Shell evolution along the Sn isotopes

Yutaka Utsuno

Advanced Science Research Center, Japan Atomic Energy Agency

Center for Nuclear Study, University of Tokyo

Collaborators

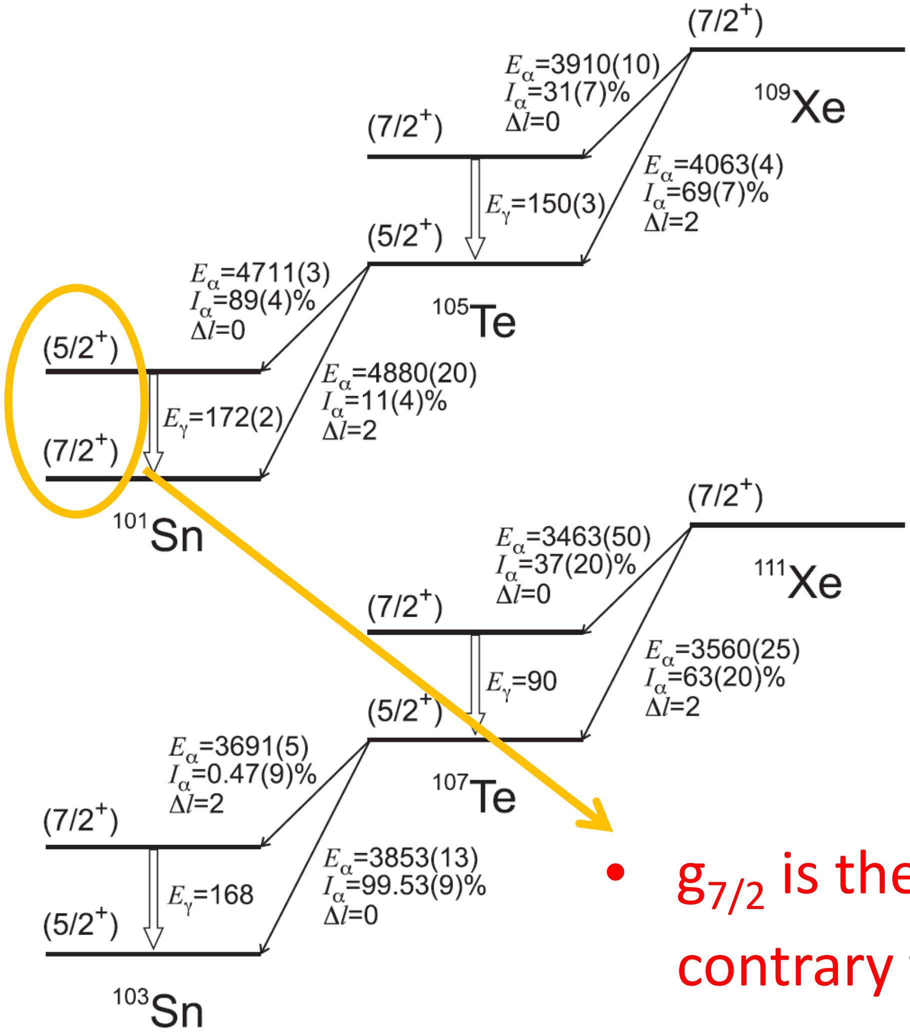
- N. Shimizu (CNS, Univ. Tokyo)
- M. Honma (Univ. Aizu)
- T. Otsuka (Univ. Tokyo/CNS/MSU)
- T. Mizusaki (Senshu Univ.)

Introduction

- What is interesting in the ^{100}Sn region?
  1. Aspect of the heaviest N=Z region
     - Super-allowed α decay
     - Enhanced proton-neutron correlation
       - Enhancement in E2 collectivity?
       - Role of proton-neutron pairing
       - Breaking of the isospin symmetry
  2. Aspect of a good playground for investigating the **shell evolution**
     - Sn (Z=50 magic) chains:
       - long stable isotope chain
       - proton-rich side: accessible with fusion reactions
       - neutron-rich side: accessible with fission or fragmentation

