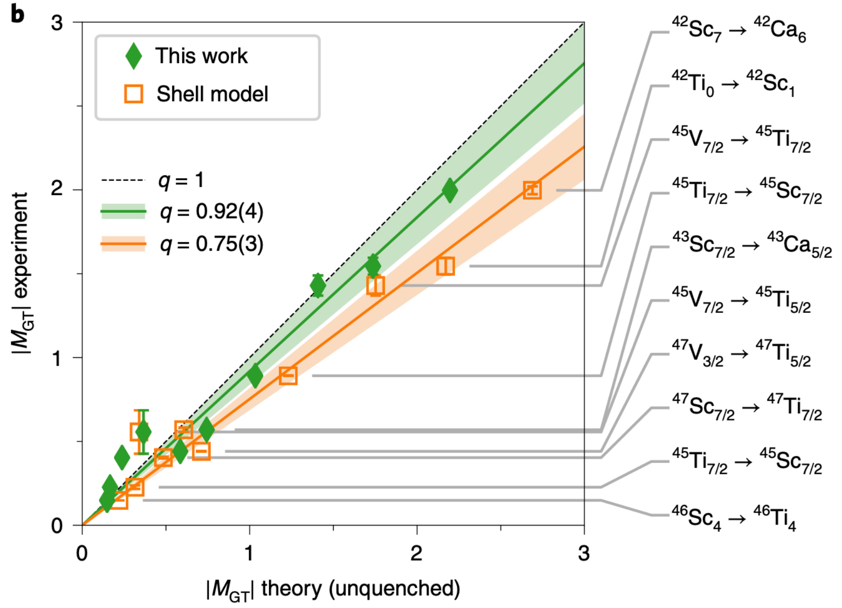
Miyagi+ PRC 102 034320



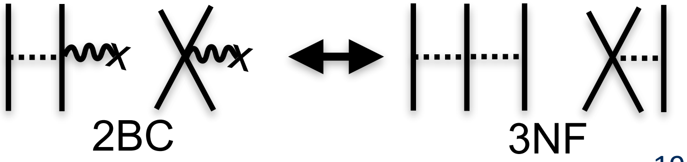
Quenching in Gamow-Teller decays



Brown, Wildenthal, Ann. Rev. Nucl. Part. Sci. 38: 29 (1988)

