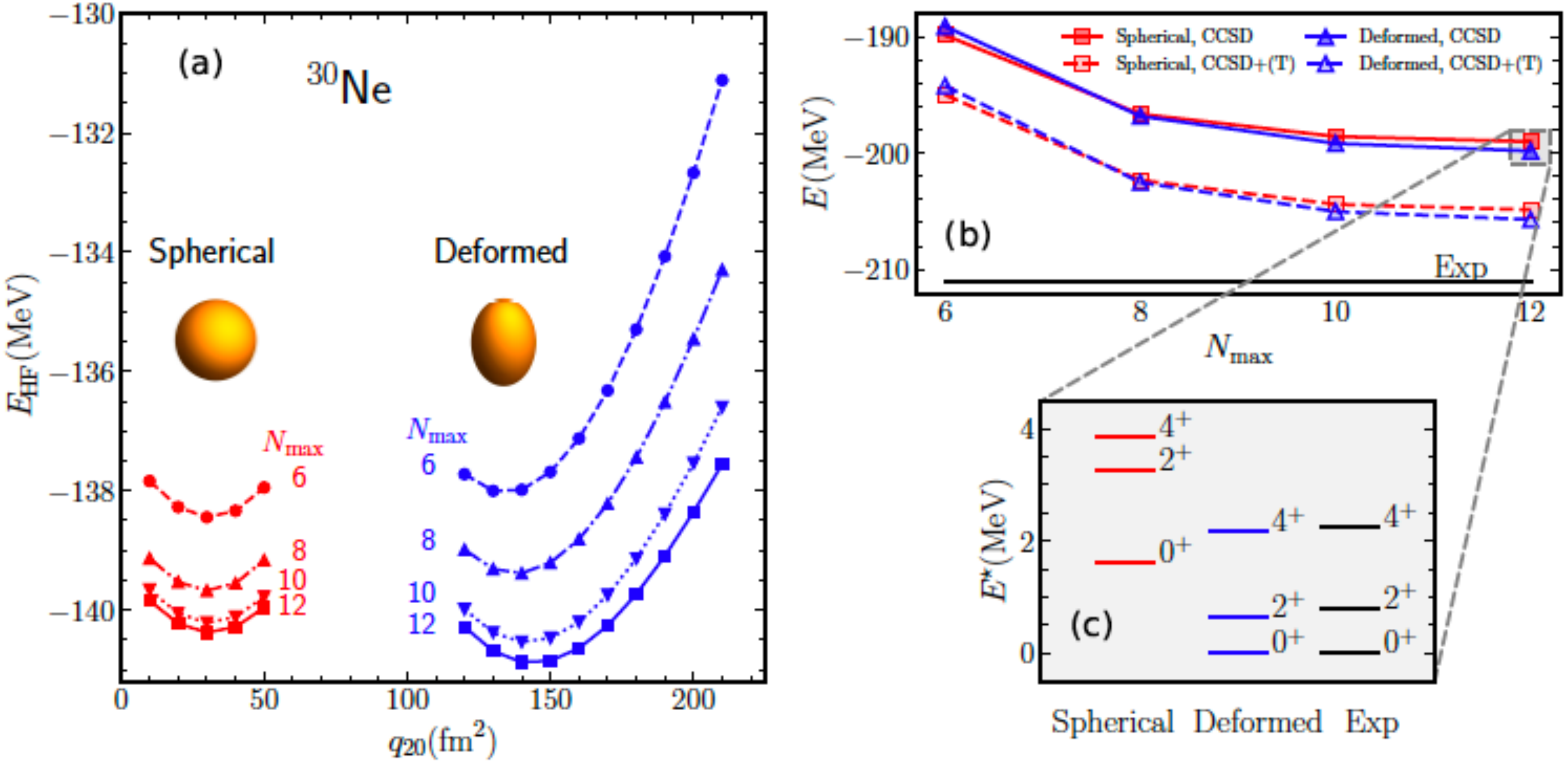
Deformed Nuclei at extreme isospin



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University of Tennessee & Oak Ridge National Laboratory

Halo Week
Gothenburg, June 10, 2024

Work supported by the US Department of Energy

SciDAC
Scientific Discovery through Advanced Computing

NUCLEI
Nuclear Computational Low-Energy Initiative

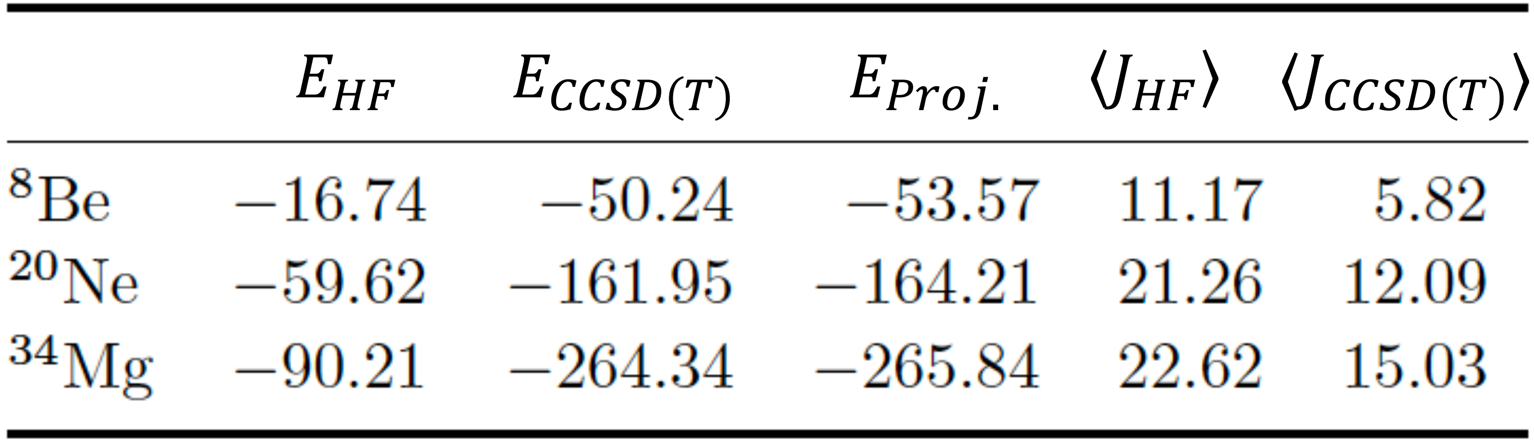
Today’s menu

- Baishan Hu, Zhonghao Sun, G. Hagen, TP, *Ab initio computations of strongly deformed nuclei around* ^{80}*Zr*, arXiv:2405.05052
- Zhonghao Sun, A. Ekström, C. Forssén, G. Hagen, G. R. Jansen, TP, *Multiscale physics of atomic nuclei from first principles*, arXiv:2404.00058
- B. Acharya, B. S. Hu, S. Bacca, G. Hagen, P. Navrátil, TP, *The magnetic dipole transition in* ^{48}*Ca*, Phys. Rev. Lett. 132, 232504 (2024).

Multiscale problem:

The bulk of the binding energy is from short-range correlations
Symmetry projection accounts for small details

1. Coester and Kümmel (1960), “Short-range correlations in nuclear wave functions”
2. Lipkin (1960), “Collective motion in many-particle systems: Part 1. the violation of conservation laws”



	E_{HF}	$E_{CCSD(T)}$	$E_{Proj.}$	$\langle J_{HF}\rangle$	$\langle J_{CCSD(T)}\rangle$
^{8}Be	−16.74	−50.24	−53.57	11.17	5.82
^{20}Ne	−59.62	−161.95	−164.21	21.26	12.09
^{34}Mg	−90.21	−264.34	−265.84	22.62	15.03

Data from Hagen et al., Phys. Rev. C 105, 064311 (2022)

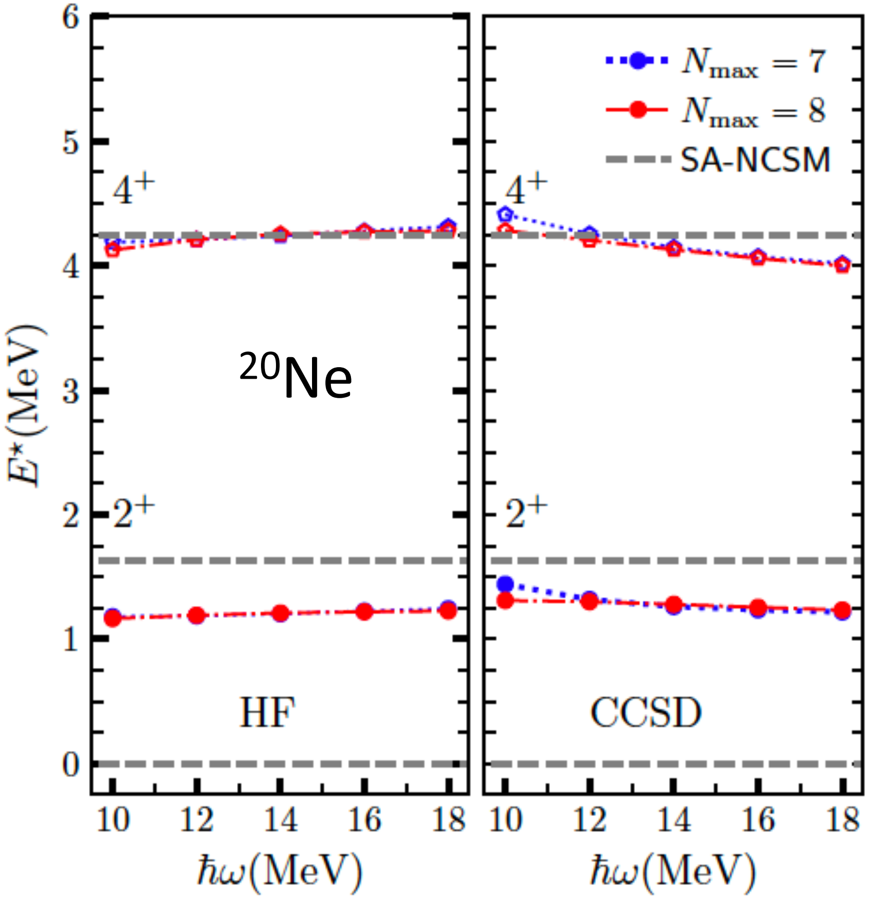
Energy gain from symmetry projection is small and not size extensive

Our approach

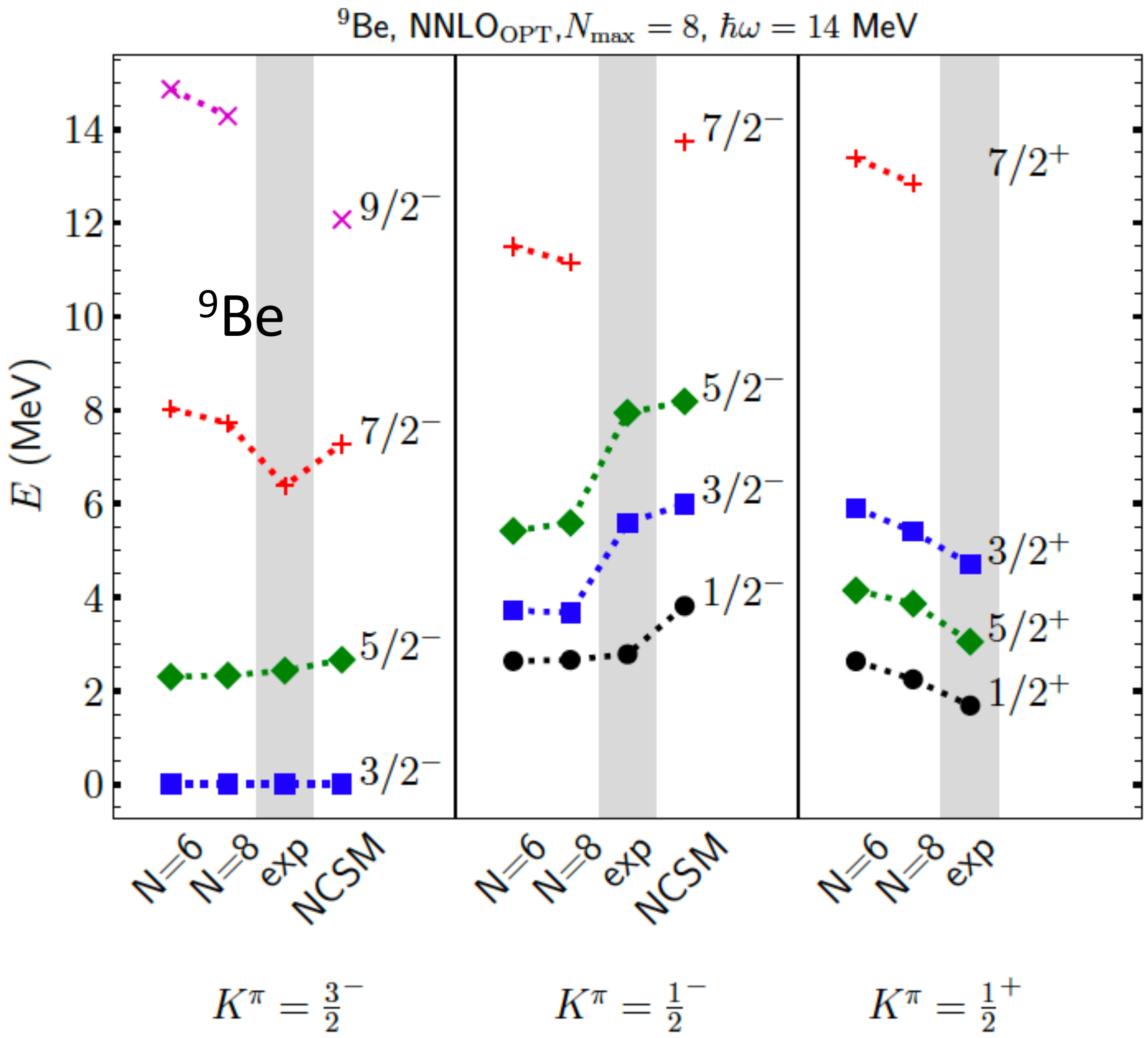
Include short-range correlations first, then long-range ones

1. Start from an axially symmetric reference state
2. Include short-range (“dynamical”) correlations via coupled cluster method
    - captures UV physics
3. Symmetry projection includes collective effects
    - captures IR physics

Meeting NCSM benchmarks



SA-NCSM: Launey, Dytrych, Sargsyan, Baker, Draayer, Eur. Phys. J. Special Topics 229, 2429 (2020).