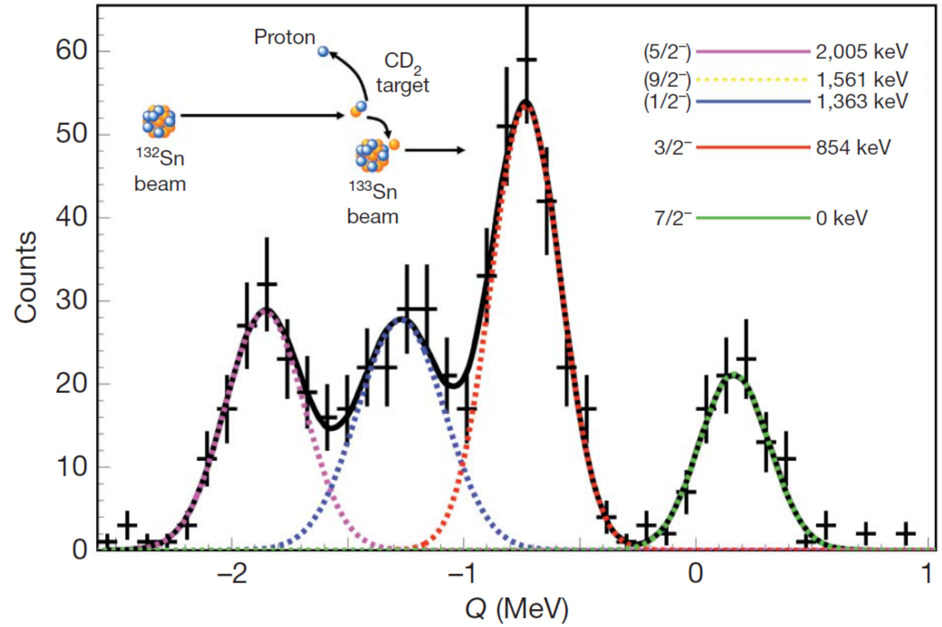
Recent experimental findings

^{100}Sn core



I. G. Darby et al., Phys. Rev. Lett. 105, 162502 (2010).

^{132}Sn core

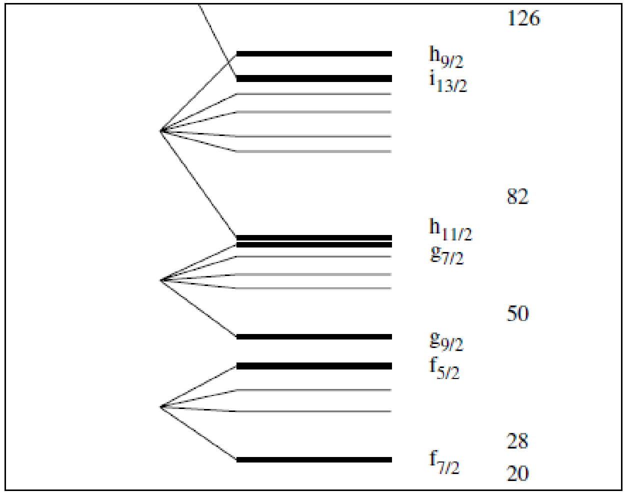


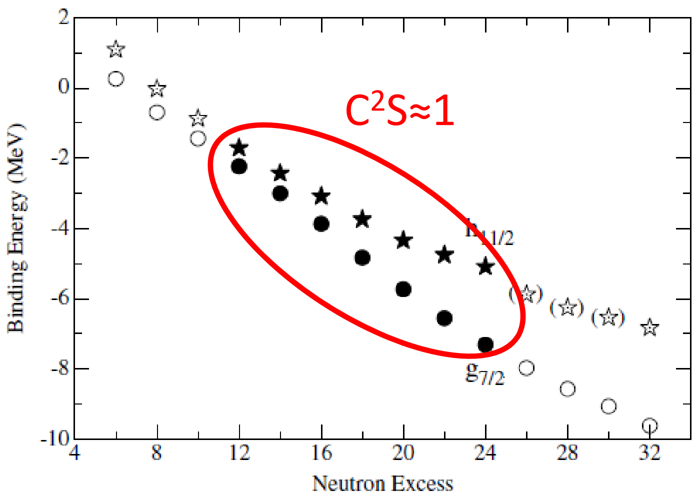
K. L. Jones et al., Nature 465, 454 (2010).

- $g_{7/2}$ is the lowest orbit on top of Z=50 contrary to conventional models.

Proton shell structure seen in $_{51}$Sb isotopes

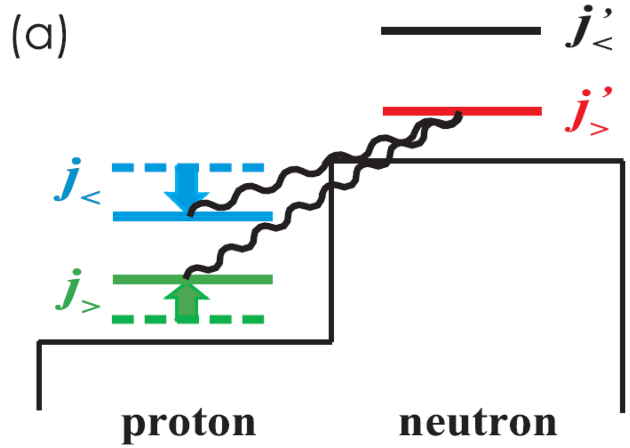
reduction of the *ls* splitting for larger N?

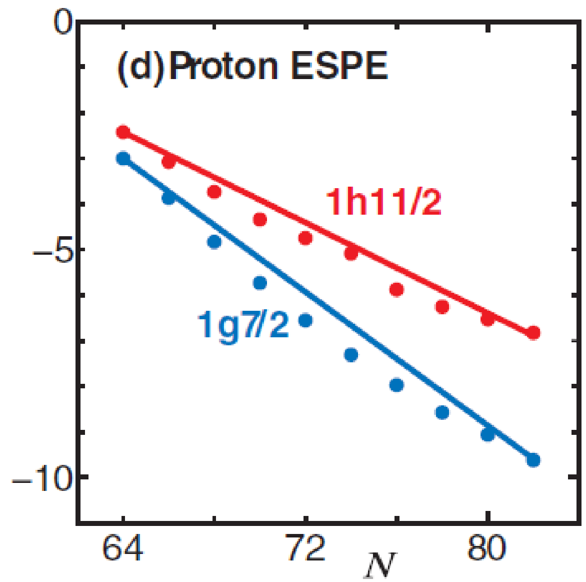




J. P. Schiffer et al., Phys. Rev. Lett. 92, 162501 (2004).

shell evolution due to the tensor force





T. Otsuka et al., Phys. Rev. Lett. 95, 232502 (2005).

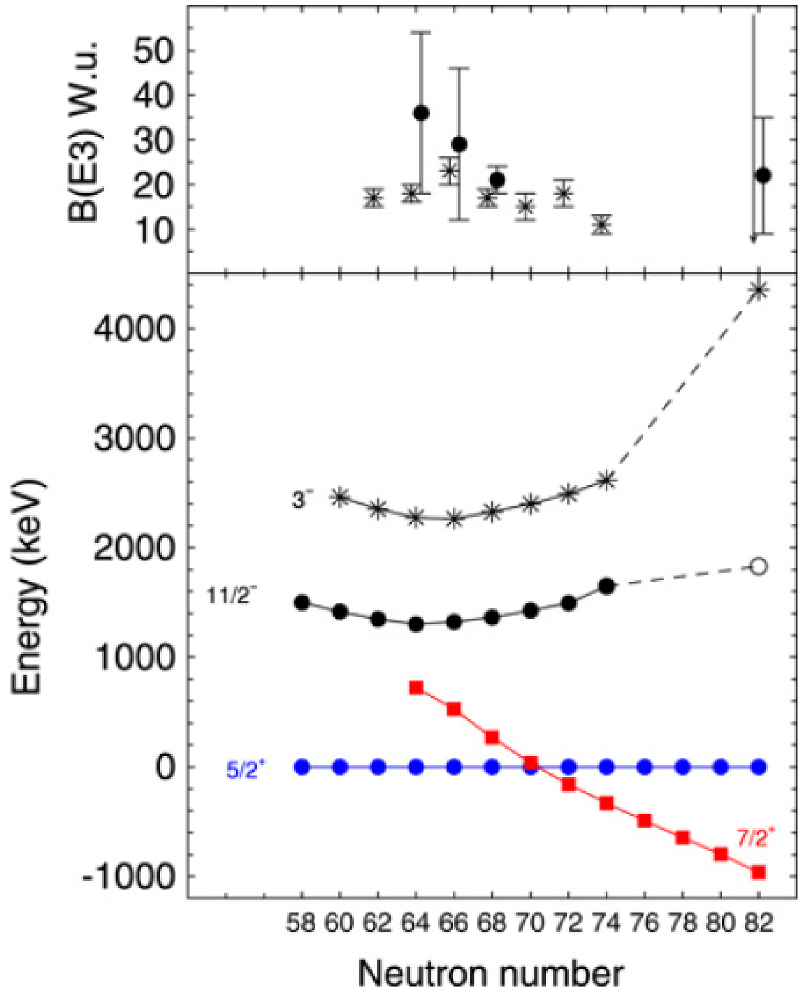
Contradicting experiment and picture

- (^{3}He, d) reaction
  - much smaller C^2S (≈0.5 for 11/2$^-$)
  - Strong influence of correlation such as $\pi(d_{5/2})$*3$^-$ has been suggested, for instance, by Sorlin et al.

this work

Shell-model calculations in the full 50≤ N(Z) ≤82 space are carried out.

- Both shell evolution and correlation are taken into account.