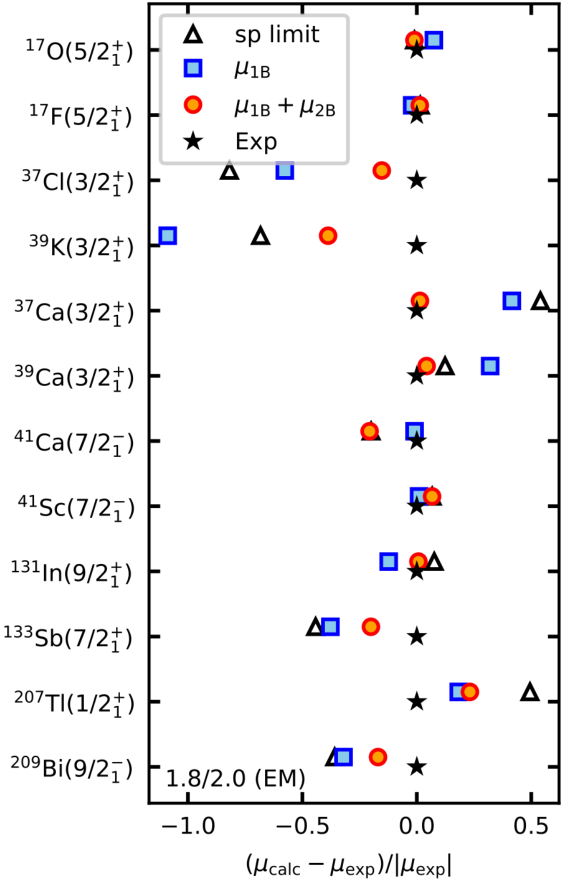


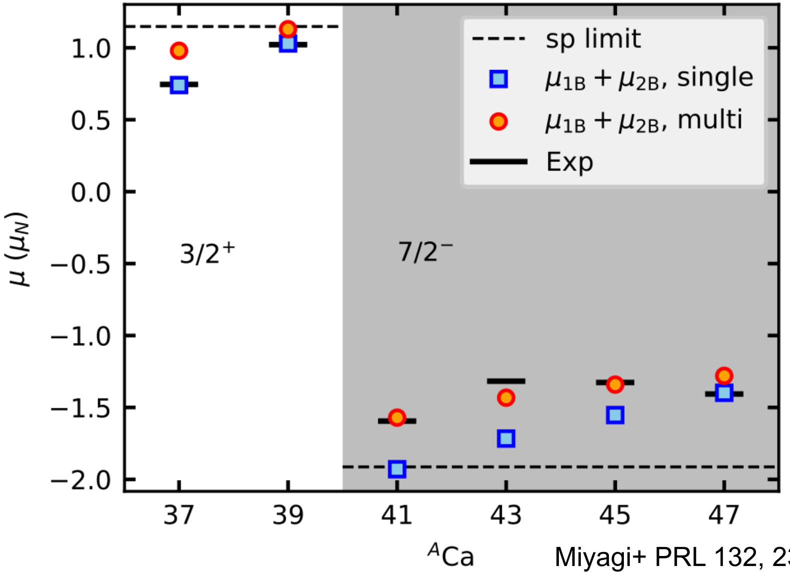
Gysbers+ Nat. Phys. 15 428 (2019)



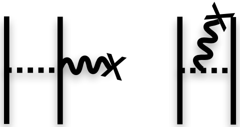
See talk by Luigi Corragio on Saturday

Magnetic moments





Miyagi+ PRL 132, 232503 (2024)

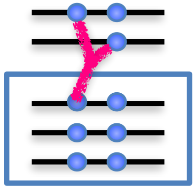


2BC

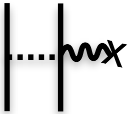
(parameter free)

Conclusion

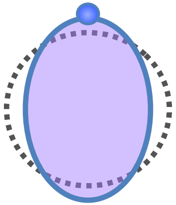
- We (mostly) understand how the basic features of the shell model arise from the NN interaction.



- We (mostly) understand the renormalization needed for single-particle operators for Gamow-Teller, M1.

