Shell model study of chiral three-nucleon force

Tokuro Fukui

RIKEN Nishina Center

RIKEN NiSHiNA CENTER

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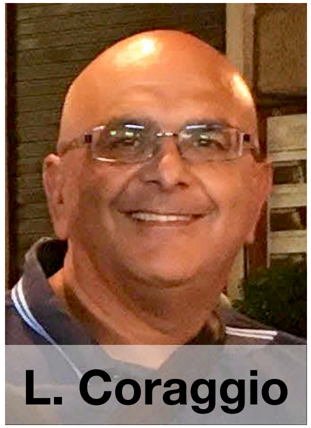
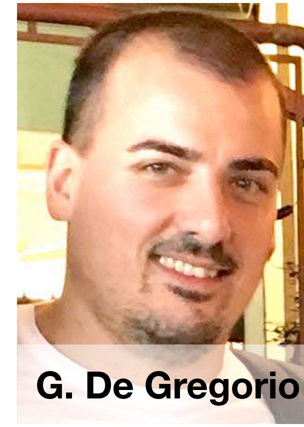
Acknowledgement to collaborators

INFN-Napoli & Univ. Campania “Luigi Vanvitelli”





Peking Univ. & South China Normal Univ.

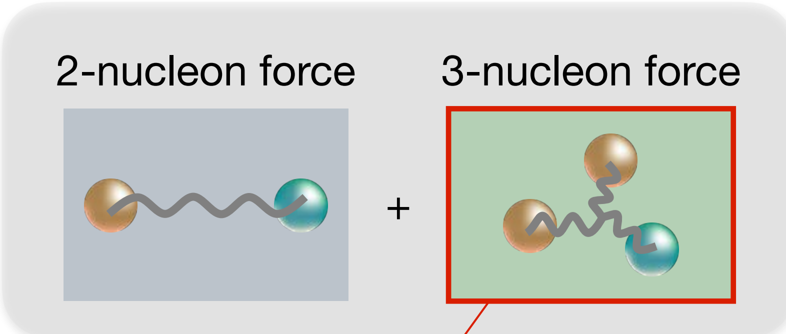
Dicette ’o pappice ’n faccia a’ noce,
damme ’o tiempo ca te spertoso!

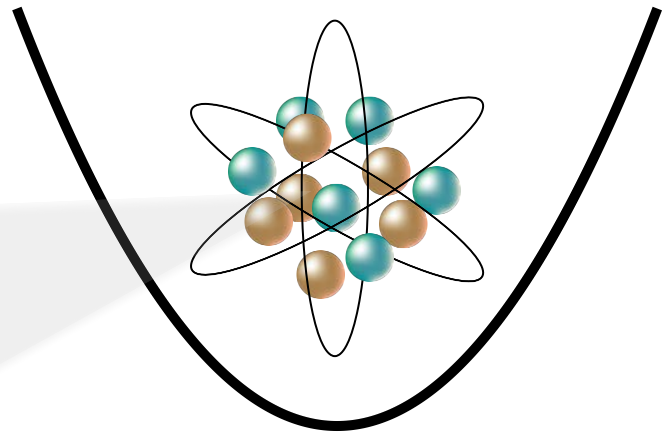
Target | 3NF in many-nucleon systems

Shell model + state-of-the-art nuclear force

From chiral effective field theory

Machleidt & Entem, PR **503**, 1 (2011)





Unresolved!

Mechanism?
How strong? How contributes?

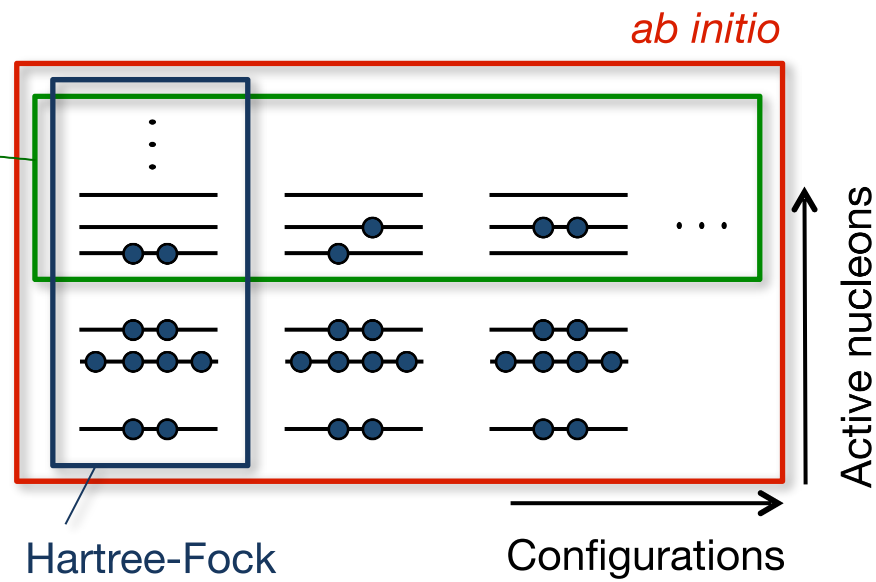
What's New:

Proper treatment of 3NF
for shell model

Valence-space diagonalization

Shell model

Diagonalization of Hamiltonian
within valence model space
using harmonic-oscillator bases



Realistic shell model (RSM)

= Shell model (valence space) with a realistic force

→ **Applicable to heavier systems**

Theoretical framework | Shell-model Hamiltonian

Realistic Hamiltonian

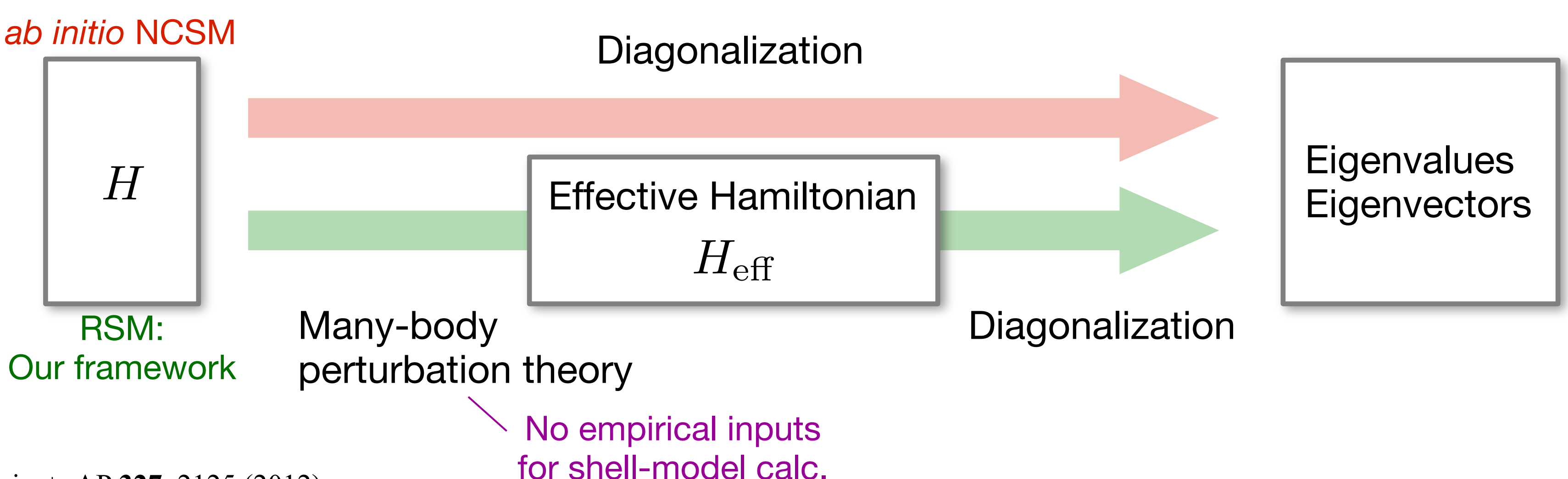
$$H = H_{1\mathrm{B}} + H_{2\mathrm{B}} + H_{3\mathrm{B}}$$

