Chiral three-body force and monopole properties of shell-model Hamiltonian

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T. Fukui *et al.*, Phys. Rev. C **98**, 04430 (2018).
Y. Z. Ma *et al.*, arXiv:1812.03284.

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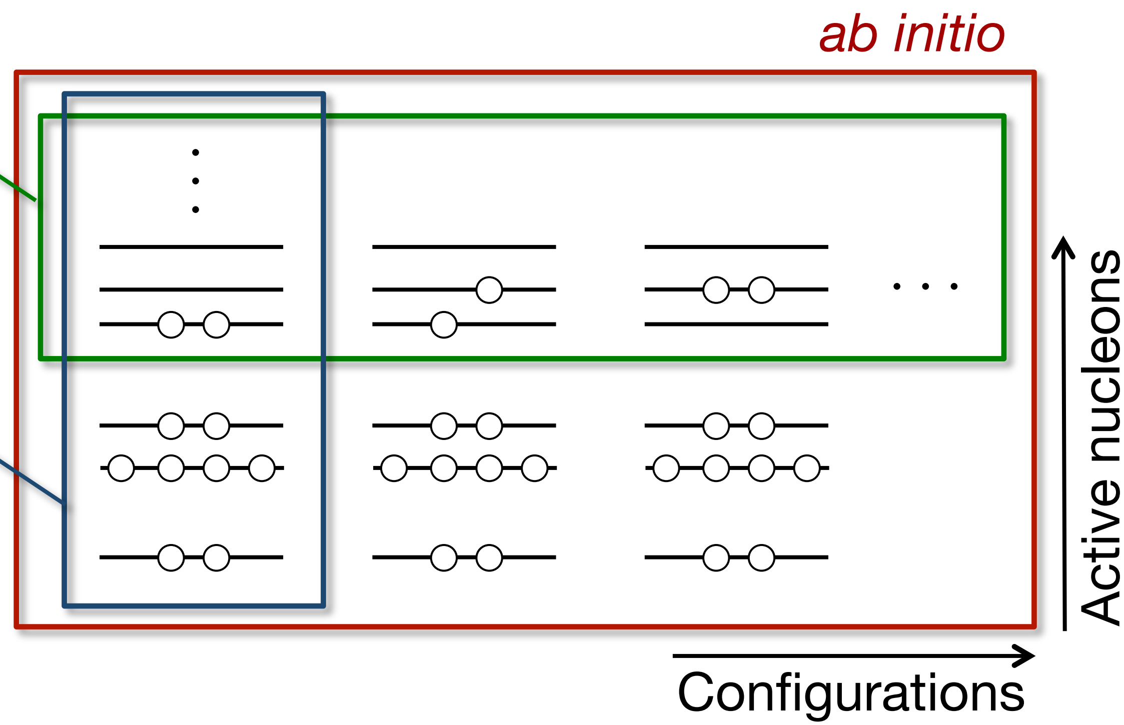
Shell model and density functional theory

Shell model

Realistic force is applicable in a straightforward way

Hartree-Fock method

Difficult to find exact Kohn-Sham potential



Example of realistic shell model (RSM)

- Shell model with chiral effective field theory
  → **Many-body force** on an equal footing

S. Weinberg, Phys. A **96**, 327 (1979).
R. Machleidt and D. Entem, Phys. Rep. **503**, 1 (2011).

3NF contribution to RSM

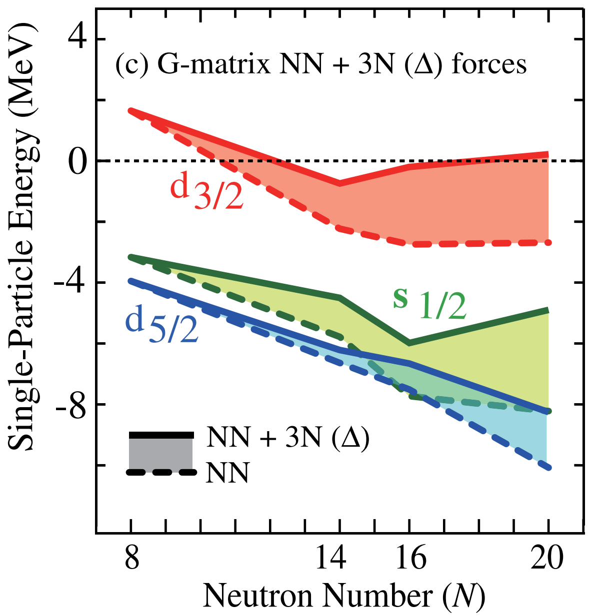
- RSM Hamiltonian needs to be revised due to **3-nucleon force (3NF)**. Specifically → **Monopole Hamiltonian**

A. P. Zuker, Phys. Rev. Lett. **90**, 042502 (2003).

cf.) Oxygen dripline and 3NF

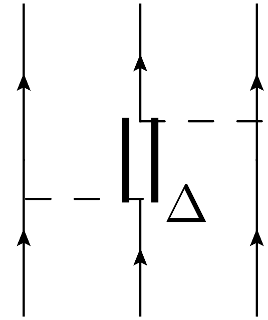
T. Otsuka *et al.*, Phys. Rev. Lett., **105**, 032501 (2010).

- The 3NF accounts for the oxygen dripline (^{24}O).



Fujita-Miyazawa 3NF

Repulsive contribution to monopole Hamiltonian



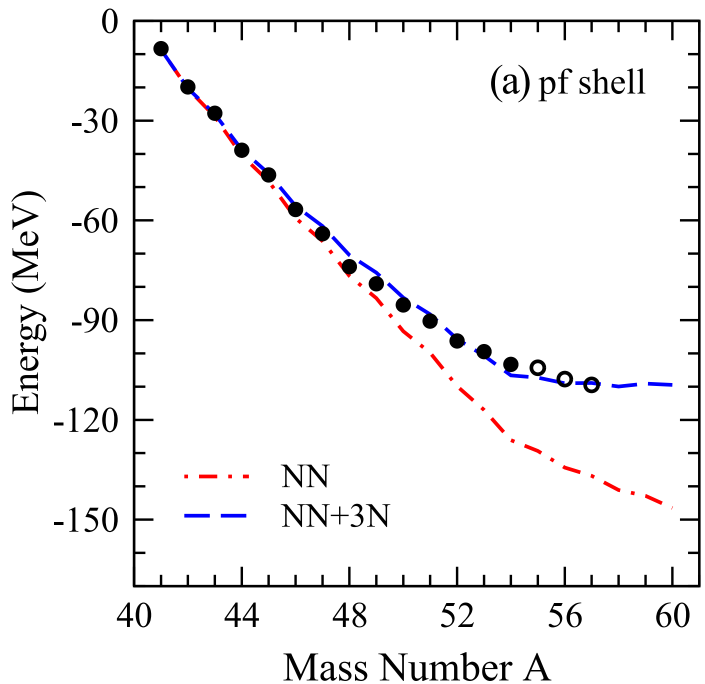
J. Fujita and H. Miyazawa, Prog. Theor. Phys. **17**, 360 (1957).

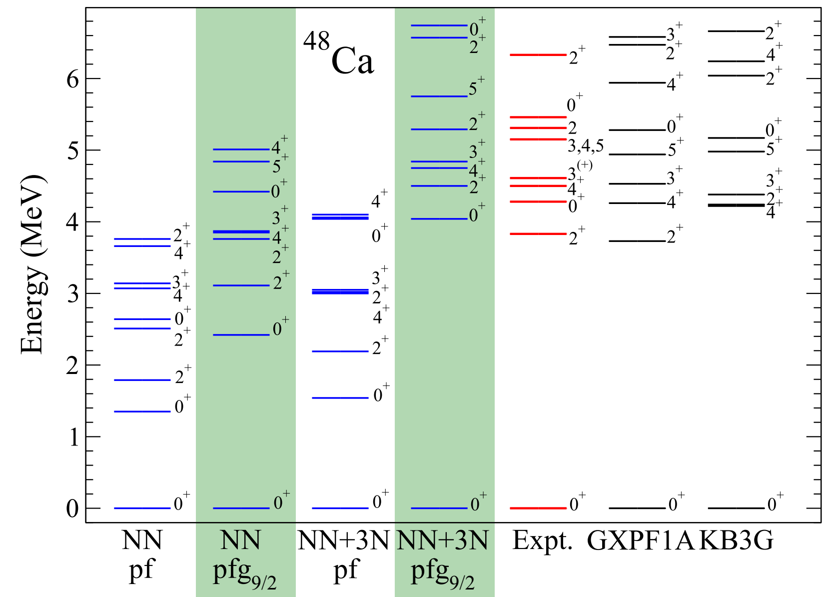
Motivation | RSM and 3NF

Shell evolution on *fp*-shell and RSM

J. D. Holt *et al.*, Phys. Rev. **90**, 024312 (2014).

- A crucial role played by 3NF (Chiral N^{2}LO) for Ca isotopes.