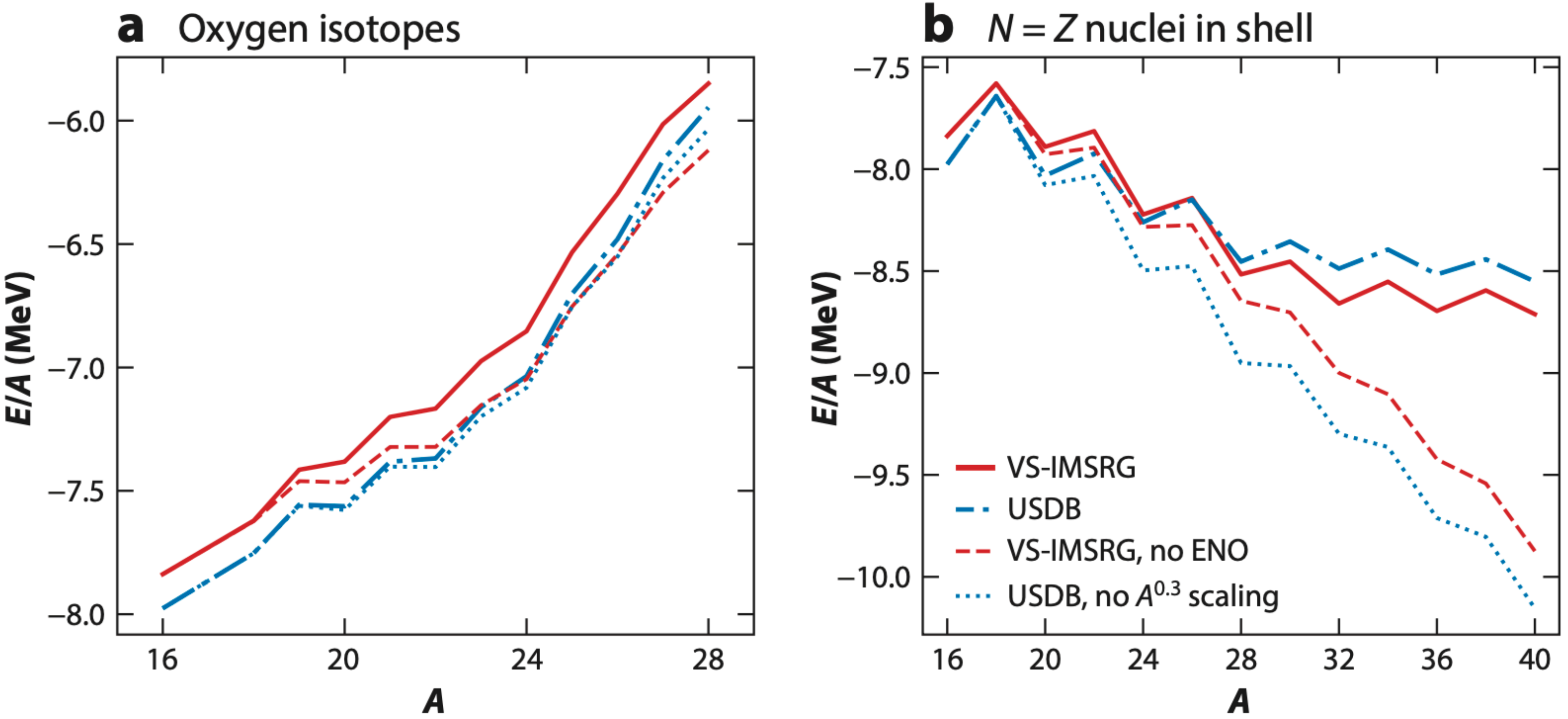


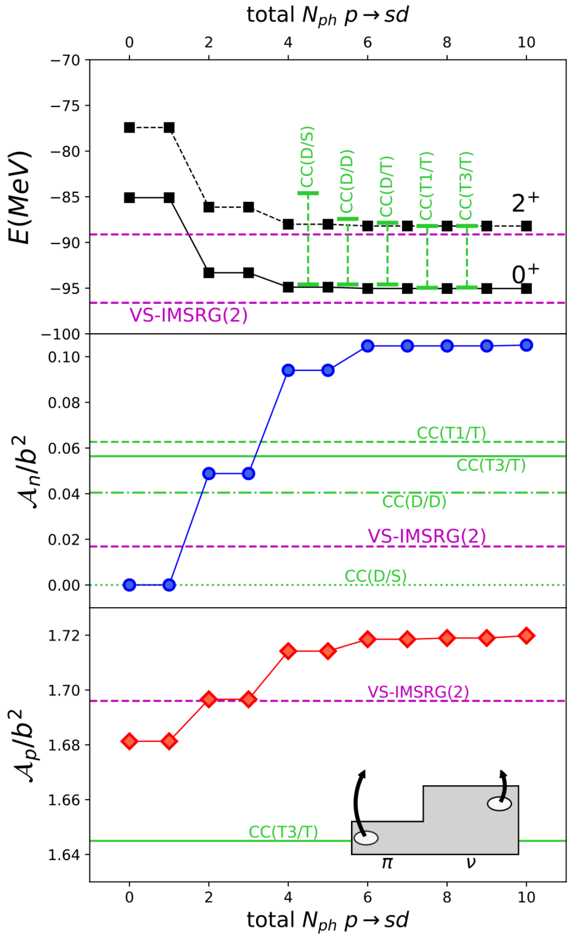
- Incorporating collective effects beyond the valence space remains challenging.



Thank You!

Extra Slides


a Oxygen isotopes
E/A (MeV)
−6.0
−6.5
−7.0
−7.5
−8.0
16
20
24
28
A
b N = Z nuclei in shell
−7.5
−8.0
−8.5
−9.0
−9.5
−10.0
VS-IMSRG
USDB
VS-IMSRG, no ENO
USDB, no A^0.3 scaling
16
20
24
28
32
36
40



total N_{ph} $p \to sd$
$E(MeV)$
CC(D/S)
CC(D/D)
CC(D/T)
CC(T1/T)
CC(T3/T)
2^+
0^+
VS-IMSRG(2)
$\mathcal{A}_n/b^2$
CC(T1/T)
CC(T3/T)
CC(D/D)
VS-IMSRG(2)
CC(D/S)
$\mathcal{A}_p/b^2$
VS-IMSRG(2)
CC(T3/T)
π
ν
total N_{ph} $p \to sd$