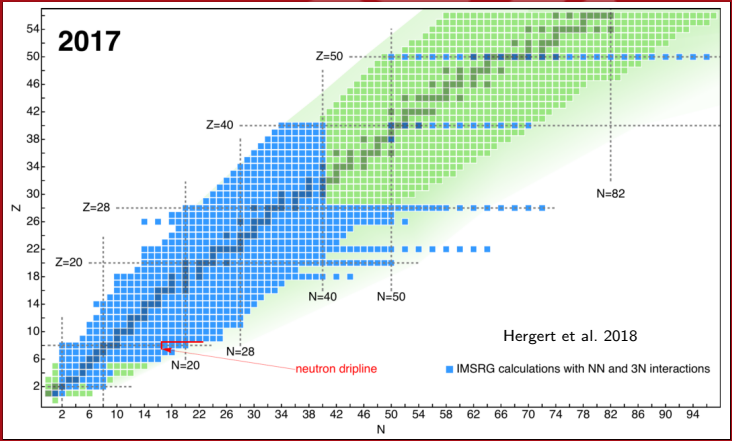
Observables in Medium-Mass Nuclei:
What can we learn?



Ragnar Stroberg

Reed College

ECT* Workshop
New Ideas in Constraining Nuclear Forces
Trento, Italy
June 4, 2018

REED COLLEGE

Discussion questions

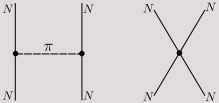
1. Should comparisons with medium-mass data be used for fitting, or only validation?

2. Should we expect the optimal power counting for few-body systems to be applicable for $A \sim 100$? Will it still be optimal?

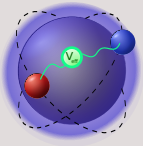
3. Is there anything to be learned from obervables related to collective phenomena?

4. Do collective phenomena amplify aspects of the interaction, or just wash them out?

Outline



1. Many-body method, interactions used
2. Liquid-drop observables
   - Energies, S_{2n}, radii
3. Beyond liquid drop
   - $E2$ transitions
   - Gamow-teller transitions
   - Spectra
   - Towards direct reactions
4. Questions

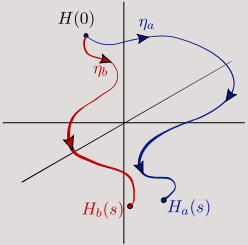


In-Medium Similarity Renormalization Group

SRG

$$H(s) \equiv U(s) H U^\dagger(s)$$

$$\frac{dH}{ds} = [\eta(s), H(s)]$$



In-Medium SRG

- Normal order w.r.t. reference $|\Phi_0\rangle$
- Transform H to decouple many-body configurations
- Flavors
  - Single ref: $|\Phi_0\rangle$ is a closed shell.
  - Multi-ref: $|\Phi_0\rangle$ is a correlated state
  - Valence space: decouple valence & diagonalize
  - Equations of Motion: ph excitations out of decoupled ground state
  - IMSRG+NCSM: use IMSRG to "soften" an interaction for NCSM

Magnus form

$$U \equiv e^{\Omega}$$

$$H(s) = e^{\Omega} H e^{-\Omega}$$

$$\mathcal{O}(s) = e^{\Omega} \mathcal{O} e^{-\Omega}$$

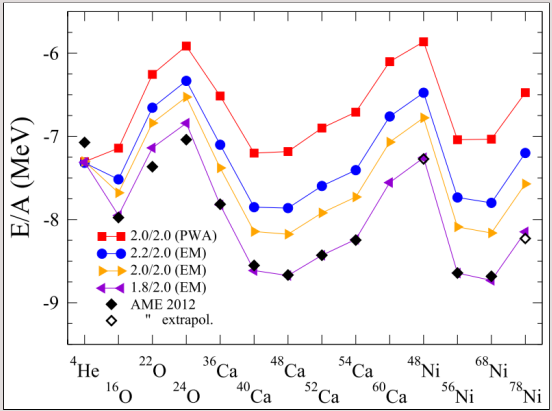
Wegner 1994; Glazek and Wilson 1994; Bogner, Furnstahl, and Perry 2007; Tsukiyama, Bogner, and Schwenk 2011; Tsukiyama, Bogner, and Schwenk 2012; Morris 2016; Parzuchowski, Morris, and Bogner 2017; Gebrerufael et al. 2017

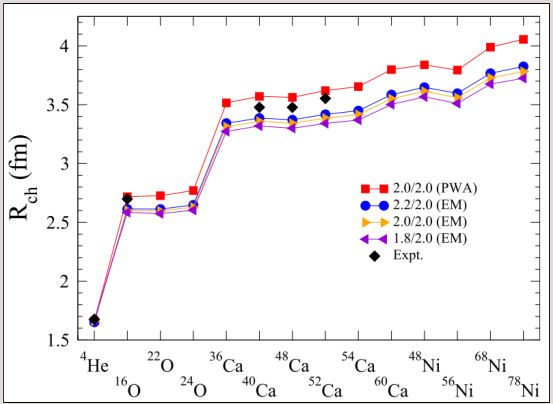
Chiral interactions

Name	Ref.	NN	3N	Λ_{NN}	Λ_{3N}	Λ_{SRG}
EM 500/400	[1][2]	N^{3}LO	N^{2}LO	500 MeV	400 MeV	2.0 fm
N^{2}LO$_{SAT}$	[3]	N^{2}LO	N^{2}LO	450 MeV	450 MeV	∞
EM 1.8/2.0 (et al.)	[1][4]	N^{3}LO	N^{2}LO	500 MeV	2.0 fm	1.8 fm (NN)
N^{3}LO LNL	[5]	N^{3}LO	N^{2}LO	500 MeV	400 MeV	2.0 fm

[1] Entem and Machleidt 2003, [2] Navrátil 2007; Gazit, Quaglioni, and Navrátil 2009, [3] Ekström et al. 2015, [4] Hebeler et al. 2011, [5] Leistenschneider et al. 2018

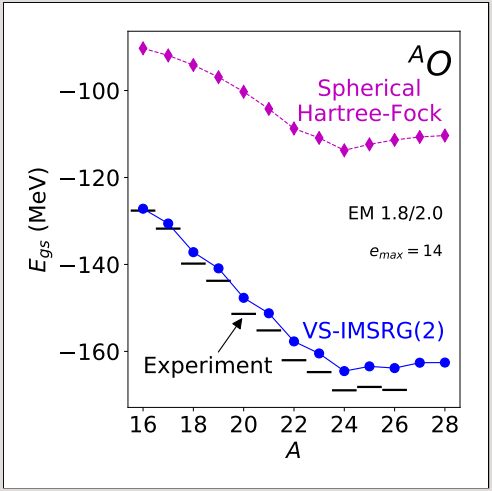
Liquid drop properties: energies and radii