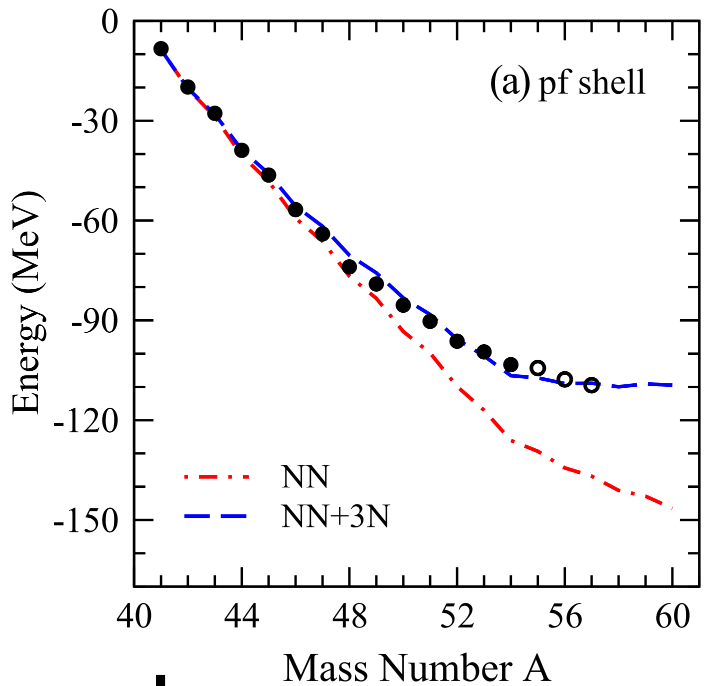


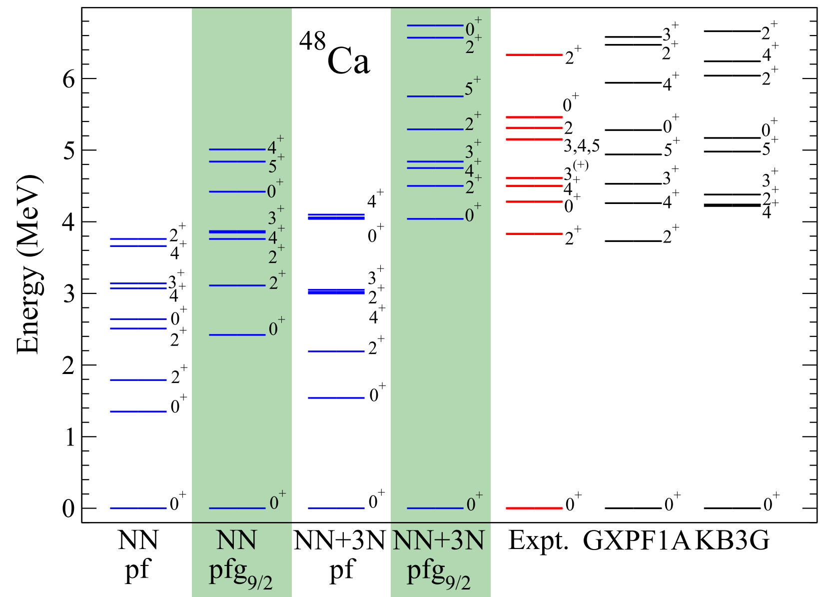
3NF contribution to monopole Hamiltonian?

Shell evolution on *fp*-shell and RSM

J. D. Holt *et al.*, Phys. Rev. **90**, 024312 (2014).

- A crucial role played by 3NF (Chiral N^{2}LO) for Ca isotopes.





This work

- We focus on the **monopole contribution** induced by the chiral N^{2}LO 3NF.
  → Shell evolution in *fp*-shell nuclei.
- We develop **our own code** for 3-body matrix elements (MEs) for RSM inputs.
  → Benchmark test for *p*-shell nuclei.

3-body ME with nonlocal regulator

Pioneering works

- Center-of-mass separation

  A. Nogga *et al*., Phys. Rev. C 73 , 064002 (2006).

- Antisymmetrization

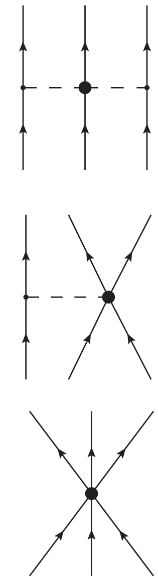
  P. Navrátil *et al*., Phys. Rev. C **61**, 044001 (2000).

- c_D and c_E terms

  P. Navrátil, Few-Body Syst. **41**, 117 (2007).

Chiral N^{2}LO 3NF

$V_{3N} =$



2π (c_1, c_3, c_4)

$+$ **1π + contact** (c_D)

$+$ **Contact** (c_E)

S. Weinberg, Phys. Lett. B **295**, 114 (1992).
U. van Kolck, Phys. Rev. C **49**, 2932 (1994).

Our new formalism

- **Triple-fold multipole expansion** for 2π term.

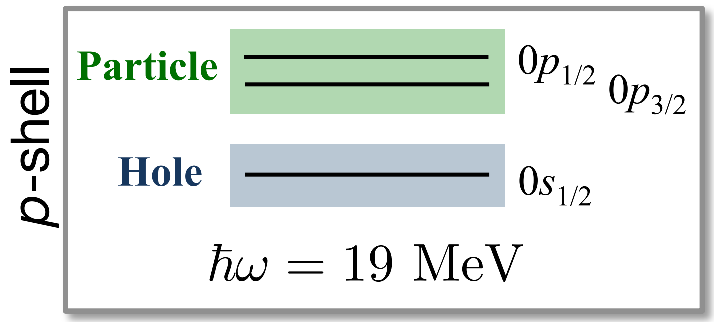
T. Fukui *et al*., Phys. Rev. C **98**, 04430 (2018).

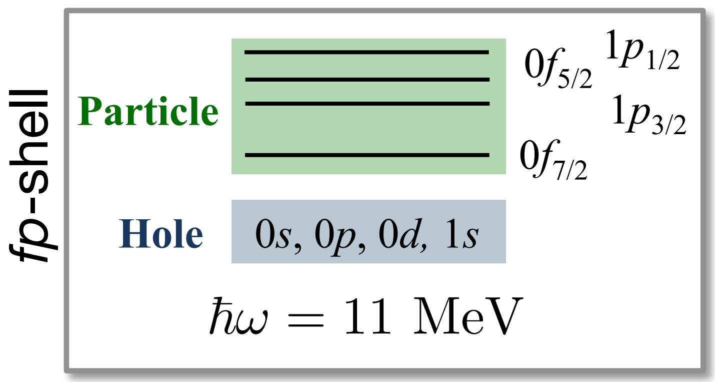
Low-energy constants

2NF: N^3LO D. R. Entem and R. Machleidt, Phys. Rev. C **68**, 041001(R) (2003).

3NF: N^2LO P. Navrátil *et al.*, Phys. Rev. Lett. **99**, 042501 (2007).

Model space





Many-body perturbation theory

$$H \approx H_{\rm eff}$$

2NF: Up to 3rd-order folded-diagram expansion

3NF: Up to 1st-order (normal-order approx.)

L. Coraggio *et al.*, Ann. Phys. **327**, 2125 (2012).

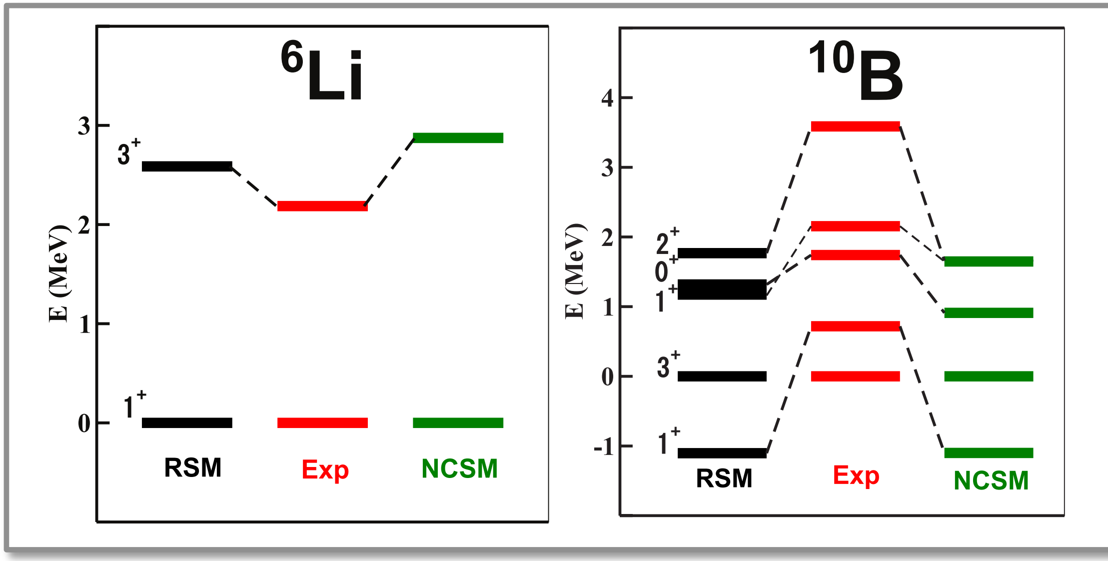
→ (1) Effective Hamiltonian $H_{\rm eff}$ involving **Q-space effect**.

(2) **Theoretical single-particle energies** and **2-body MEs**.

