JICFuS

HPCI project field 5
"The origin of matter and the universe"

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Large-scale shell-model calculations of nuclei around N=80

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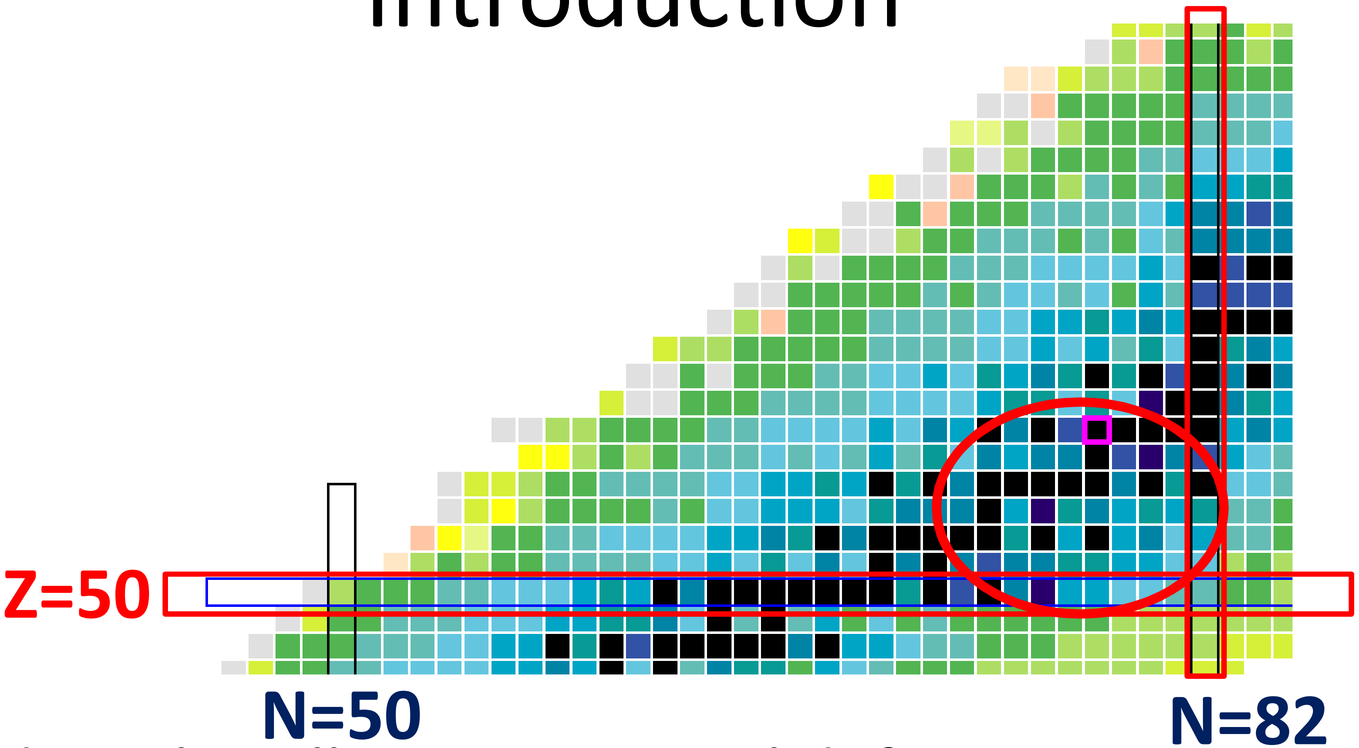
Introduction



- Quadrupole collectivity, triaxial deformation, mixed symmetry state, E(5) critical point symmetry, scissors mode, isomers, ...
- Shell-model study is a challenge in this region due to huge configuration space

E. Teruya *et al.,* PRC 92, 034320 (2015), C. Qi *et al.,* PRC 86 044323 (2014), C. Bianco *et al.,* PRC 85, 034332 (2012), K. Sieja *et al*. PRC 80, 054311 (2009), B. A. Brown et al., PRC 71, 044317 (2005) ...