NCSM: Caprio, Maris, Vary, Smith, Int. J. Mod. Phys. E 24, 1541002 (2015).

Shape coexistence

States with different shapes that are close in energy

Reviews: Heyde and Wood, Rev. Mod. Phys. 83, 1467 (2011); Gade and Liddick, J. Phys. G 43, 024001 (2016); Bonatsos, et al., Atoms 11, 117 (2023).

Observed in ^{30}Mg by Schwerdtfeger et al., Phys. Rev. Lett. 103, 012501 (2009) and in ^{32}Mg by Wimmer et al., Phys. Rev. Lett. 105, 252501 (2010).

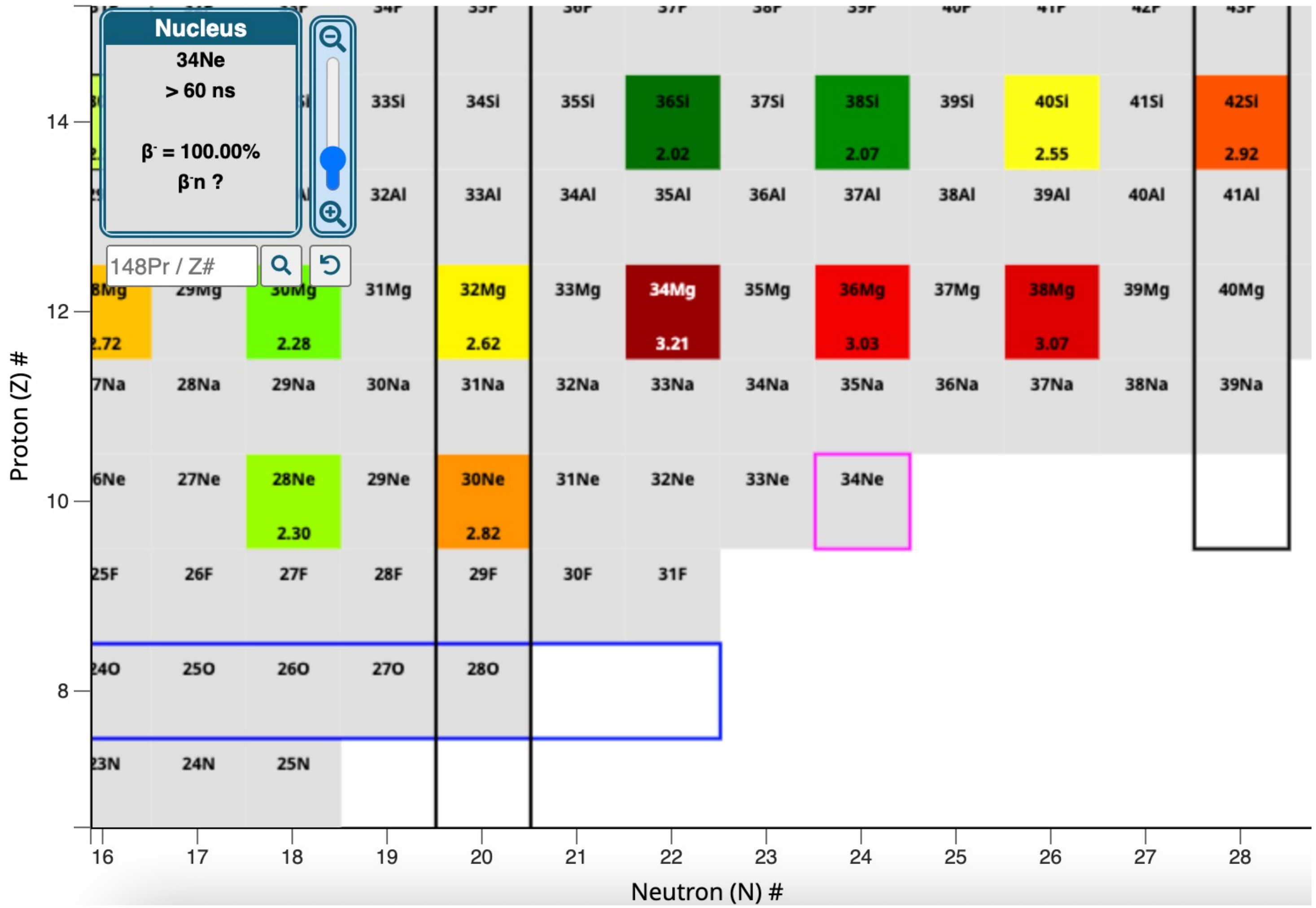
Theoretical descriptions: Reinhard et al., Phys. Rev. C 60, 014316 (1999); Rodríguez-Guzmán, Egido, and Robledo, Nucl. Phys. A 709, 201 (2002); Péru and Martini, Eur. Phys. J. A 50, 88 (2014); Caurier, Nowacki, and Poves, Phys. Rev. C 90, 014302 (2014); see also Tsunoda et al., Nature 587, 66 (2020).

Neutron-rich nuclei beyond $N \geq 20$ are deformed

$$R_{4/2} \equiv \frac{E_{4^+}}{E_{2^+}}$$

$R_{4/2} = 10/3$ for a rigid rotor

Simple picture: Spherical states (magic $N = 20$ number in the traditional shell model) coexist with deformed ground states



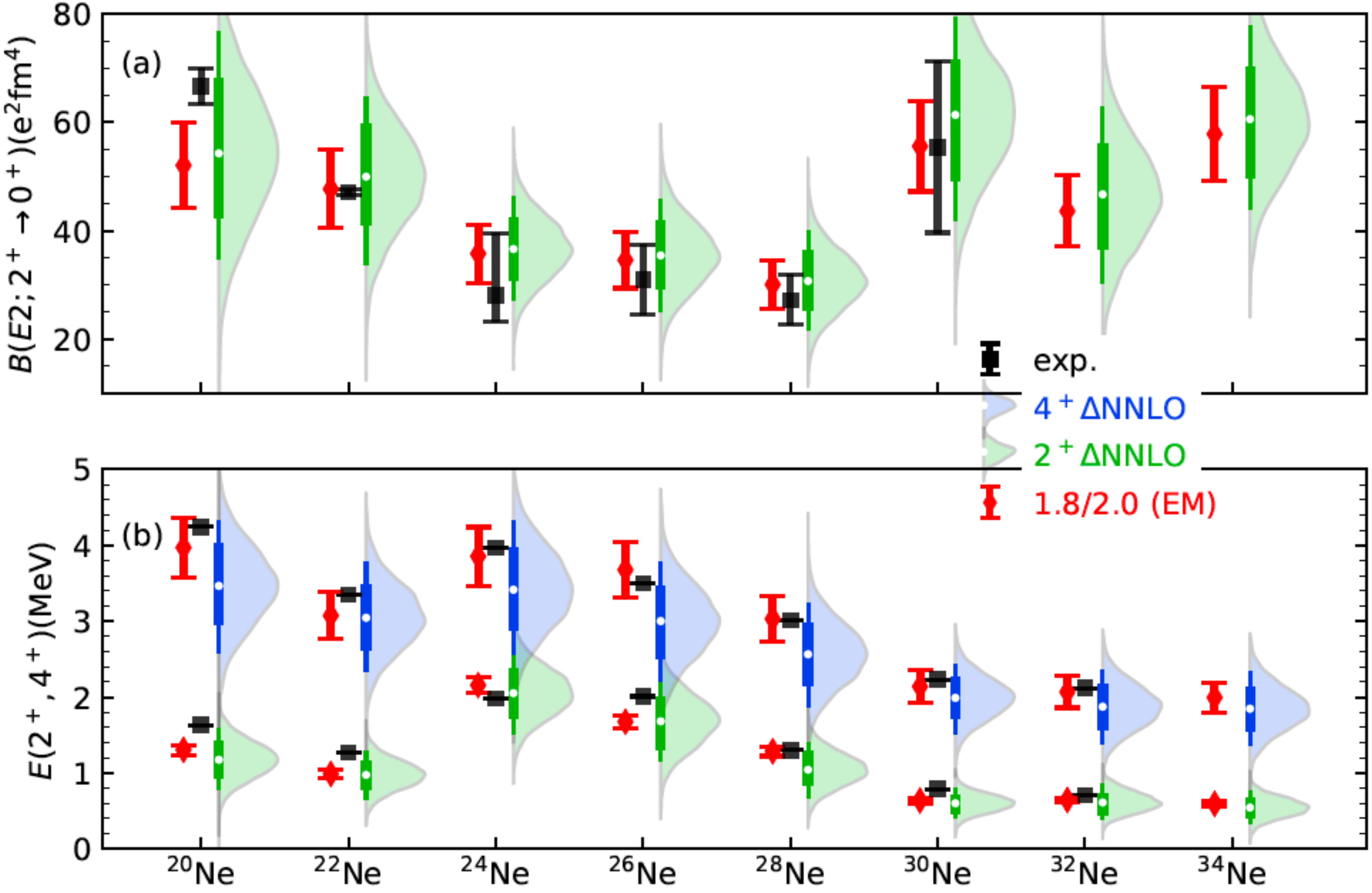
Nucleus
34Ne
> 60 ns

β- = 100.00%
β-n ?

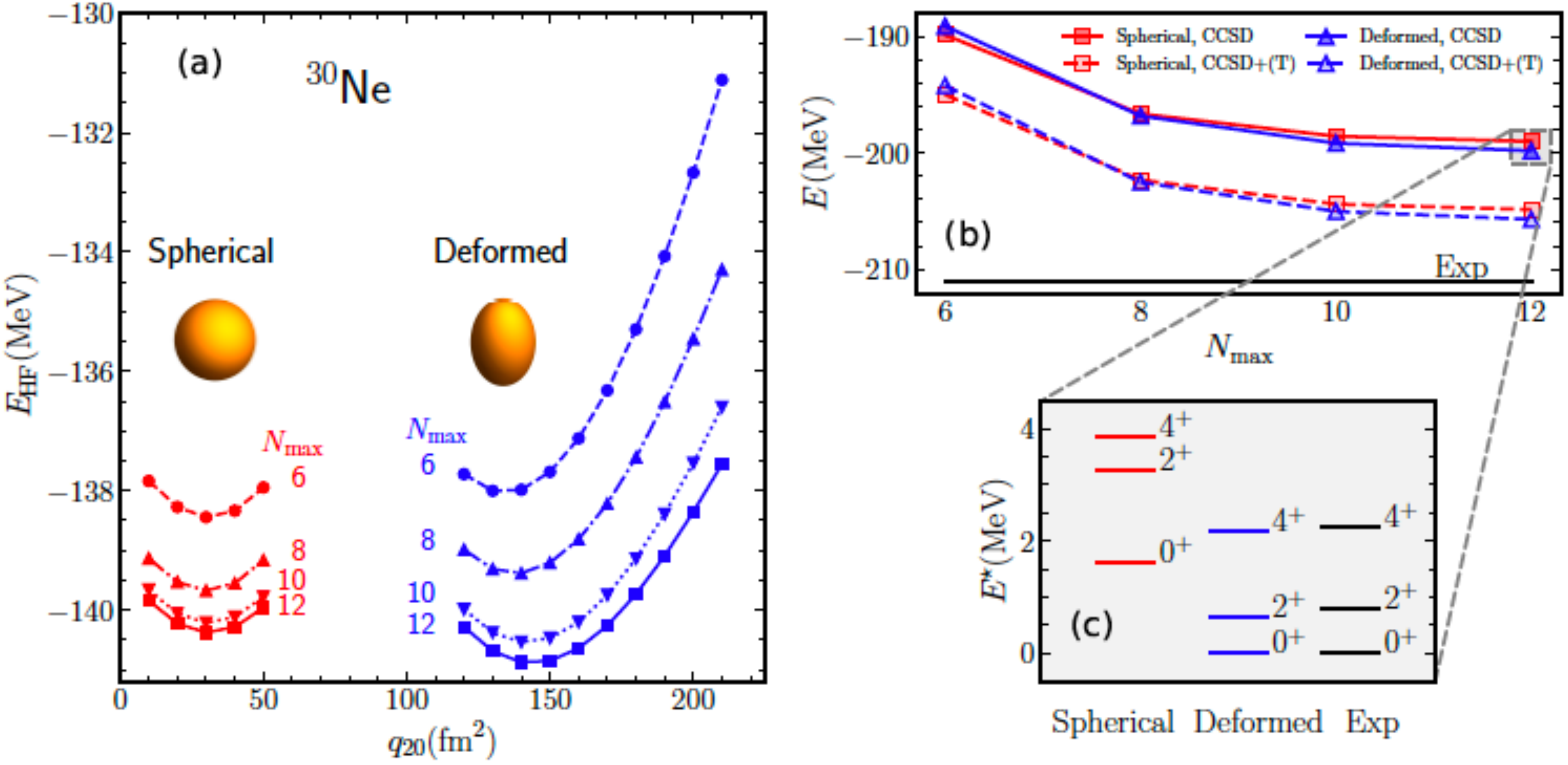
Proton (Z) #	16	17	18	19	20	21	22	23	24	25	26	27	28
14				33Si	34Si	35Si	36Si 2.02	37Si	38Si 2.07	39Si	40Si 2.55	41Si	42Si 2.92
				32Al	33Al	34Al	35Al	36Al	37Al	38Al	39Al	40Al	41Al
12	8Mg .72	29Mg	30Mg 2.28	31Mg	32Mg 2.62	33Mg	34Mg 3.21	35Mg	36Mg 3.03	37Mg	38Mg 3.07	39Mg	40Mg
	7Na	28Na	29Na	30Na	31Na	32Na	33Na	34Na	35Na	36Na	37Na	38Na	39Na
10	6Ne	27Ne	28Ne 2.30	29Ne	30Ne 2.82	31Ne	32Ne	33Ne	34Ne				
	25F	26F	27F	28F	29F	30F	31F						
8	24O	25O	26O	27O	28O								
	23N	24N	25N										