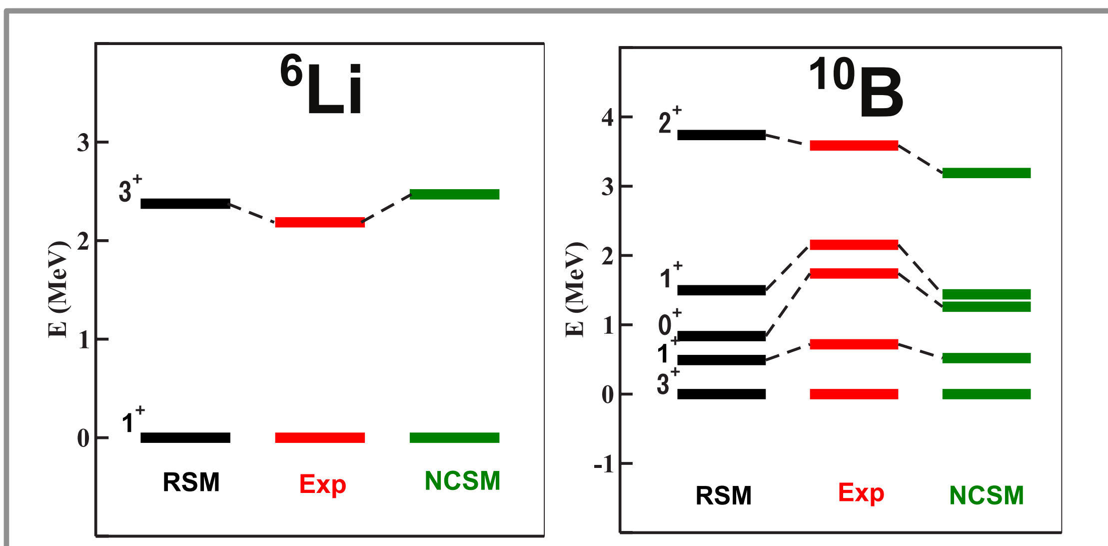
No empirical input

Comparison with *ab initio* no-core shell model (NCSM)

2NF only



2NF + 3NF

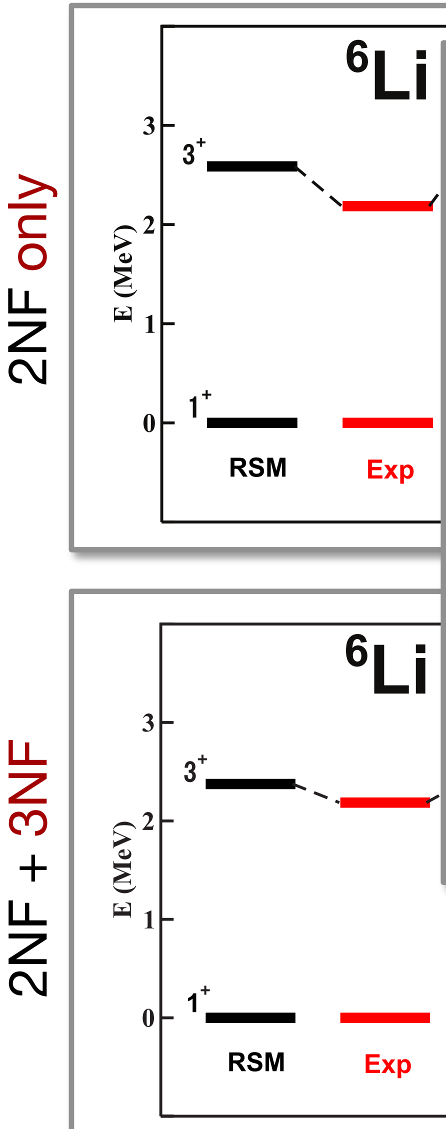


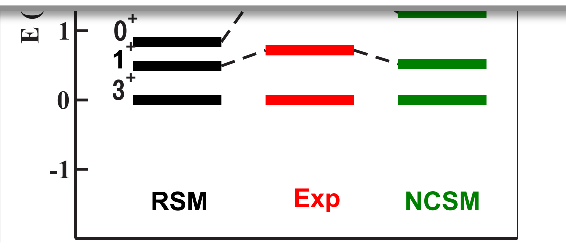
- **RSM** and **NCSM** agree with each other for **low-lying states**.
- Significant 3NF effect can be seen.

NCSM

P. Navrátil *et al.*, Phys. Rev. Lett. **99**, 042501 (2007).

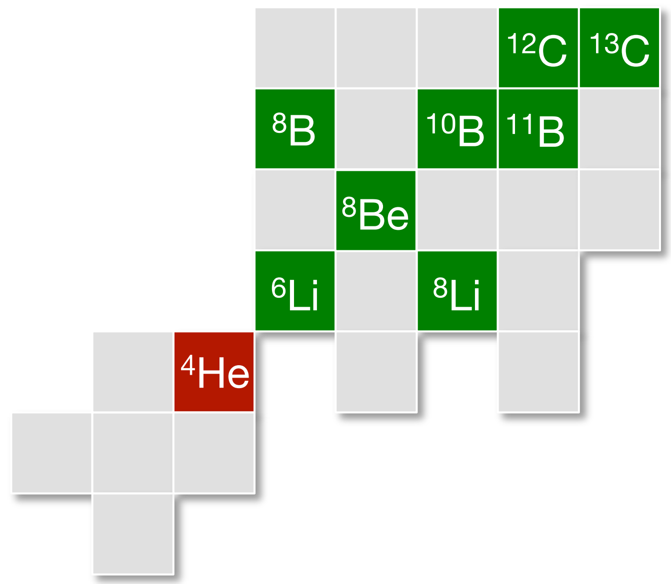
Comparison with *ab initio* no-core shell model (NCSM)





Similar results for other *p*-shell nuclei

→ **Satisfactory consequences**



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h each other
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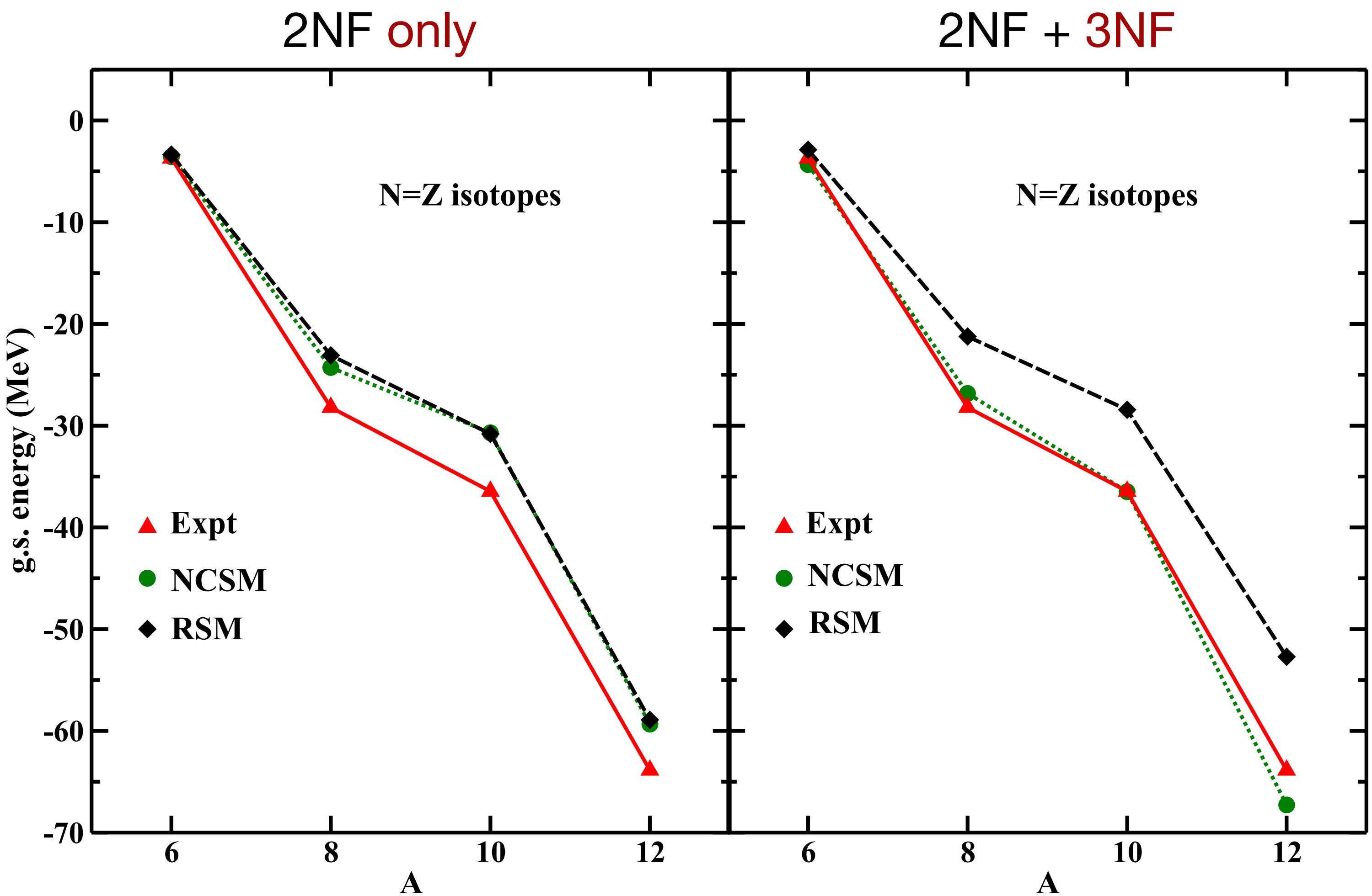
NCSM

P. Navrátil *et al.*,
Phys. Rev. Lett. **99**, 042501 (2007).

Ground-state energies

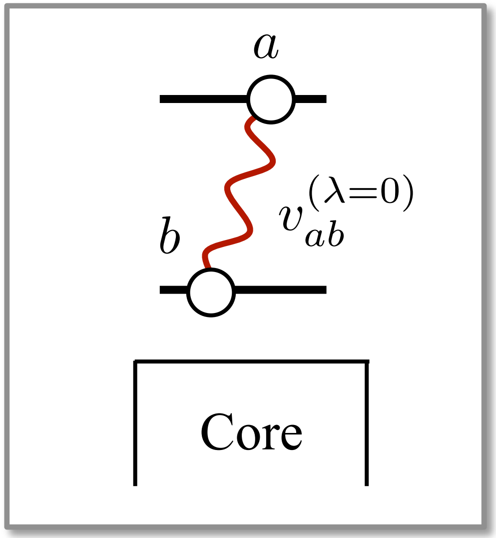


- At maximum ~ 1 MeV discrepancy
- Higher-order 3NF contribution may be necessary.

