Shell evolution based on chiral nuclear force

Progress in Ab Initio Techniques in Nuclear Physics
Feb 28 - Mar 3, 2017 @TRIUMF

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Special thanks

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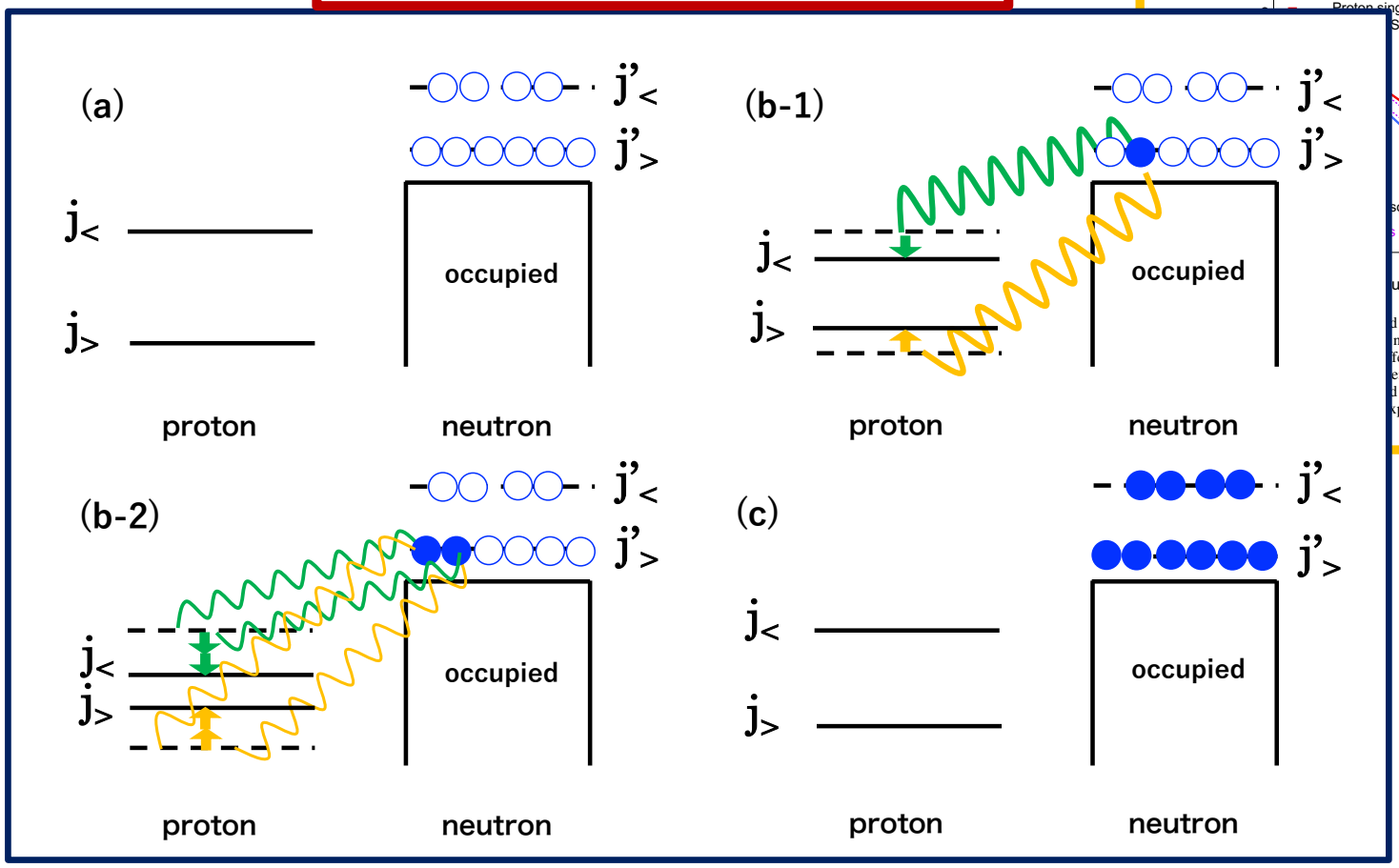
Ragnar Stroberg (TRIUMF)