Two tools for shell-model calculations

$3\text{x}10^{14}$ M-scheme dim. for ^{140}Ho

- Large-scale shell model calculations (LSSM)
  - conventional Lanczos method in parallel computation
  - Max: ~O(10^{10}) M-scheme dimension

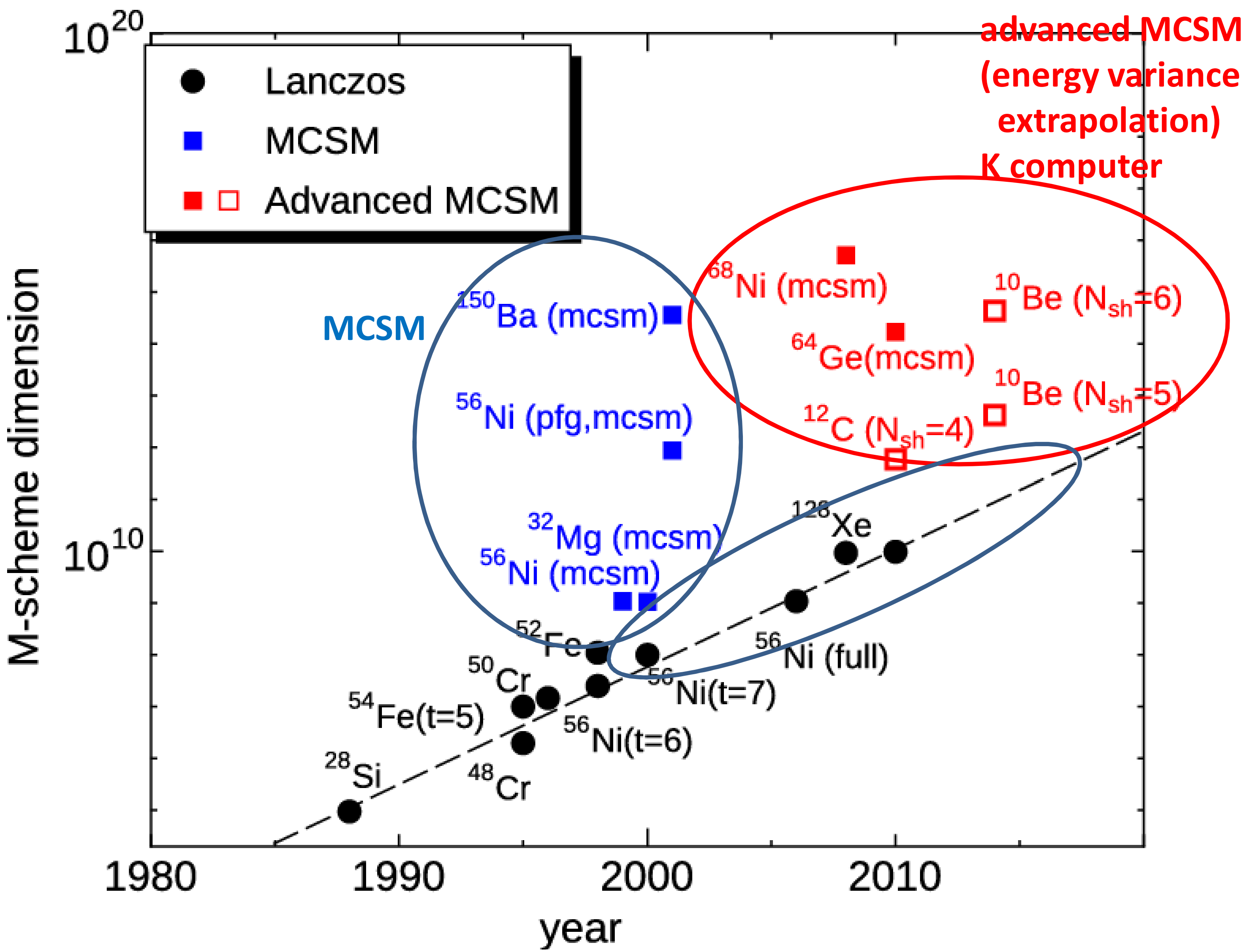
- advanced Monte Carlo shell model (MCSM)
  - a tool to go beyond Lanczos limit
  - variation after superposition of *J*-projected Slater determinants
  - extrapolation utilizing energy variance

$$|\Psi^{IM\pi}(N_b)\rangle = \sum_{d=1}^{N_b} f^{(d)} \sum_{K=-I}^{I} g_K^{(d)} \; \hat{P}^{\pi} \hat{P}_{MK}^{I} \, |\varphi(D^{(d)})\rangle$$