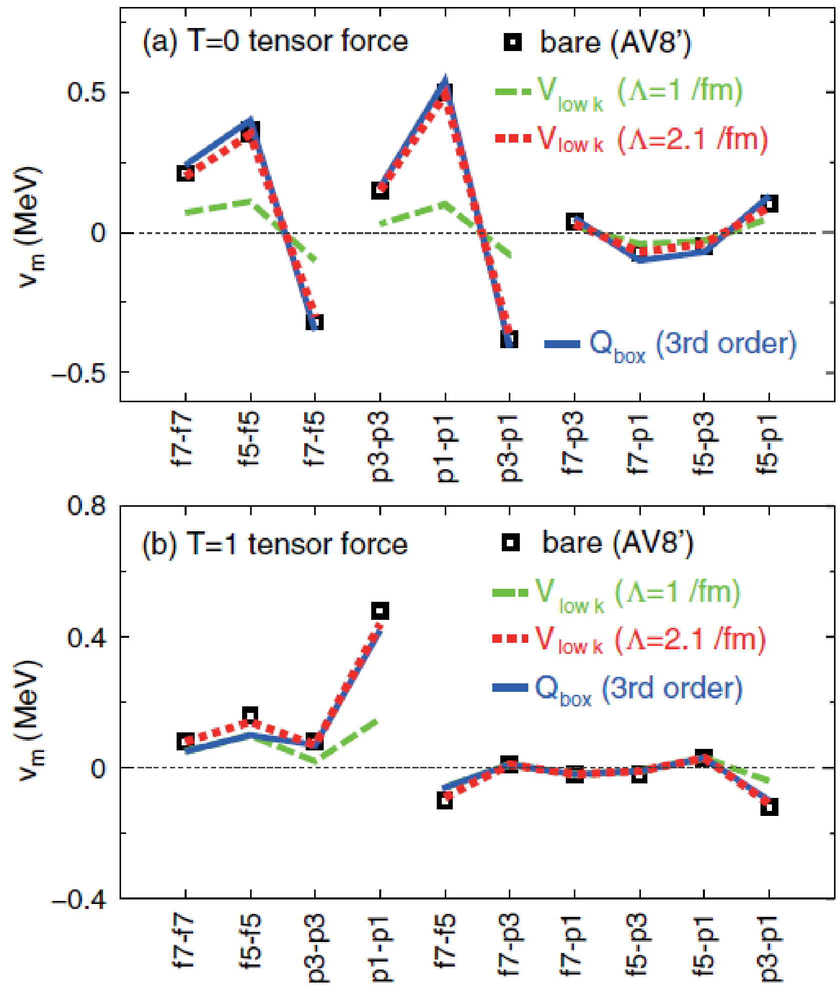


O. Sorlin and M.-G. Porquet, Prog. Part. Nucl. Phys. 61, 602 (2008).

V_{MU}: monopole-based universal interaction

- proposed for a universal shell evolution: two ingredients
  1. tensor force
  - The "bare" tensor force appears good, but it is not obvious whether it works as the effective interaction
  - From microscopic theory, the effective tensor force is almost irrelevant to the normalization procedures due to
    - short-range correlation
    - finite size of model space

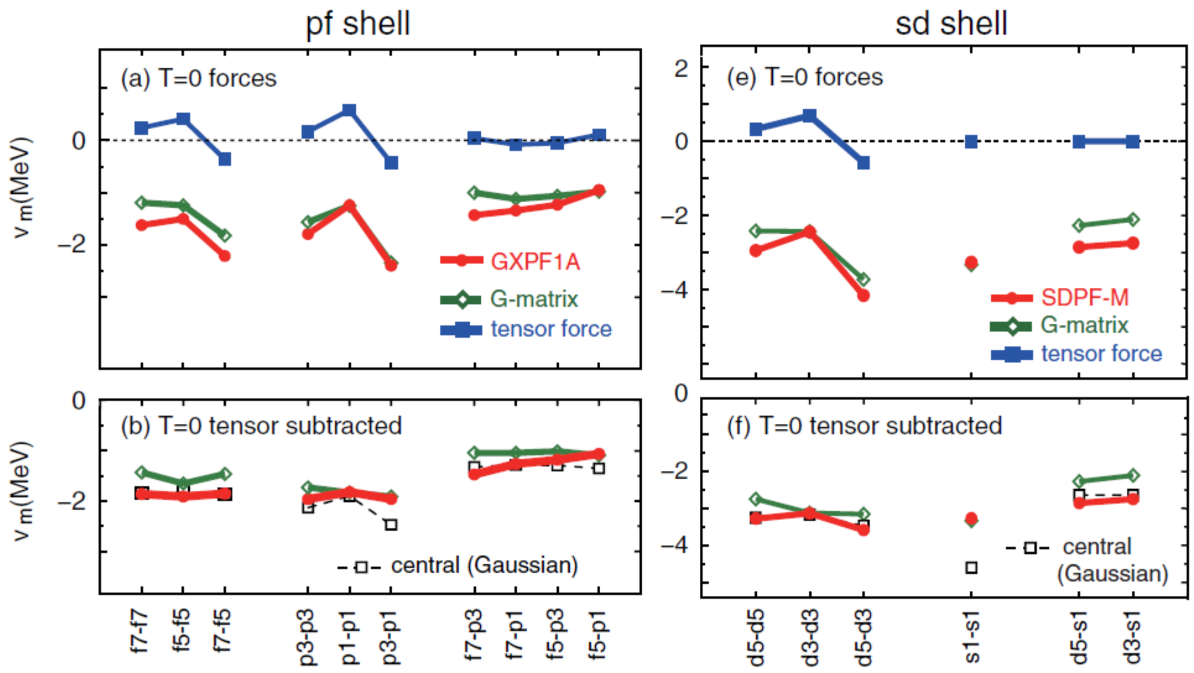
⇨ Use of π+ρ tensor force is justified by "renormalization persistency."



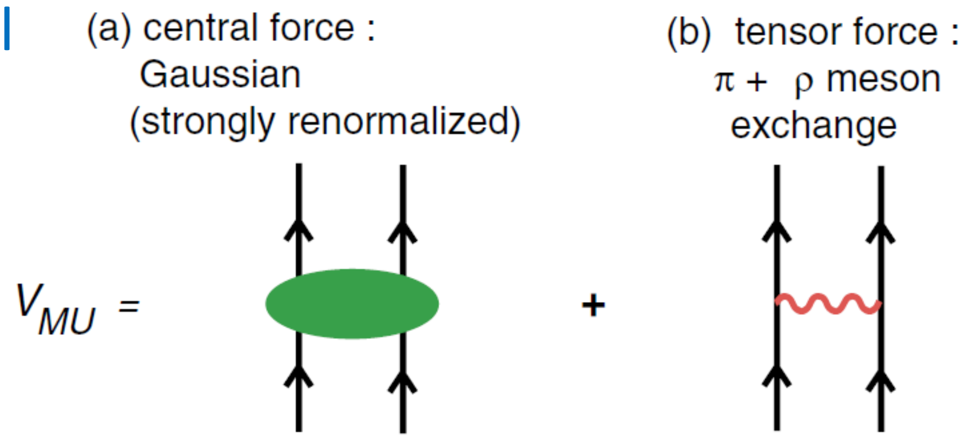
T. Otsuka et al., Phys. Rev. Lett. 104, 012501 (2010);
N. Tsunoda, T. Otsuka et al., Phys. Rev. C 84, 044322 (2011).