Single-particle energy

Chiral 2NF at N³LO + Coulomb

Chiral 3NF at N²LO

Shell-model framework



Coraggio +, AP **327**, 2125 (2012)

RSM calculations | Numerical details

Low-energy constants ($\Lambda = 500$ MeV)

2NF (N^3LO): Determined from *NN* scattering up to 300 MeV

Entem & Machleidt, PRC **68**, 041001(R) (2003)

3NF (N^2LO): Determined from ^{3}H- and ^{3}He binding energies

Navrátil +, PRL **99**, 042501 (2007)

Model space

Standard 1-major shell

(+ a lowest orbit of higher shell if necessary)

Many-body perturbation theory (degenerate)

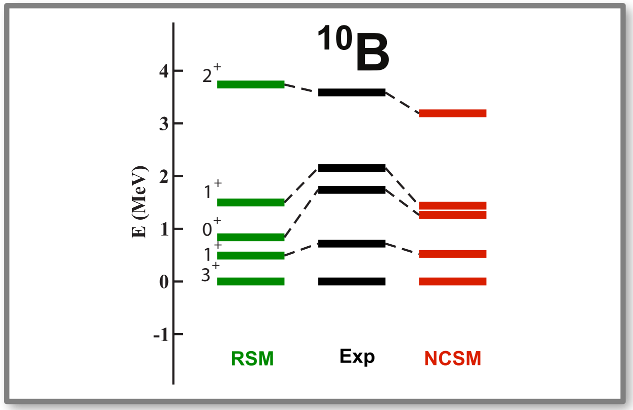
$$H \to H_{\mathrm{eff}}$$

2NF: Up to 3rd-order folded-diagram expansion
3NF: Up to 1st-order (normal-order approx.)

Coraggio + AP **327**, 2125 (2012)
Roth +, PRL **109** , 052501 (2012)

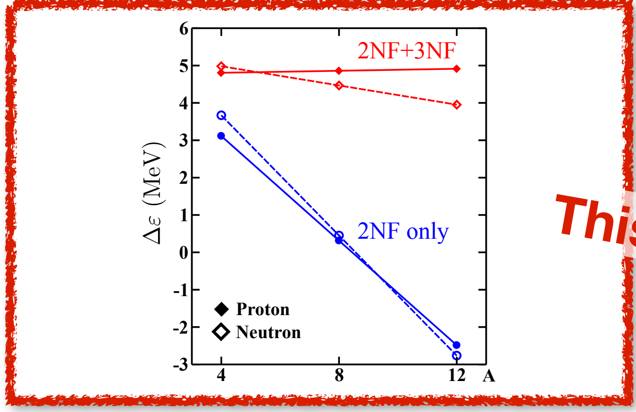
Achievements

Benchmark



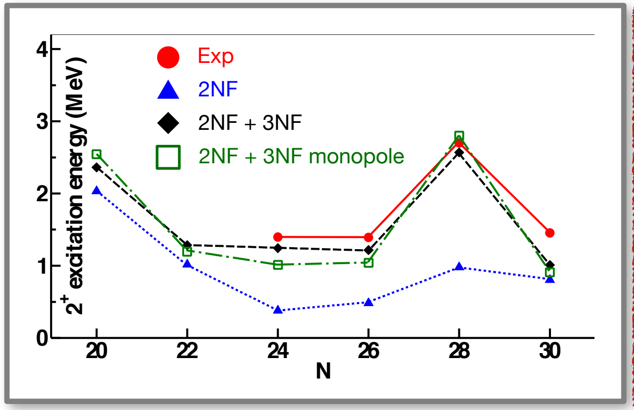
Fukui +, PRC **98**, 044305 (2018)

Spin-orbit splitting and 3NF



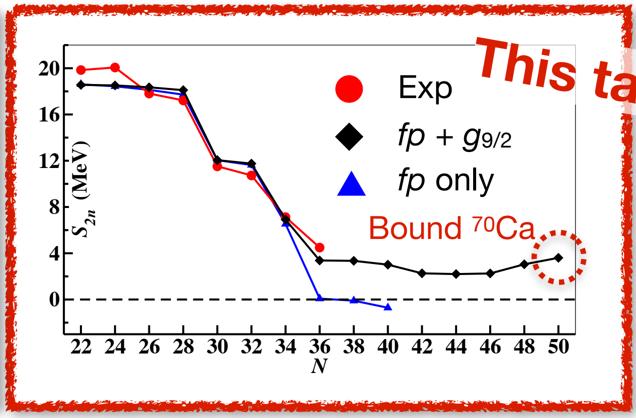
Fukui +, PRC **98**, 044305 (2018)
Ma +, PRC **100**, 034324 (2019)

3NF-induced monopole



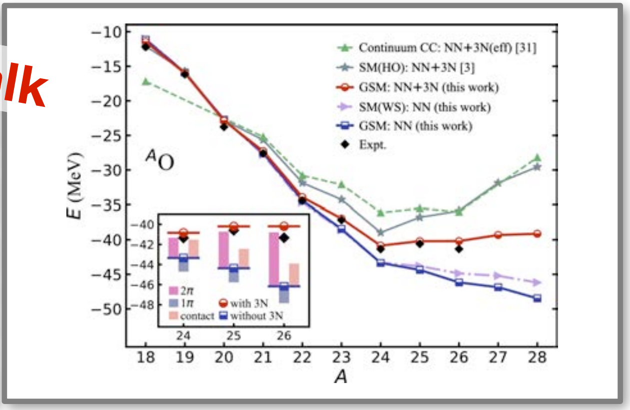
Ma +, PRC **100**, 034324 (2019)

Towards Ca- and Ti-drip lines



Coraggio +, PRC **102**, 054326 (2020)
Coraggio +, PRC **104**, 054304 (2021)

Beyond drip line



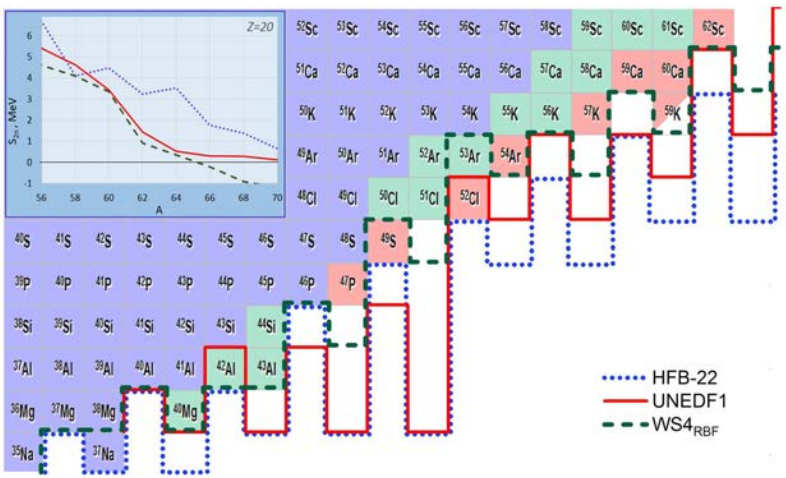
Ma +, PLB **802**, 135257 (2020)