MCSM basis dimension ≈ 100

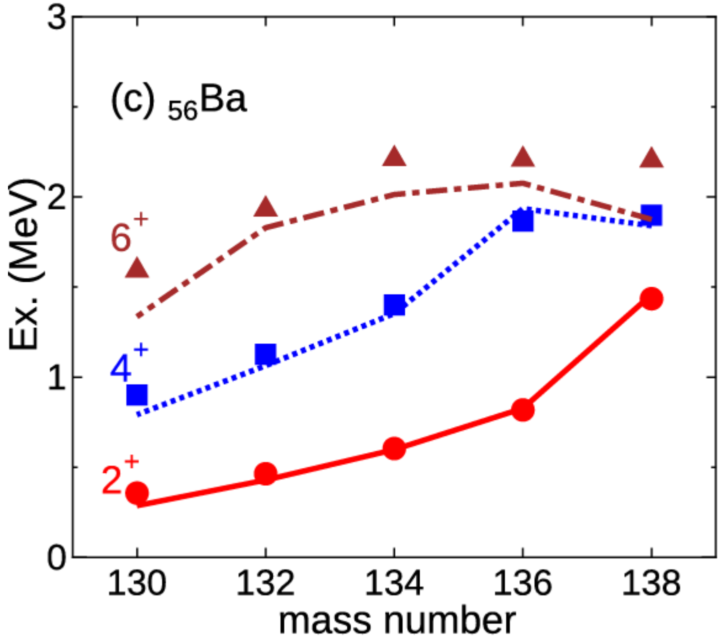
superposition — projection onto good quantum numbers — optimized Slater determinant