Poves & Retamosa (1987); Warburton, Becker, and Brown (1990); …

Coupled cluster theory: collectivity of neon nuclei



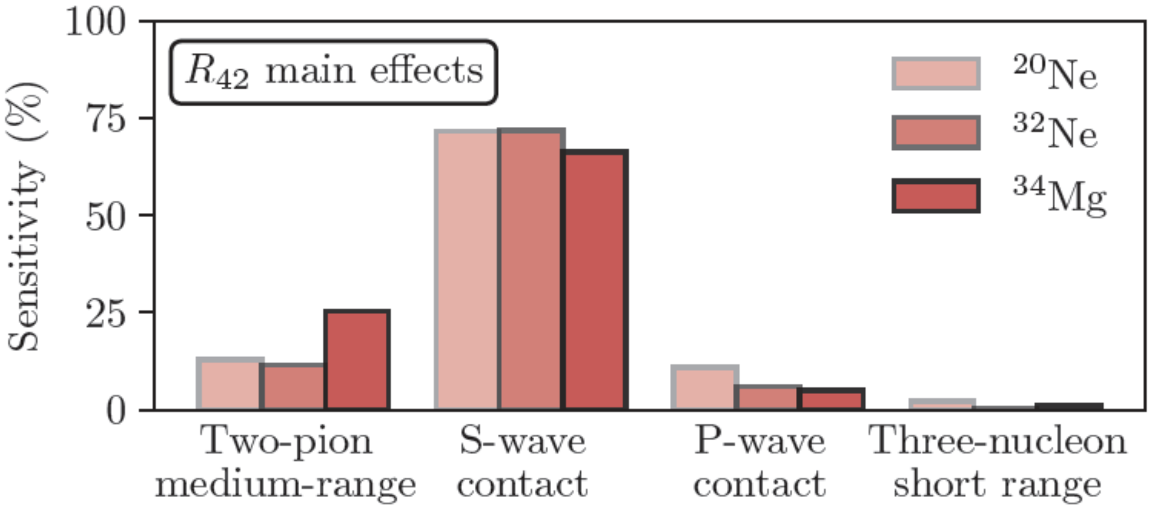
Prediction: Shape coexistence in ^{30}Ne



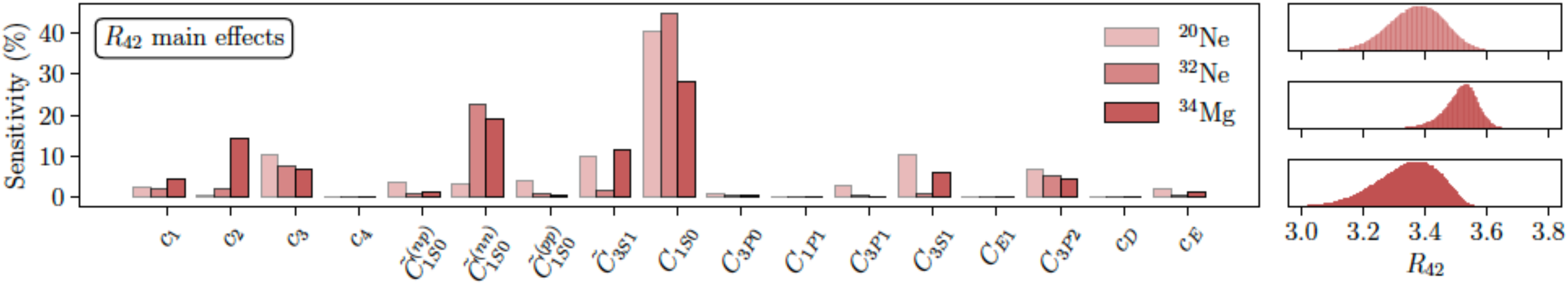
Zhonghao Sun et al., arXiv:2404.00058

What drives nuclear deformation in chiral EFT?

Executive summary



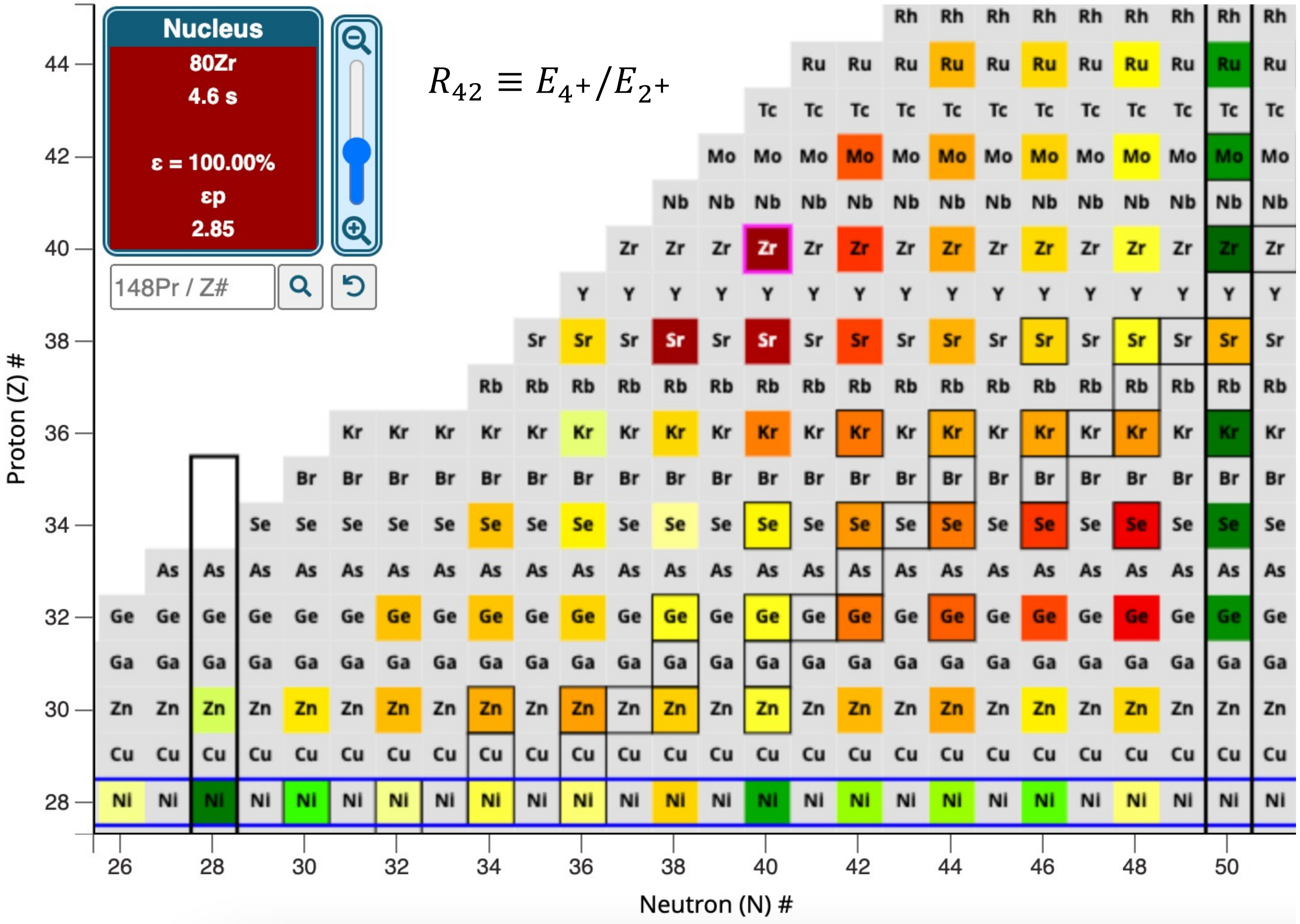
More detailed view



Zhonghao Sun et al., arXiv:2404.00058

The region around ^{80}Zr

$$R_{42} \equiv E_{4^+}/E_{2^+}$$

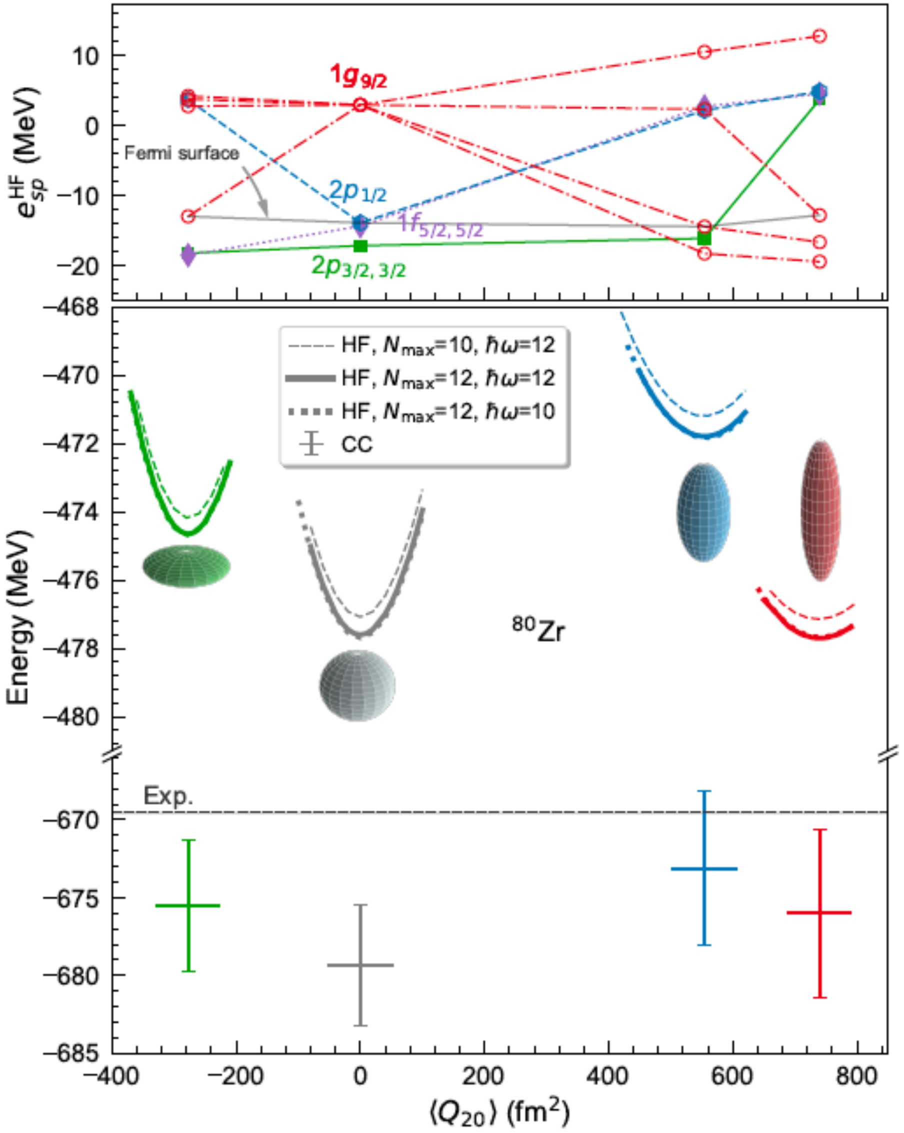


Nucleus
80Zr
4.6 s
ε = 100.00%
εp
2.85

148Pr / Z#

Baishan Hu, Zhonghao Sun et al., arXiv:2405.05052

Shapes of ^{80}Zr



Quadrupole constrained HF computations

- several minima identified
- angular momentum projected

Shape coexistence identified

- coupled-cluster computations too uncertain to predict shape of ground state

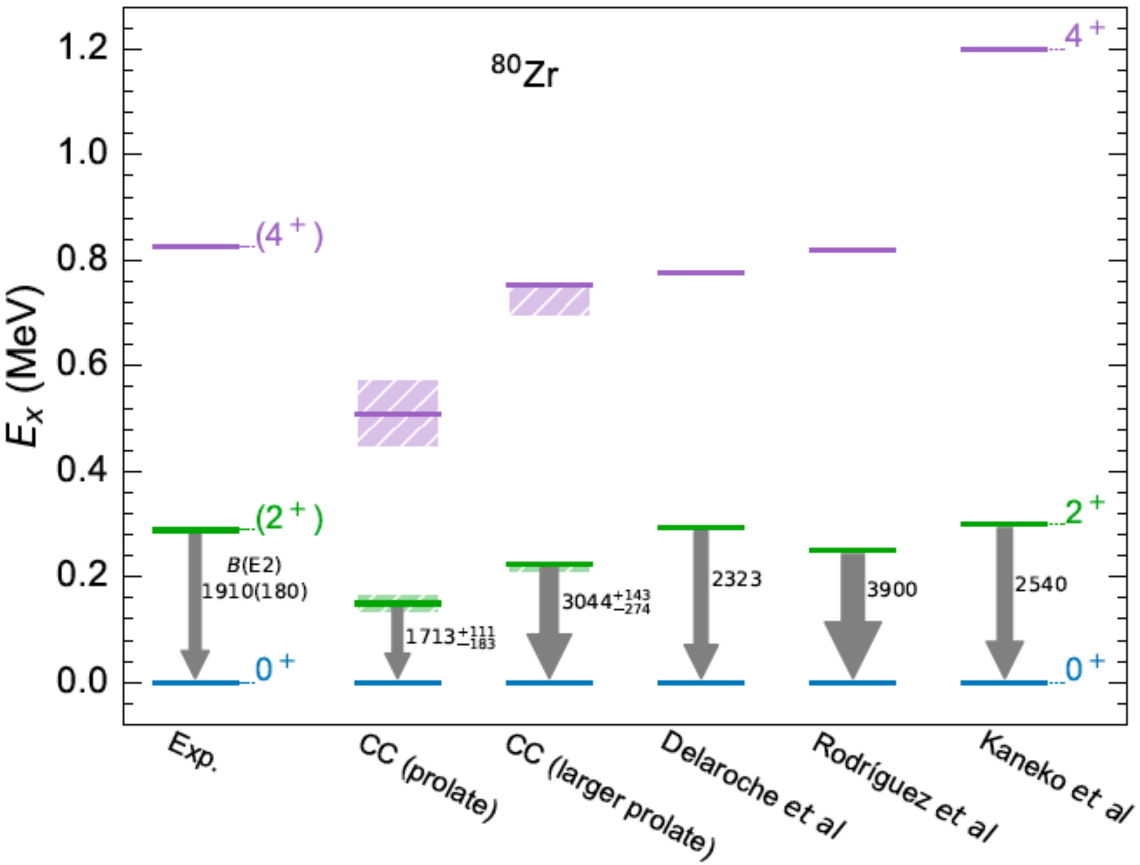
Used Miyagi (2023) for 3NFs in large model spaces