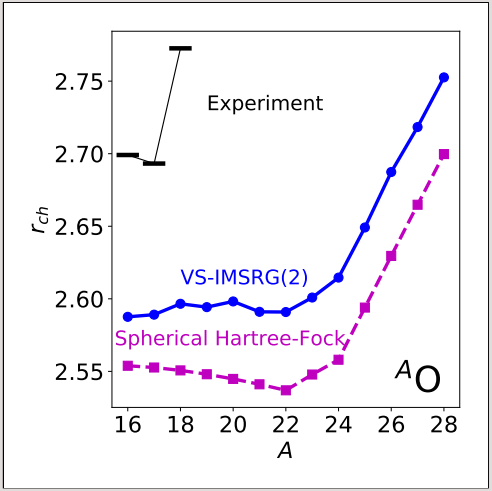




Hebeler et al. 2011; Simonis et al. 2017

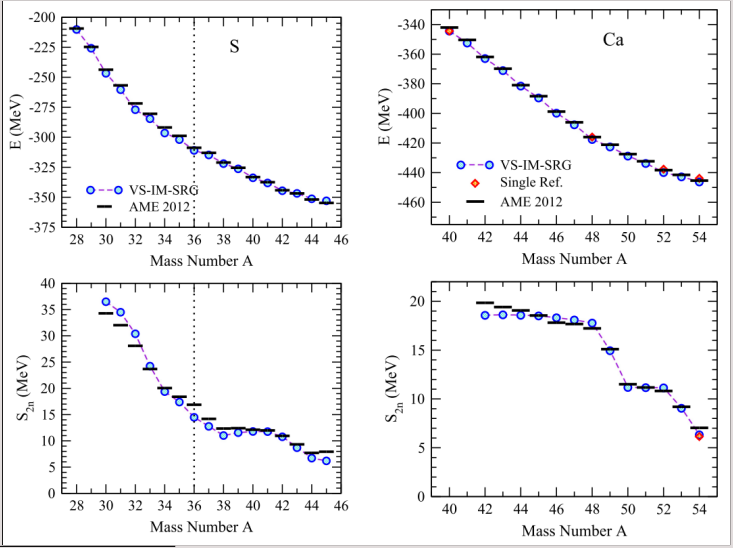
Liquid drop properties: energies and radii





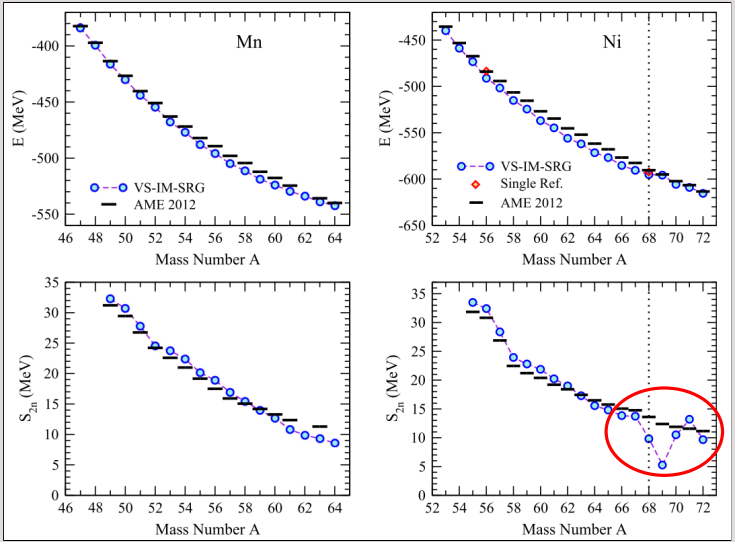
Hebeler et al. 2011; Simonis et al. 2017