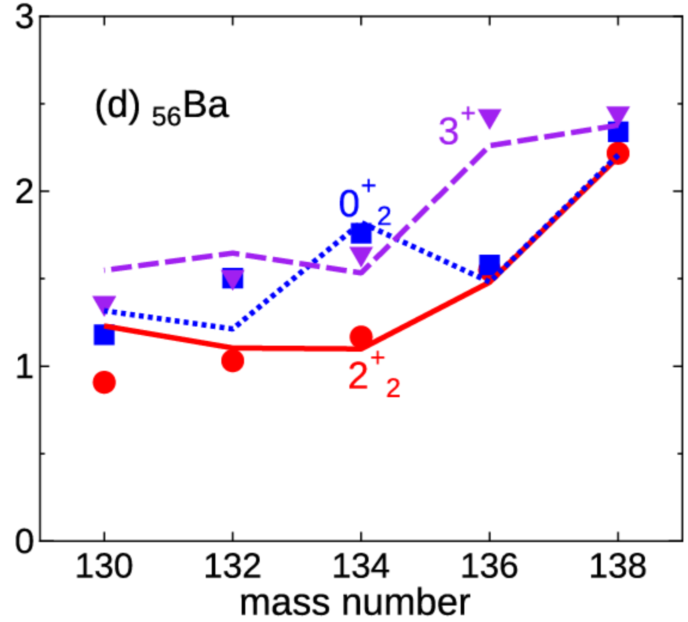
M-scheme dimension vs. year



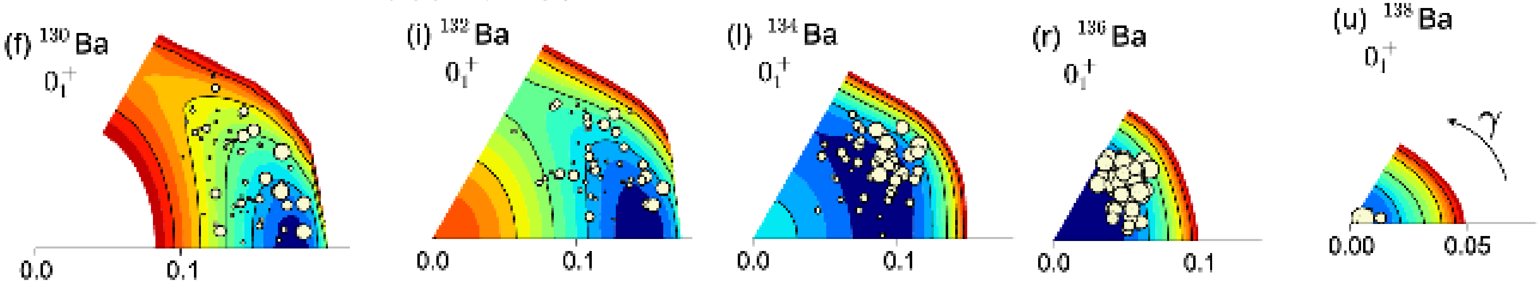
symbol: exp.
line : theory

Shape evolution of Ba isotopes with Monte Calo Shell Model and P+QQ int.





model space: 50<N,Z<82



PES is calculated by Q-constraint HFB calc.

Monte Carlo Shell Model wave function

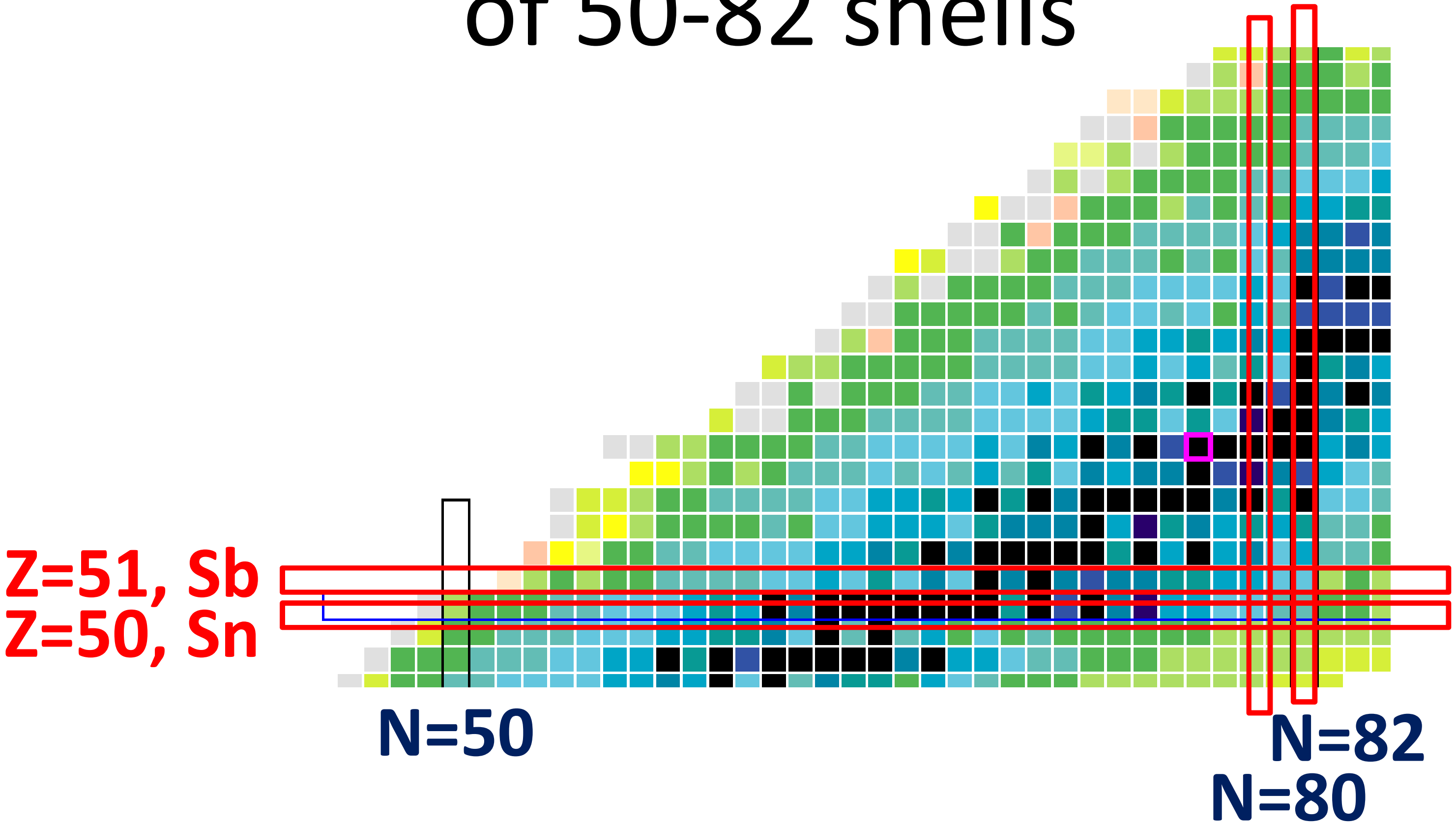
$$|\Psi\rangle = \sum_{k=1}^{N_{MCSM}\sim 100} f_k P^{J,\pi} |\phi_k\rangle$$