Towards Ca/Ti-drip line

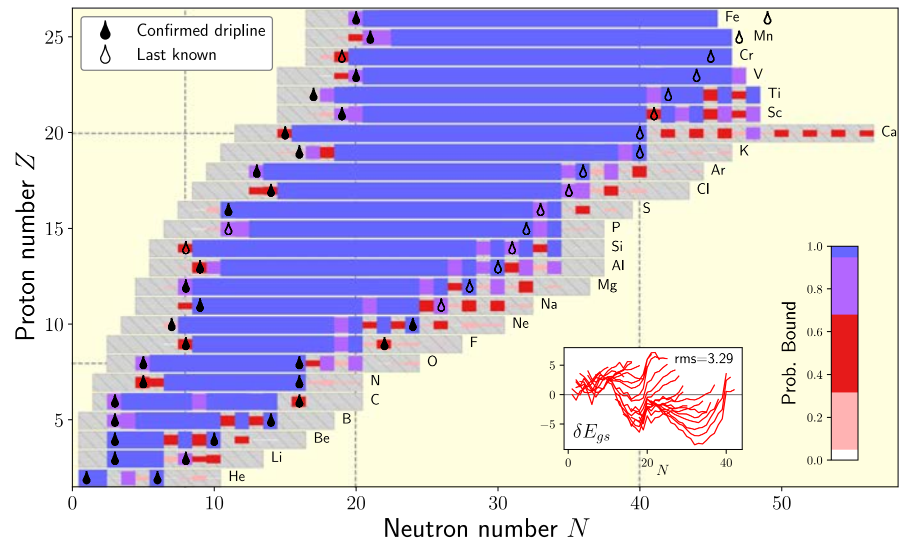
Towards drip line | Ca isotopes

Experimental and theoretical efforts

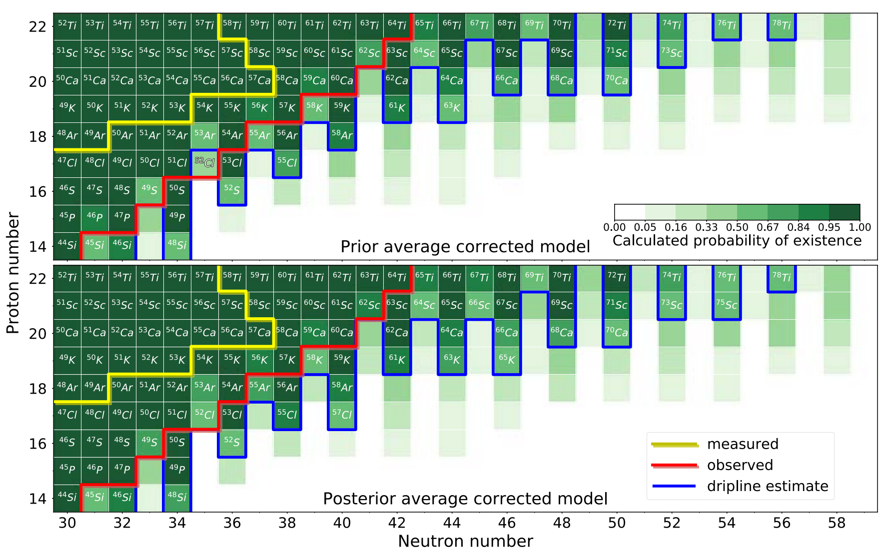
Tarasov +, PRL **121**, 022501 (2018)



Stroberg +, PRL **126**, 022501 (2021)



Neufcourt +, PRL **122**, 062502 (2019)



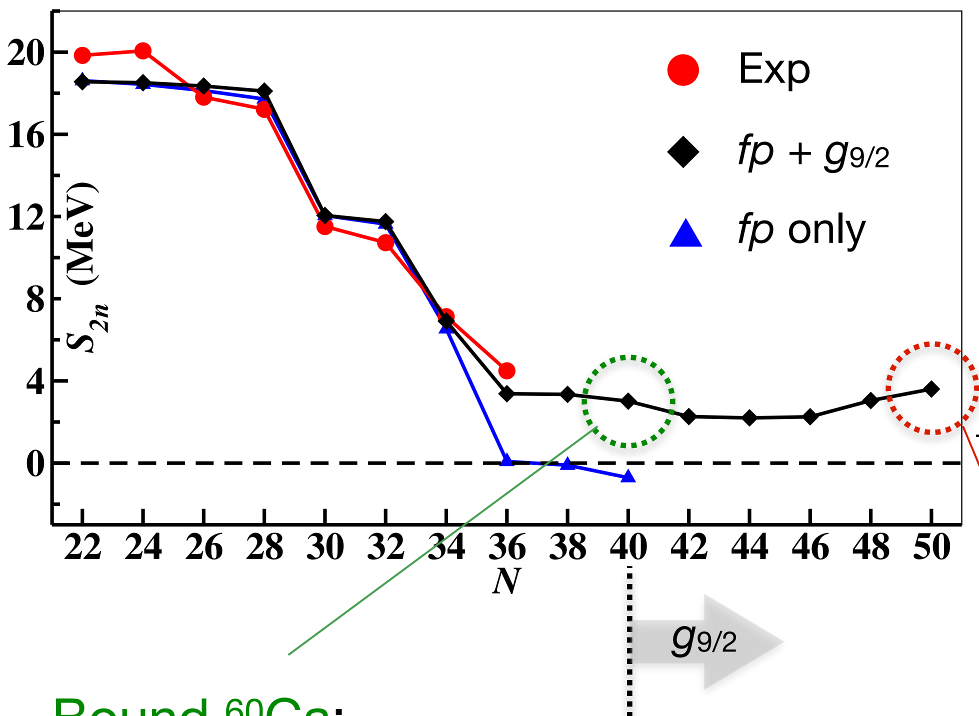
Where is the Ca-drip line?

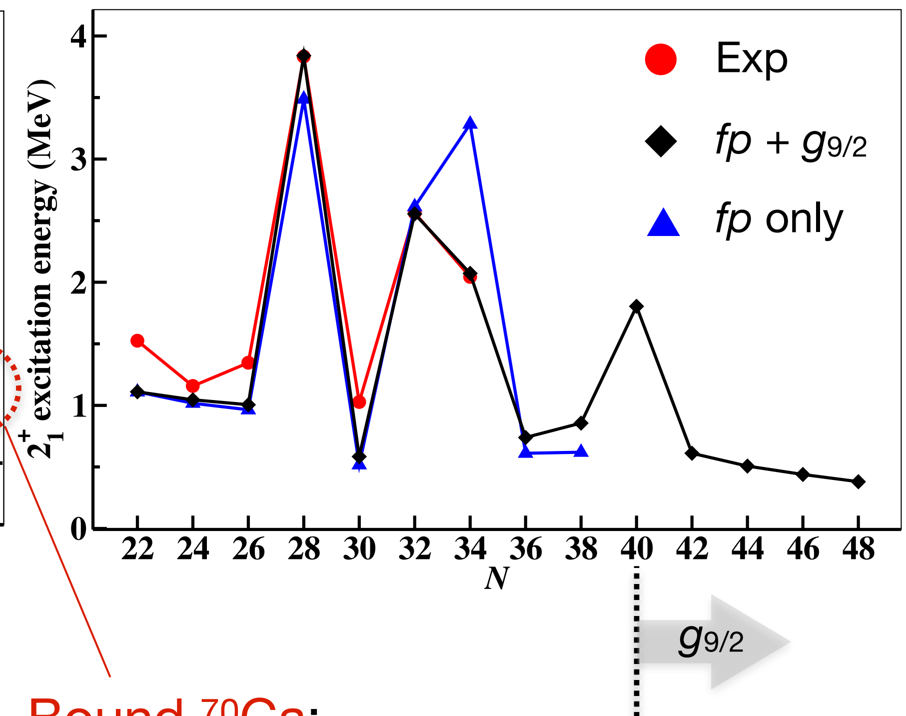
→ Our RSM studies

Towards drip line | Ca isotopes

Ground and low-lying structure

Coraggio+, PRC **102**, 054326 (2020)