V_{MU}: monopole-based universal interaction

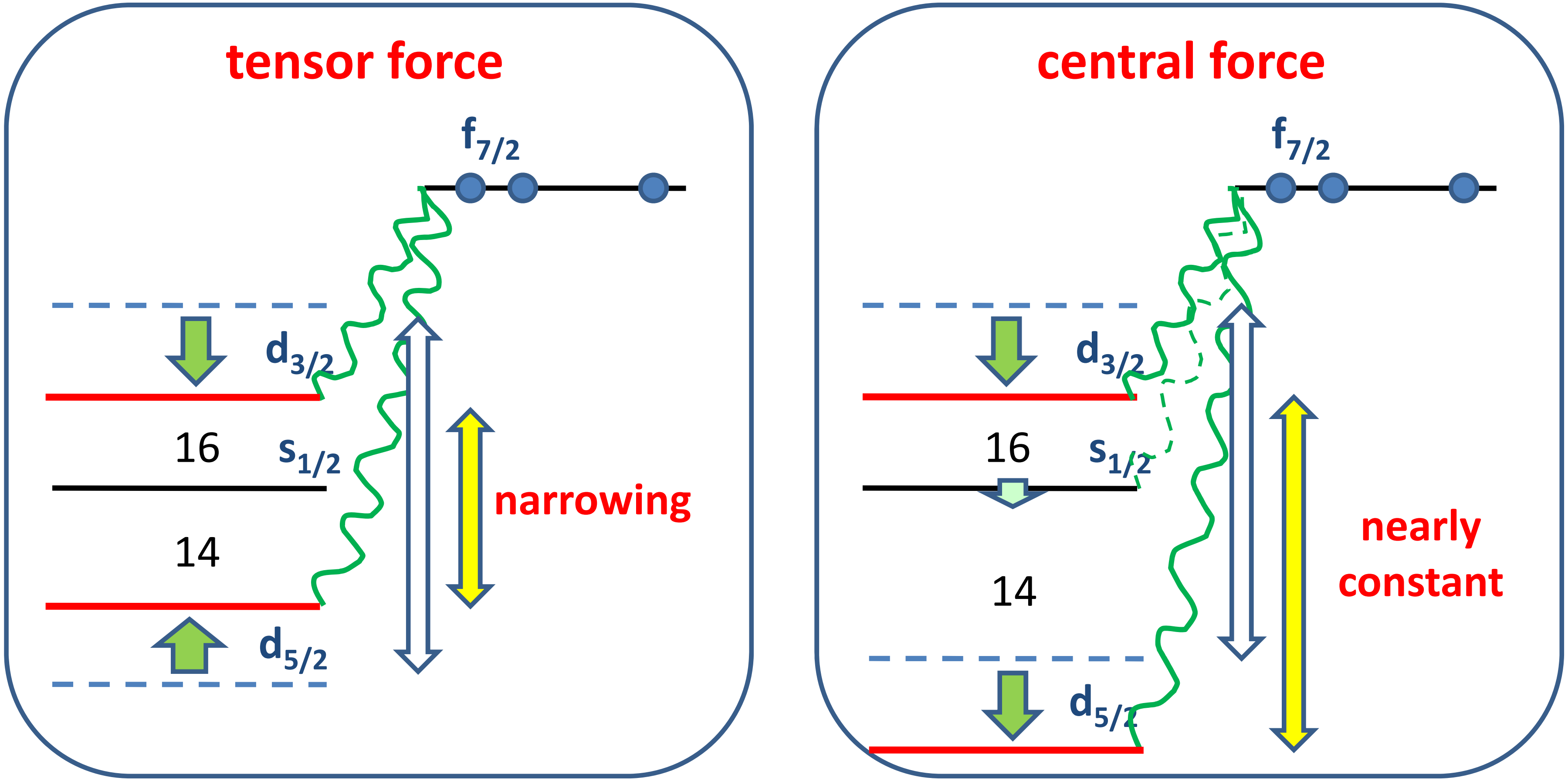
- two ingredients
  2. central force
  - phenomenological simplicity for the tensor-subtracted force



➡ proposed universal effective force:



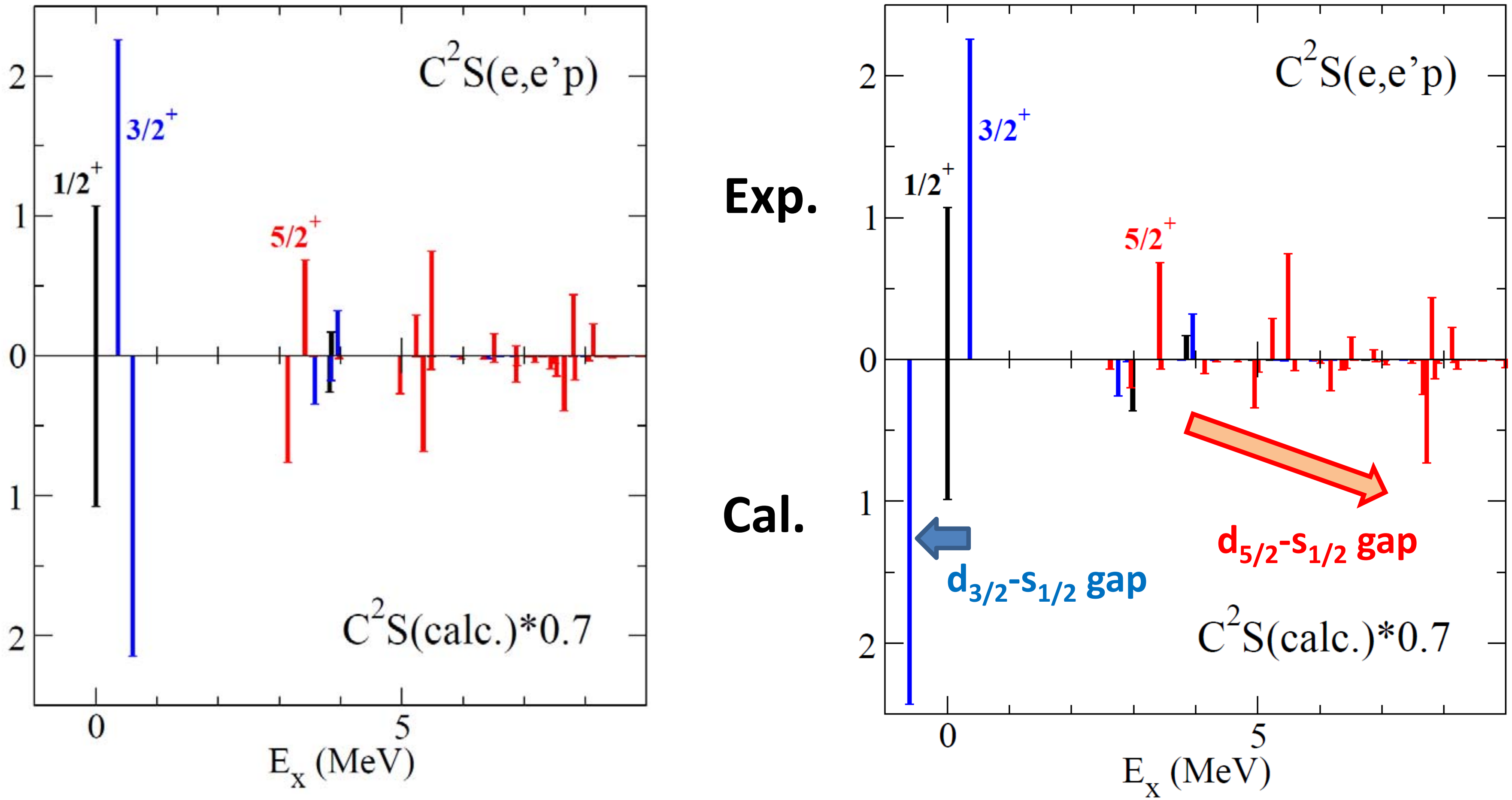
Qualitative difference between central and tensor in terms of shell evolution