Monopole interaction $v_{ab}^{(\lambda=0)}$

= J-averaged 2-body interaction

$$v_{ab}^{(\lambda=0)} = \frac{\sum_J (2J+1) \langle ab; J \,|\, V \,|\, ab; J \rangle}{\sum_J (2J+1)}$$



$v_{ab}^{(\lambda=0)}$

→ Effective single-particle energy (ESPE) ε'_a

= Evolved single-particle energy $\varepsilon_a \xrightarrow{v_{ab}^{(\lambda=0)}} \varepsilon'_a$

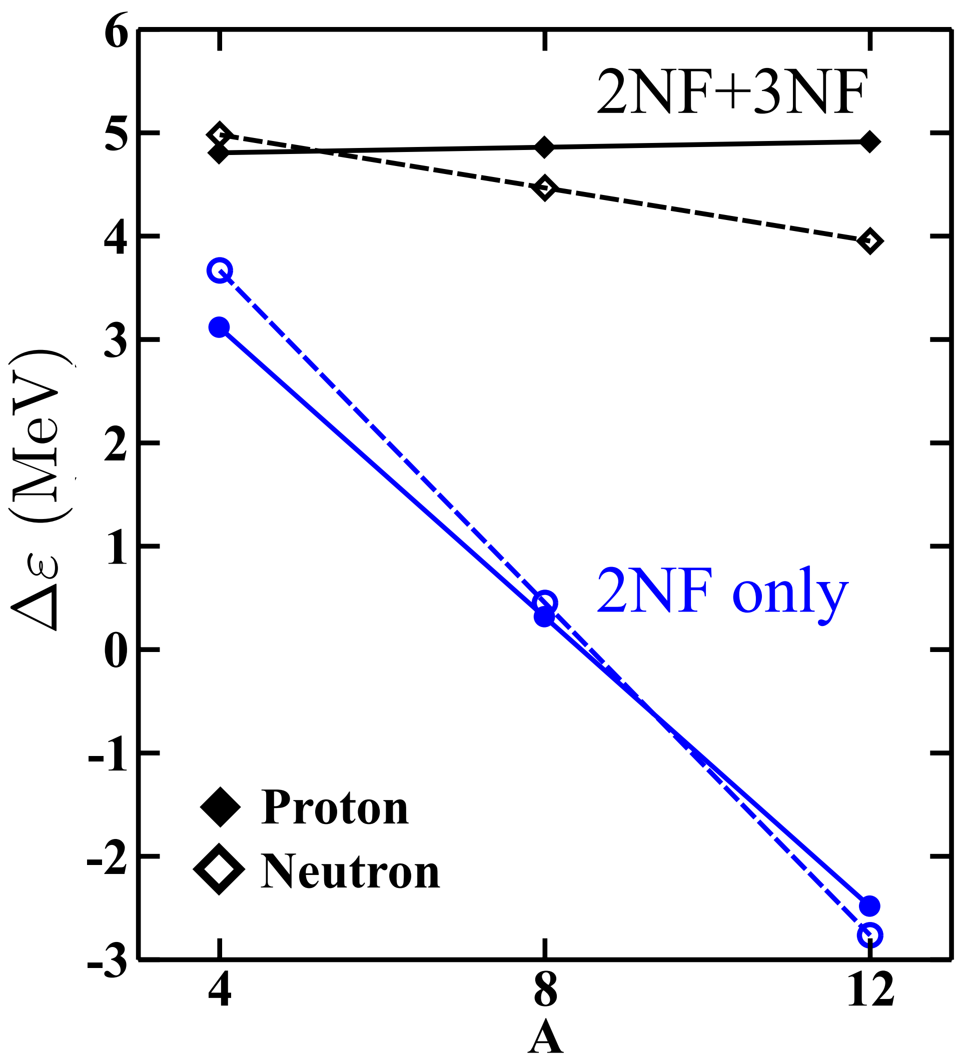
→ Monopole-Hamiltonian ME

$= \varepsilon_a + \varepsilon_b + v_{ab}^{(\lambda=0)}$

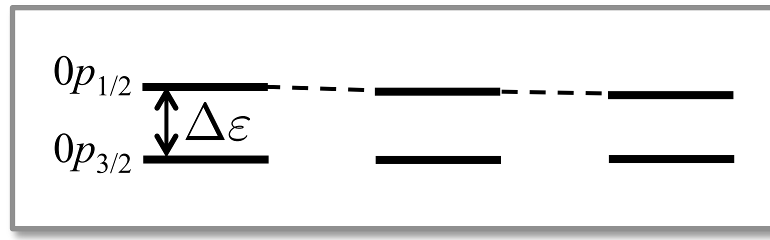
Spherical mean field

Monopole interaction | *p*-shell nuclei

ESPEs



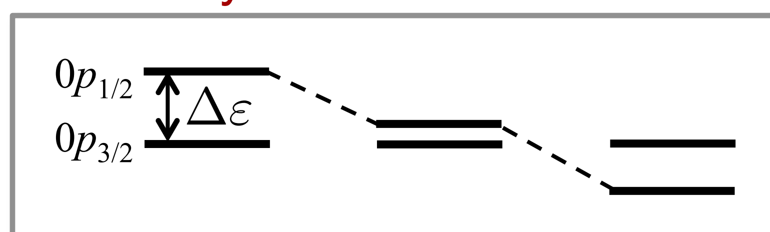
2NF + 3NF



- $\Delta\varepsilon$ is almost constant.

→ **Better closure properties**

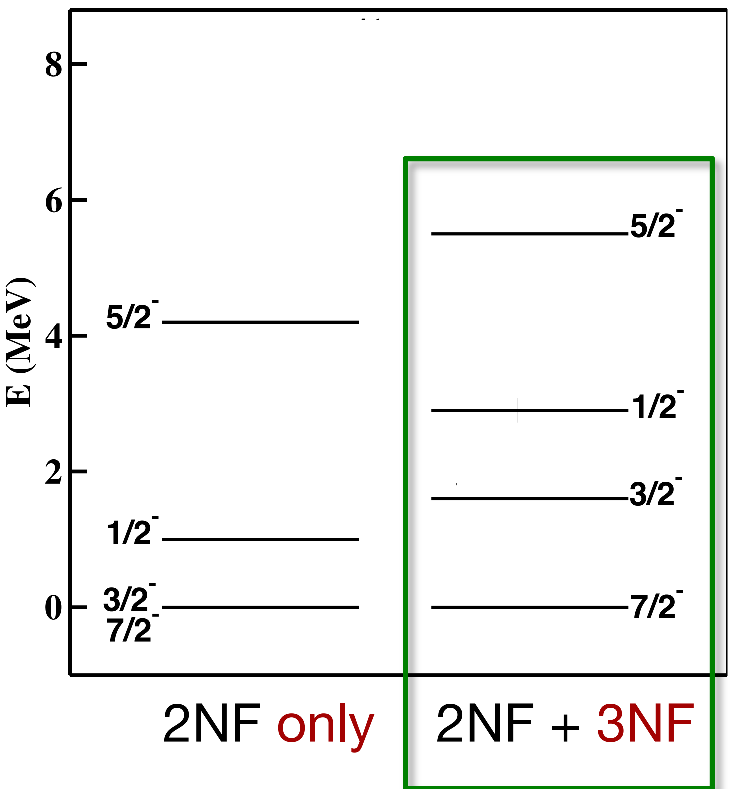
2NF only



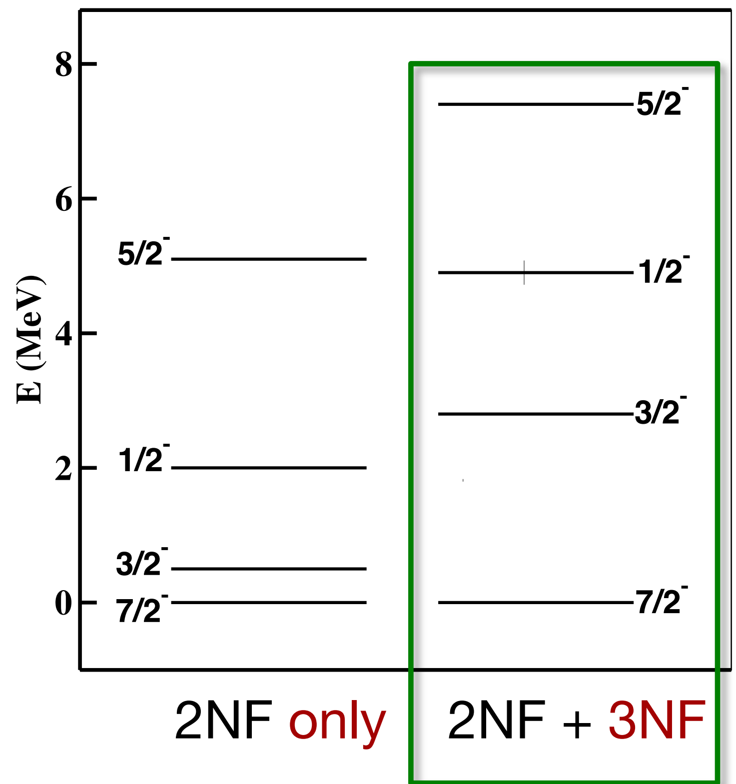
- $\Delta\varepsilon$ decreases with A, and $p_{3/2}$-$p_{1/2}$ orbits become inverted.