Energies with EM 1.8/2.0



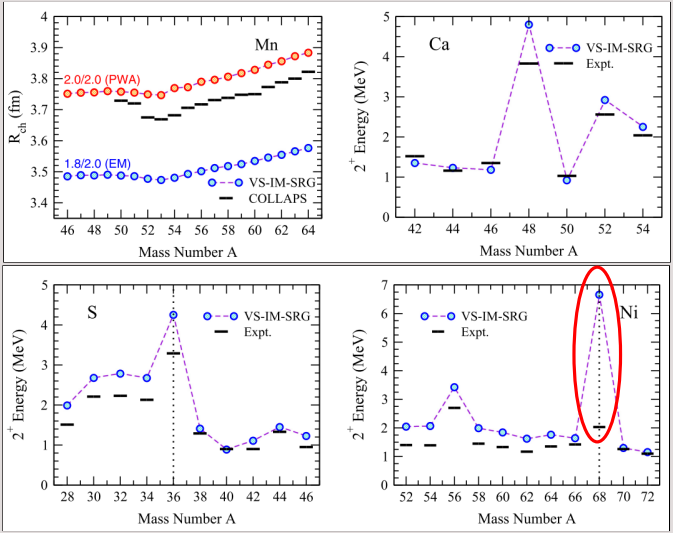
Simonis et al. 2017

Energies with EM 1.8/2.0



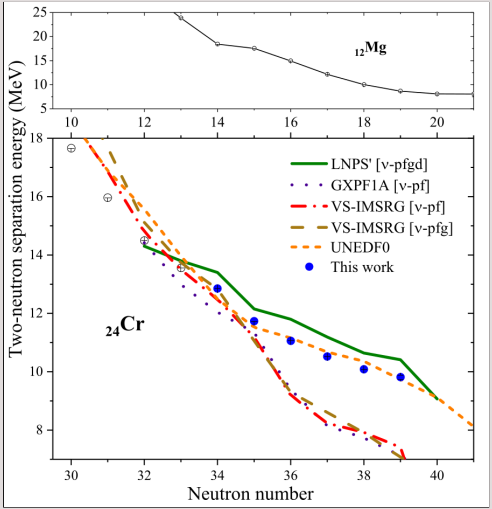
Simonis et al. 2017

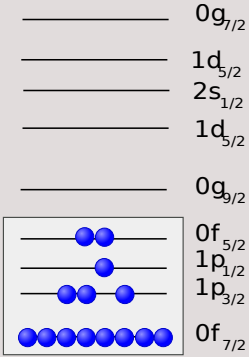
Energies with EM 1.8/2.0



Simonis et al. 2017

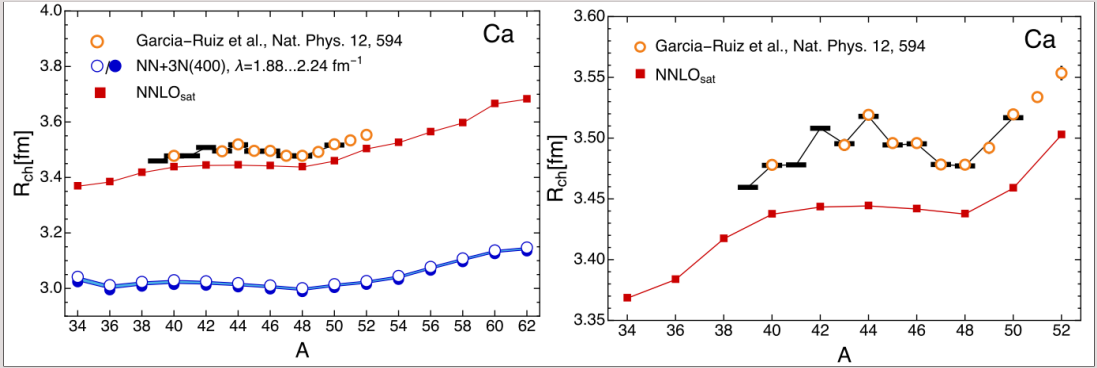
Energies with EM 1.8/2.0





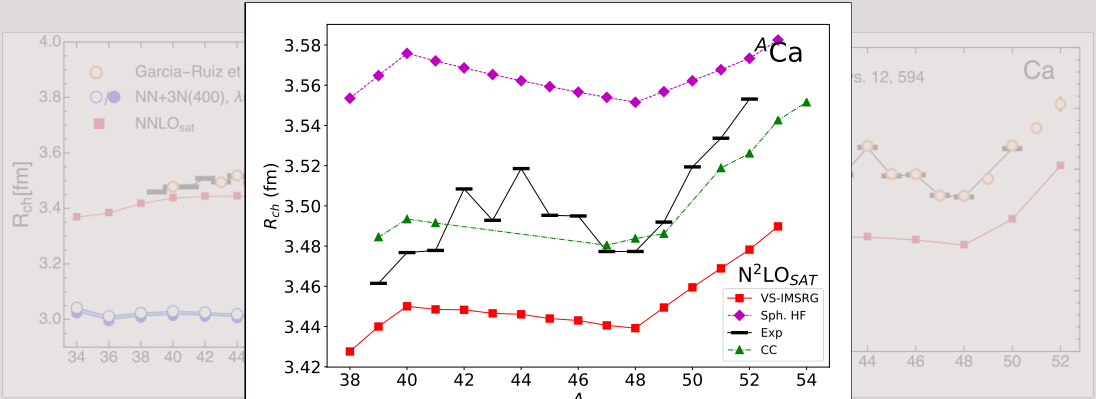
Mougeot et al. (accepted PRL)

Radii—corrections to mean field



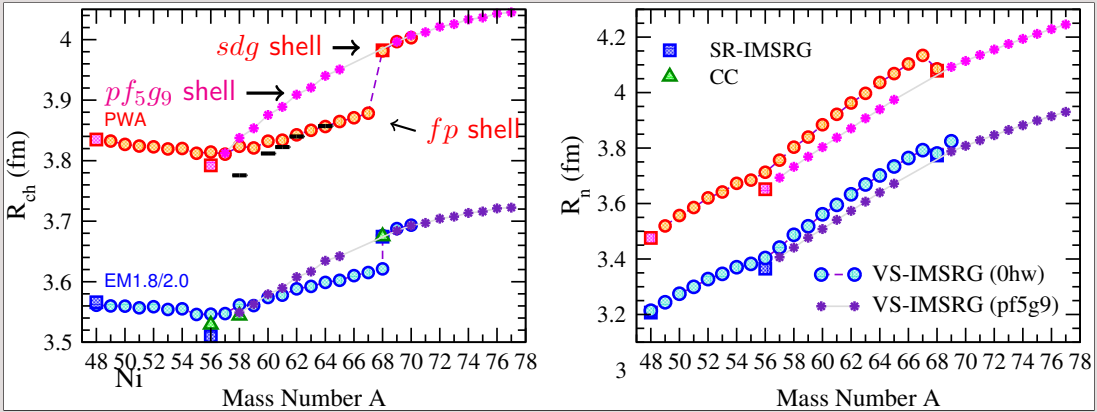
Hergert et al. 2018; Garcia Ruiz et al. 2016

Radii—corrections to mean field



Hergert et al. 2018; Garcia Ruiz et al. 2016

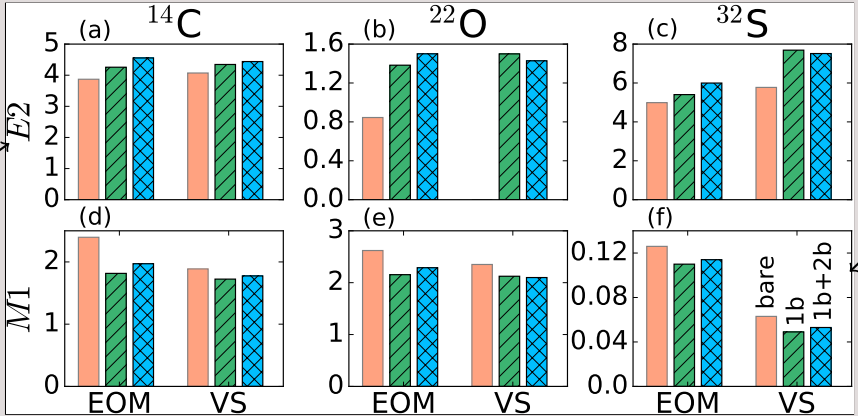
Radii—corrections to mean field



Beyond liquid drop:

- $E2$ transitions
- Gamow-Teller transitions
- Spectra
- Towards direct reactions

$E2$—impact of operator evolution



$\langle 0^+ \| E2 \| 2^+ \rangle$ (e^2fm)