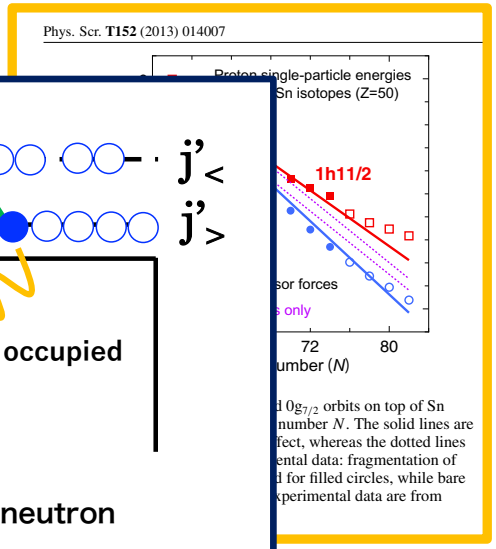
THE UNIVERSITY OF TOKYO

Materials Education program for the future leaders in Research, Industry, and Technology

Shell evolution due to the tensor force

$$(2j_> + 1)\, v^T_{\mathrm{m};\, j_>,\, j'} + (2j_< + 1)\, v^T_{\mathrm{m};\, j_<,\, j'} = 0,$$




Phys. Scr. **T152** (2013) 014007

Proton single-particle energies
Sn isotopes (Z=50)

1h11/2

sor forces
s only

72 80
umber (*N*)

d $0g_{7/2}$ orbits on top of Sn
number *N*. The solid lines are
fect, whereas the dotted lines
ental data: fragmentation of
d for filled circles, while bare
xperimental data are from

FIG. from SY master's thesis

As N increases,
single particle energies evolve

central : parallel shift
tensor : widen/reduce
spin-orbit : widen (small)

Shell evolution due to the tensor force

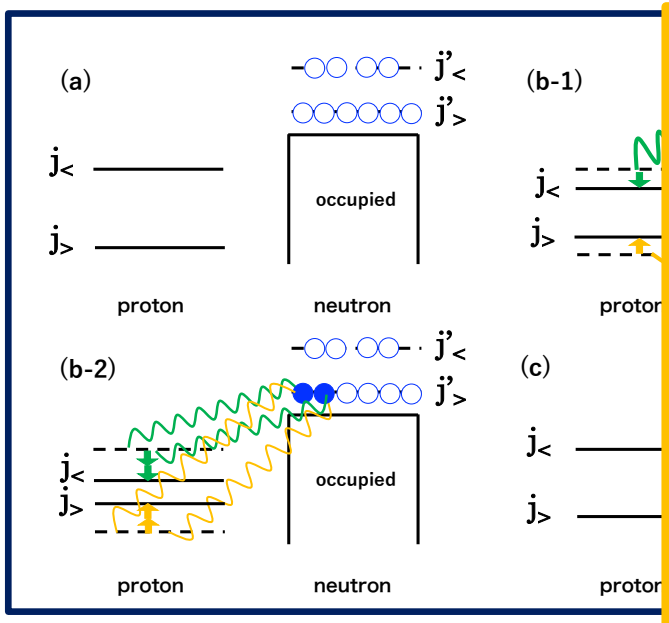


FIG. from
Phys. Scr. **T152** (2013) 014007
T. Otsuka

based on **π+ρ tensor**

How about chiral forces ?