fp-shell nuclei | Calculated SPEs

Proton (^{41}Sc)



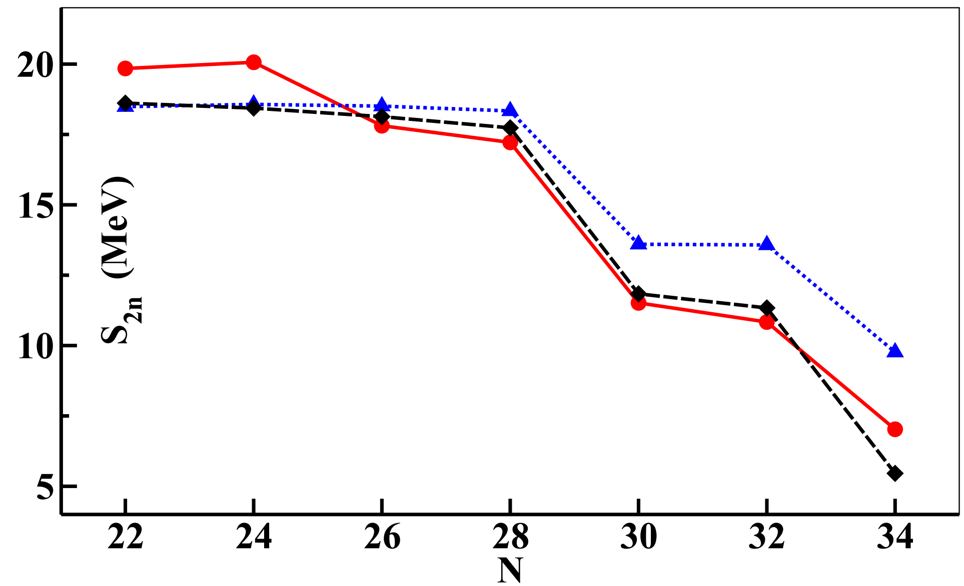
Neutron (^{41}Ca)

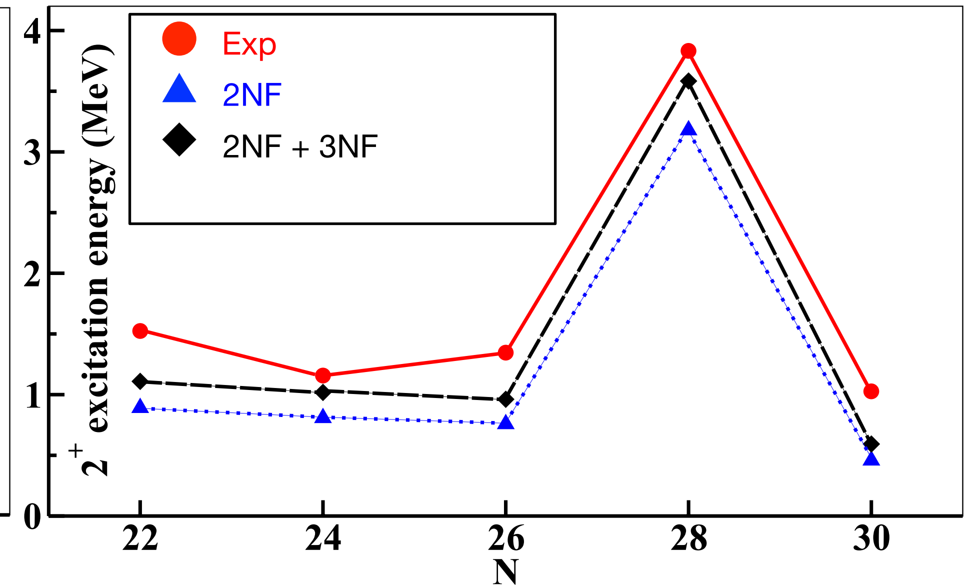


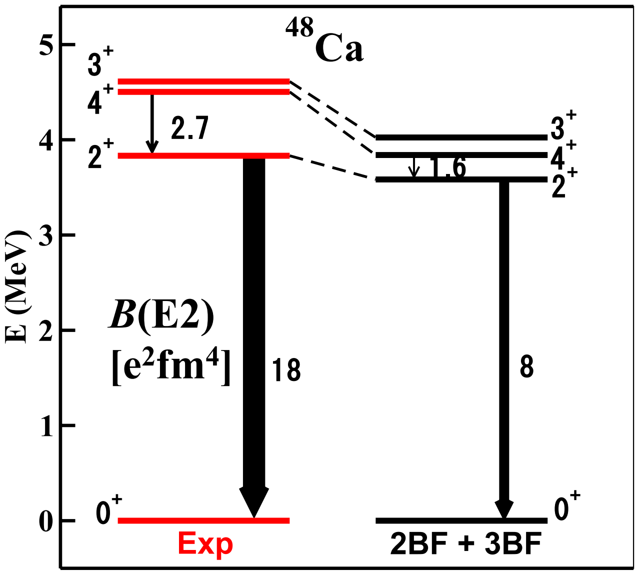
- 2NF only must not work.
  → **Always we adopt the 2NF + 3NF SPEs.**

Focus only on monopole component

Ca isotopes

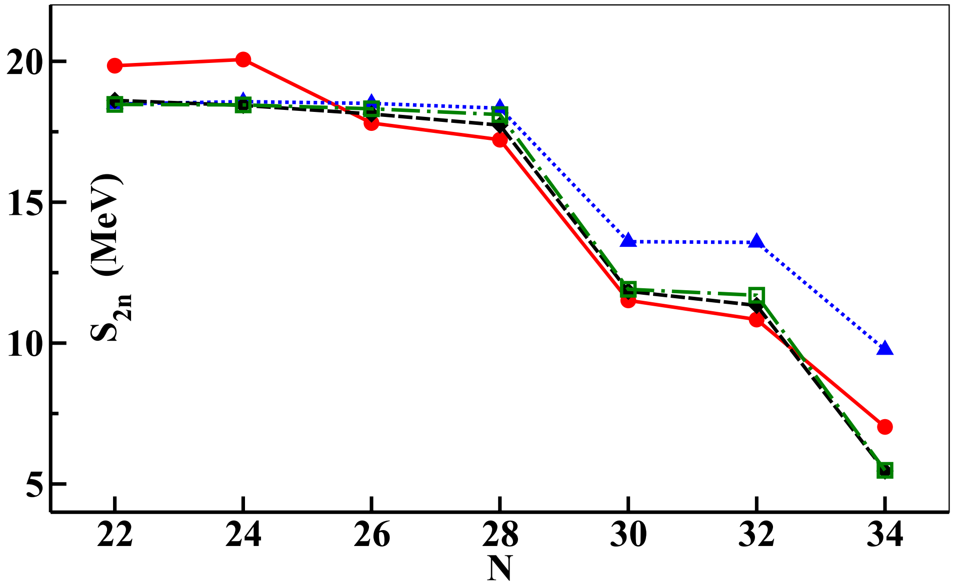


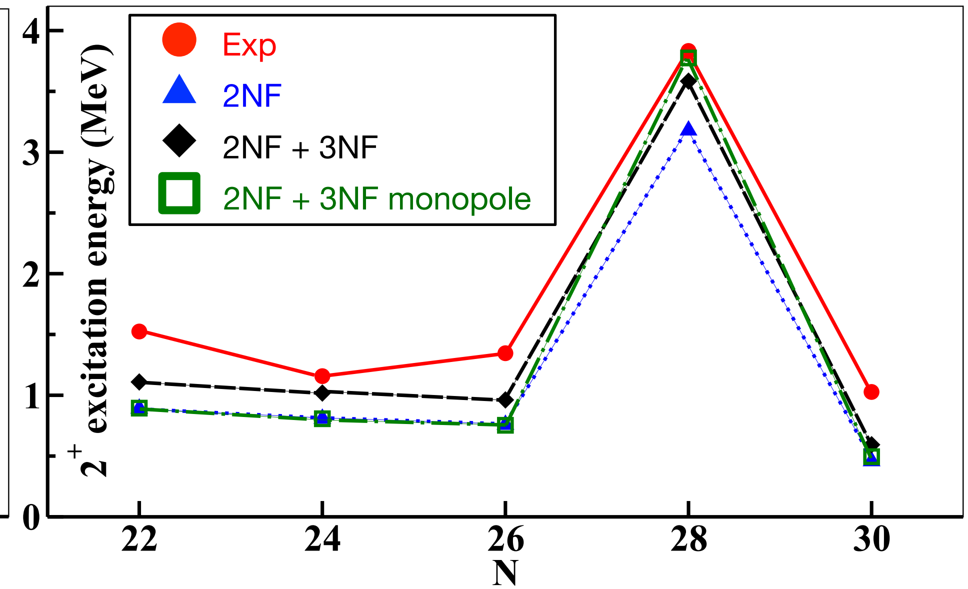


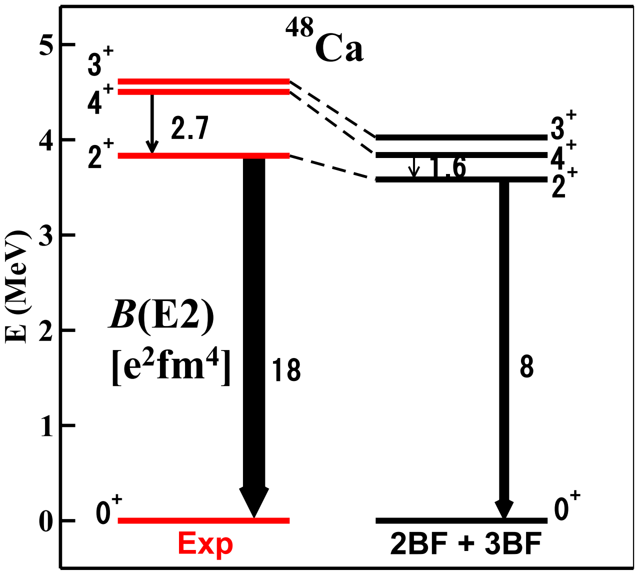


- Even **2NF** reasonably accounts for **experimental** behavior of 2*n*-separation energies S_{2n} and closure properties.