Location of circle : quadrupole deformation of $|\phi_k\rangle$

Area of circle : overlap probability $\frac{1}{N_k}\left|\langle\Psi|P^{J,\pi}|\phi_k\rangle\right|^2$

N. Shimizu, T. Otsuka, T. Mizusaki, Y. Utsuno, M. Honma, and Y. Tsunoda, submitted

Investigate realistic effective interaction
Towards unified description
of 50-82 shells



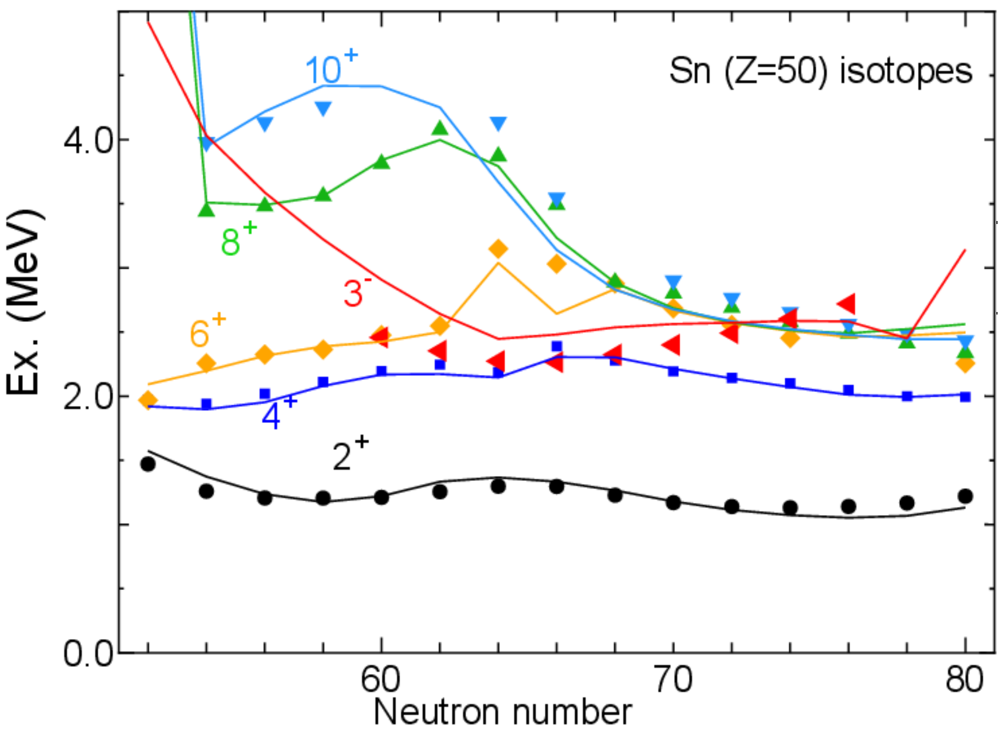
M.Honma *et al.*, RIKEN Accel. Prog. Rep. 45 (2012) 35