Bound ^{60}Ca:
Consistent with experiment

Tarasov +, PRL **121**, 022501 (2018)

Bound ^{70}Ca:
Consistent with other predictions

- Density functional theories
- Bayesian analysis
- Valence-space in-medium SRG

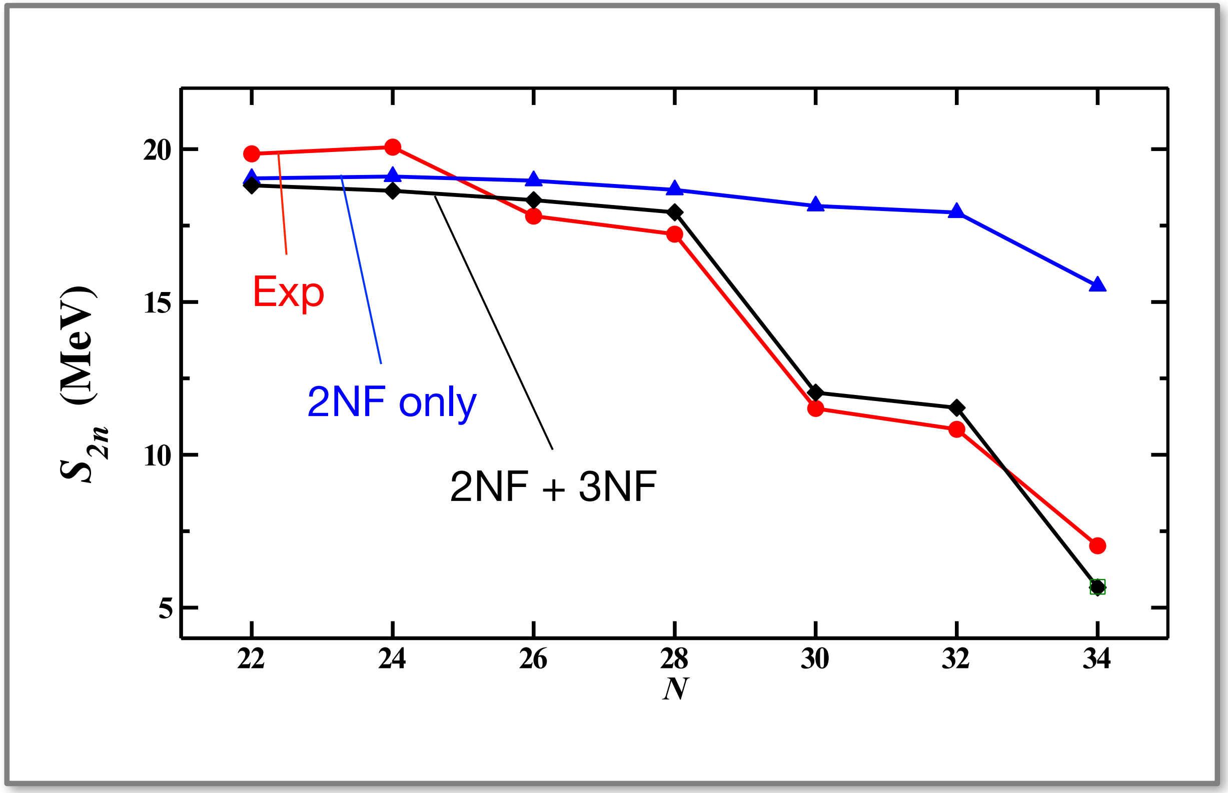
We also predict bound ^{70}Ti.

Coraggio+, Phys. Rev. C **104**, 054304 (2021)

Kortelainen +, PRC **85**, 024304 (2012), Goriely +, PRC **88**, 024308 (2013), Wang +, PLB **734**, 215 (2014)
Neufcourt +, PRL **122**, 062502 (2019), Stroberg +, PRL **126**, 022501 (2021)

3NF contributions | Ca isotopes

Significant 3NF effect

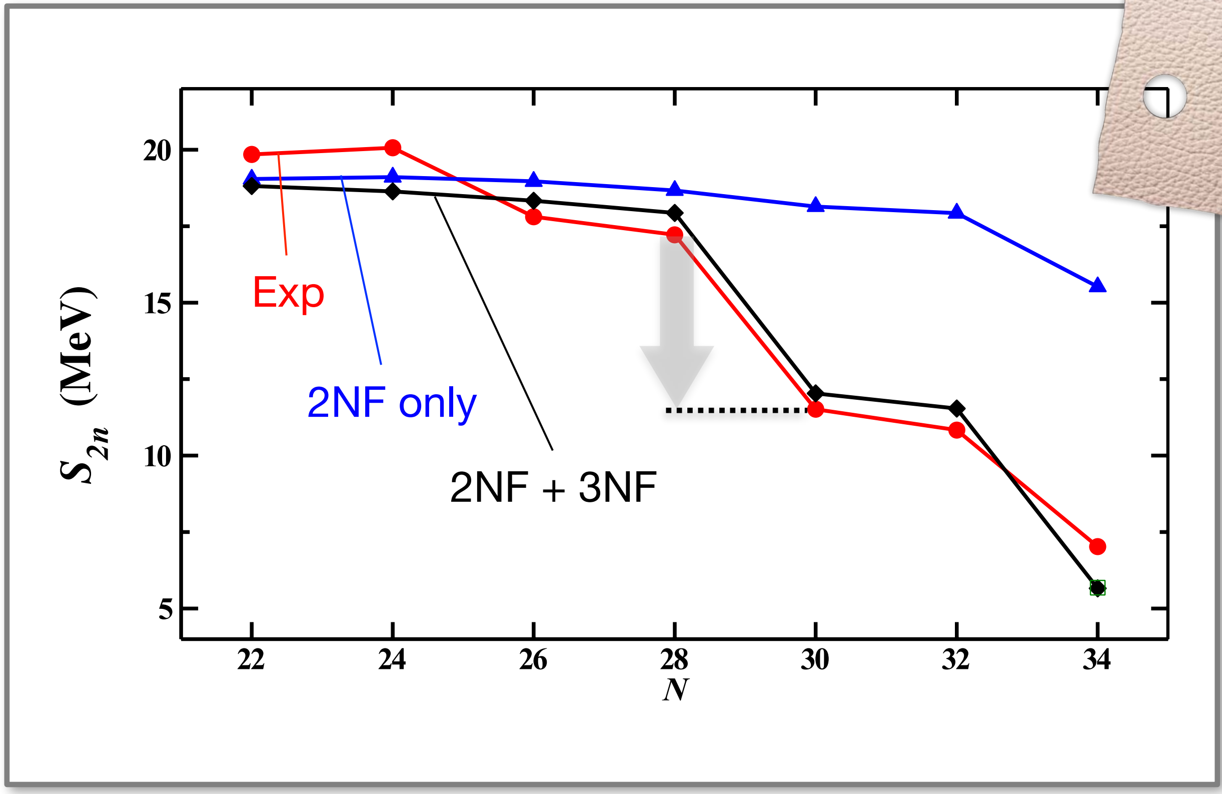


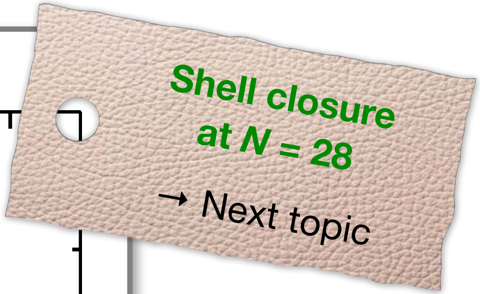
Vital 3NF contributions to monopole interaction