- tensor: spin dependence → responsible for $l \cdot s$ term
- central: node dependence → responsible for l^2 term

Example of success of V_{MU}: ls splitting of ^{48}Ca

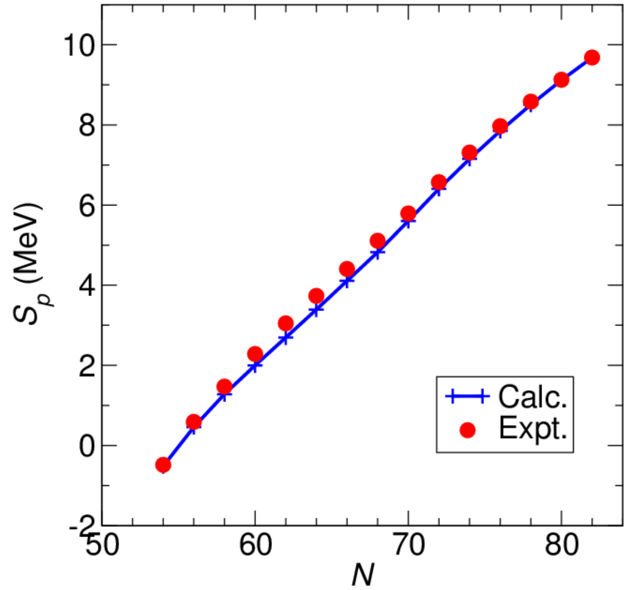
full V_{MU} interaction (w/ tensor) **w/o tensor in the cross shell**

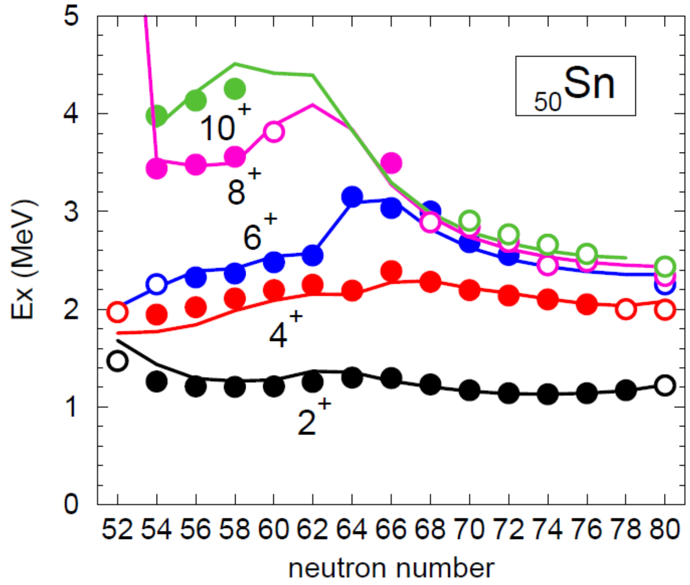


Y. Utsuno et al., Phys. Rev. C 86, 051301(R) (2012).

Some details about the interaction

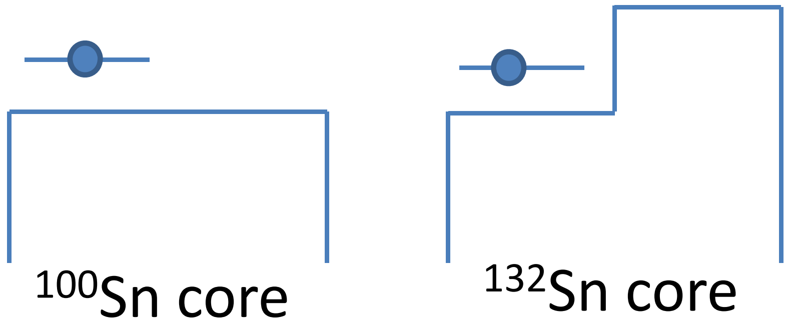
- Proton-neutron interaction
  - dominating the evolution in Sb isotopes
  - The overall strength of the central part of V_{MU} is tuned so as to reproduce the proton separation energies of Sb isotopes.
    → only one free parameter
- Neutron-neutron interaction
  - responsible for making "Sn core"
  - SNBG3 (n-n) interaction by Honma et al.
    - a semi-empirical interaction fitted to Sn isotopes





M. Honma et al., RIKEN Accel. Prog. Rep. (2012).

Proton single-particle energies



- lack of data on SPE on top of ^{100}Sn (except 1st excited state in ^{101}Sn)
- reference states: ^{133}Sb (N=82)
  - single-particle(-like) states below 3 MeV because the 1st excited state in ^{132}Sn is as high as 4 MeV.
- Single-particle levels of ^{101}Sb are thus a prediction.

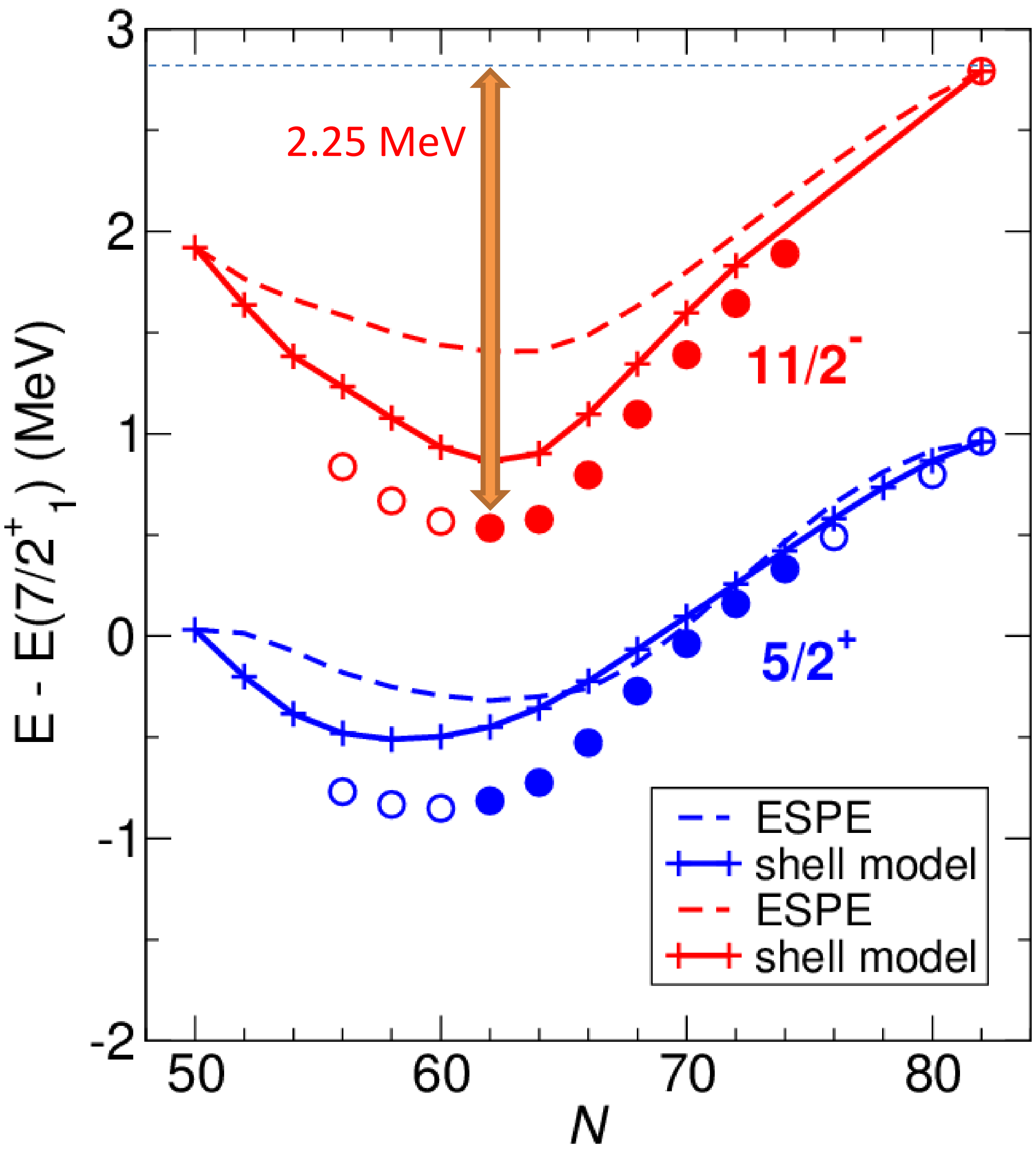
Proton single-particle energies on top of ^{132}Sn core