SNBG3 interaction

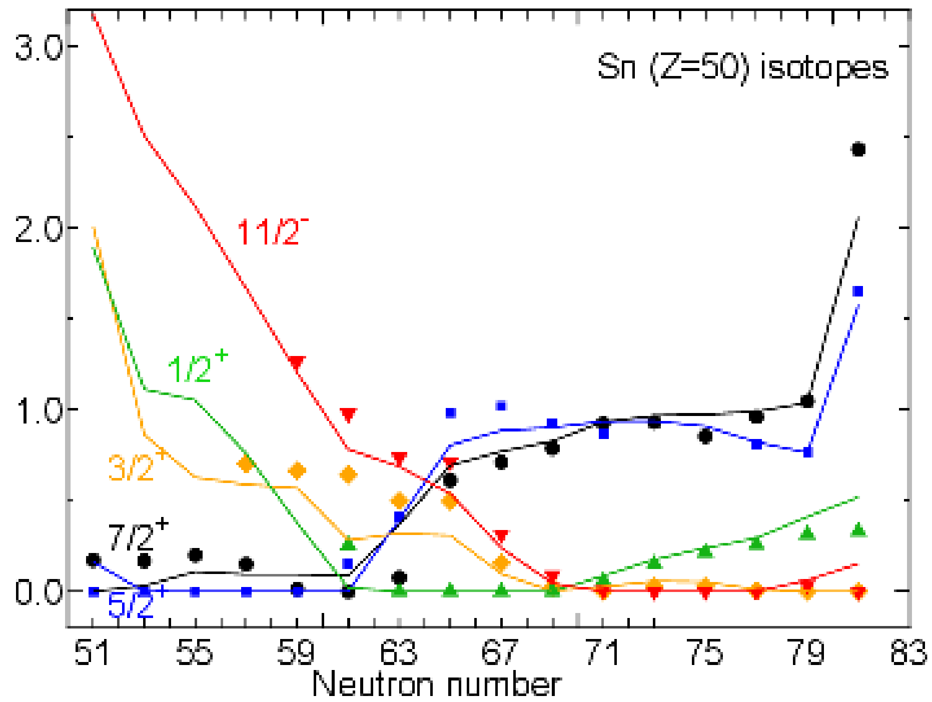
Realistic interaction for 50<N<82 Sn isotopes

- start with N3LO + G-matrix
- chi-square fit with linear-combination method for ~300 experimental data including 3^- states

Even nuclei

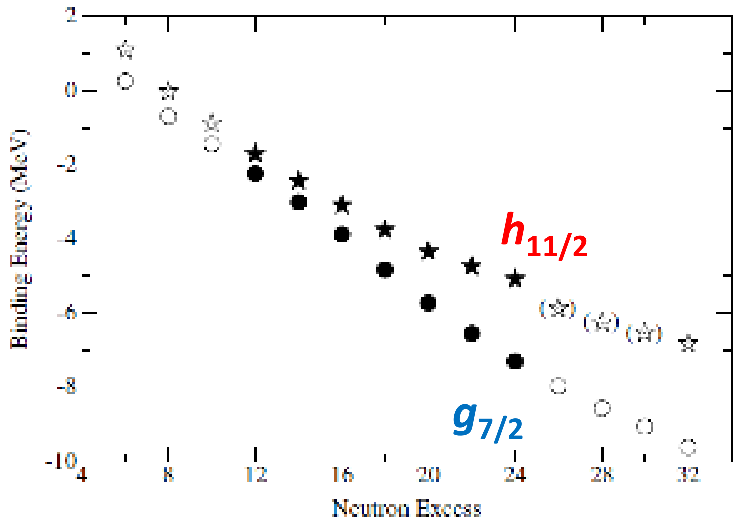


Odd nuclei



Shell evolution in Sb isotopes

- Shell evolution
  - Important not only in single-particle energy levels but also in collectivity
- How to deduce?
  - Follow the change of "single-particle energies" along a long isotope chain.
- Purity of single-particle (SP) states
  - Controversial levels in Sb (Z=51) isotopes
    - SP (Schiffer et al., 2004) or coupling to collective (Sorlin and Porquet, 2008)
    - Absolute values of C^2S: ambiguous