$E2$ operator used

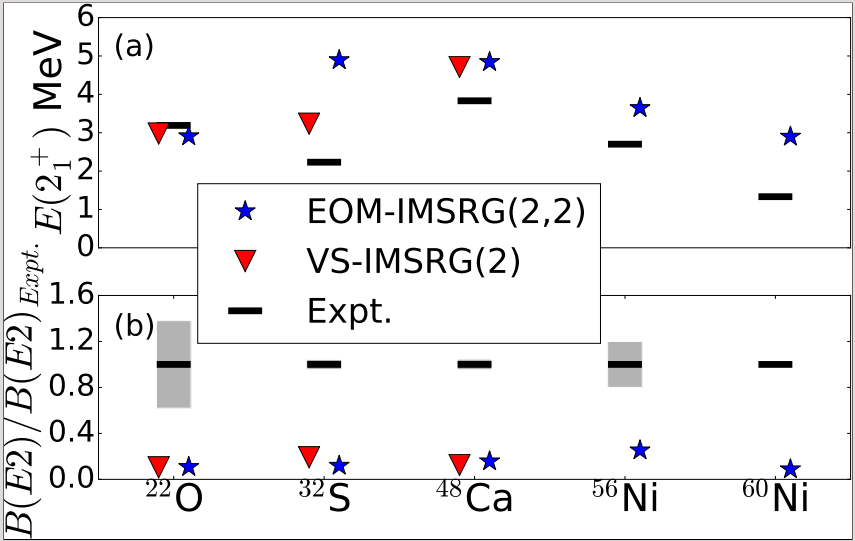
interaction: EM 500/400

Equations-of-Motion IMSRG

Valence Space IMSRG

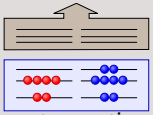
Parzuchowski et al. 2017; Entem and Machleidt 2003; Navrátil 2007; Gazit, Quaglioni, and Navrátil 2009

$E2$ transitions—severe underprediction of strength

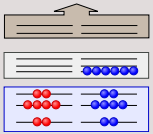


Parzuchowski et al. 2017

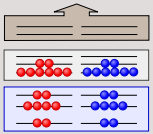
Dependence on choice of interaction



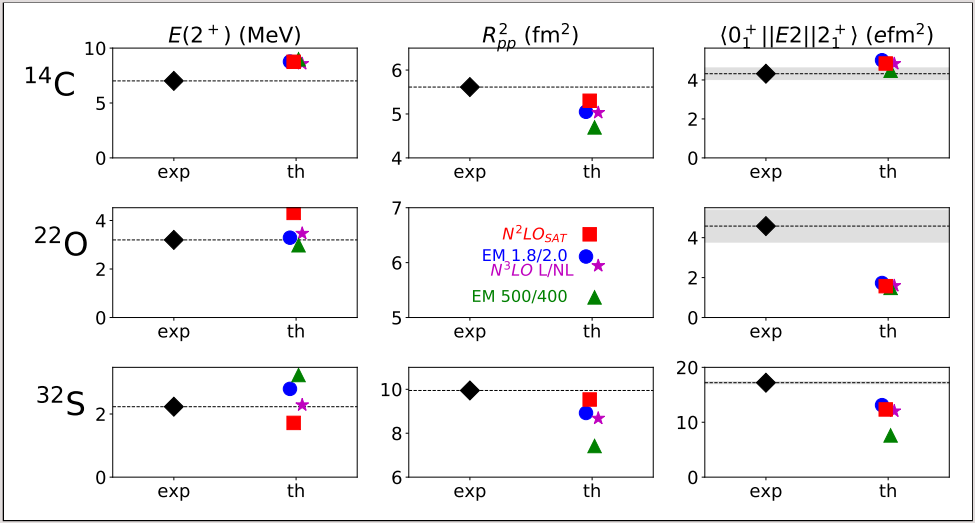
protons active



neutrons active

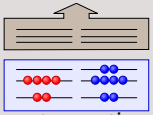


both active

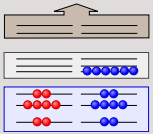


Entem and Machleidt 2003; Navrátil 2007; Gazit, Quaglioni, and Navrátil 2009; Ekström et al. 2015; Simonis et al. 2017

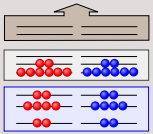
Dependence on choice of interaction



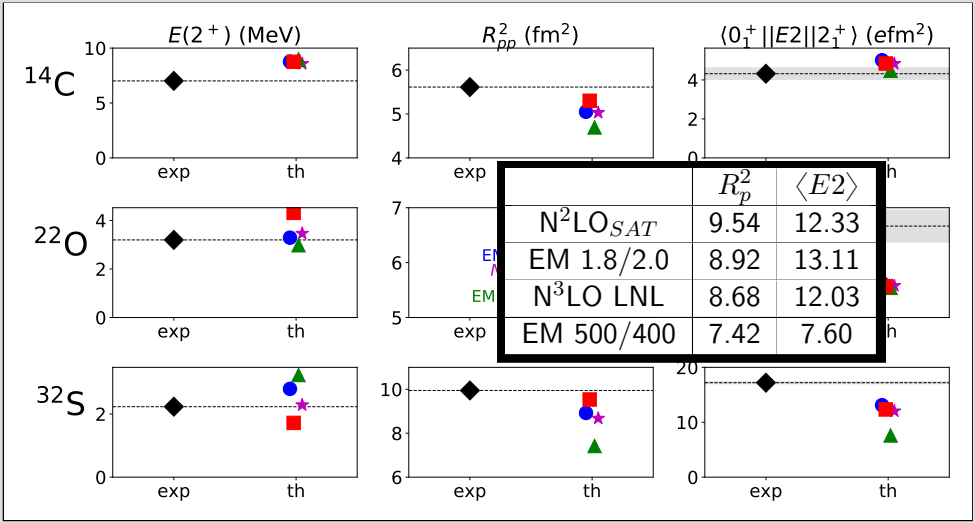
protons active



neutrons active



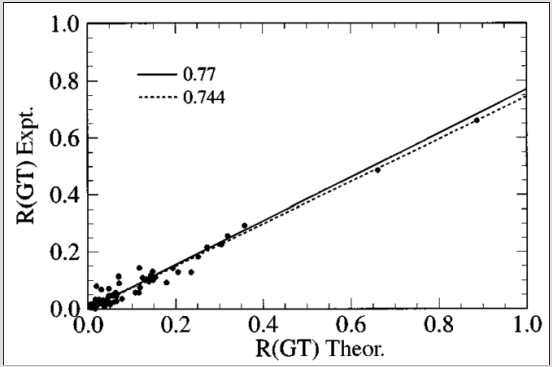
both active

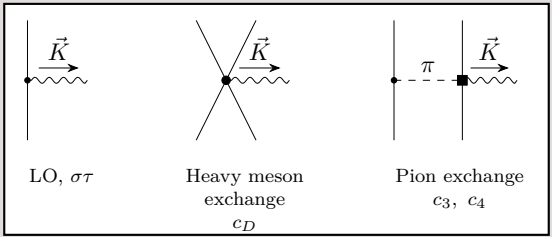


	R_p^2	$\langle E2 \rangle$
N^{2}LO$_{SAT}$	9.54	12.33
EM 1.8/2.0	8.92	13.11
N^{3}LO LNL	8.68	12.03
EM 500/400	7.42	7.60

Entem and Machleidt 2003; Navrátil 2007; Gazit, Quaglioni, and Navrátil 2009; Ekström et al. 2015; Simonis et al. 2017