Fun fact: ^{80}Zr has higher energy than two ^{40}Ca nuclei

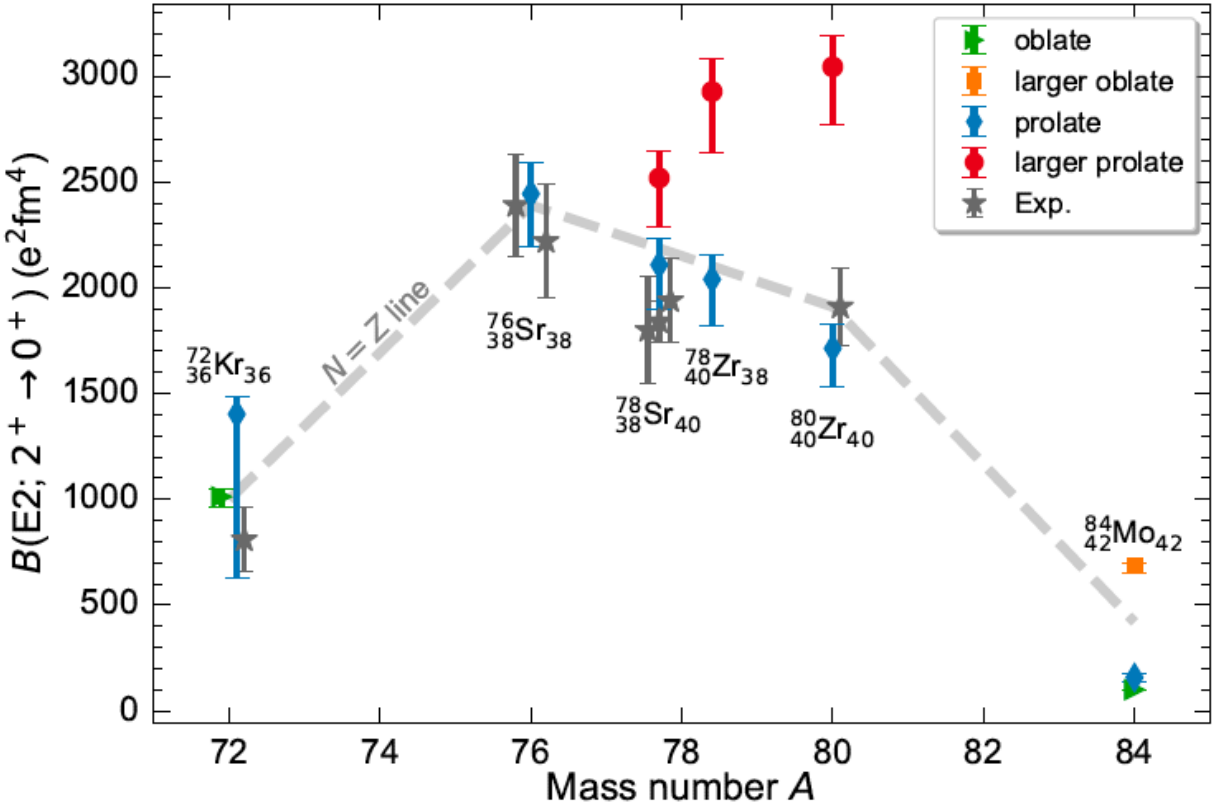
Baishan Hu, Zhonghao Sun et al., arXiv:2405.05052

The region around ^{80}Zr

Spectrum prefers larger prolate shape



$B(E2)$ prefers prolate band



Baishan Hu, Zhonghao Sun et al., arXiv:2405.05052

Why do people care about M1 transitions?

Supernova 1987A

February 24, 1987
Las Campanas Observatory

M1 spin excitations are dominated by isovector contributions.

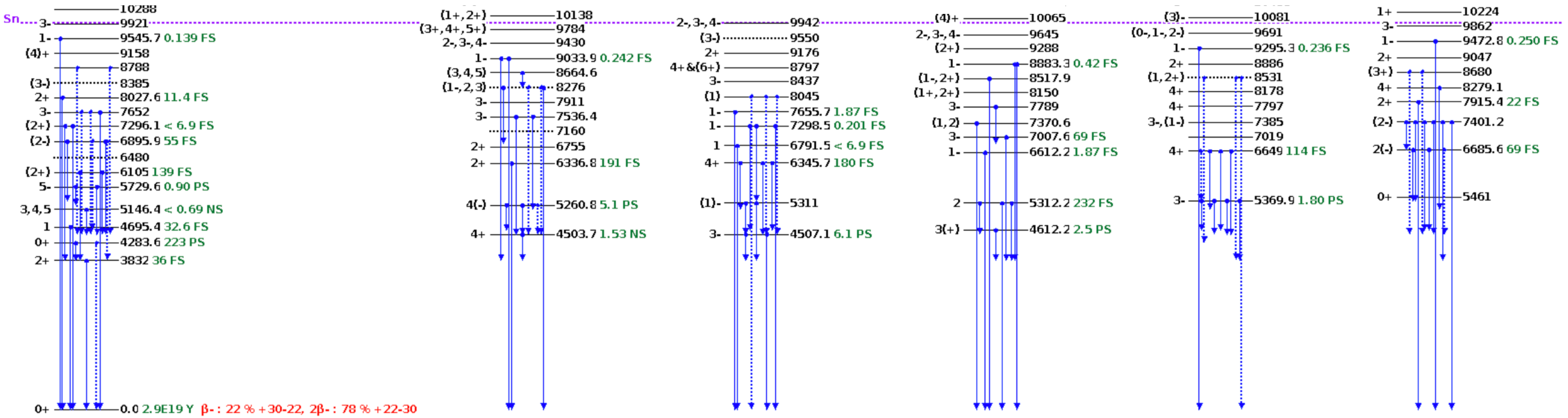
The isovector-0 component of the Gamow-Teller operator translates to inelastic neutral-current neutrino-nucleus reactions at energies relevant for supernovae.

Our understanding of M1 impacts supernovae signals and dynamics.

Lüttge, von Neumann-Cosel, Neumeyer, Richter, Nucl Phys A (1996);
Langanke, Martinez-Pinedo, von Neumann-Cosel, Richter, Phys Rev Lett (2004);
Loens, Langanke, Martinez-Pinedo, Sieja, EPJA (2012);
Tornow et al, Phys Letts B (2022).

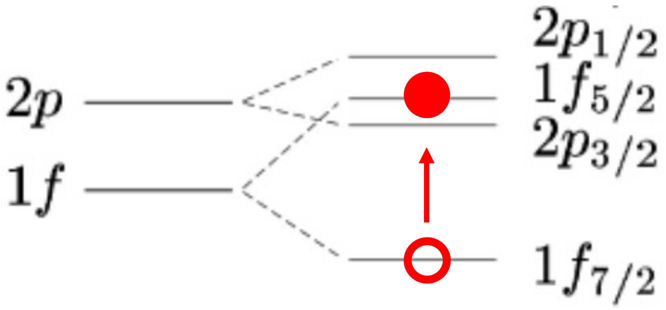
Review on $M1$:
K. Heyde, P. von Neumann-Cosel, A. Richter, Rev. Mod. Phys. 82, 2365 (2010).

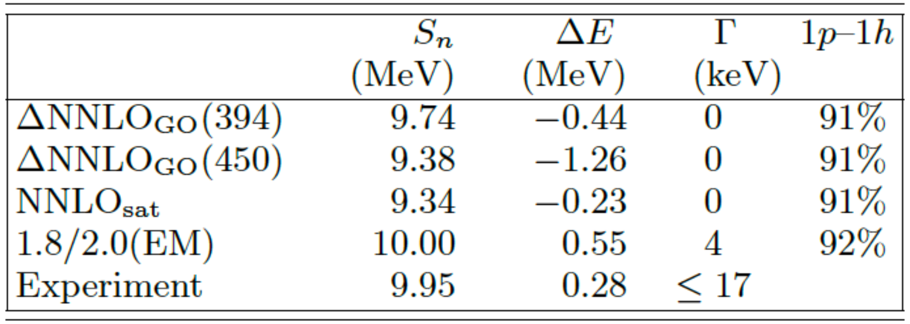
The resonant 1^+ HALO state in ^{48}Ca at 10.224 MeV



Scattering / reactions that probe the 1^+ state: (e, e'), (p, p'), (p, n), or (γ, n)

Simple picture of the 1^+ state: neutron 1p-1h excitation; extreme single-particle model: $B(M1) = 12\ \mu_N^2$





	S_n (MeV)	ΔE (MeV)	Γ (keV)	$1p$–$1h$
ΔNNLO$_{\rm GO}$(394)	9.74	−0.44	0	91%
ΔNNLO$_{\rm GO}$(450)	9.38	−1.26	0	91%
NNLO$_{\rm sat}$	9.34	−0.23	0	91%
1.8/2.0(EM)	10.00	0.55	4	92%
Experiment	9.95	0.28	≤ 17	

Bijaya Acharya et al., Phys. Rev. Lett. 132, 232504 (2024)

The status

(e,e') scattering:	$B(M1) = 4.0 \pm 0.3\ \mu_N^2$	[Steffen et al 1980; 1983]
(γ,n) scattering:	$B(M1) = 6.8 \pm 0.5\ \mu_N^2$	[Tompkin et al 2011]
(p,p') scattering:	$B(M1) = 3.85(32) - 4.63(38)\ \mu_N^2$	[Birkhan et al 2016]

Extreme s.p. model: $B(M1) = 12\ \mu_N^2$

Theory has a hard time to reproduce a large amount of quenching

A. Harting, W. Weise, H. Toki, and A. Richter, Physics Letters B 104, 261 (1981).

Meson-exchange currents claimed to explain small $B(M1)$

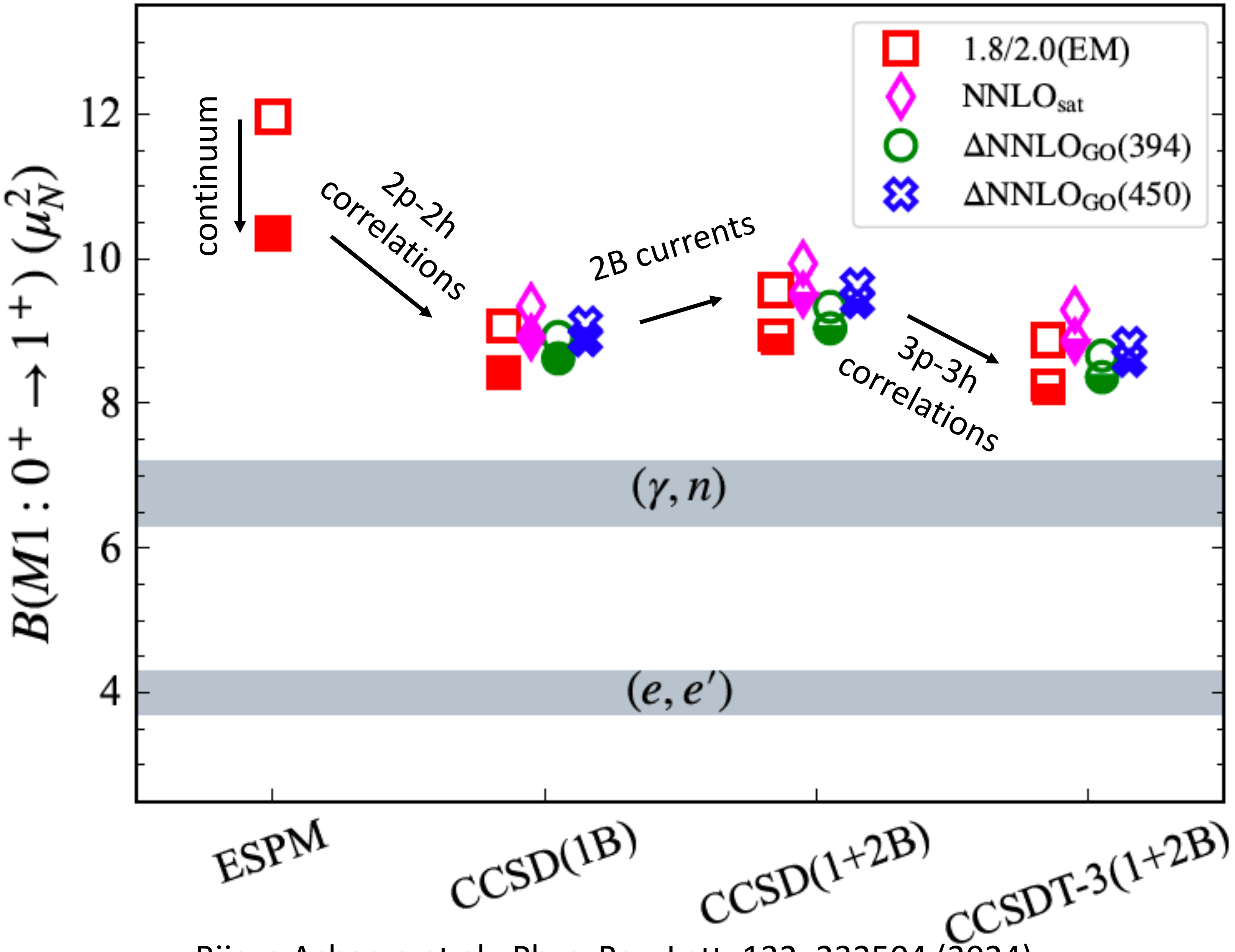
J. B. McGrory and B. H. Wildenthal, Phys. Lett. B 103, 173 (1981).
Toru Suzuki, S. Krewald, and J. Speth, Phys. Lett. B 107, 9 (1981).
G. F. Bertsch, Nucl. Phys. A 354, 157 (1981).
M. Kohno and D. W. L. Sprung, Phys. Rev. C 26, 297 (1982).
K. Takayanagi, K. Shimizu, and A. Arima, Nucl. Phys. A 481, 313 (1988).
M. G. E. Brand, K. Allaart, and W. H. Dickhoff, Nucl. Phys. A 509, 1 (1990).
B. A. Brown and W. A. Richter, Phys. Rev. C 58, 2099 (1998).

All too high $B(M1)$;
$B(M1) = 7 - 8\mu_N^2$;
$B(M1) > 5.1\mu_N^2$;

J. D. Holt, J. Menendez, J. Simonis, and A. Schwenk, Phys. Rev. C 90, 024312 (2014).
J. Wilhelmy, et al., Phys. Rev. C 98, 034315 (2018).