Ca isotopes

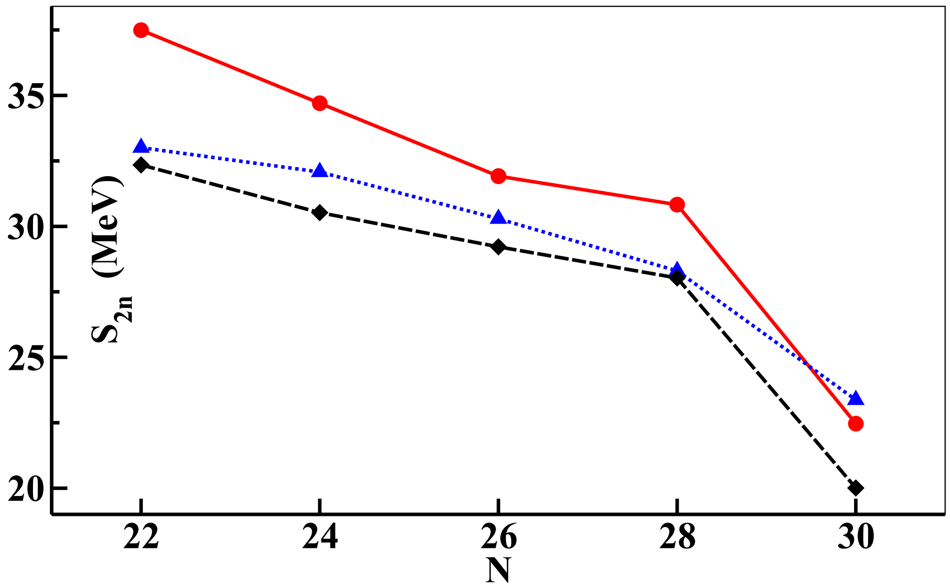


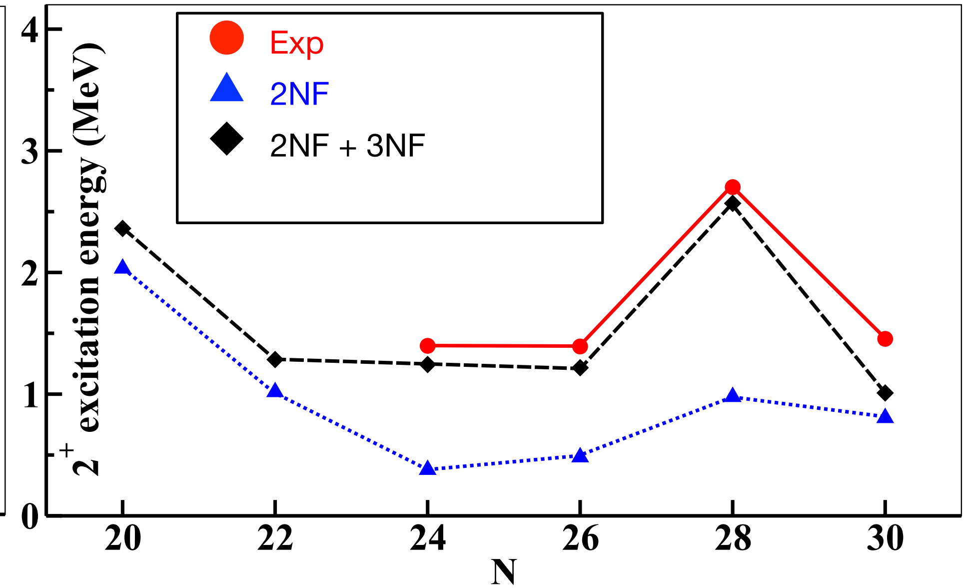


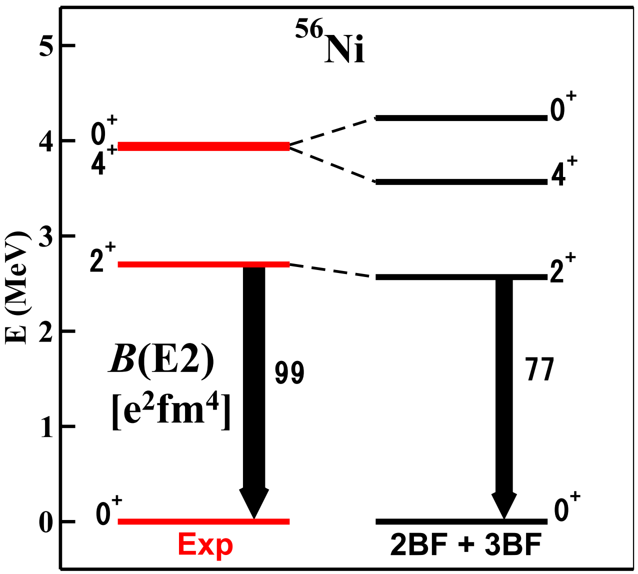


- Even **2NF** reasonably accounts for **experimental** behavior of 2*n*-separation energies S_{2n} and closure properties.
- The **3NF monopole component** is small except for ^{48}Ca.

Ni isotopes

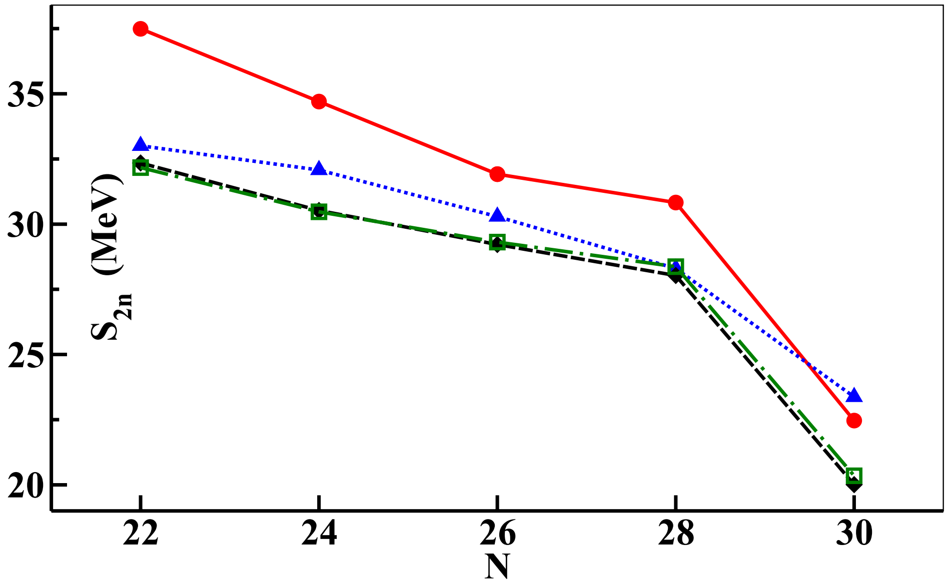


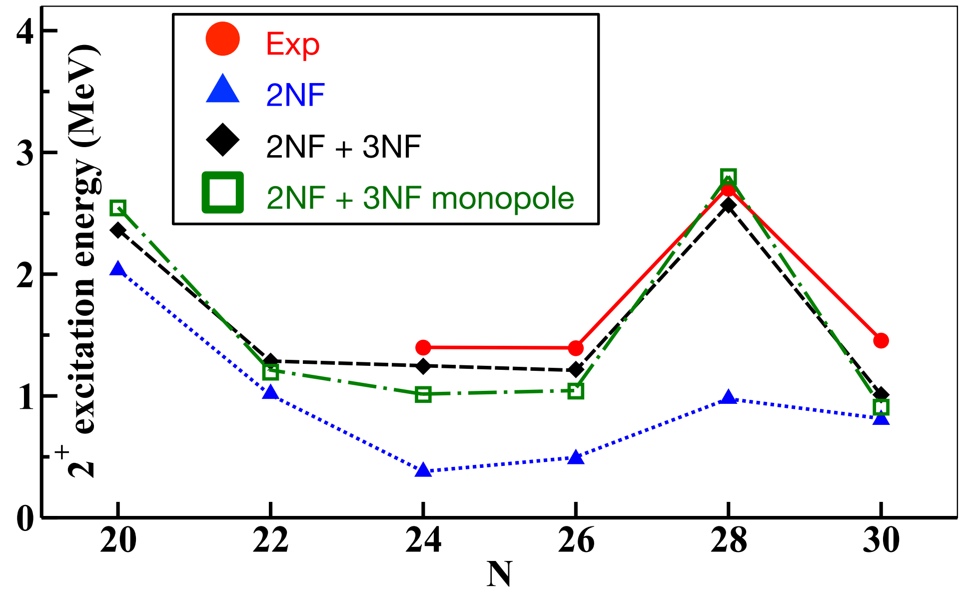


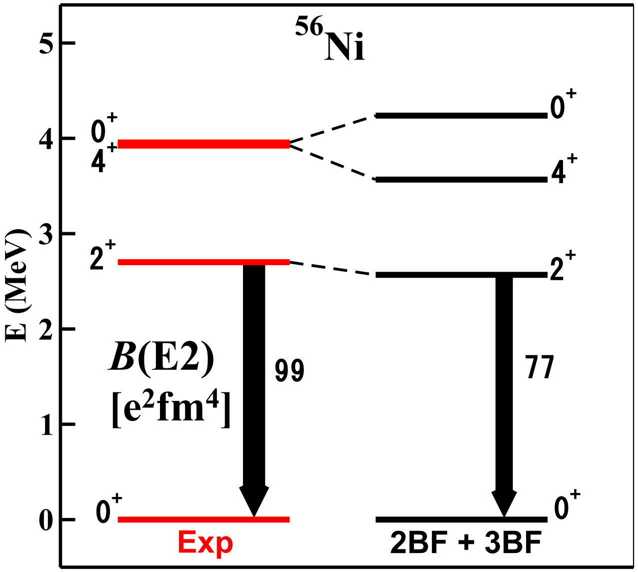


- **2NF** fails and **3NF** plays an important role to explain **experimental** data.