Cf. Zuker, PRL **90**, 042502 (2003)

3NF contributions | Ca isotopes

Significant 3NF effect





Vital 3NF contributions to monopole interaction

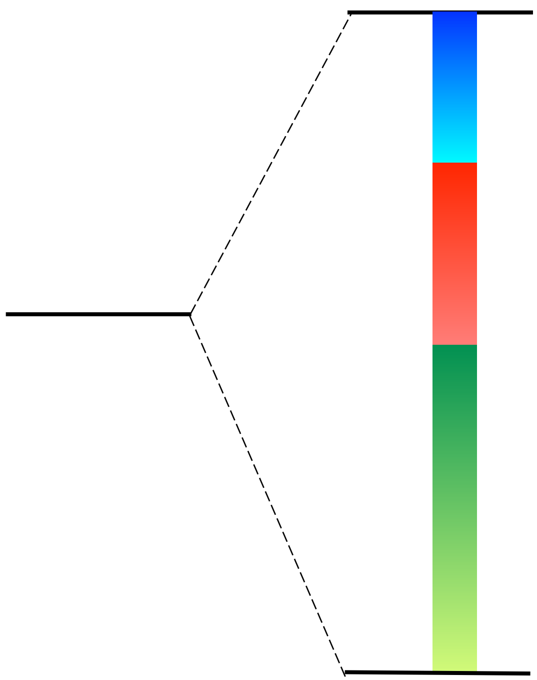
Cf. Zuker, PRL **90**, 042502 (2003)

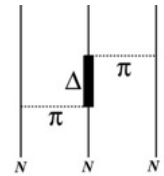
Spin-orbit splitting and 3NF

Spin-orbit splitting | Microscopic origin

Courtesy: T. Uesaka

Scheerbaum, Nucl. Phys. A 257 (1976) 77.
Ando and Bando, Prog. Theor. Phys. 66 (1981) 227.
Pieper and Pandharipande, Phys. Rev. Lett. 70 (1993) 2541.



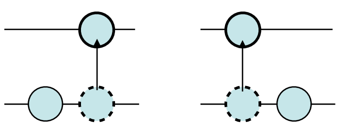


3N force

"Spin-orbit coupling in heavy nuclei"
Fujita and Miyazawa, PTP 17 (1957) 366.

Tensor force

Wigner & Feingold, PR 79 (1950) 221.
Terasawa, PTP 23 (1960) 87.



NN LS interaction
σ and ω exchange
isoscaler in nature

NOT fully understood

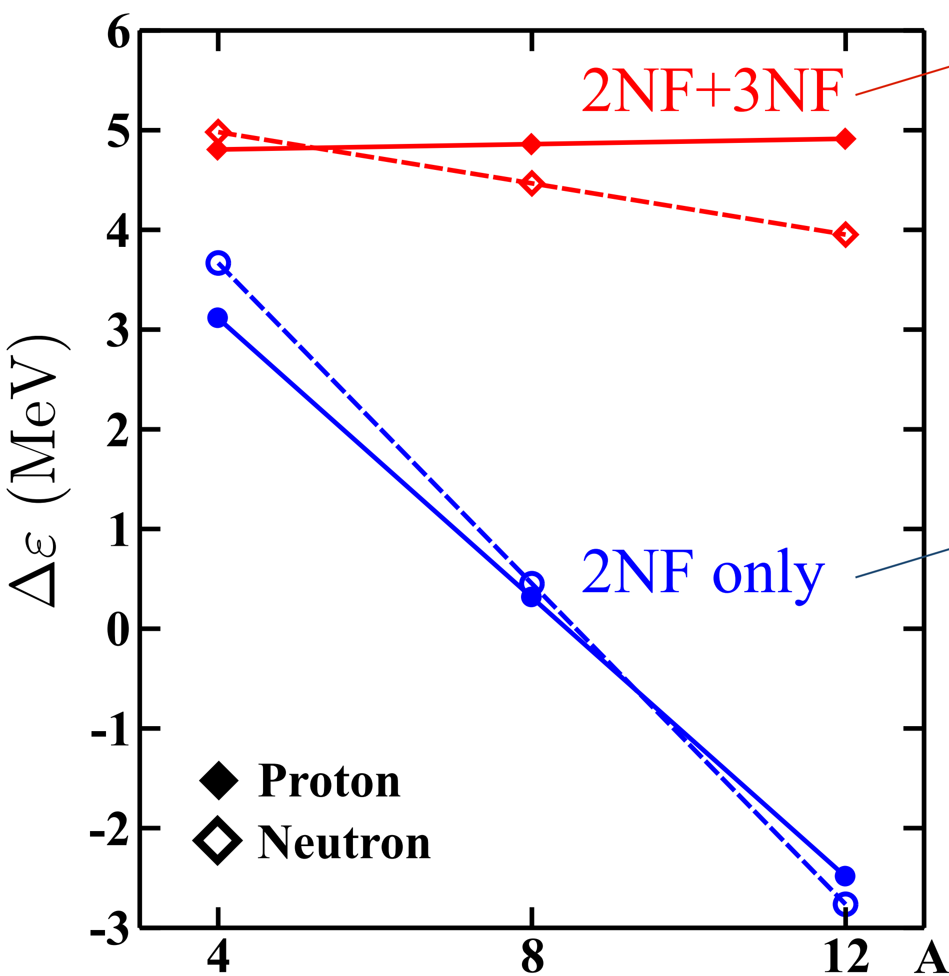
Microscopic origin
→ Particularly **3NF**

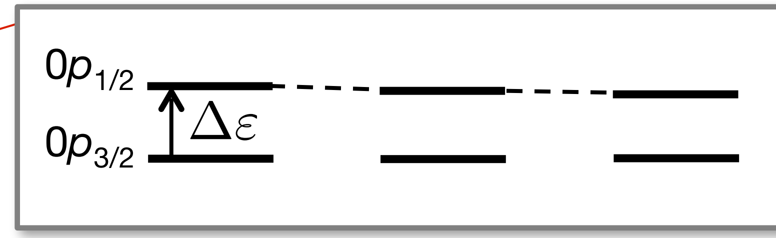
Closure property | *p*-shell nuclei

Effective single-particle energies (ESPEs)