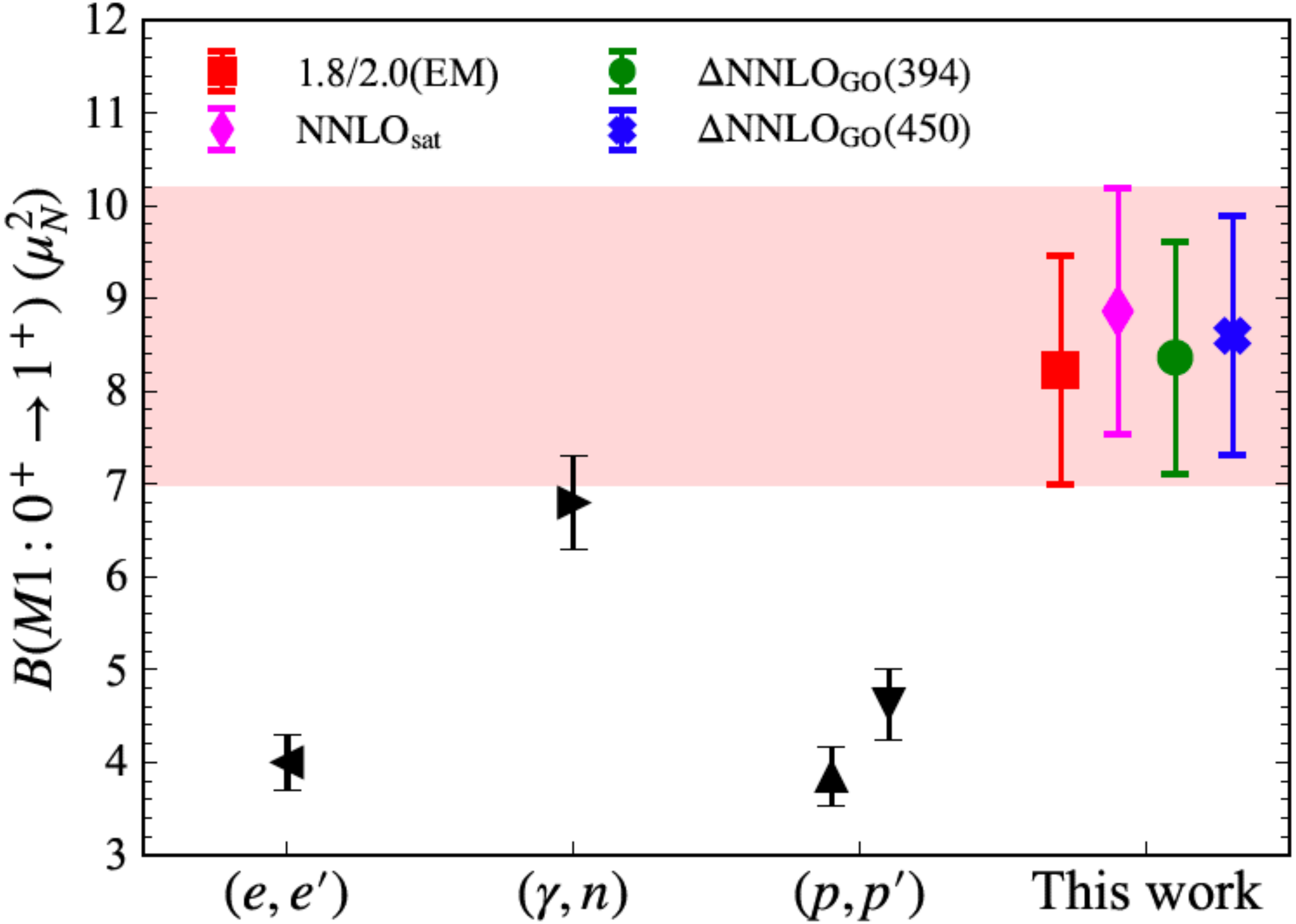
Reproduce (e,e') $B(M1)$ if quenched

Contributions to $B(M1)$



Bijaya Acharya et al., Phys. Rev. Lett. 132, 232504 (2024)

Final result



Bijaya Acharya et al., Phys. Rev. Lett. 132, 232504 (2024)

Summary

Breaking and restoring symmetries

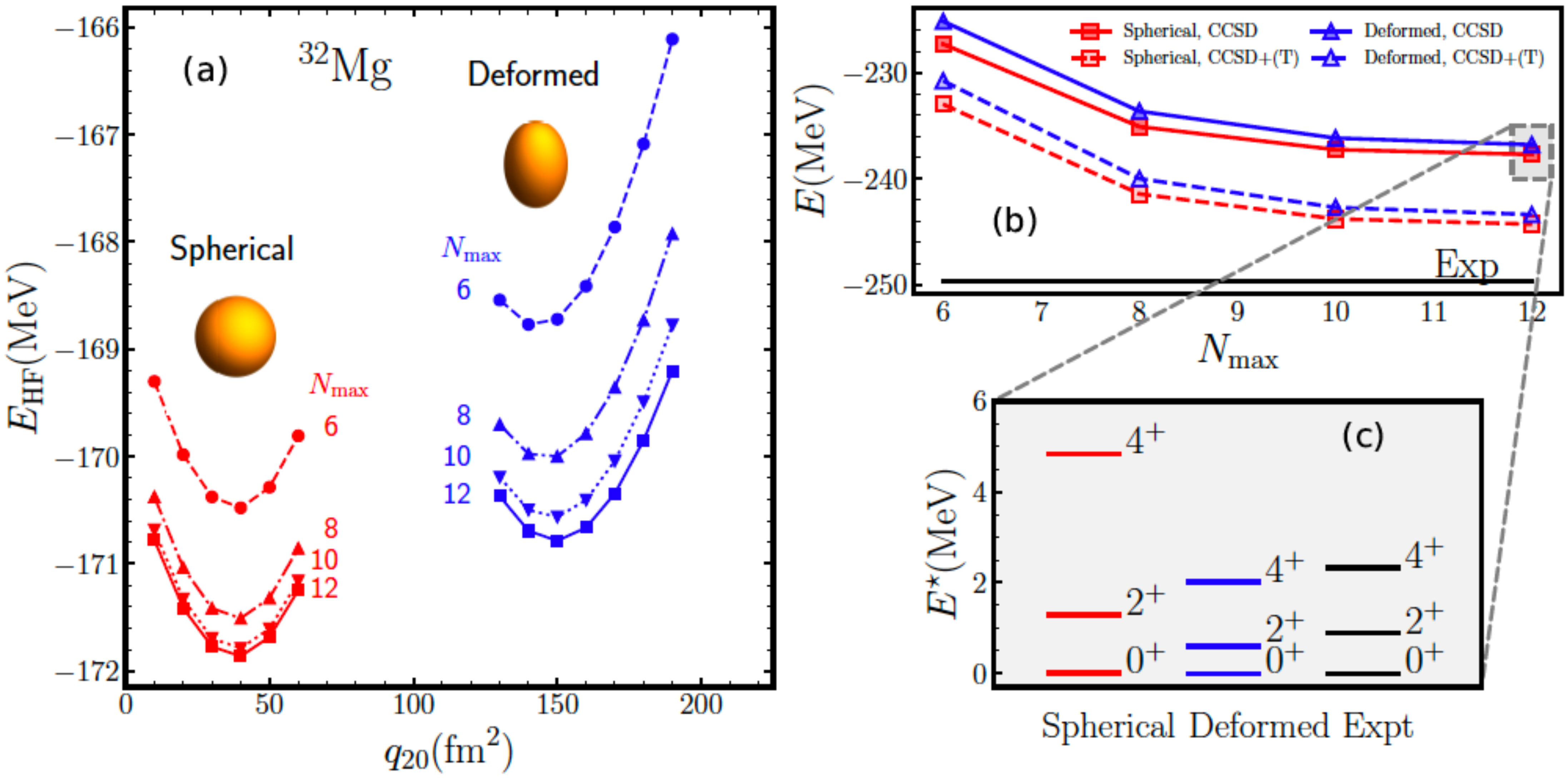
Exploits separation of scale between universal collective and specific UV physics

Conceptually simple & computationally affordable

- Shape coexistence in ^{30}Ne
- Connected deformation to microscopic forces
- Much improved B(E2) values
- ^{3x}Ne, ^{3x}Mg, ^{80}Zr
- B(M1) in ^{48}Ca larger than (e,e’) but in agreement with (n,γ)
- Two-body currents do not quench B(M1)

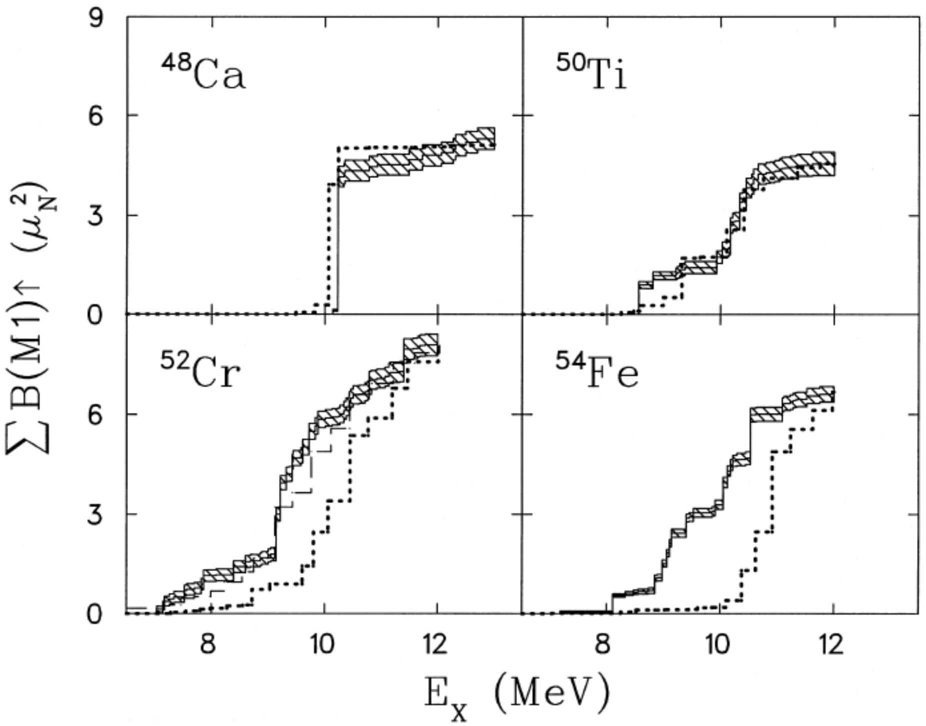
Thank you!

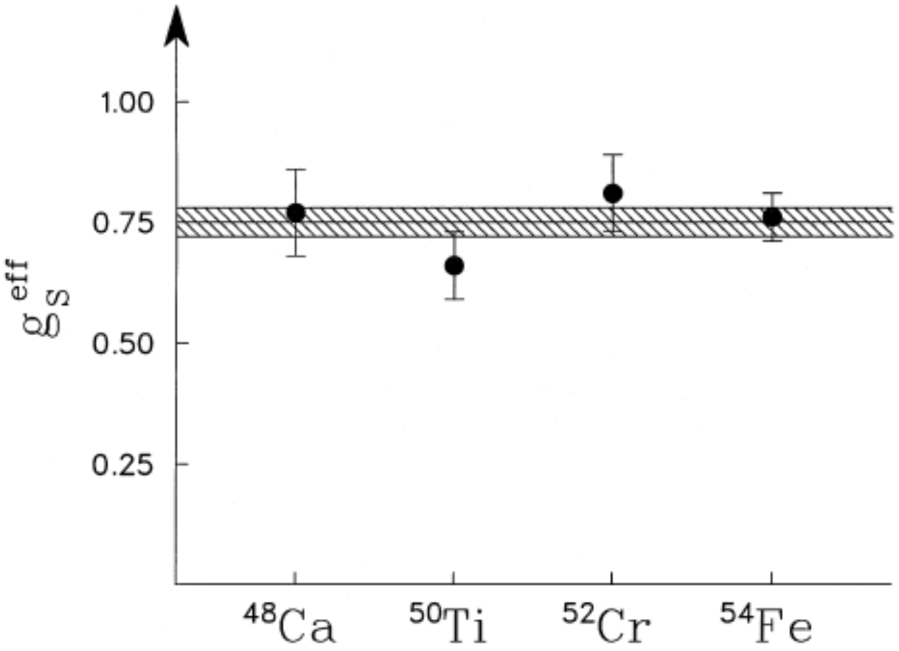
Confirmation: Shape coexistence in ^{32}Mg



Zhonghao Sun et al., arXiv:2404.00058

Why could/should there be quenching?





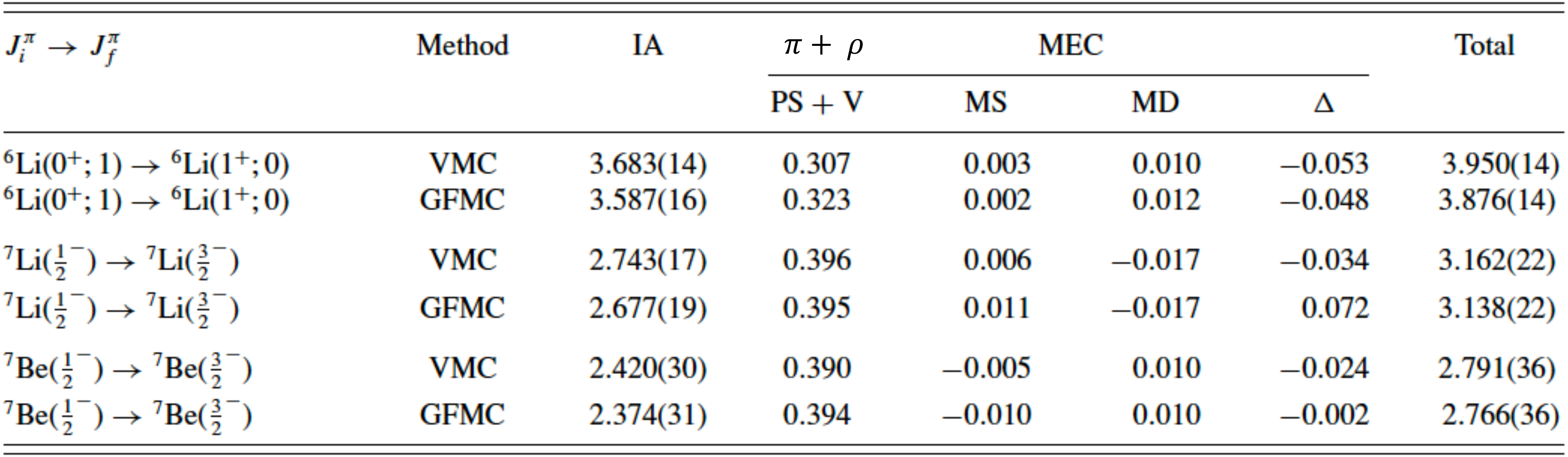
Results from (e, e') scattering match quenched shell-model results