Phys. Scr. **T152** (2013) 014007

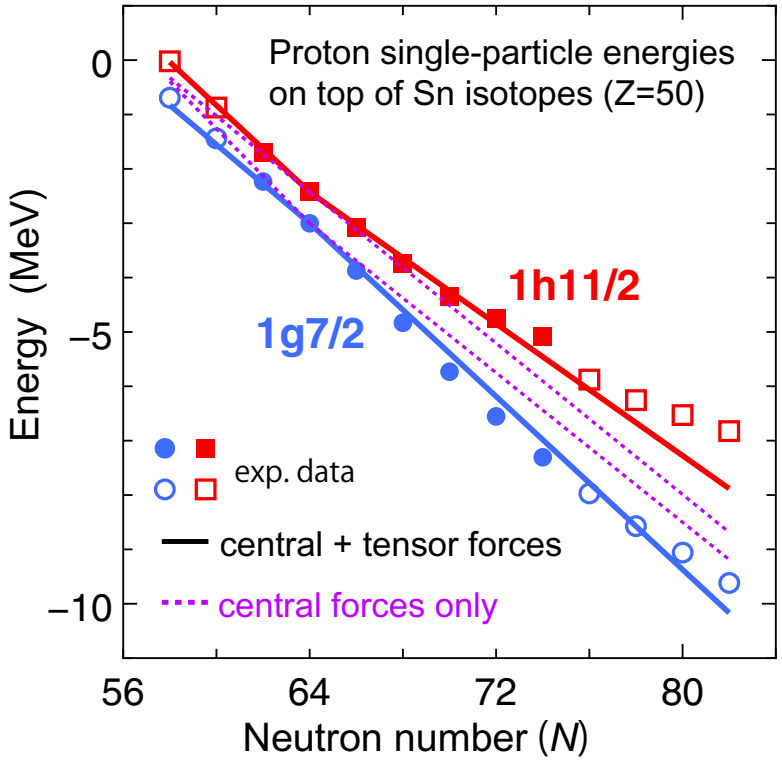


Figure 7. SPEs of proton $0h_{11/2}$ and $0g_{7/2}$ orbits on top of Sn isotopes as functions of the neutron number N. The solid lines are calculations with the tensor-force effect, whereas the dotted lines are without it. Symbols are experimental data: fragmentation of single-particle strength is considered for filled circles, while bare levels are used for open symbols. Experimental data are from Schiffer *et al* [15].

The wide variety of NN/NNN in chiral EFT

●NN

EM : Λ = 500, ~~600~~ MeV

EGM : Λ/Λ_{SFR} = 450/500 MeV
450/700 MeV
550/600 MeV
600/600 MeV
600/700 MeV

EM
D. R. Entem and R. Machleidt,
PRC **68**, 041001(R) (2003).
D. R. Entem and R. Machleidt,
Phys. Rept. **503**, 1 (2011).

EGM
E. Epelbaum, W. Gloöckle, and U.-G. Meißner,
Eur. Phys. J. A **19**, 401 (2004).
E. Epelbaum, W. Gloöckle, and U.-G. Meißner,
Nucl. Phys. A **747**, 362 (2005).

●NNN

- LEC for NNN

  e.g., $-0.3 < \mathbf{c_D} < -0.1$, $-0.220 < \mathbf{c_E} < -0.189$

  c.f. D. Gazit, S. Quaglioni, and P. Navrátil, PRL **103**, 102502 (2009).

- How to include

  N.O. w.r.t. the reference state

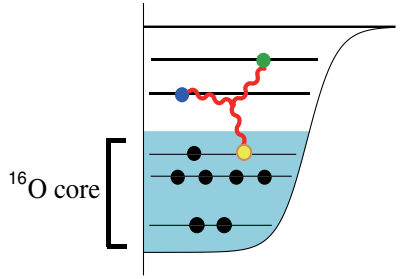
  N.O. w.r.t. the Fermi gas

- ~~A_{3N}~~ & ~~regulator form~~

The conditions for MBPT

NN(SRG) EM500 → MBPT + 3NF(SRG) NO2B eff2NF → **Int. a) ``NO2B"**

hw=12 MeV ※
emax=16, e3max=10
$\lambda = 2.0$ fm^{-1}



※ strong repulsion in ind-3N

NN(bare) + 3NF (bare) Fermi gas eff 2NF → softening V_{lowk}/SRG → MBPT → **Int. b) ``gas"**

hw=12 MeV
emax=16
$\lambda = 1.8 - 2.2$ fm^{-1} / $\Lambda_{lowk} = 2.1$ fm^{-1}

$$\exp\left[-(p'/\Lambda_{3N})^6 - (p/\Lambda_{3N})^6\right] \text{ and } \Lambda_{3N} = 500 \text{ MeV}$$