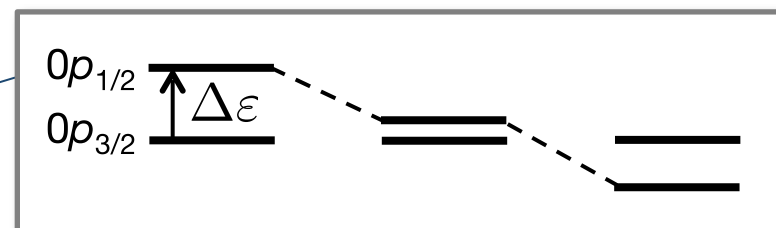
Fukui +, PRC **98**, 044305 (2018)

= SPEs modified by average 2NF (+3NF)





Better closure properties



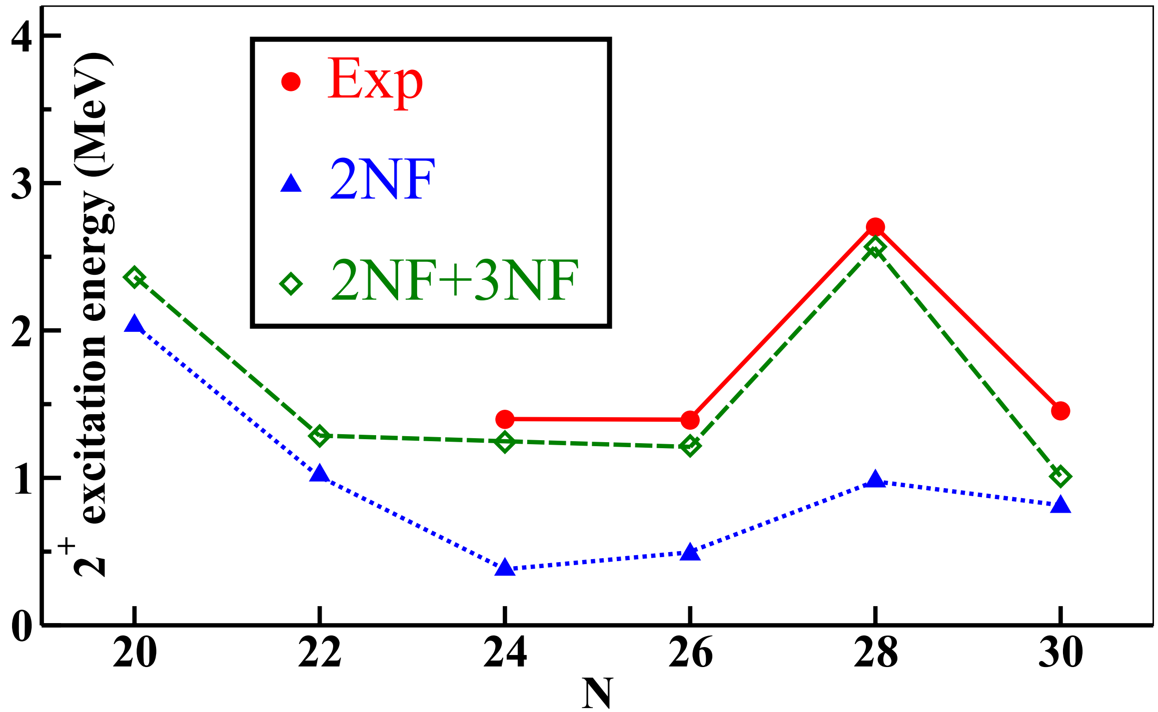
- Repulsive 3NF is needed
- $0p_{1/2}$ nucleon interacts more

Closure property | *pf*-shell nuclei

Ni isotopes

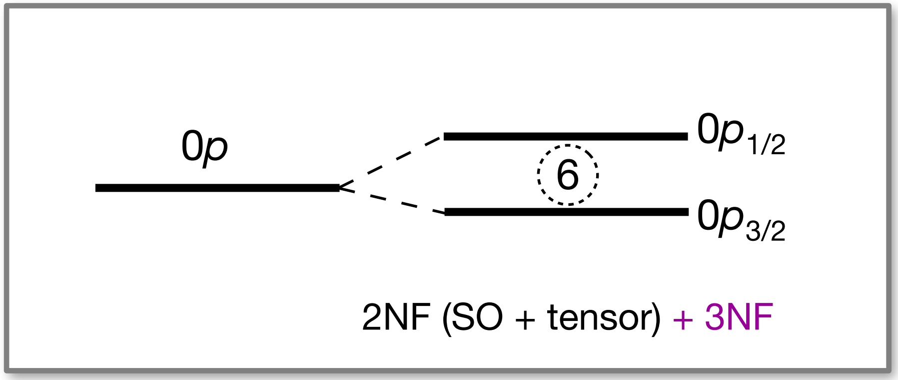
Ma +, PRC **100**, 034324 (2019)

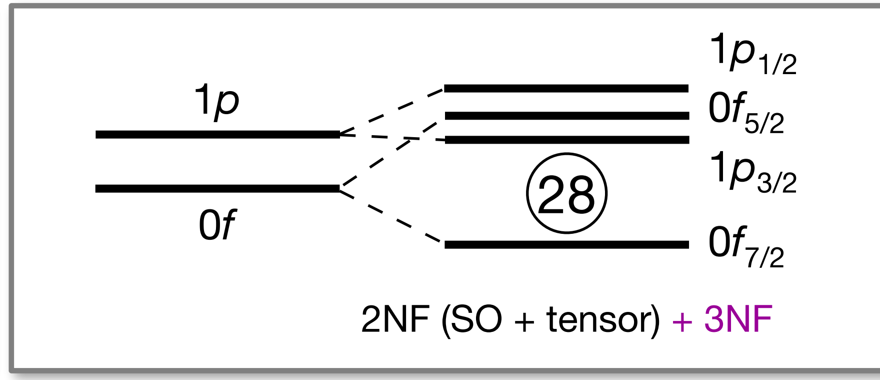
- **2NF**: Fails
- **3NF**: Consistent with **experimental** data.



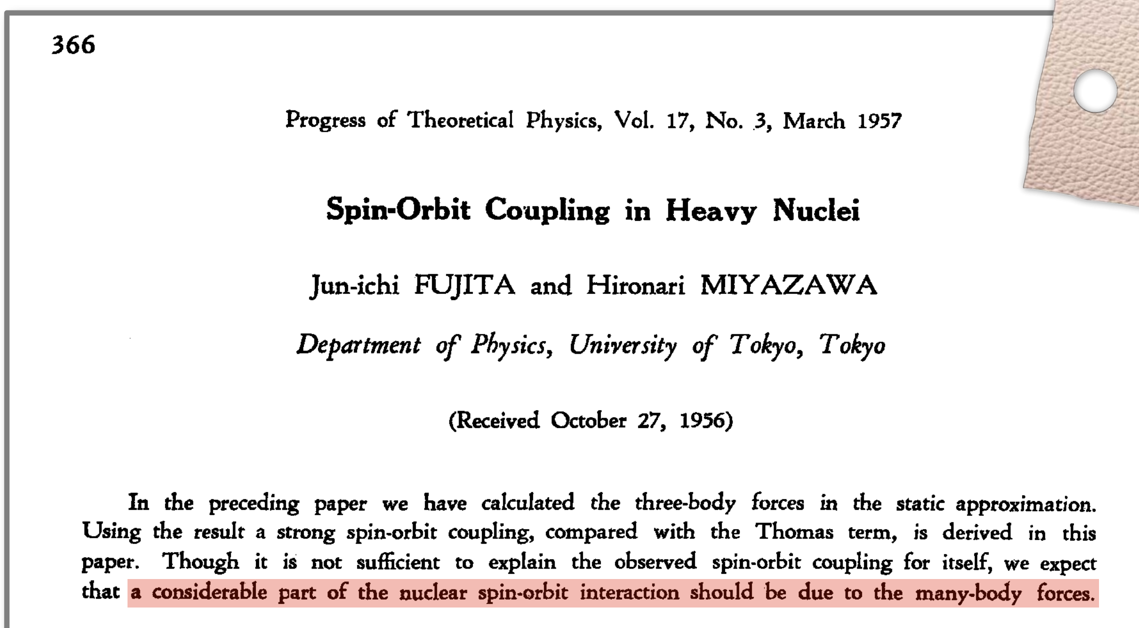
Spin-orbit splitting and 3NF

Spin-orbit splitting stabilized by 3NF





Revisit Fujita & Miyazawa (1957)