Von Neumann-Cosel, Poves, Retamosa, Richter, Phys Letts B (1998)

Proposed: $B(M1)$ is quenched similarly to $B(GT)$ in pf shell nuclei

→ Impacts (re)analyses of (p, p') experiments using the “unit cross section” method

Two-body currents do not quench M1 transitions in light nuclei



$J_i^\pi \to J_f^\pi$	Method	IA	$\pi + \rho$	MEC			Total
			PS + V	MS	MD	Δ	
^{6}Li$(0^+;1) \to {}^6$Li$(1^+;0)$	VMC	3.683(14)	0.307	0.003	0.010	−0.053	3.950(14)
^{6}Li$(0^+;1) \to {}^6$Li$(1^+;0)$	GFMC	3.587(16)	0.323	0.002	0.012	−0.048	3.876(14)
^{7}Li$(\frac{1}{2}^-) \to {}^7$Li$(\frac{3}{2}^-)$	VMC	2.743(17)	0.396	0.006	−0.017	−0.034	3.162(22)
^{7}Li$(\frac{1}{2}^-) \to {}^7$Li$(\frac{3}{2}^-)$	GFMC	2.677(19)	0.395	0.011	−0.017	0.072	3.138(22)
^{7}Be$(\frac{1}{2}^-) \to {}^7$Be$(\frac{3}{2}^-)$	VMC	2.420(30)	0.390	−0.005	0.010	−0.024	2.791(36)
^{7}Be$(\frac{1}{2}^-) \to {}^7$Be$(\frac{3}{2}^-)$	GFMC	2.374(31)	0.394	−0.010	0.010	−0.002	2.766(36)

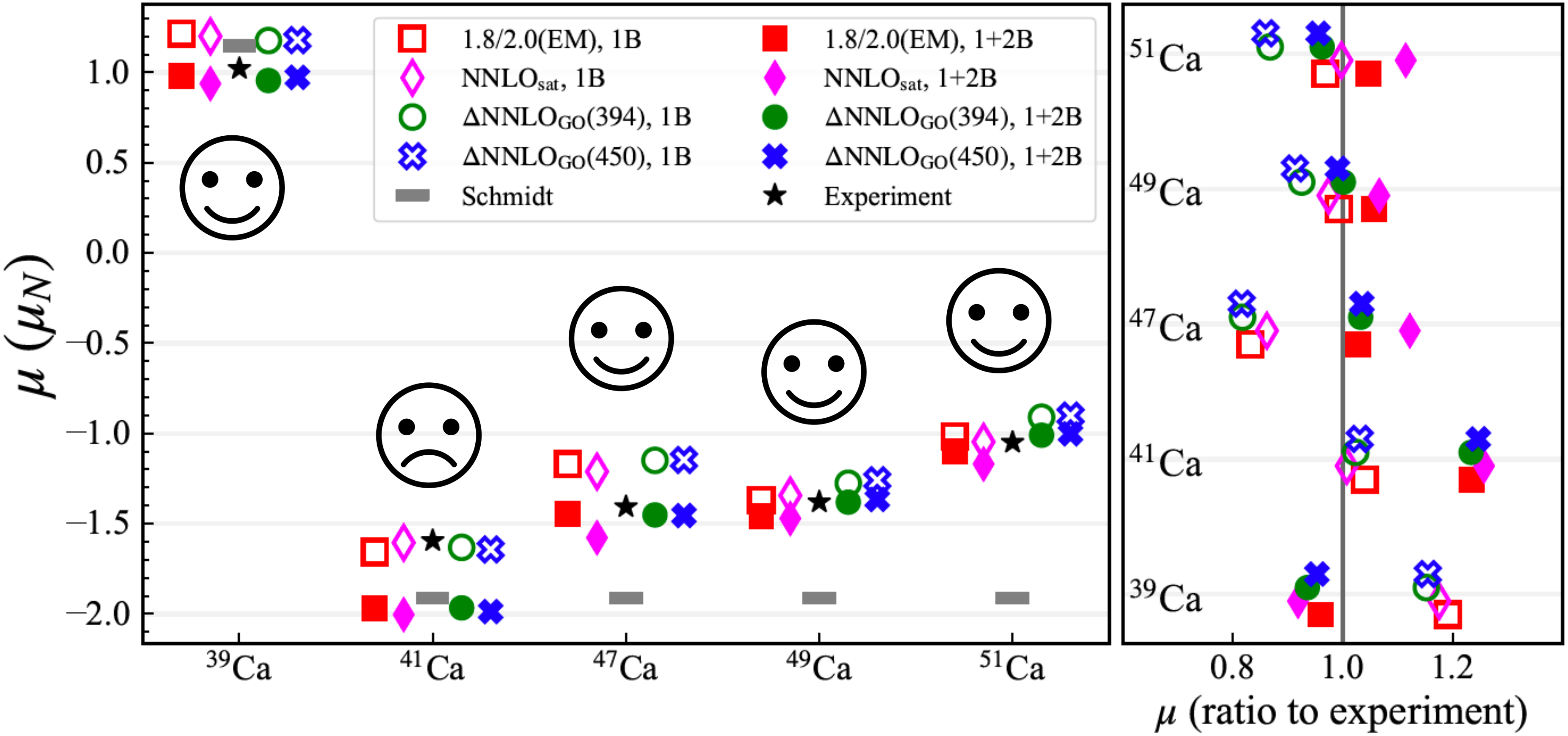
Marcucci, Muslema Pervin, Pieper, Schiavilla,
Wiringa, Phys Rev C 78, 065501 (2008)

This is similar to what we will use

This is perhaps similar to what people used in the 1980s

Two-body currents for $M1$ transitions differ from those for Gamow-Teller transitions

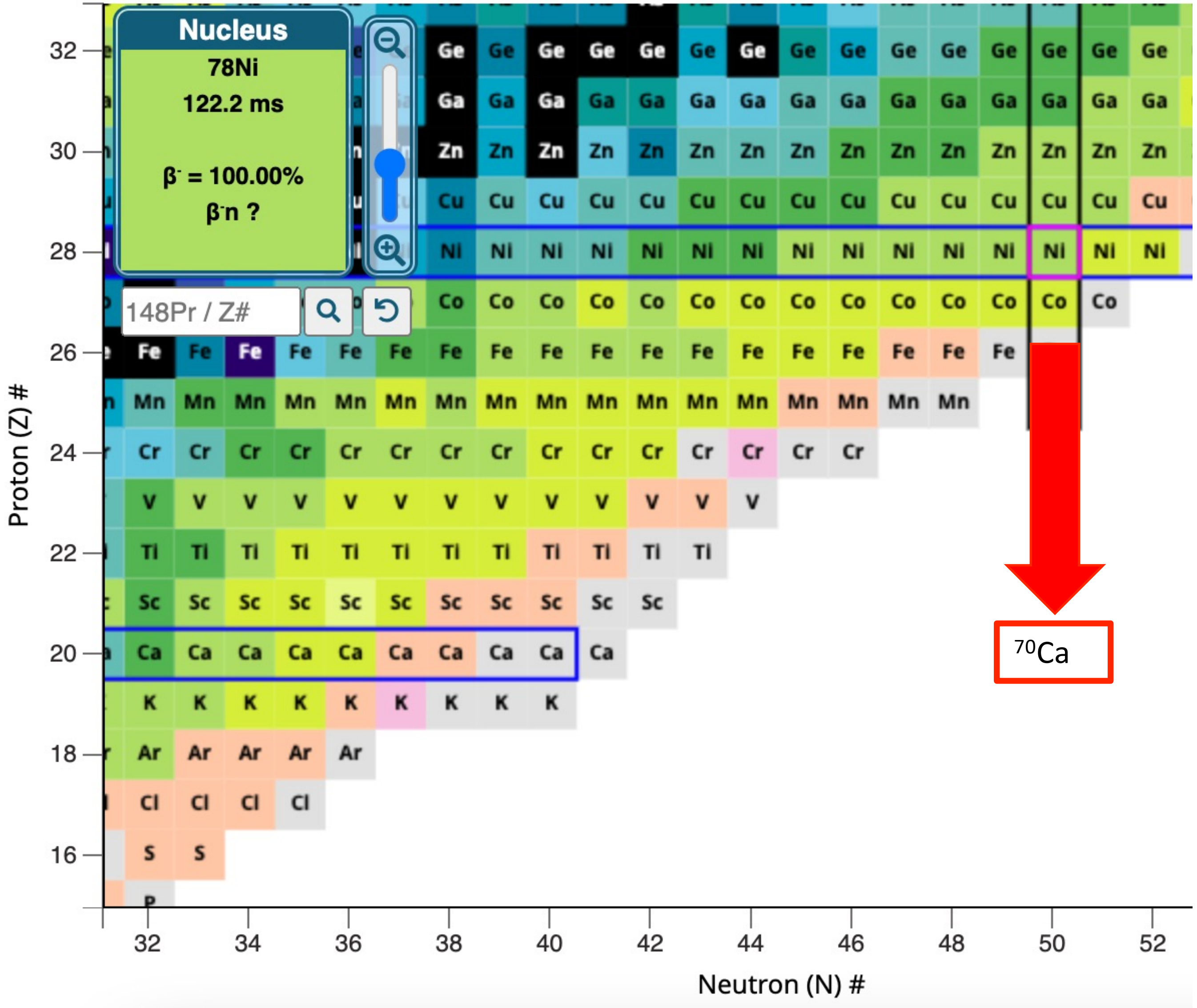
Magnetic moments



Bijaya Acharya et al., Phys. Rev. Lett. 132, 232504 (2024)

Takayuki Miyagi et al., Phys. Rev. Lett. 132, 232503 (2024): multi-shell VS-IMSRG calculation accurate for ^{41}Ca.

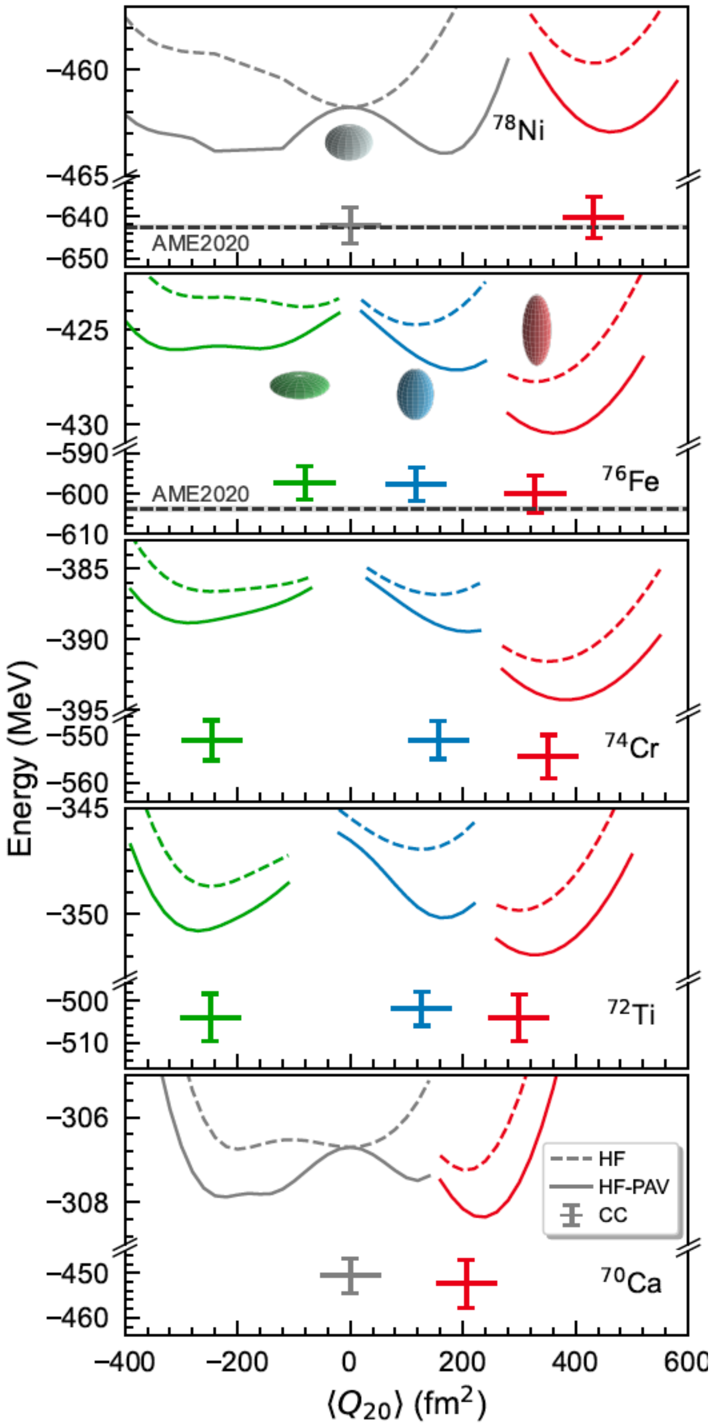
South of ^{78}Ni



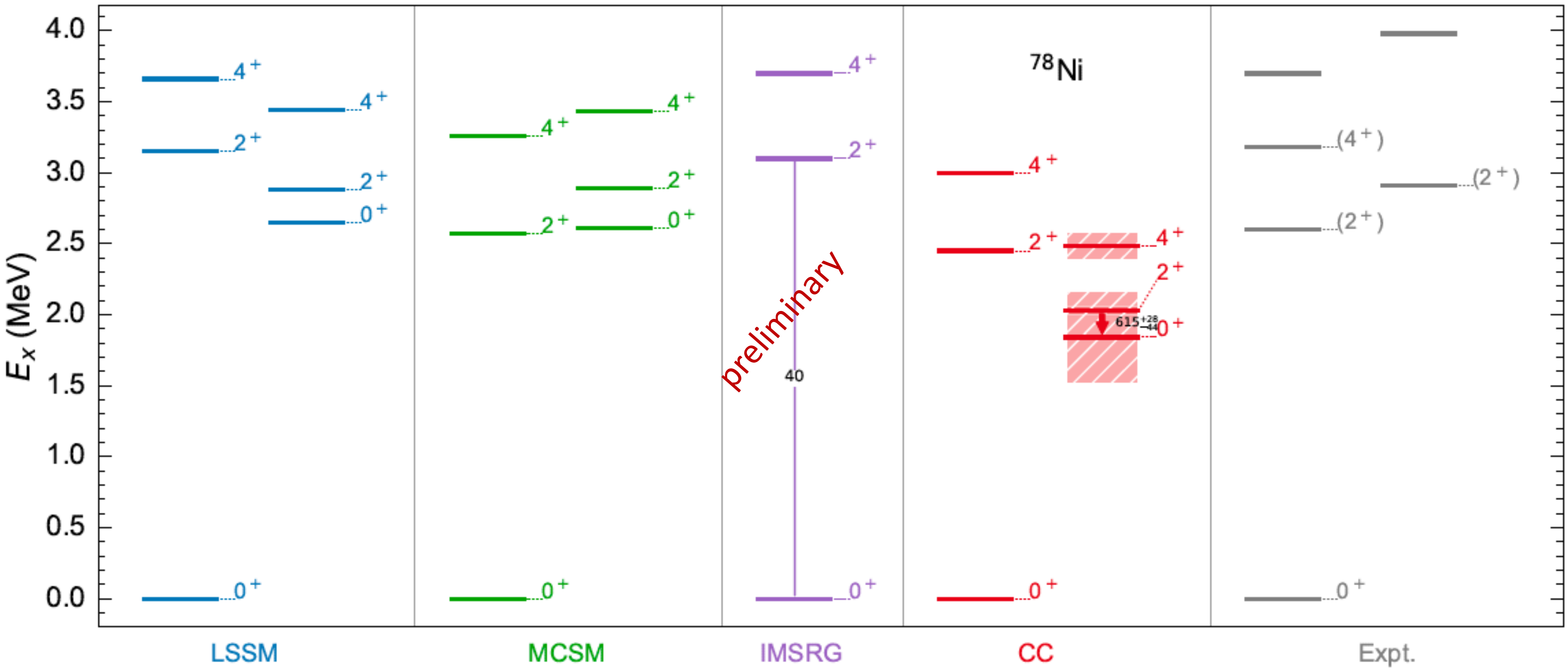
Nucleus
78Ni
122.2 ms

β- = 100.00%
β-n ?