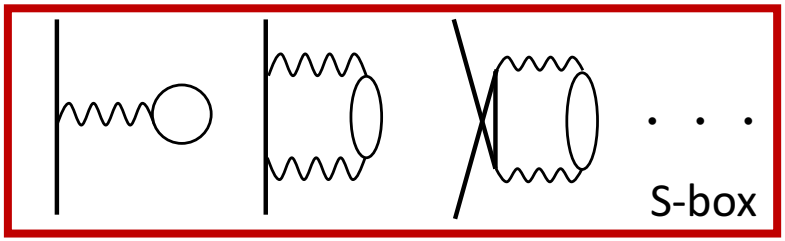
shell model effective interaction

$$H = \sum_i E_i a_i^\dagger a_i + \sum_{ijkl} V_{ij,kl}\, a_i^\dagger a_j^\dagger a_k a_l,$$

SPE TBME

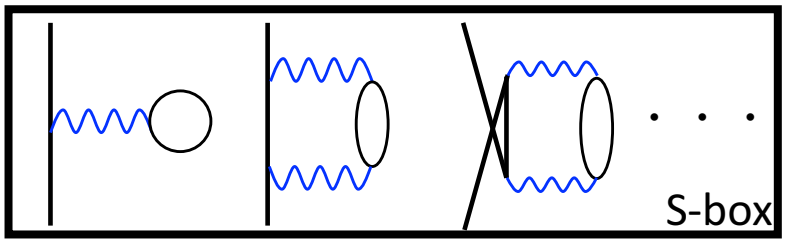
- **SPE**

a)



+NO1B

b)

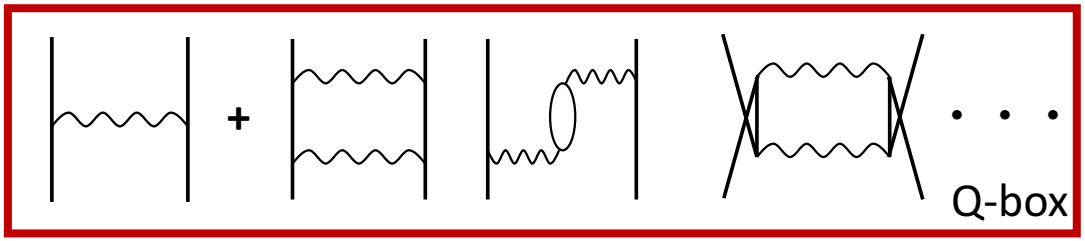


+1-body term by gas approx.

the effect of 3NF is only taken via TBME

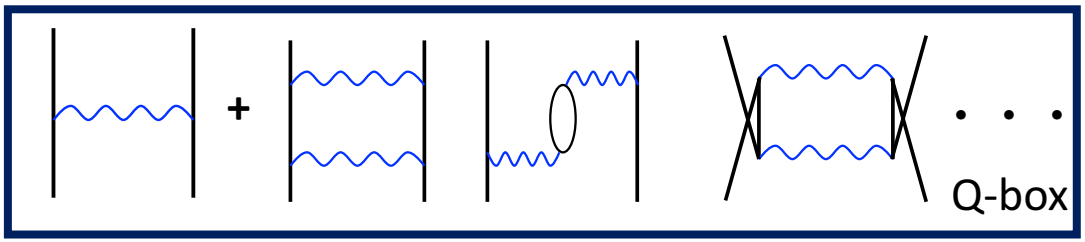
- **TBME**

a)