366

Progress of Theoretical Physics, Vol. 17, No. 3, March 1957

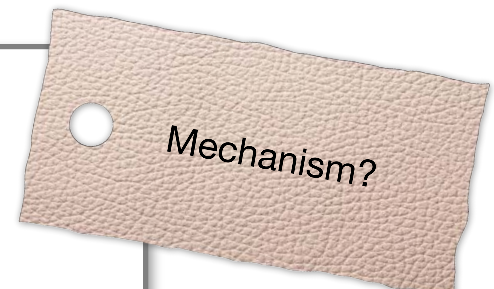
Spin-Orbit Coupling in Heavy Nuclei

Jun-ichi FUJITA and Hironari MIYAZAWA

Department of Physics, University of Tokyo, Tokyo

(Received October 27, 1956)

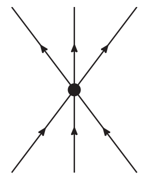
In the preceding paper we have calculated the three-body forces in the static approximation. Using the result a strong spin-orbit coupling, compared with the Thomas term, is derived in this paper. Though it is not sufficient to explain the observed spin-orbit coupling for itself, we expect that a considerable part of the nuclear spin-orbit interaction should be due to the many-body forces.



Tensorial structure of chiral N^2LO 3NF

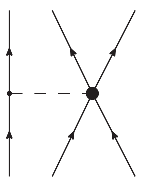
Preliminary!!

Contact



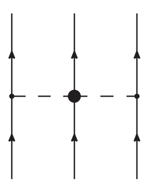
Central

1π + contact



Central + Tensor

2π



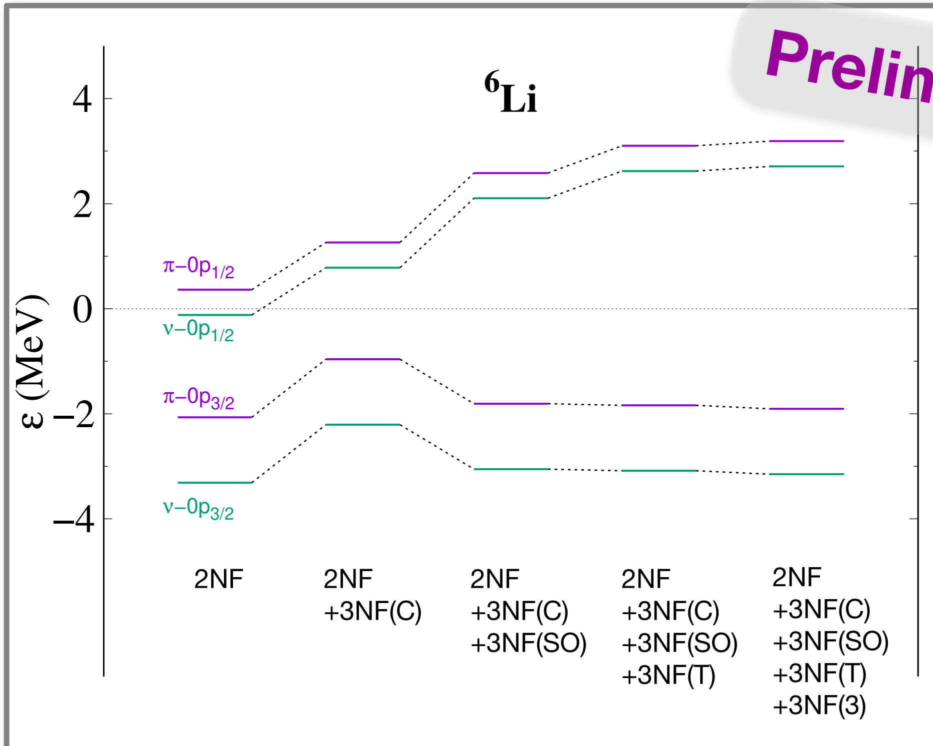
Central + Spin orbit + Tensor + Rank 3

New decomposition formalism!

Spin-orbit splitting and 3NF | *p*-shell nuclei

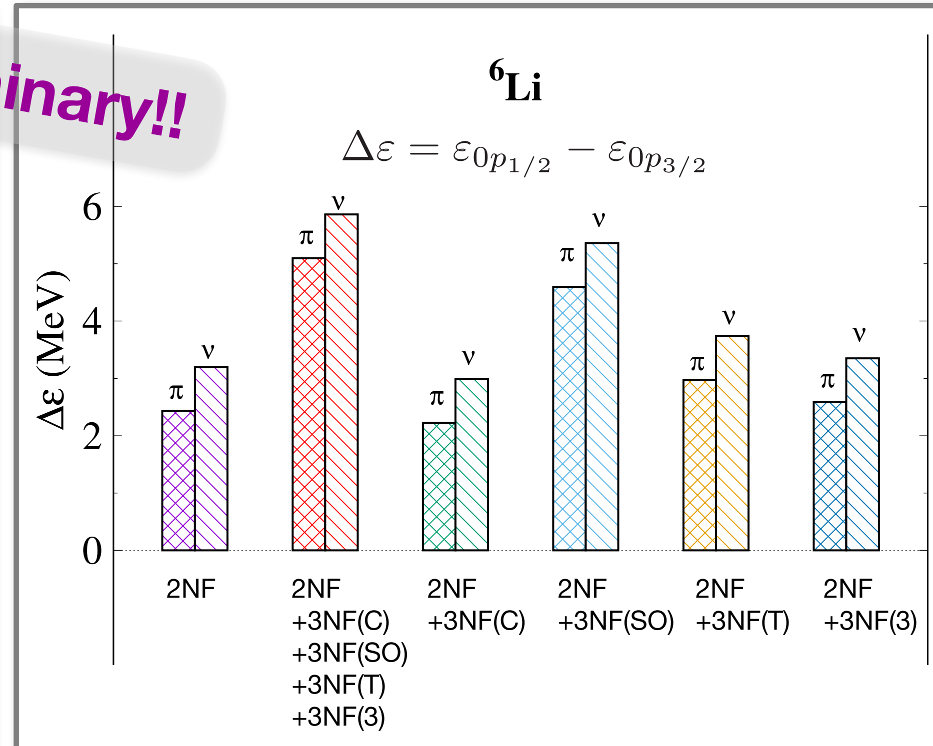
ESPEs

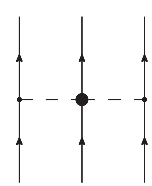
Cumulative calculations



Preliminary!!