level	7/2+	5/2+	3/2+	11/2-	1/2+
Ex. (MeV)	0	0.962	2.440	2.791	2.990

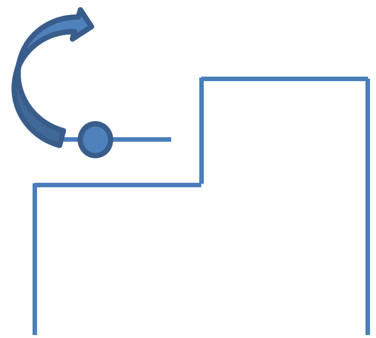
Experimental value except $1/2^+$ taken from systematics of W. J. Baldridge et al.

Evolution of the energy levels

- $11/2^-_1$ and $5/2^+_1$ levels measured from $7/2^+_1$
  - full shell-model results vs. estimate from effective single-particle energies (ESPE)
  - Non-monotonic evolution is reproduced well.
  - Most of the decrease of 11/2- level (2.25 MeV from N=82 to 62) is explained with the shell model, but is not with the ESPE.



Estimate from ESPE



- Definition of ESPE
  - For an assumed core $|\mathrm{core}\rangle$, ESPE of the orbit *j* is defined as

    $$\tilde{\varepsilon}_i = \langle \mathrm{core} | a_i H a_i^\dagger | \mathrm{core} \rangle - \langle \mathrm{core} | H | \mathrm{core} \rangle$$

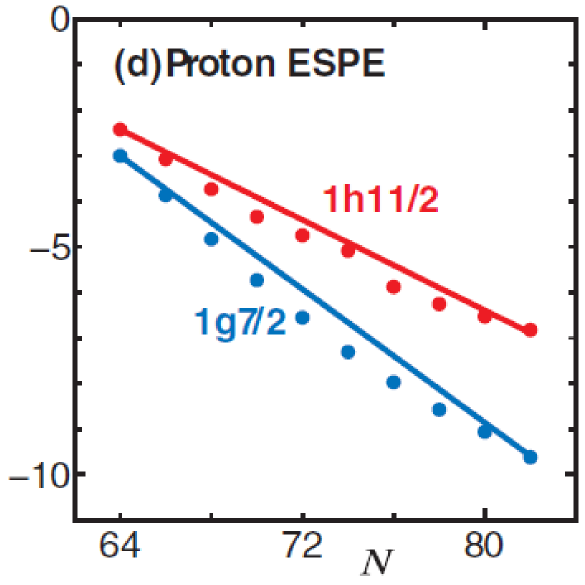
    $$= \varepsilon_i + \sum_{j:occupied} v_{i,j} n_j$$

  - Two ways of assumed core (different in terms of n_j)
    1. naïve filling configuration (ESPE1)
    2. calculated ground state of Sn isotopes (ESPE2)

Evolution of the $11/2^{-}$–$7/2^{+}$ spacing

- Consider the change from N=64 (to 82): 2.215 MeV in expt.
  - ESPE1: no correlation
    - (6, 8, 0, 0, 0) for occupation in ($d_{5/2}$, $g_{7/2}$, $h_{11/2}$, $s_{1/2}$, $d_{3/2}$) $n(j_<)-n(j_>)=2$
    - tensor only: 1.93 MeV
    - central + ls + tensor: 1.93 MeV
  - ESPE2: n-n correlation only
    - (4.76, 5.91, 1.74, 0.69, 0.91) $n(j_<)-n(j_>)=0.32$
    - tensor only: 1.21 MeV
    - central + ls + tensor: 1.38 MeV
  - shell-model calculation: full correlation
    - central + ls + tensor: 1.89 MeV