+ NO2B

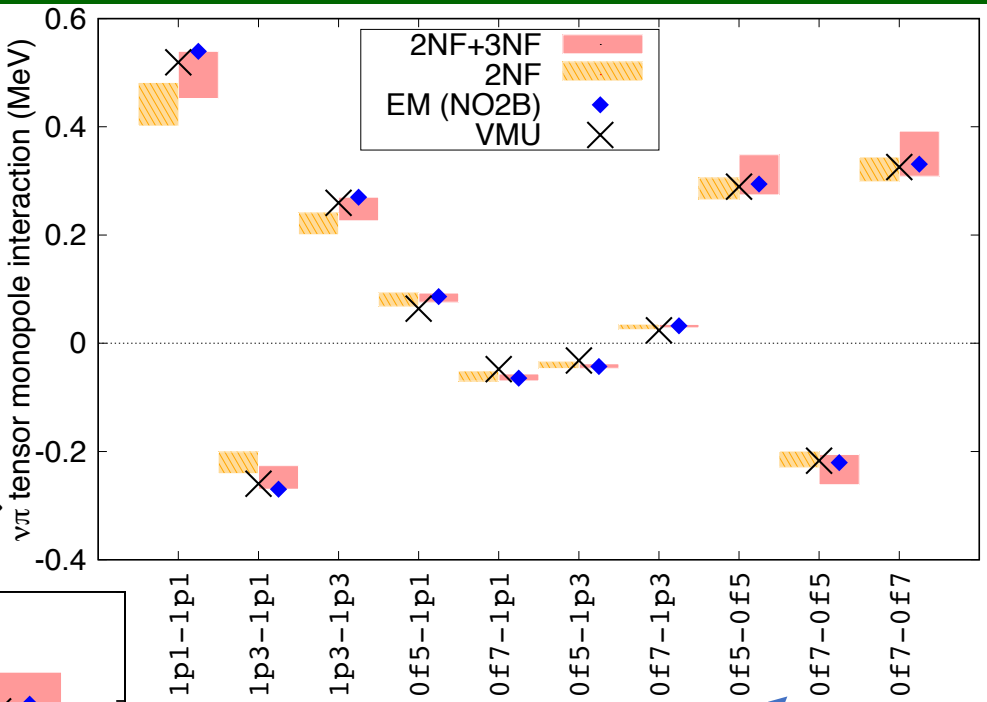
b)



The robustness of tensor forces

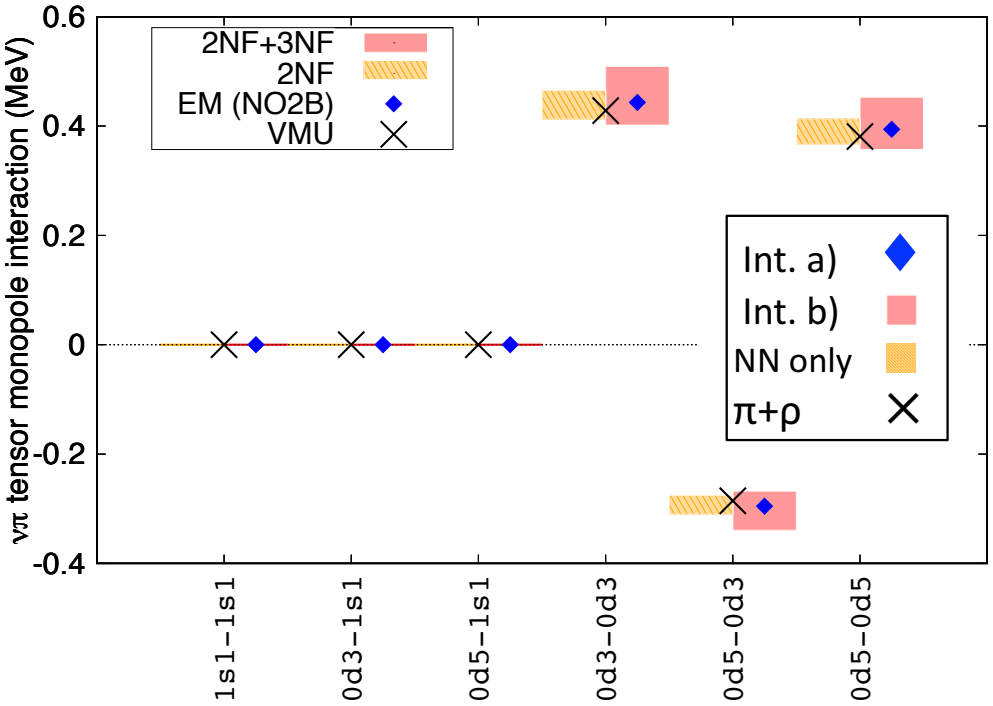
angular averaged tensor force in neutron-proton interaction