Ni isotopes





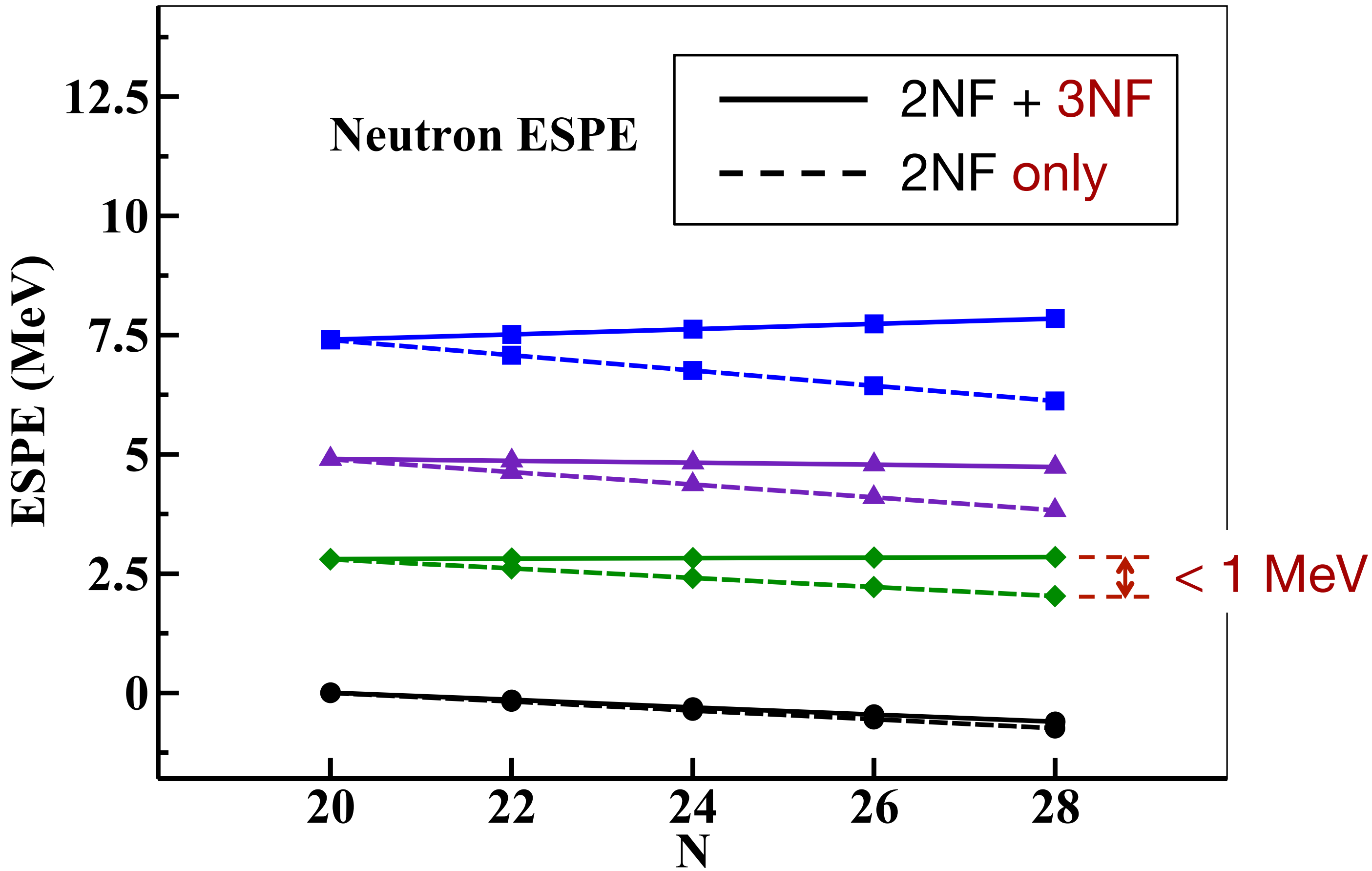


- **2NF** fails and **3NF** plays an important role to explain **experimental** data.
- The **3NF monopole component** is essentially improves the calculations.

Why opposite from Ca?

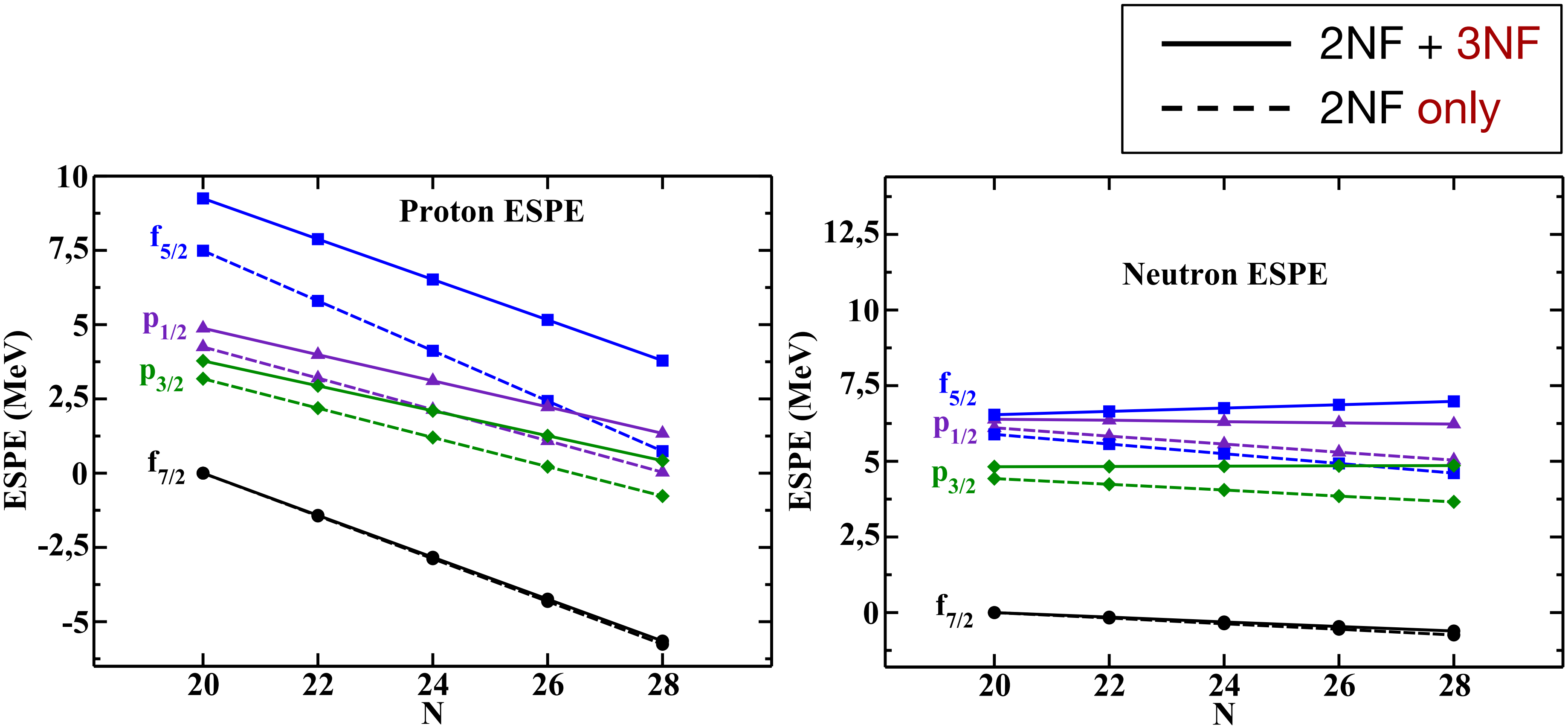
ESPEs relevant for Ca isotopes

- Very small difference from 2NF to 2NF + 3NF.