~500 keV is accounted for by the p-n correlation

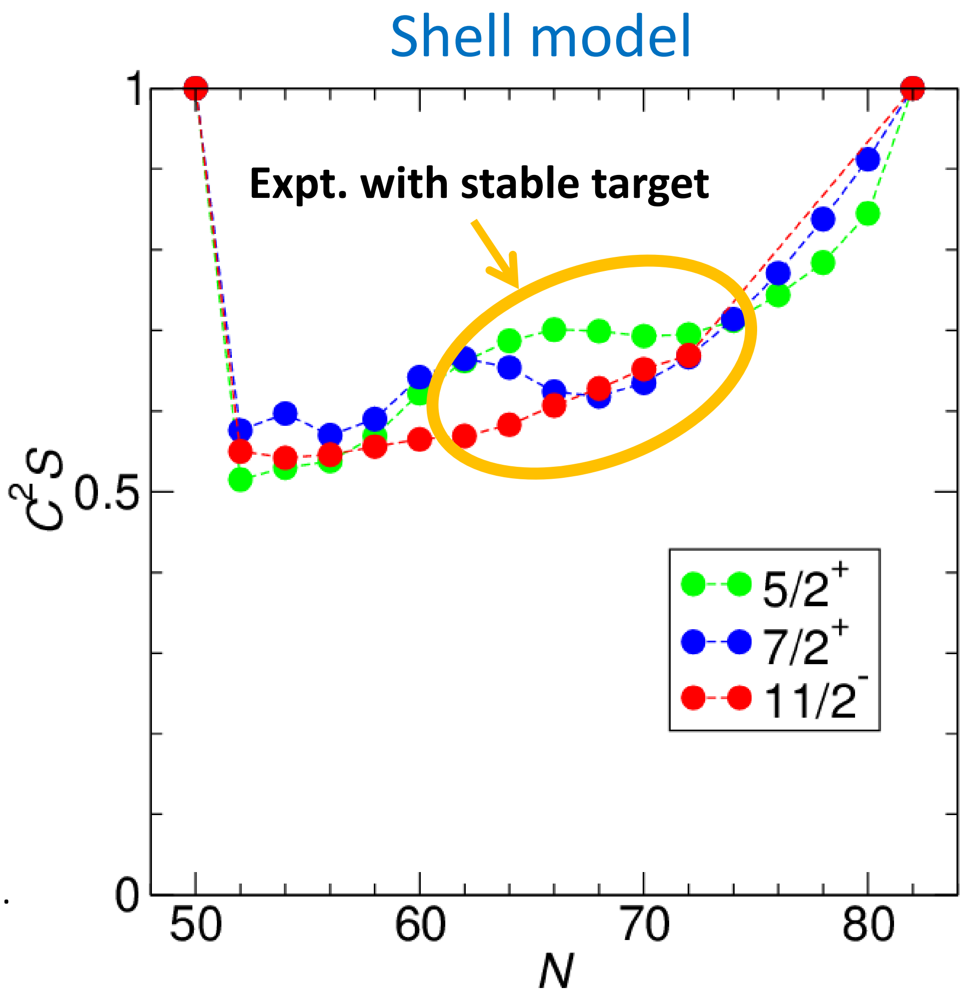


T. Otsuka et al., Phys. Rev. Lett. 95, 232502 (2005).

Single-particle strength

N	7/2$^+$		11/2$^-$	
	Conjeaud et al.	Schiffer et al.	Conjeaud et al.	Schiffer et al.
62	0.94	0.99	0.4	0.84
64	0.85	1.10		0.93
66	0.81	0.95	0.53	0.97
68	0.79	0.88	0.63	0.99
70	0.7	1.13	0.63	1.12
72	0.84	0.98	0.49	1.00
74	0.74	1.00	0.75	1.12

(^{3}He, d): M. Conjeaud et al., Nucl. Phys. A 117, 449 (1968).
(α, t): J. P. Schiffer et al., Phys. Rev. Lett. 92, 162501 (2004).



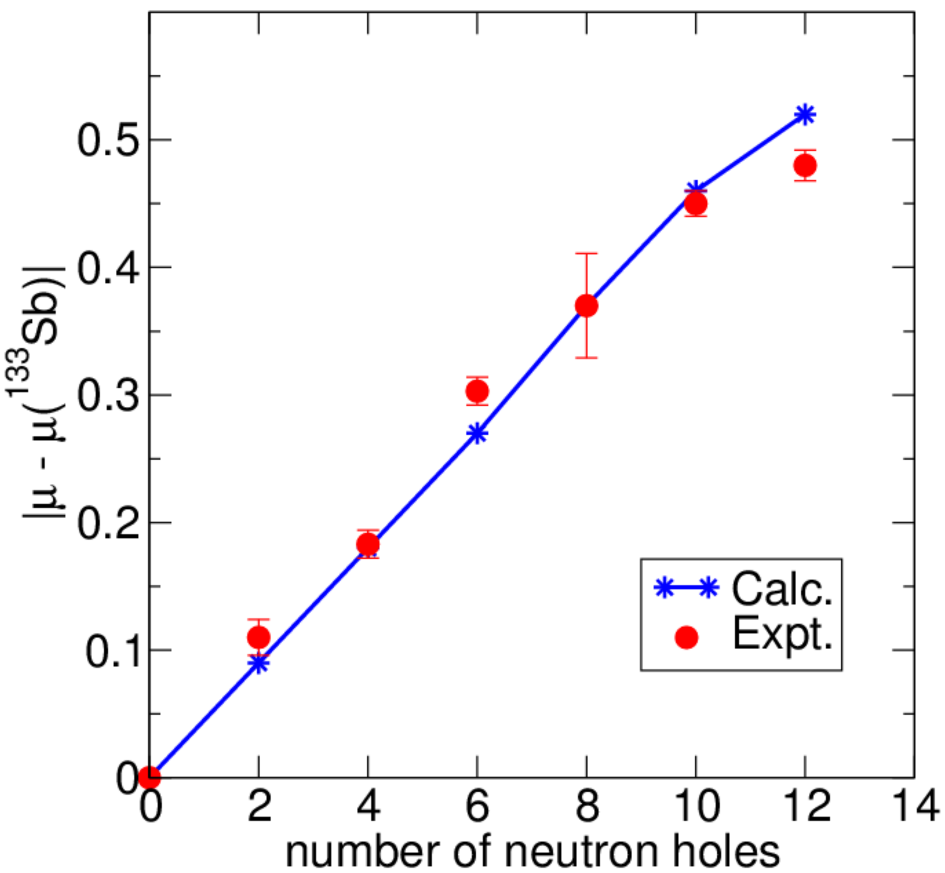
- Relative quantities are very stable from N=62 to 74.
- the absolute strength: should be large or small?

Evolution of μ from N=70 to 82

- μ (magnetic moment): very good probe to examine the single-particle property
  - Configuration mixing should change μ from the single-particle value.
  - Particle-vibration coupling

$$\mu(j) = \left(1 - \frac{3}{j(j+1)} \frac{\alpha^2}{1+\alpha^2}\right)\mu_{\rm sp}(j) + \frac{3}{2(j+1)} \frac{\alpha^2}{1+\alpha^2} \mu(2_1^+),$$

- Excellent agreement with experiment indicating the increase of mixing



effective nucleon *g* factor adopted:
isovector shift g_l(IV)=0.1, spin quenching factor 0.6

$\mu(^{133}Sb)$=2.97 (calc.) vs. 3.00(1) (expt.)

How about μ of $11/2^-$?

- Only ^{115,117}Sb are available experimentally.
- Mixing almost always reduces μ of $11/2^-$ because single-particle value 7.18 is very large (due to $j_>$ with high l).
  - For instance, μ of $\pi(d_{5/2})*3^-$ is 3.27 using the shell-model wave function for 3^-.
- Calculated value is reduced from the single-particle value to some extent and agrees well with experiment: Considerable configuration mixing should occur.