- **gas (red bands)** **: density-dependent**
- **NO2B** ◆ **:normal ordering w.r.t. ^{16}O(*sd*) and ^{40}Ca(*pf*)**



pf shell→

↓ sd shell



important for
N=34 magic number in Ca

VMU: embodies shell evolution

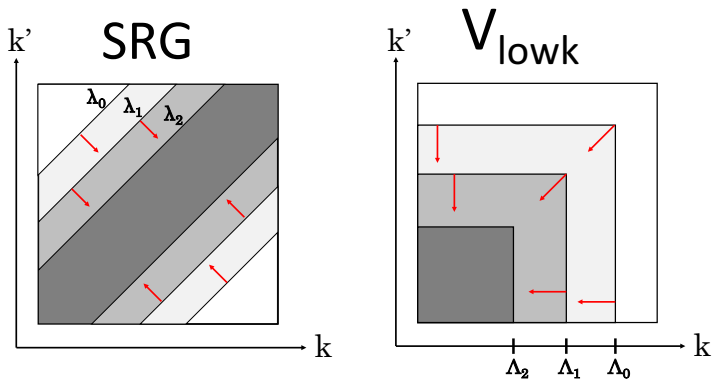
T. Otsuka *et al*. PRL. **95**, 232502 (2005); **104**, 012501 (2010)

tensor force in chiral forces is consistent with that of VMU(π+ρ)

Tensor forces are robust against

1. softening procedure (SRG/V_{lowk})

not sensitive to the λ/Λ (natural)



2. renormalization procedure (MBPT)

non-trivial (summation of Q-box diagrams)

Renormalization Persistency

N. Tsunoda *et al*. PRC **84**, 044322 (2011).

3. effective 2NF from 3NF (Fermi gas / N.O. w.r.t. the core)