"Quenching"

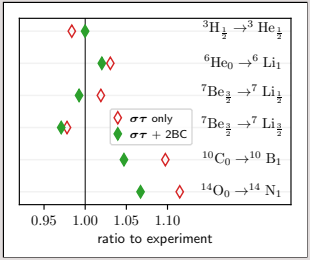




Martínez-Pinedo et al. 1996

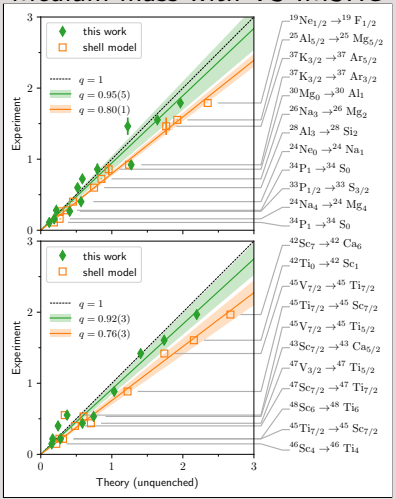
Gamow-Teller decays

Light nuclei with No Core Shell Model

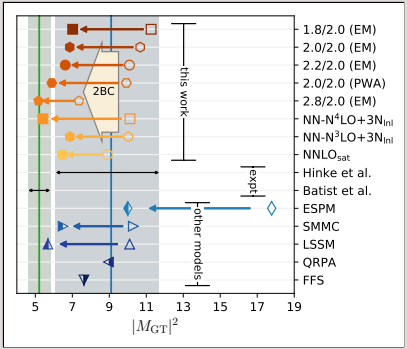


N^{4}LO LNL
(other interactions give similar results).

Medium-mass with VS-IMSRG



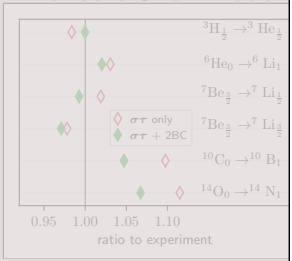
^{100}Sn with Coupled Cluster



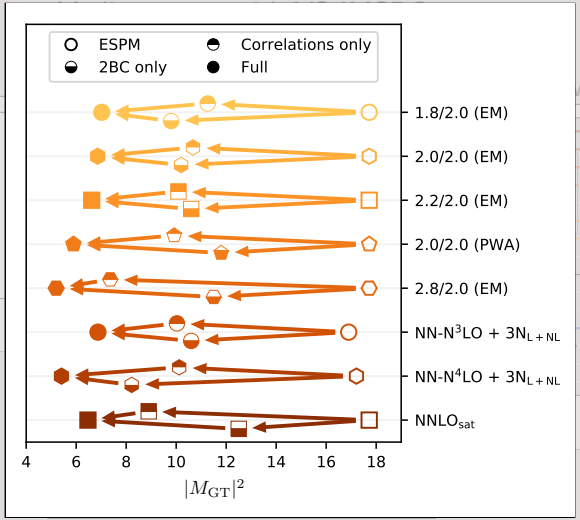
Gysbers et al (under review)

Gamow-Teller decays

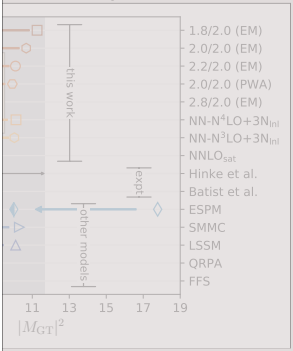
Light nuclei with No Core Shell Model



N^4LO LNL (other interactions give similar results).

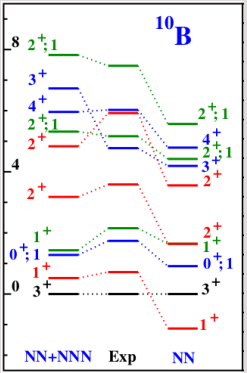


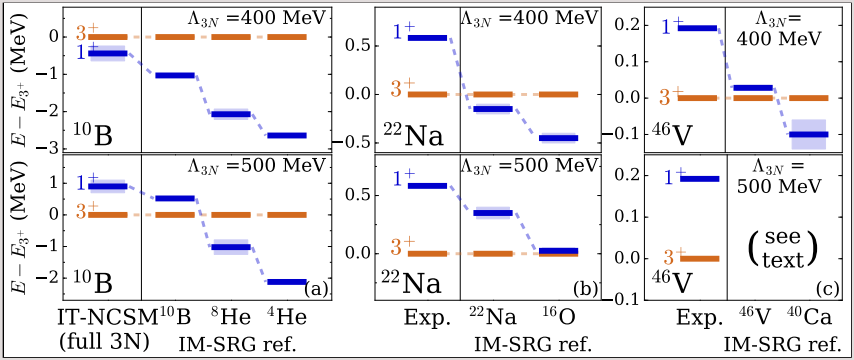
with Coupled Cluster



Gysbers et al (under review)

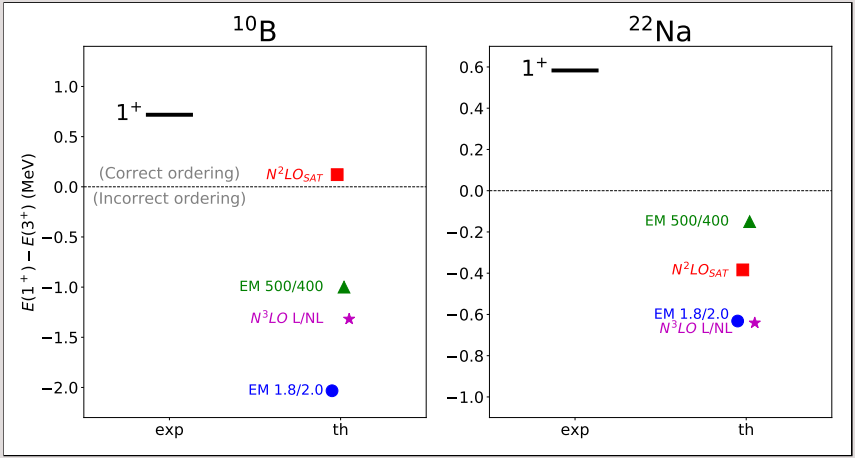
Capturing valence 3N effects w/ NN machinery:



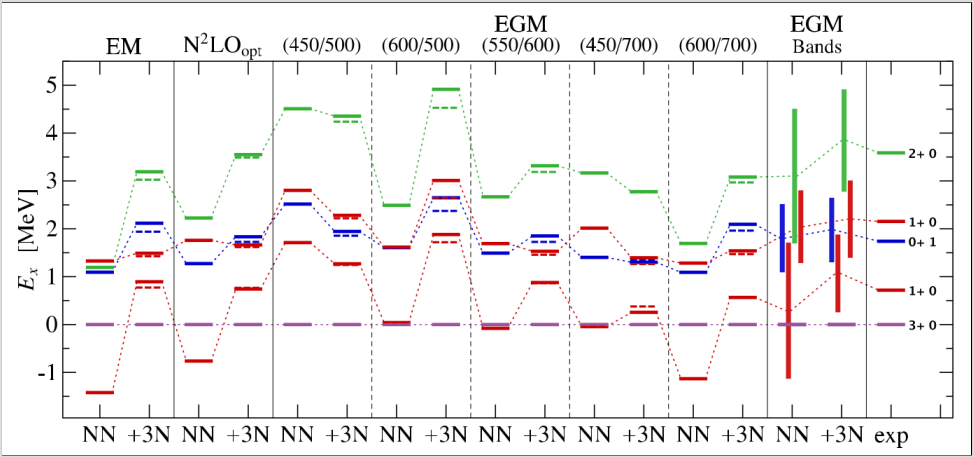


Navrátil 2007; Stroberg et al. 2017

3^+-1^+ level inversion

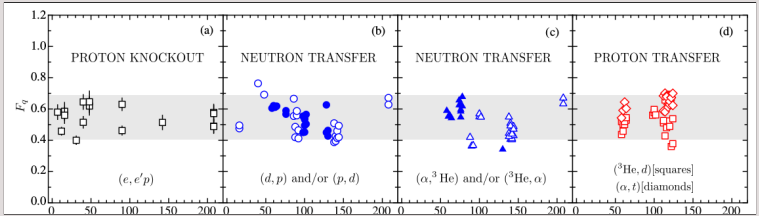


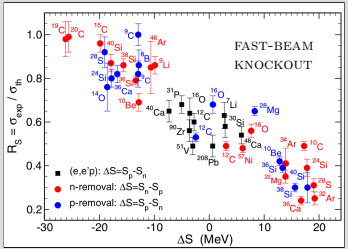
3^+-1^+ level inversion

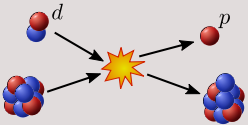


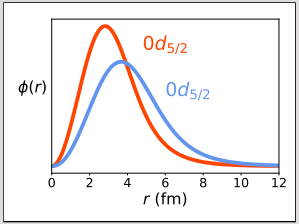
Calci and Roth 2016

Towards direct reactions









$$\sigma^{th} = \underbrace{\sigma^{sp}}_{\text{single-particle cross section}} \times \underbrace{\left|\langle \Psi^A \| a^\dagger \| \Psi^{A-1} \rangle\right|^2}_{\text{spectroscopic factor}}$$

Kay, Schiffer, and Freeman 2013; Tostevin and Gade 2014; Barbieri 2009; Jensen et al. 2011b; Vorabbi, Finelli, and Giusti 2016; Rotureau et al. 2017

Towards direct reactions

PRL **103,** 202502 (2009) PHYSICAL REVIEW LETTERS week ending 13 NOVEMBER 2009

Role of Long-Range Correlations in the Quenching of Spectroscopic Factors

C. Barbieri
Theoretical Nuclear Physics Laboratory, RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198 Japan
(Received 16 September 2009; published 9 November 2009)

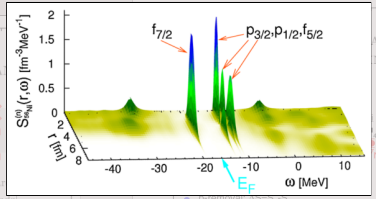
We consider the proton and neutron quasiparticle orbits around the closed-shell ^{56}Ni and ^{48}Ca isotopes. It is found that large model spaces (beyond the capability of shell model applications) are necessary for predicting the quenching of spectroscopic factors. The particle-vibration coupling is identified as the principal mechanism. Additional correlations—due to configuration with several particle-hole excitations—are estimated using shell model calculations and generate an extra reduction which is $\lesssim 4\%$ for most quasiparticle states. The theoretical calculations nicely agree with $(e, e'p)$ and inverse kinematics knockout experiments. These results open a new path for a microscopic understanding of the shell model.

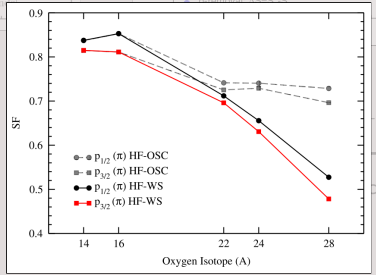
PRL **107,** 032501 (2011) PHYSICAL REVIEW LETTERS week ending 15 JULY 2011

Quenching of Spectroscopic Factors for Proton Removal in Oxygen Isotopes

Ø. Jensen,[1] G. Hagen,[2,3] M. Hjorth-Jensen,[1] B. Alex Brown,[4,5] and A. Gade[4,5]
[1]*Department of Physics and Center of Mathematics for Applications, University of Oslo, N-0316 Oslo, Norway*
[2]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[3]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[4]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824-1321, USA*
[5]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
(Received 8 April 2011; published 11 July 2011)

We present microscopic coupled-cluster calculations of the spectroscopic factors for proton removal from the closed-shell oxygen isotopes ^{14,16,22,24,28}O with a chiral nucleon-nucleon interaction at next-to-next-to-next-to-leading order. We include coupling-to-continuum degrees of freedom by using a Hartree-Fock basis built from a Woods-Saxon single-particle basis. This basis treats bound and continuum states on an equal footing. We find a significant quenching of spectroscopic factors in the neutron-rich oxygen isotopes, pointing to enhanced many-body correlations induced by strong coupling to the scattering continuum above the neutron emission thresholds.