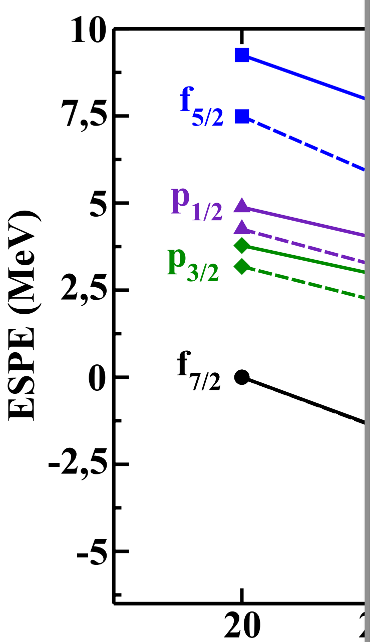
ESPEs relevant for Ni isotopes

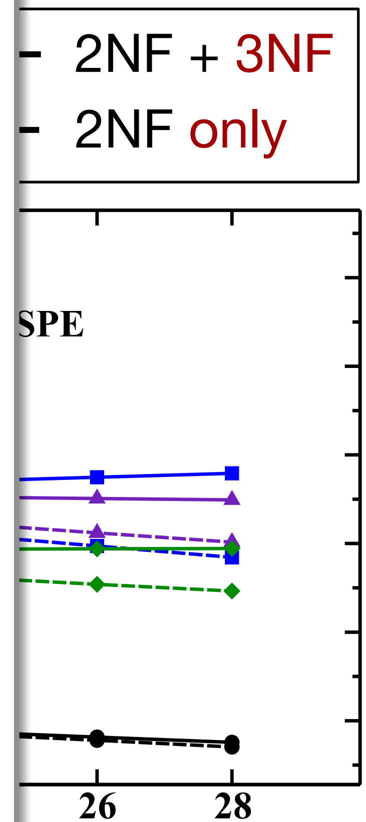
- Drastic evolution of ESPEs due to 3NF.



ESPEs rele…

- Drastic ev…

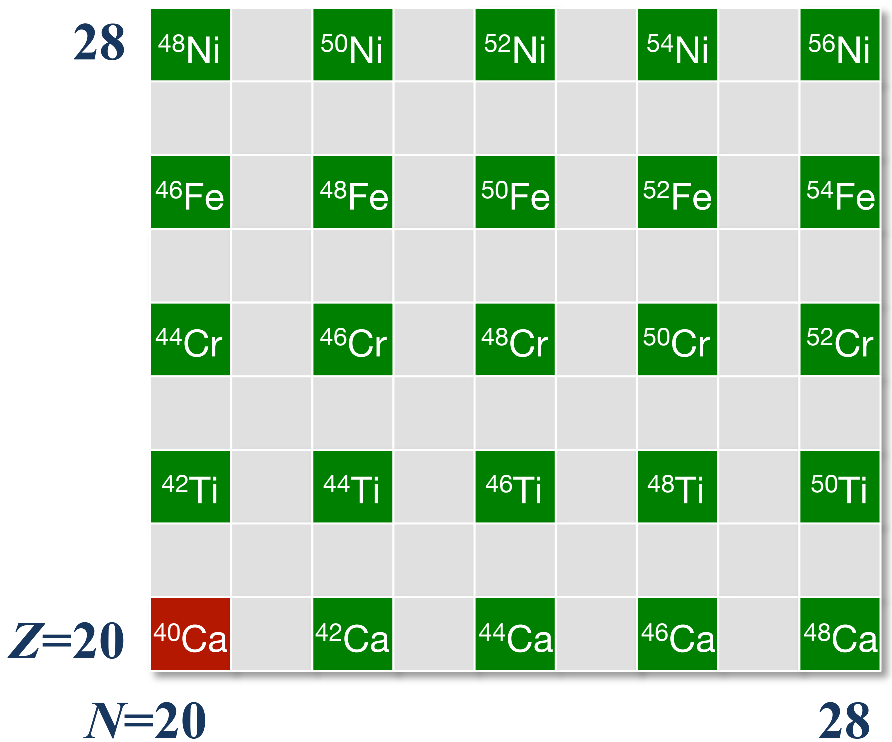




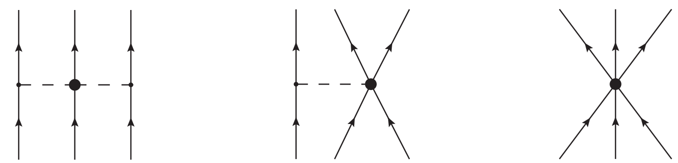
Similar results for other *fp*-shell nuclei.

→ **Well described**

- **monopole component**
- **ESPE**
- **shell closure**



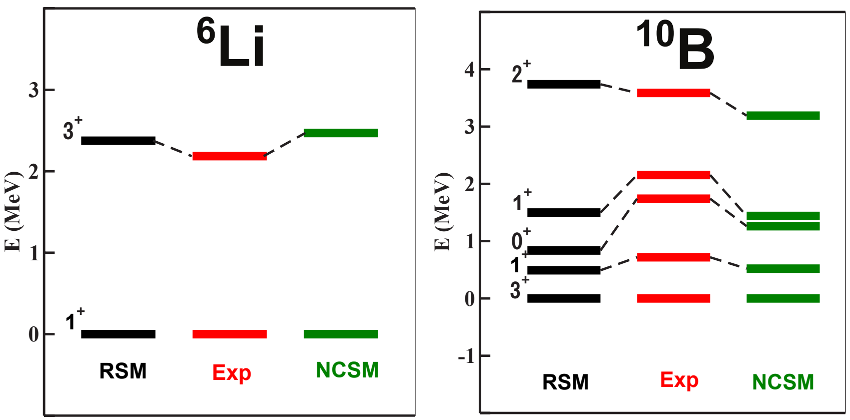
Chiral N²LO 3NF for shell model



3-body MEs with nonlocal regulator

$$ {}_A\left\langle \left[[\bullet\bullet]\bullet \right]_{JT} \right| V_{3N} \left| \left[[\bullet\bullet]\bullet \right]_{JT} \right\rangle_A $$

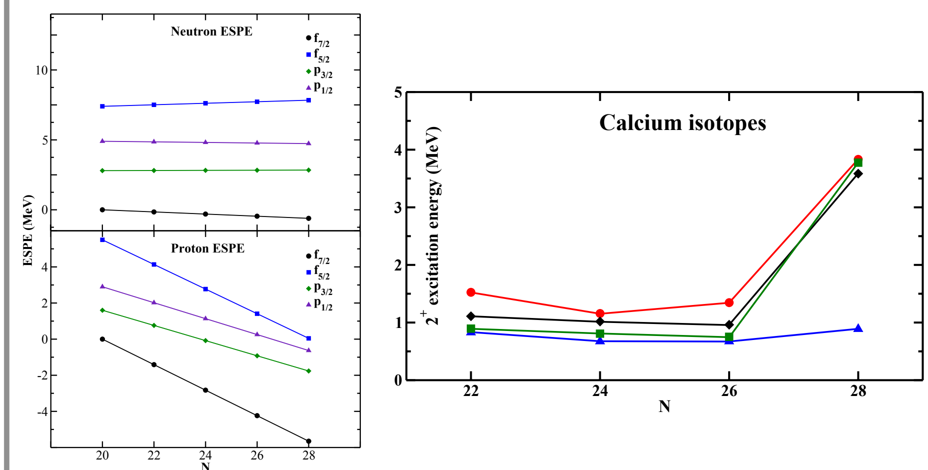
Benchmark test for *p*-shell



→ **Our RSM calculations with 3NF are satisfactorily comparable to the *ab initio* results.**

T. Fukui *et al.*, Phys. Rev. C **98**, 04430 (2018).

Monopole properties of *fp*-shell

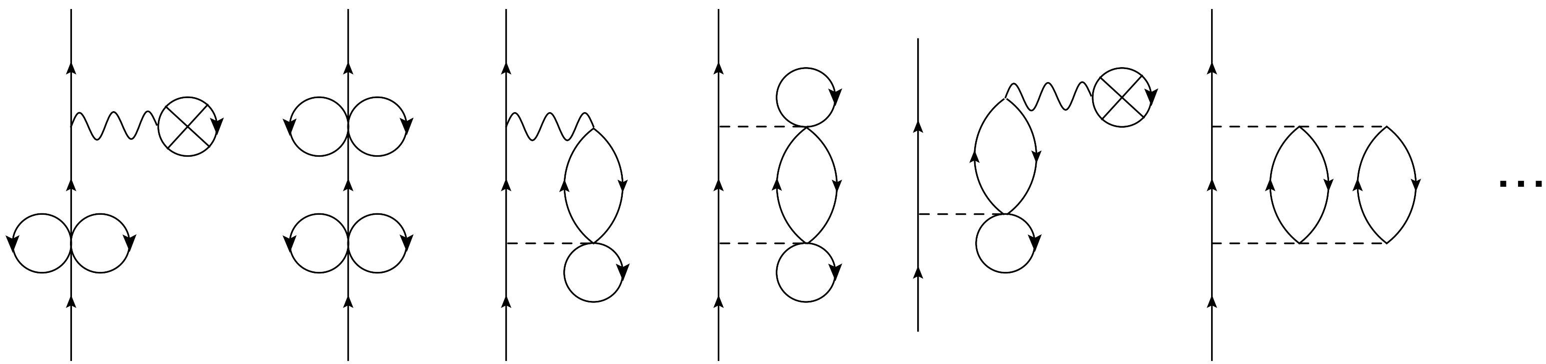


→ **The 3NF-induced monopole Hamiltonian is essential to explain the measured shell evolution.**

Y. Z. Ma *et al.*, arXiv:1812.03284.

Extension of theoretical framework

- Contribution of the $g_{9/2}$ orbit
- Beyond 1st-order contribution



13 diagrams for 2nd-order one-body term

Study of neutrinoless double β decay

RSM calculations with chiral 3NF
for **^{76}Ge, ^{82}Se, ^{130}Te, ^{136}Xe**, etc.

3NF in open quantum system

Gamow shell model calculations with chiral 3NF.