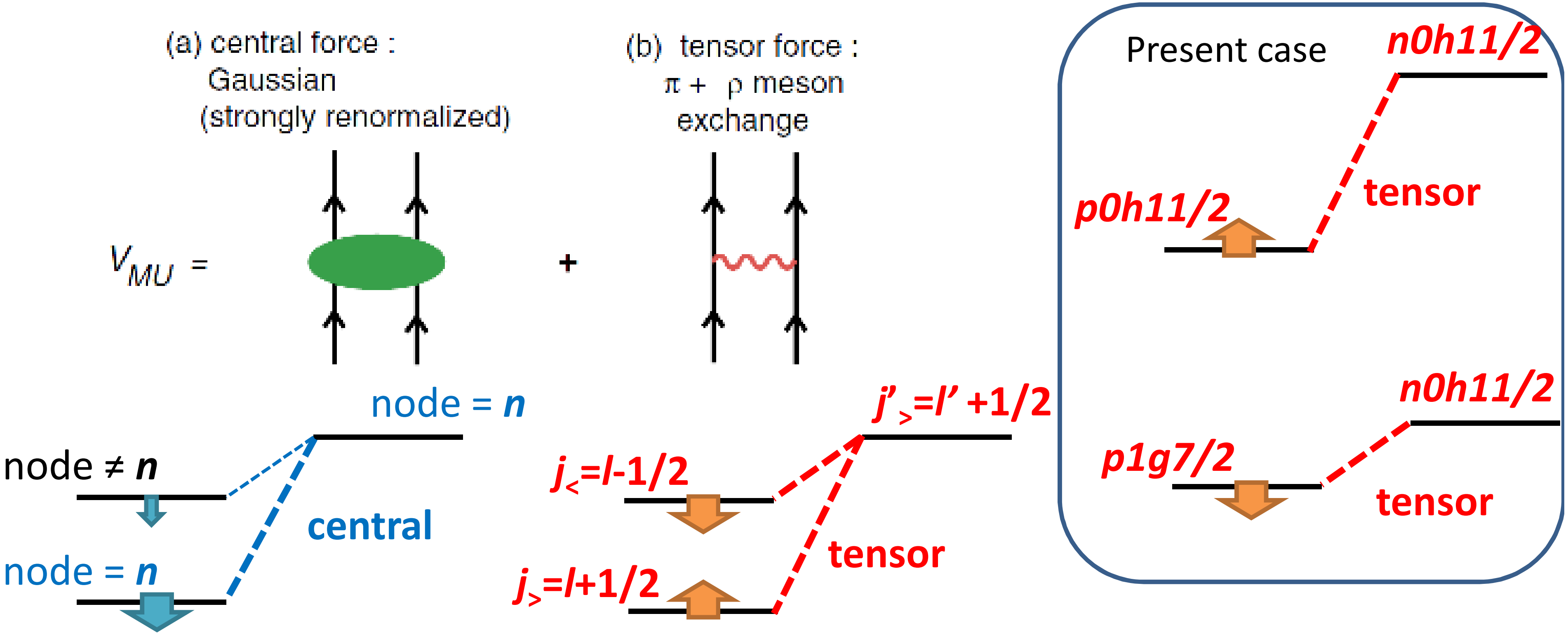
J. P. Schiffer et al., Phys. Rev. Lett. 92, 162501 (2004).

Many-body calculations with a suitable shell-evolution mechanism are needed.

Two major sources of evolution in *p*-n channel

For a review of shell-evolution mechanism, see T. Otsuka, Phys. Scr. T152, 014007 (2013).