Kay, Schiffer, and Freeman 2013; Tostevin and Gade 2014; Barbieri 2009; Jensen et al. 2011b; Vorabbi, Finelli, and Giusti 2016; Rotureau et al. 2017

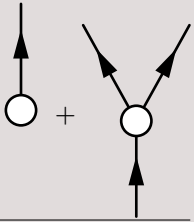
Towards direct reactions

$$\sigma^{th} = \sigma^{sp} \times |\langle \Psi^A \| a^\dagger \| \Psi^{A-1} \rangle|^2$$

$$\begin{aligned}\langle \Psi^A \| a^\dagger \| \Psi^{A-1} \rangle &= \langle \Psi^A \| U^\dagger U a^\dagger U^\dagger U \| \Psi^{A-1} \rangle \\ &= \langle \Psi^A_{SM} \| a^\dagger_{SM} \| \Psi^{A-1}_{SM} \rangle\end{aligned}$$

$$\begin{aligned}a^\dagger_{SM} =& e^{\Omega} a^\dagger e^{-\Omega} \\ &= a^\dagger + [\Omega, a^\dagger] + \tfrac{1}{2}[\Omega, [\Omega, a^\dagger]] + \dots\end{aligned}$$

$a^\dagger_{SM} \sim$



$+ \dots$

Jensen et al. 2010; Jensen et al. 2011a; **H. Zhang, Reed College senior thesis**

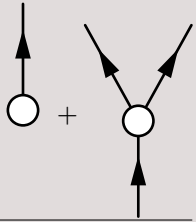
Towards direct reactions

$$\sigma^{th} = \sigma^{sp} \times |\langle \Psi^A \| a^\dagger \| \Psi^{A-1} \rangle|^2$$

$$\langle \Psi^A \| a^\dagger \| \Psi^{A-1} \rangle = \langle \Psi^A \| U^\dagger U a^\dagger U^\dagger U \| \Psi^{A-1} \rangle$$
$$= \langle \Psi^A_{SM} \| a^\dagger_{SM} \| \Psi^{A-1}_{SM} \rangle$$

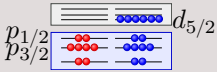
$$a^\dagger_{SM} = e^{\Omega} a^\dagger e^{-\Omega}$$
$$= a^\dagger + [\Omega, a^\dagger] + \tfrac{1}{2}[\Omega, [\Omega, a^\dagger]] + \ldots$$

$a^\dagger_{SM} \sim$

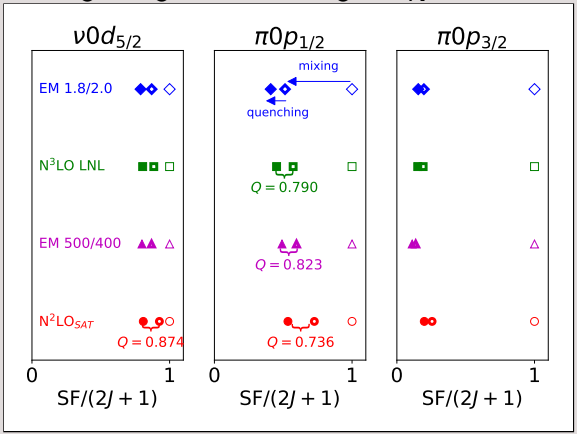


$+ \ldots$

[*very* preliminary]

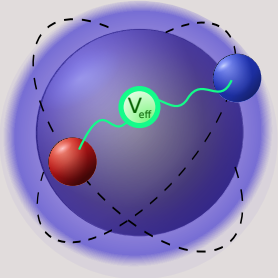


$^{22}O \rightarrow {}^{21}O$ $\quad$ $^{22}O \rightarrow {}^{21}N$



Jensen et al. 2010; Jensen et al. 2011a; **H. Zhang, Reed College senior thesis**

Thank you!



Collaborators:

- TRIUMF — A. Calci, J. Holt, P. Navrátil
- NSCL/MSU — S. Bogner, H. Hergert
- OSU — N. Parzuchowski
- LLNL — S. Quaglioni, K. Wendt
- ORNL/UT — G. Hagen, G. Jansen, T. Morris, T. Papenbrock
- TU Darmstadt — K. Hebeler, A. Schwenk, J. Simonis
- Reed College — H. Zhang

Discussion questions

1. Should comparisons with medium-mass data be used for fitting, or only validation?

2. Should we expect the optimal power counting for few-body systems to be applicable for $A \sim 100$? Will it still be optimal?

3. Is there anything to be learned from obervables related to collective phenomena?

4. Do collective phenomena amplify aspects of the interaction, or just wash them out?

References I

Barbieri, C. (2009). "Role of Long-Range Correlations in the Quenching of Spectroscopic Factors". In: *Physical Review Letters* 103.20, p. 202502. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.103.202502. URL: http://link.aps.org/doi/10.1103/PhysRevLett.103.202502.

Bogner, S. K., R. J. Furnstahl, and R. J. Perry (2007). "Similarity renormalization group for nucleon-nucleon interactions". In: *Physical Review C* 75.6, p. 061001. ISSN: 0556-2813. DOI: 10.1103/PhysRevC.75.061001. URL: http://link.aps.org/doi/10.1103/PhysRevC.75.061001.

Calci, Angelo and Robert Roth (2016). "Sensitivities and correlations of nuclear structure observables emerging from chiral interactions". In: *Physical Review C* 94.1, p. 014322. ISSN: 2469-9985. DOI: 10.1103/PhysRevC.94.014322. arXiv: 1601.07209. URL: http://link.aps.org/doi/10.1103/PhysRevC.94.014322http://arxiv.org/abs/1601.07209.

Ekström, A. et al. (2015). "Accurate nuclear radii and binding energies from a chiral interaction". In: *Physical Review C* 91.5, p. 051301. ISSN: 0556-2813. DOI: 10.1103/PhysRevC.91.051301. URL: http://link.aps.org/doi/10.1103/PhysRevC.91.051301.

Entem, D. R. and R. Machleidt (2003). "Accurate charge-dependent nucleon-nucleon potential at fourth order of chiral perturbation theory". In: *Physical Review C* 68.4, p. 041001. ISSN: 0556-2813. DOI: 10.1103/PhysRevC.68.041001. URL: http://link.aps.org/doi/10.1103/PhysRevC.68.041001.

Garcia Ruiz, R. F. et al. (2016). "Unexpectedly large charge radii of neutron-rich calcium isotopes". en. In: *Nature Physics* 12.6, pp. 594–598. ISSN: 1745-2473. DOI: 10.1038/nphys3645. URL: http://www.nature.com/nphys/journal/vaop/ncurrent/pdf/nphys3645.pdfhttp://dx.doi.org/10.1038/nphys3645http://www.nature.com/doifinder/10.1038/nphys3645.

Gazit, Doron, Sofia Quaglioni, and Petr Navrátil (2009). "Three-Nucleon Low-Energy Constants from the Consistency of Interactions and Currents in Chiral Effective Field Theory". In: *Physical Review Letters* 103.10, p. 102502. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.103.102502. URL: http://link.aps.org/doi/10.1103/PhysRevLett.103.102502.

Gebrerufael, Eskendr et al. (2017). "Ab Initio Description of Open-Shell Nuclei: Merging No-Core Shell Model and In-Medium Similarity Renormalization Group". In: *Physical Review Letters* 118.15, p. 152503. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.118.152503. URL: http://link.aps.org/doi/10.1103/PhysRevLett.118.152503.