μ of the $11/2^-$ states

	Expt.	Calc.
^{115}Sb	5.53(8)	5.53
^{117}Sb	5.35(9)	5.63

Expt.: taken from ENSDF

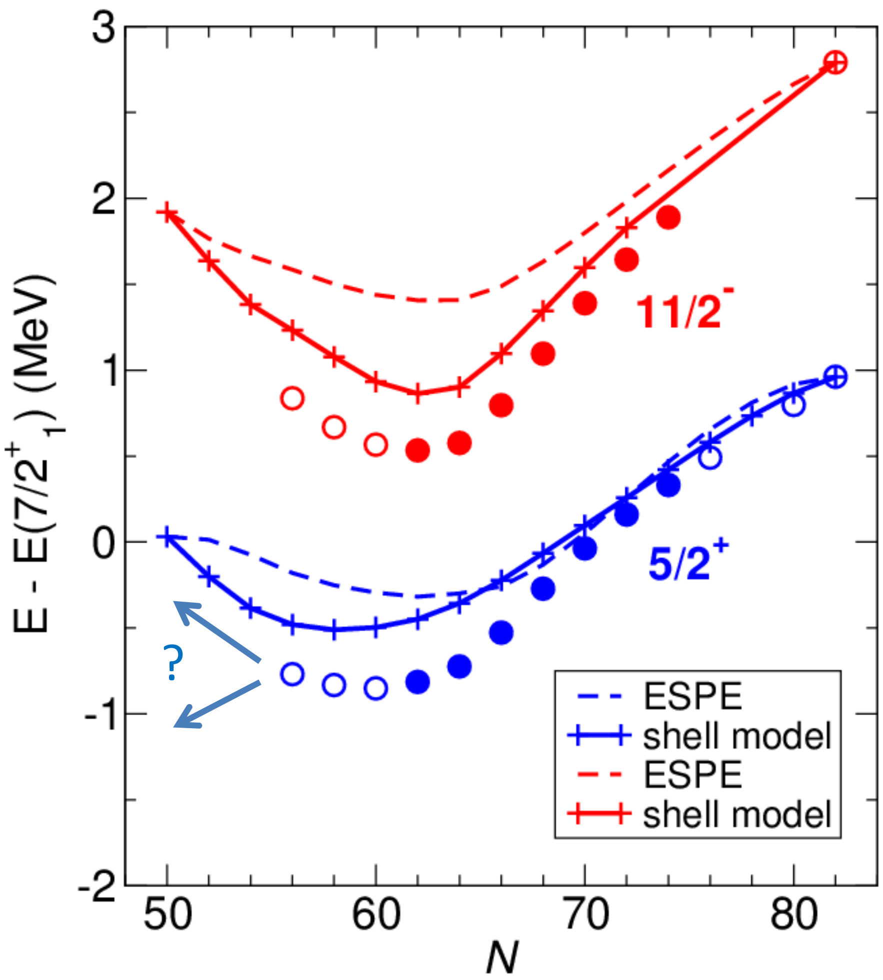
effective nucleon *g* factor adopted:

isovector shift g_l(IV)=0.1,

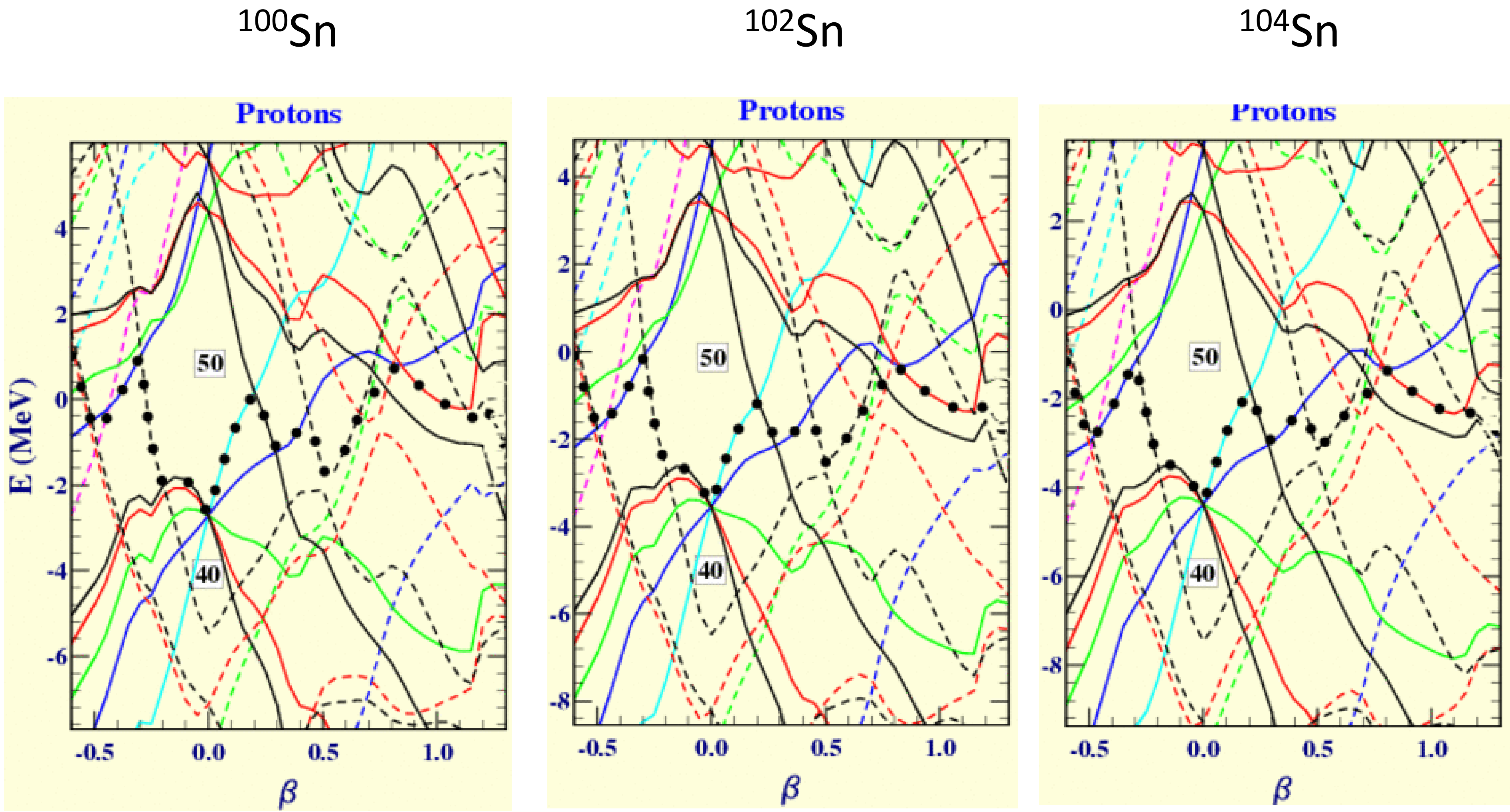
spin quenching factor 0.6

Possible experiment at JAEA Tandem

- $5/2^+$: goes up or down toward ^{101}Sb?
  - SPE due to the Gogny D1S does not show the turning.
- Previous α decay experiment of ^{109}I (C. Mazzaocchi et al., Phys. Rev. Lett. 98, 212501 (2007).) did not observe a γ ray.
  - severe competition with proton decay?



Proton SPE due to Gogny DIS



Summary

- The evolution of the low-lying energy levels in Sb isotopes is studied with large-scale shell-model calculations.
  - shell evolution vs. correlation
  - universal treatment of the p-n interaction using V_{MU}: most important part for the shell evolution
- Experimental energy levels of $11/2^-$ and $5/2^+$ measured from $7/2^+$ are reproduced satisfactorily.
  - The evolution of SPE mainly due to the tensor force accounts for them partially, but the correlation is important from a quantitative point of view.
  - The spectroscopic factors around the mid-shell are almost half a single-particle limit, which is supported by the evolution of the magnetic moment.
  - It is expected that predicted levels are measured at JAEA Tandem under the collaboration of JAEA, York, and Oak Ridge.