Individual contributions



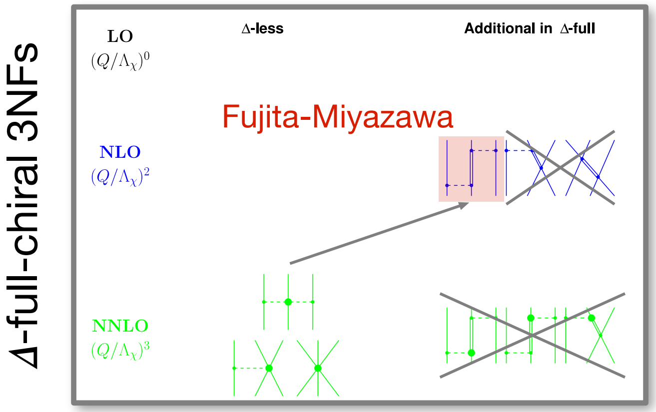
2π  Central + Spin orbit + Tensor + Rank 3

Crucial contributions

2π-exchange 3NF | Dominant contributions

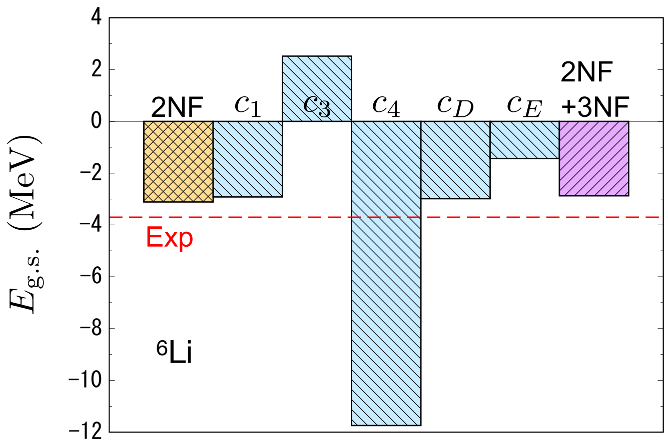
3NF: 2π-exchange dominant

- Fujita-Miyazawa 3NF
  → lower order (NLO)



Machleidt & Entem, PR **503**, 1 (2011)

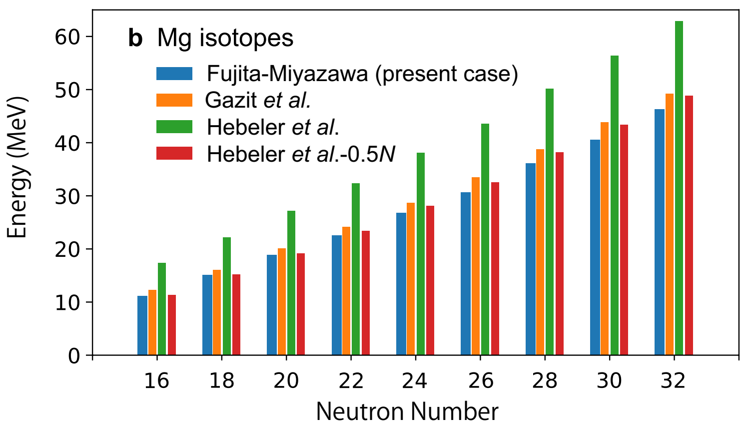
- Numerically confirmed
  (ground-state energies)



Fukui +, EPJWC **223**, 01018 (2019)

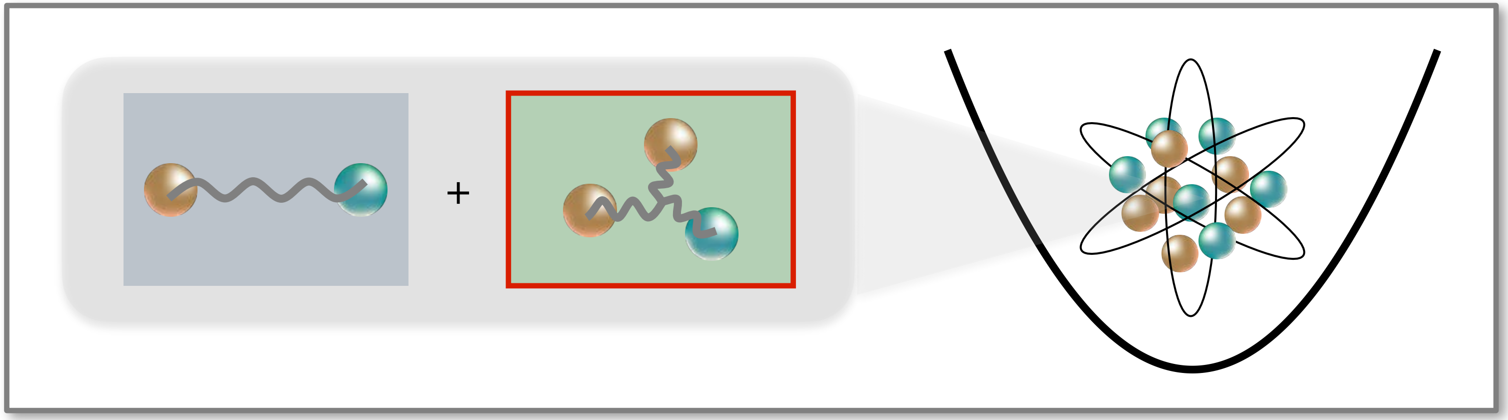
- Fujita-Miyazawa 3NF:
  Good approx. of chiral-3NF

Fujita & Miyazawa, PTP **17**, 360 (1957)
Tsunoda +, Nature **587**, 66 (2020)

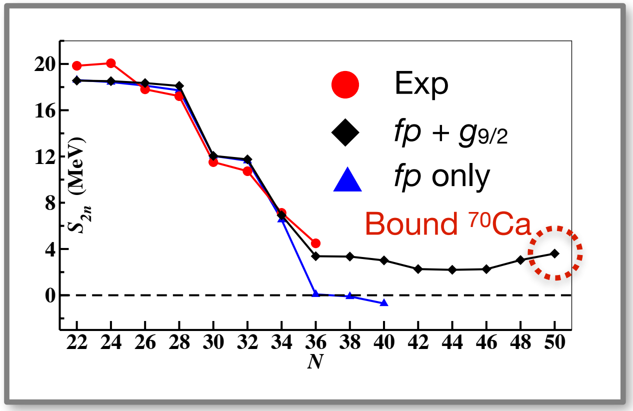


Summary | Spin-orbit splitting and 3NF

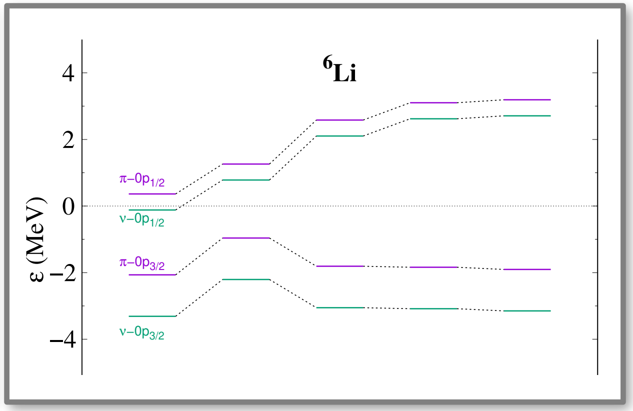
Shell model + chiral EFT



Drip lines:
Possibly bound ^{70}Ca/^{70}Ti



SO splitting:
Crucial 2π-SO term



Future

- Beyond $g_{9/2}$ & continua
- Higher-ℓ SO splitting & 3NF
- SO splitting & 3NF in unstable nuclei