tensor force from 3NFs enhances original 2NFs,
but not large

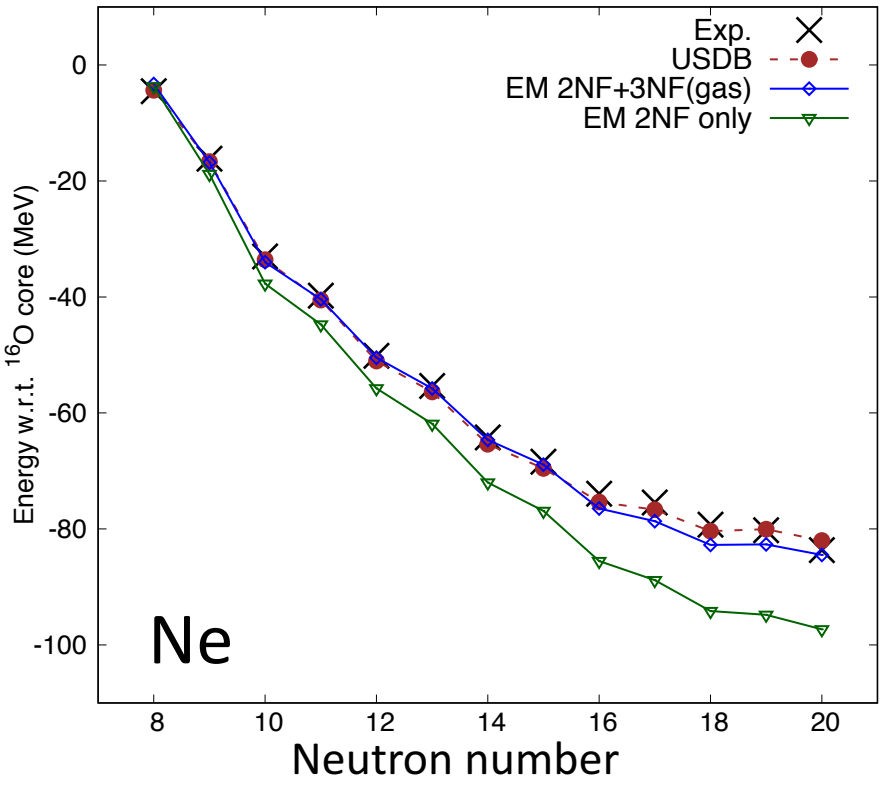
Summary

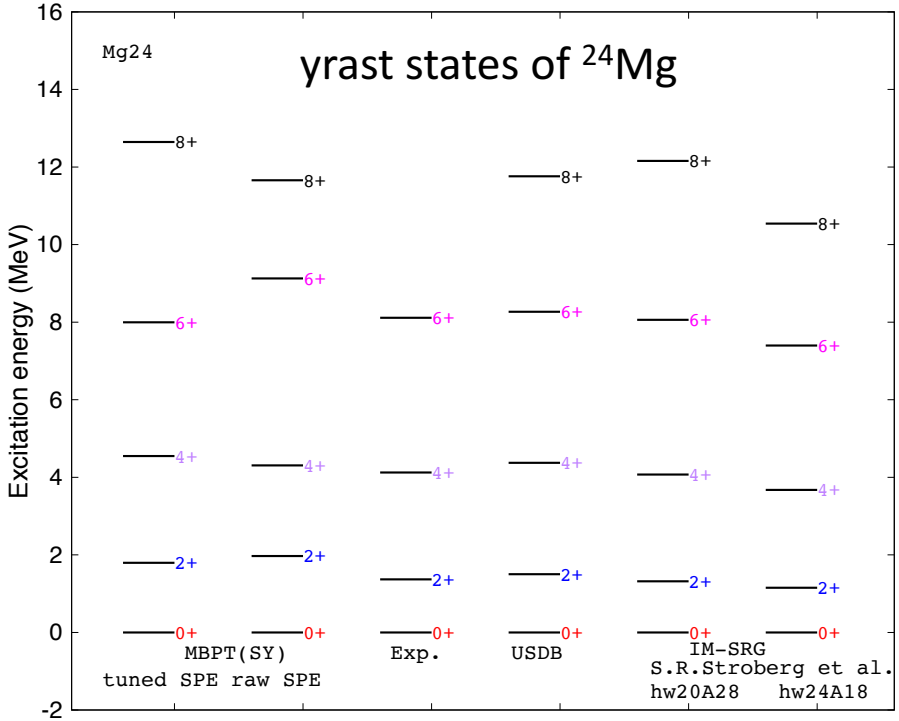
- The strength of tensor force which embodies shell evolution can be also understood by chiral forces

  V_{lowk}/SRG, MBPT, the way to handle 3NF

Int. b)

- SPEs should be improved, but the density-dependent NN force from NNLO 3NF picks up the *essence* of 3NF as well as Int. a)

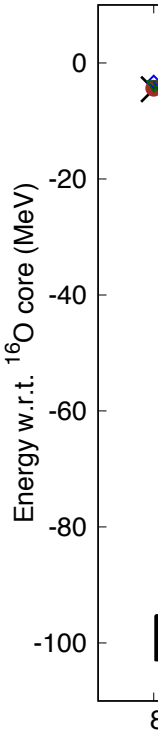


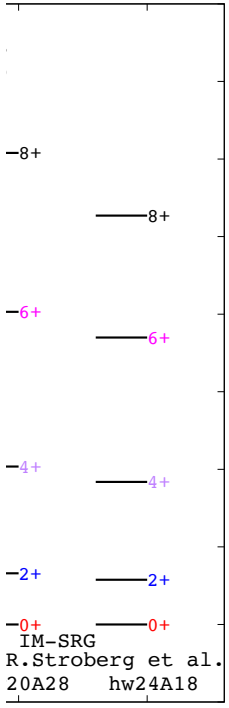


Summ

spectra for all *sd*-shell nuclei

- Th tion
  ca
- Sh N
  fo ll as
  In





monopole analysis of TBME (Q-box)