148Pr / Z#



Structure of ^{78}Ni



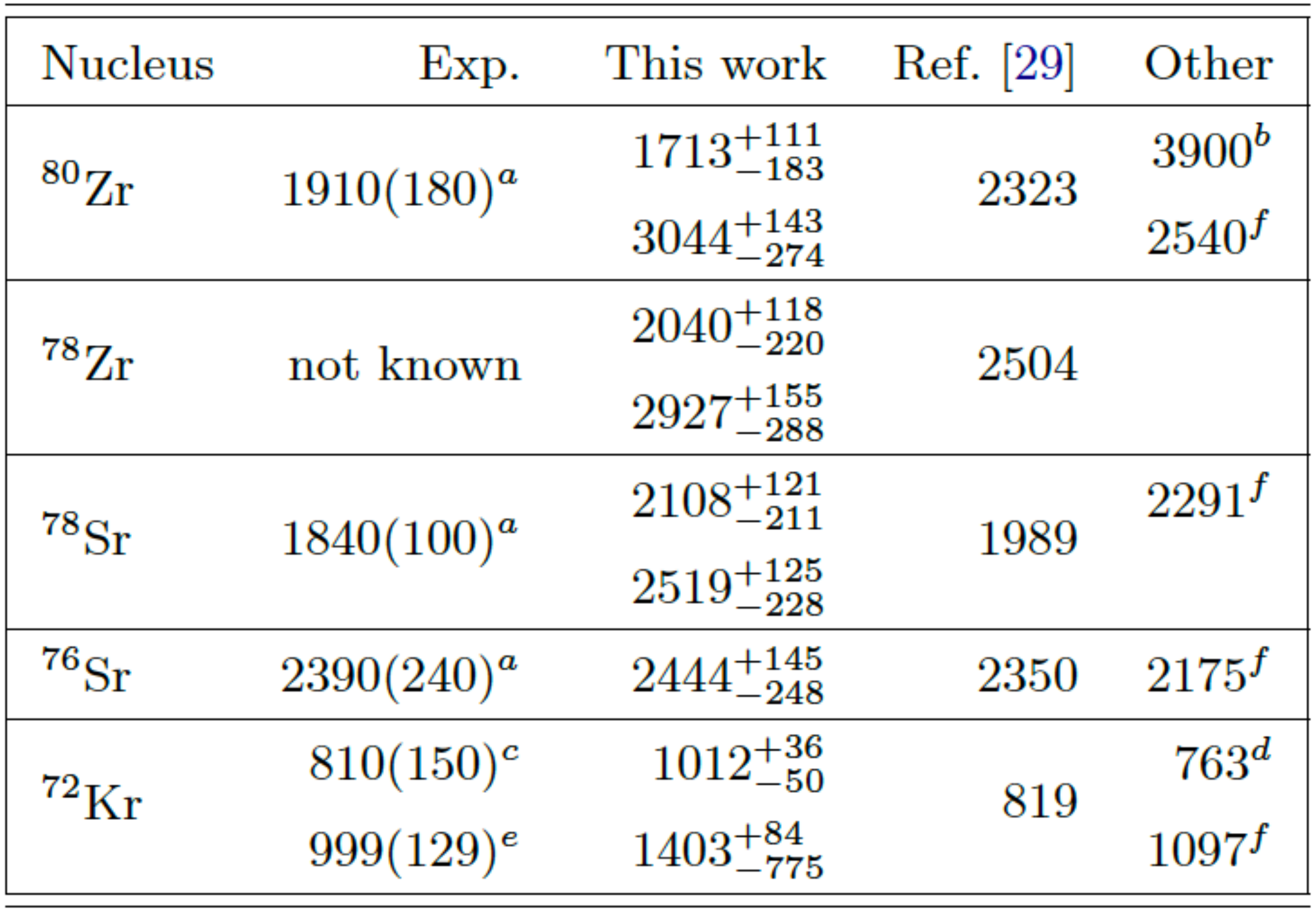
Nowacki, Poves, Caurier, Bounthong (2016)

Taniuchi et al. (2019)

Tichai, Kapás, Miyagi, Werner, Legeza, Schwenk, Zarand (2024)

Taniuchi et al. (2019)

Ab initio comparable to mean field computations

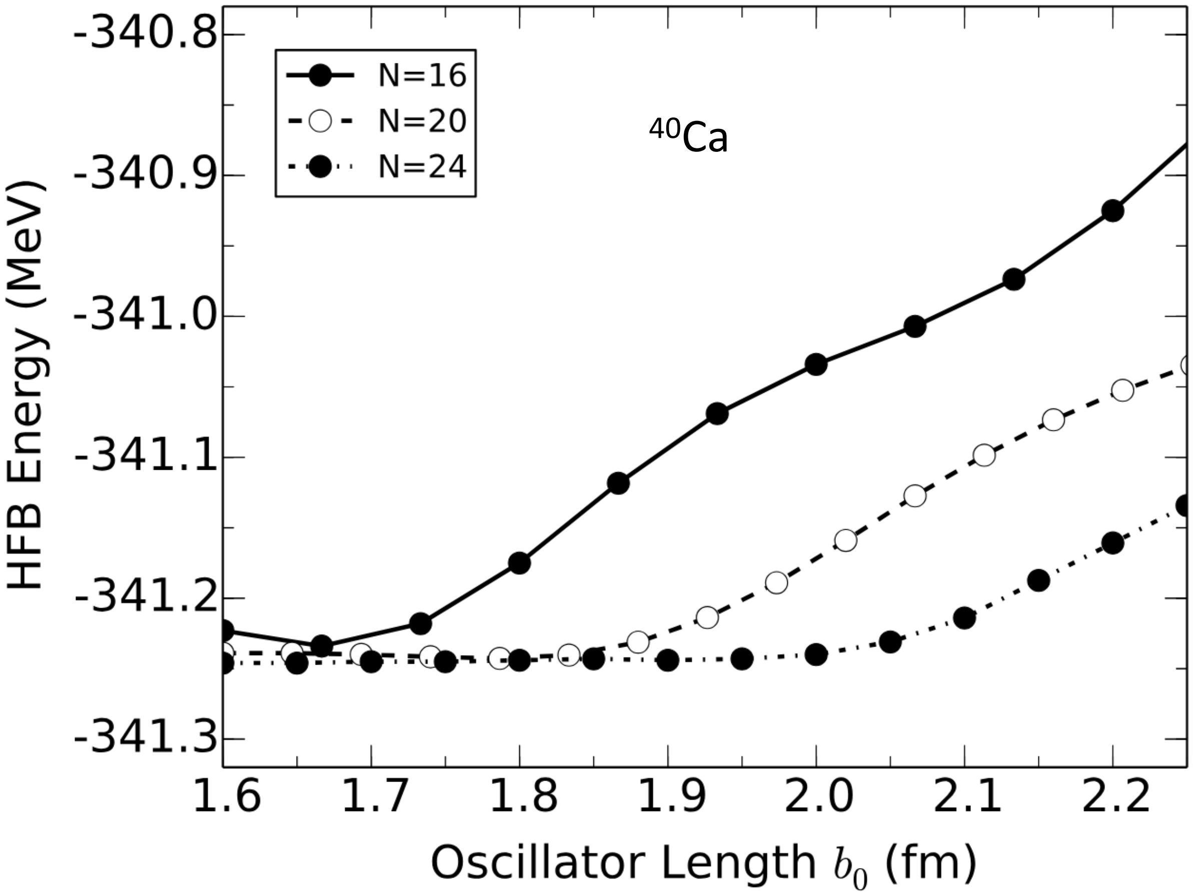


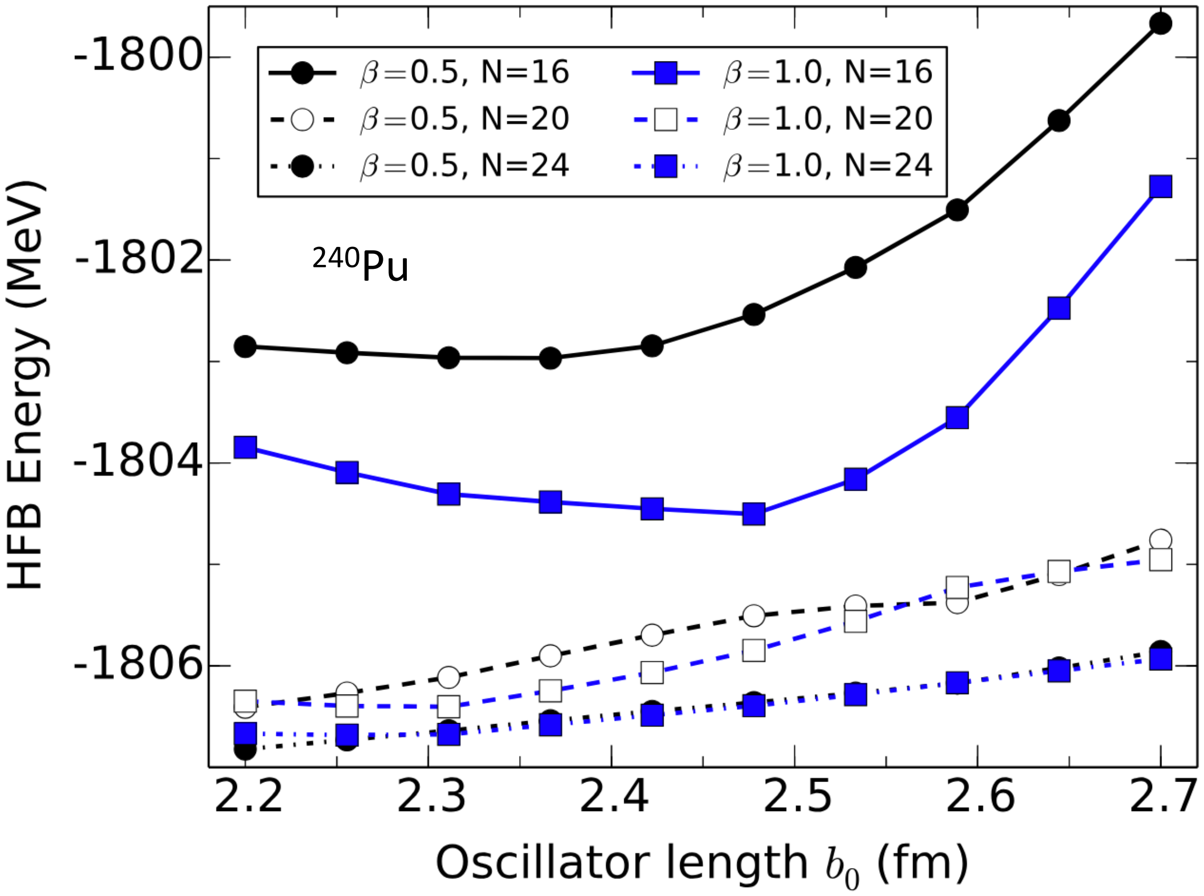
Nucleus	Exp.	This work	Ref. [29]	Other
^{80}Zr	$1910(180)^a$	1713^{+111}_{-183} 3044^{+143}_{-274}	2323	3900^b 2540^f
^{78}Zr	not known	2040^{+118}_{-220} 2927^{+155}_{-288}	2504	
^{78}Sr	$1840(100)^a$	2108^{+121}_{-211} 2519^{+125}_{-228}	1989	2291^f
^{76}Sr	$2390(240)^a$	2444^{+145}_{-248}	2350	2175^f
^{72}Kr	$810(150)^c$ $999(129)^e$	1012^{+36}_{-50} 1403^{+84}_{-775}	819	763^d 1097^f

[29] = Delaroche et al, PRC (2010)
b = Rodriguez & Egido, Phys Lett B (2011)
d = Bender, Bonche, Heenen, PRC (2006)
f = Kaneko, Shimizu, Mizusaki, Phys Lett B (2021)