References II

Glazek, Stanislaw D. and Kenneth G. Wilson (1994). "Perturbative renormalization group for Hamiltonians". In: *Physical Review D* 49.8, pp. 4214–4218. ISSN: 0556-2821. DOI: 10.1103/PhysRevD.49.4214. URL: http://journals.aps.org.ezproxy.library.ubc.ca/prd/abstract/10.1103/PhysRevD.49.4214http://link.aps.org/doi/10.1103/PhysRevD.49.4214.

Hebeler, K. et al. (2011). "Improved nuclear matter calculations from chiral low-momentum interactions". In: *Physical Review C* 83.3, p. 031301. ISSN: 0556-2813. DOI: 10.1103/PhysRevC.83.031301. URL: http://link.aps.org/doi/10.1103/PhysRevC.83.031301.

Hergert, Heiko et al. (2018). "Nuclear Structure from the In-Medium Similarity Renormalization Group". In: arXiv: 1805.09221. URL: http://arxiv.org/abs/1805.09221.

Jensen, Ø. et al. (2010). "Computation of spectroscopic factors with the coupled-cluster method". In: *Physical Review C* 82.1, p. 014310. ISSN: 0556-2813. DOI: 10.1103/PhysRevC.82.014310. URL: https://link.aps.org/doi/10.1103/PhysRevC.82.014310.

Jensen, Ø. et al. (2011a). "Closed-shell properties of O 24 with ab initio coupled-cluster theory". In: *Physical Review C* 83.2, p. 021305. ISSN: 0556-2813. DOI: 10.1103/PhysRevC.83.021305. URL: https://link.aps.org/doi/10.1103/PhysRevC.83.021305.

Jensen, Ø. et al. (2011b). "Quenching of Spectroscopic Factors for Proton Removal in Oxygen Isotopes". In: *Physical Review Letters* 107.3, p. 032501. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.107.032501. URL: http://link.aps.org/doi/10.1103/PhysRevLett.107.032501.

Kay, B. P., J. P. Schiffer, and S. J. Freeman (2013). "Quenching of cross sections in nucleon transfer reactions". In: *Physical Review Letters* 111.4, pp. 1–5. ISSN: 00319007. DOI: 10.1103/PhysRevLett.111.042502.

Leistenschneider, E. et al. (2018). "Dawning of the N = 32 Shell Closure Seen through Precision Mass Measurements of Neutron-Rich Titanium Isotopes". In: *Physical Review Letters* 120.6, arXiv:1710.08537. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.120.062503. arXiv: 1710.08537. URL: http://arxiv.org/abs/1710.08537http://dx.doi.org/10.1103/PhysRevLett.120.062503https://link.aps.org/doi/10.1103/PhysRevLett.120.062503.

Martínez-Pinedo, G. et al. (1996). "Effective g A in the pf shell". In: *Physical Review C* 53.6, R2602–R2605. ISSN: 0556-2813. DOI: 10.1103/PhysRevC.53.R2602. URL: http://journals.aps.org/prc/abstract/10.1103/PhysRevC.53.R2602https://link.aps.org/doi/10.1103/PhysRevC.53.R2602.

References III

Morris, T. D. (2016). "A Novel Approach to Solving the In-Medium SRG". PhD thesis. Michigan State University.

Navrátil, P. (2007). "Local three-nucleon interaction from chiral effective field theory". In: *Few-Body Systems* 41.3-4, pp. 117–140. ISSN: 0177-7963. DOI: 10.1007/s00601-007-0193-3. URL: http://link.springer.com/10.1007/s00601-007-0193-3.

Parzuchowski, N. M., T. D. Morris, and S. K. Bogner (2017). "Ab initio excited states from the in-medium similarity renormalization group". In: *Physical Review C* 95.4, p. 044304. ISSN: 2469-9985. DOI: 10.1103/PhysRevC.95.044304. URL: http://link.aps.org/doi/10.1103/PhysRevC.95.044304.

Parzuchowski, N. M. et al. (2017). "Ab initio electromagnetic observables with the in-medium similarity renormalization group". In: *Physical Review C* 96, p. 034324. ISSN: 2469-9985. DOI: 10.1103/PhysRevC.95.044304. arXiv: 1705.05511. URL: http://arxiv.org/abs/1705.05511.

Rotureau, J. et al. (2017). "Optical potential from first principles". In: *Physical Review C* 95.2, p. 024315. ISSN: 2469-9985. DOI: 10.1103/PhysRevC.95.024315. URL: https://link.aps.org/doi/10.1103/PhysRevC.95.024315.

Simonis, J. et al. (2017). "Saturation with chiral interactions and consequences for finite nuclei". In: *Physical Review C* 96.1, p. 014303. ISSN: 2469-9985. DOI: 10.1103/PhysRevC.96.014303. arXiv: 1704.02915. URL: http://arxiv.org/abs/1704.02915http://link.aps.org/doi/10.1103/PhysRevC.96.014303.

Stroberg, S. R. et al. (2017). "Nucleus-Dependent Valence-Space Approach to Nuclear Structure". In: *Physical Review Letters* 118.3, p. 032502. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.118.032502. URL: http://link.aps.org/doi/10.1103/PhysRevLett.118.032502.

Tostevin, J. A. and A. Gade (2014). "Systematics of intermediate-energy single-nucleon removal cross sections". In: *Physical Review C* 90.5, p. 057602. ISSN: 0556-2813. DOI: 10.1103/PhysRevC.90.057602. arXiv: 1409.6576. URL: http://arxiv.org/abs/1409.6576https://link.aps.org/doi/10.1103/PhysRevC.90.057602.

Tsukiyama, K., S. K. Bogner, and A. Schwenk (2011). "In-Medium Similarity Renormalization Group For Nuclei". In: *Physical Review Letters* 106.22, p. 222502. ISSN: 0031-9007. DOI: 10.1103/PhysRevLett.106.222502. URL: http://link.aps.org/doi/10.1103/PhysRevLett.106.222502.

References IV

Tsukiyama, K., S. K. Bogner, and A. Schwenk (2012). "In-medium similarity renormalization group for open-shell nuclei". In: *Physical Review C* 85.6, p. 061304. ISSN: 0556-2813. DOI: 10.1103/PhysRevC.85.061304. URL: http://link.aps.org/doi/10.1103/PhysRevC.85.061304.

Vorabbi, Matteo, Paolo Finelli, and Carlotta Giusti (2016). "Theoretical optical potential derived from nucleon-nucleon chiral potentials". In: *Physical Review C* 93.3, p. 034619. ISSN: 2469-9985. DOI: 10.1103/PhysRevC.93.034619. URL: https://link.aps.org/doi/10.1103/PhysRevC.93.034619.

Wegner, Franz (1994). "Flow-equations for Hamiltonians". In: *Annalen der Physic* 3, pp. 77–91.