Baishan Hu, Zhonghao Sun et al., arXiv:2405.05052

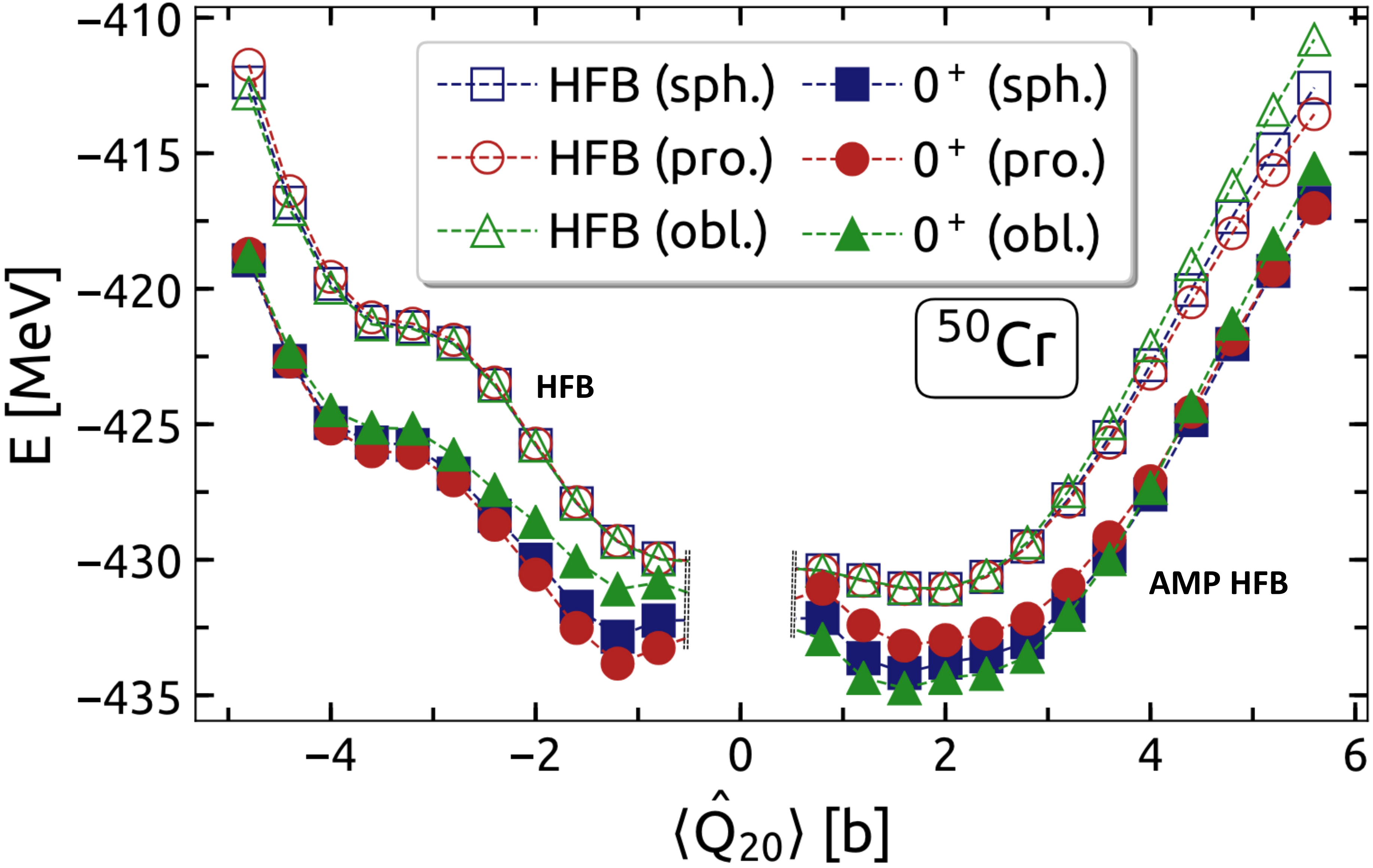
Convergence of mean-field computations





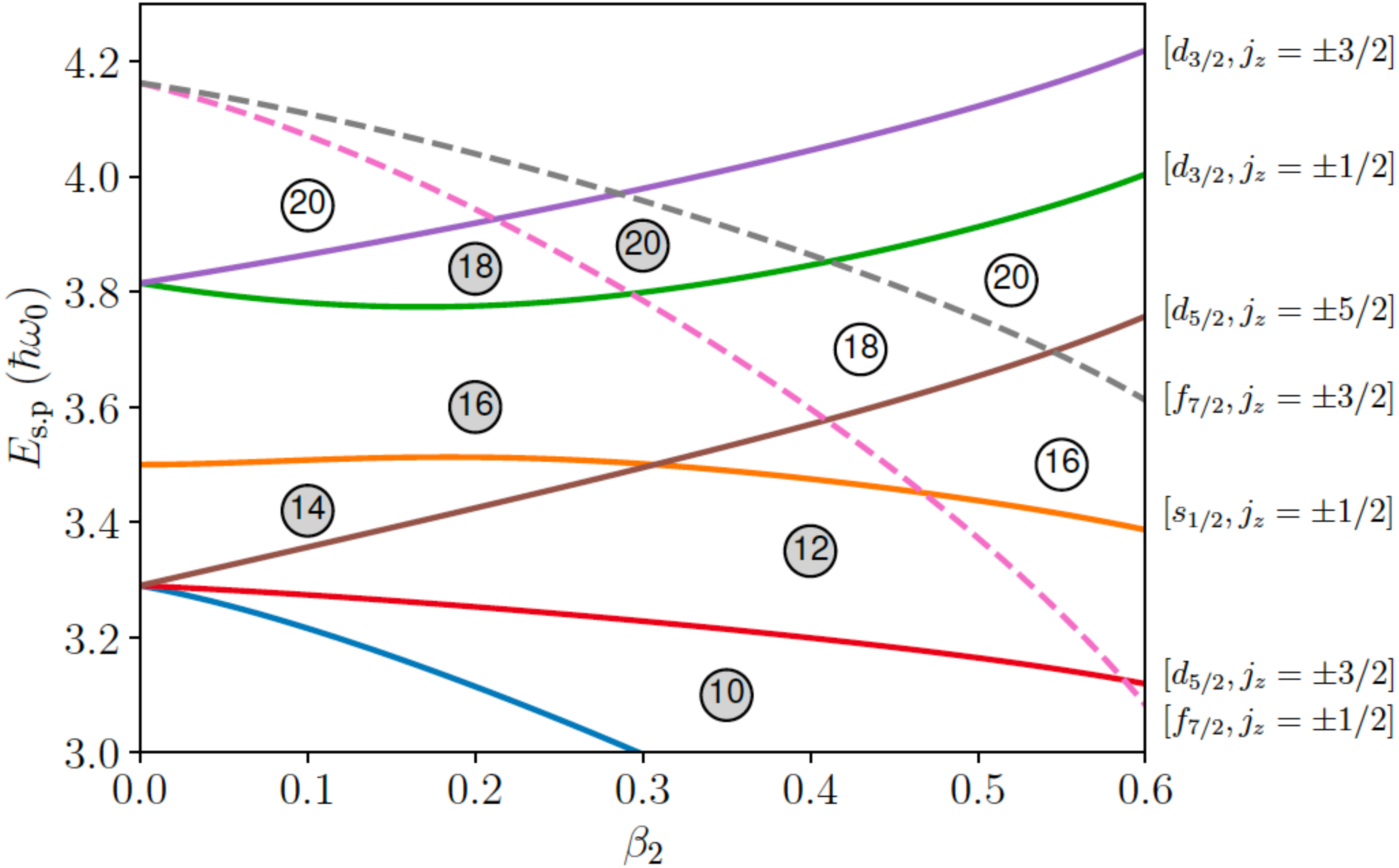
Schunck, McDonnell, Sarich, Wild, Higdon, J Phys G (2015)

Convergence of mean-field computations

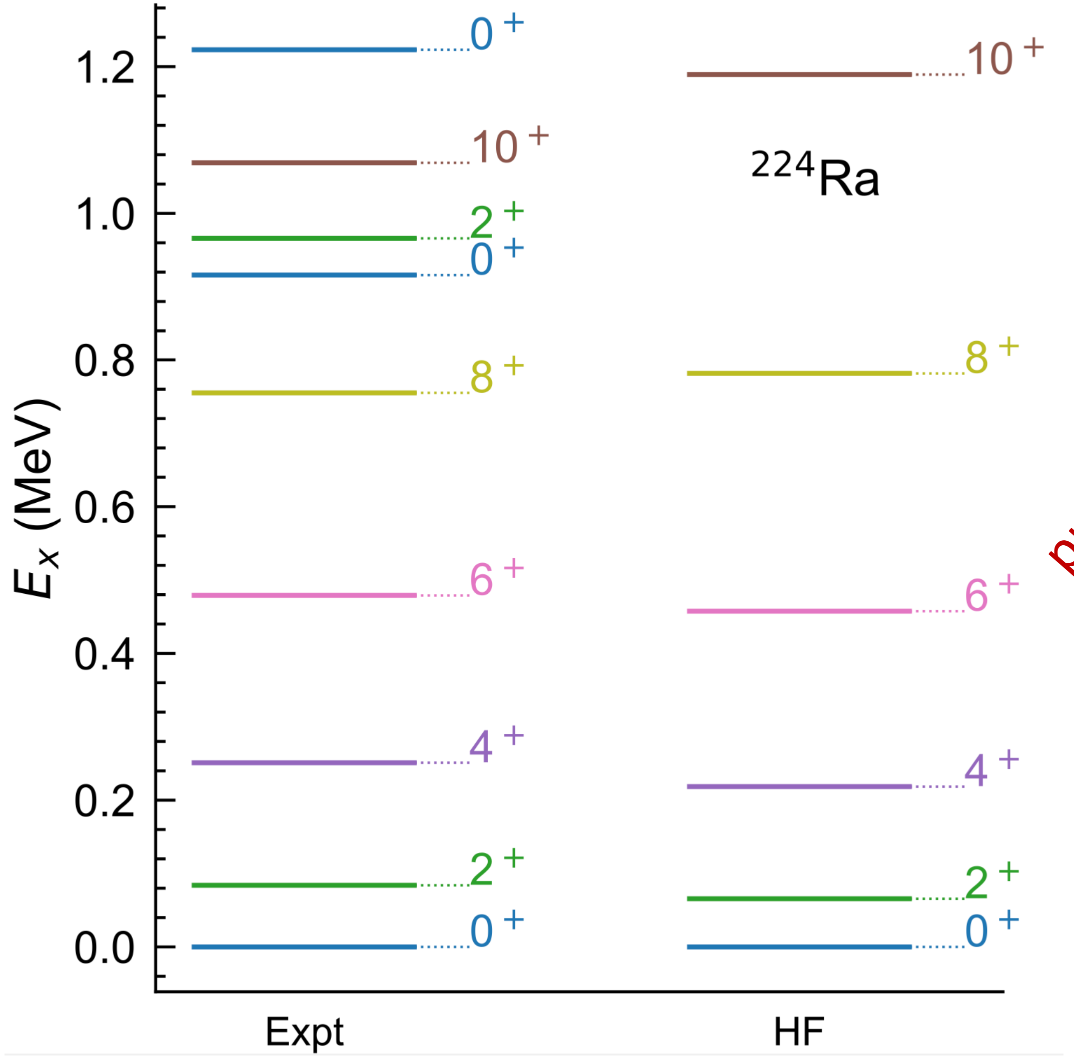


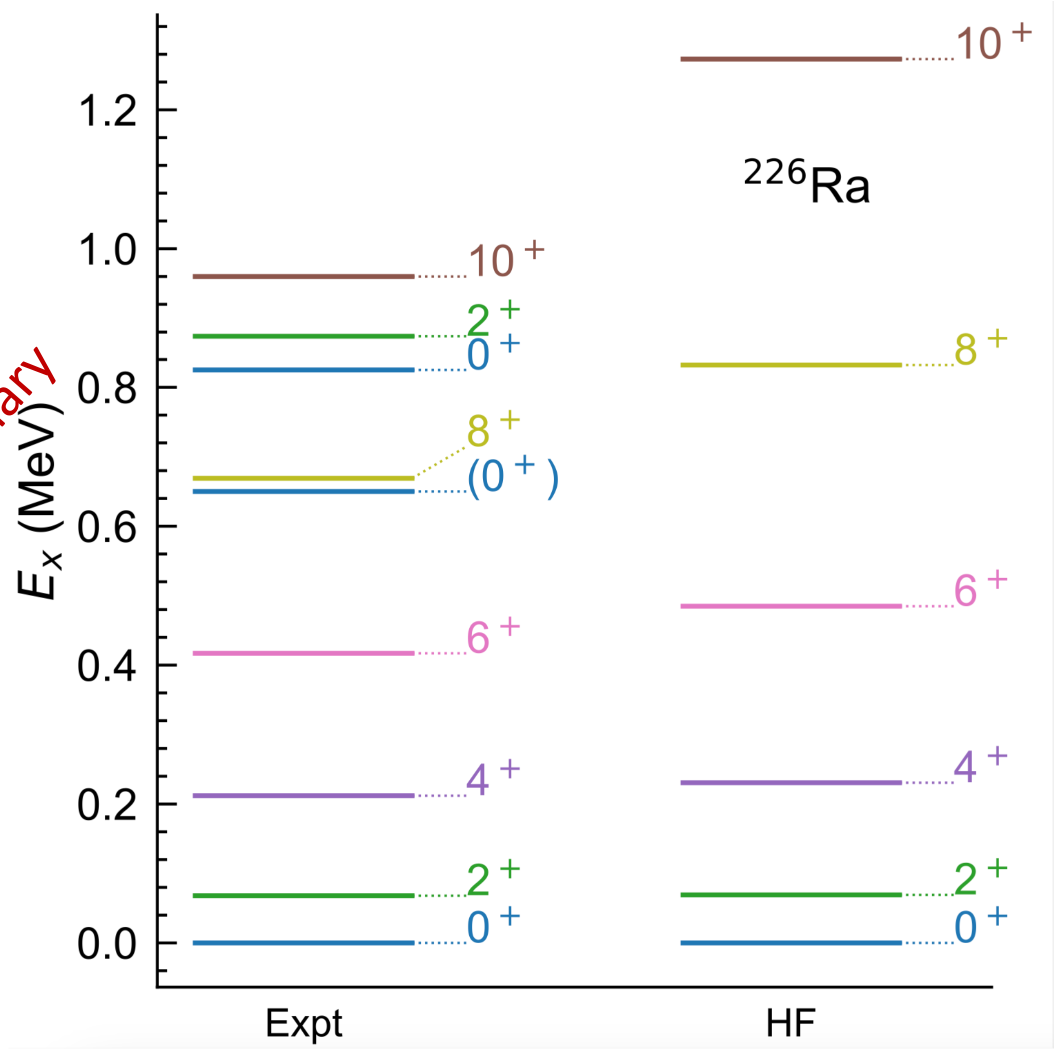
Marevic, Schunck, Ney, Navarro Pérez, Verriere, O'Neal, Comp. Phys. Comm. (2022)

Nilsson model reminder



Towards coupled cluster computations of Schiff moments in radium nuclei





Baishan Hu, Zhonghao Sun, G. Hagen, TP, … work in progress