- Central and tensor forces



known for several decades

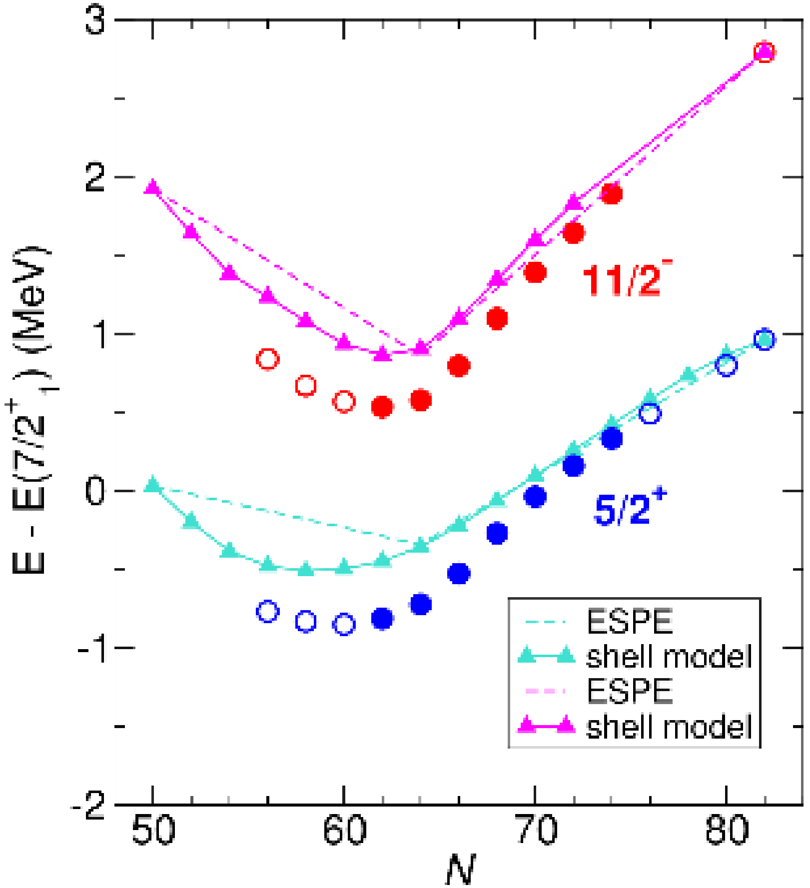
known for a decade: Otsuka mechanism (2005)

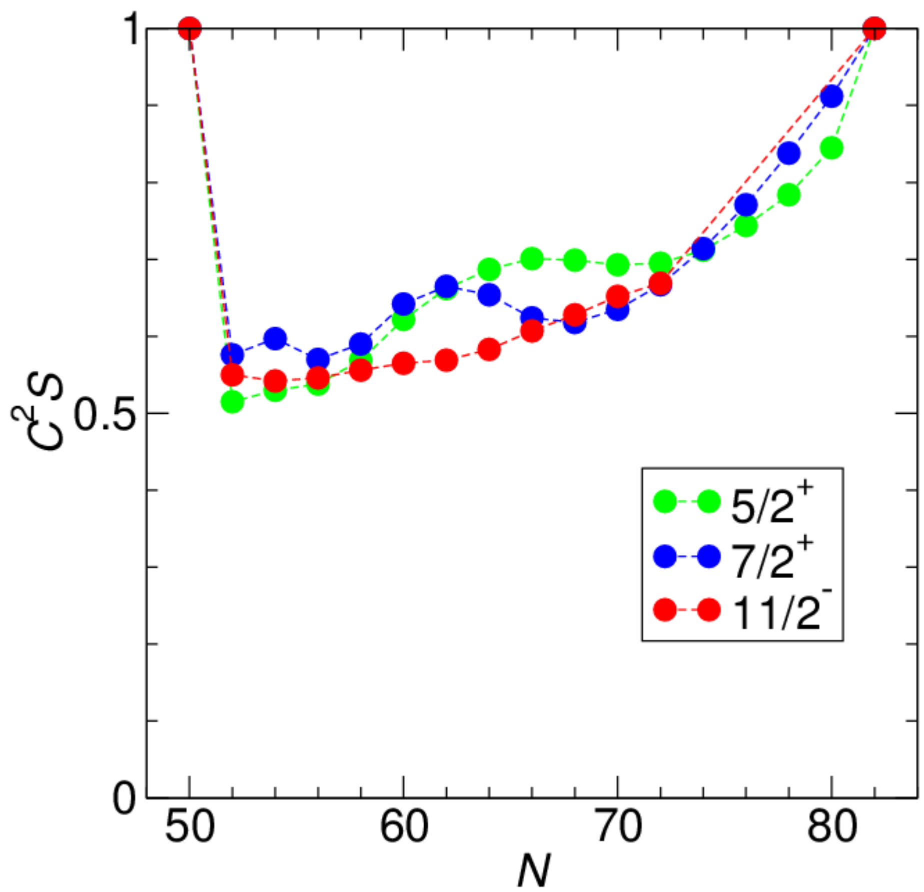
- Monopole-based universal interaction V_{MU} (Otsuka et al., 2010)
  – Quantitative implementation of this concept on a microscopic basis of “Renormalization Persistency” (N. Tsunoda et al., 2011)

Sb (*Z*=51) isotopes

Y. Utsuno *et al.*, in preparation

- Shell-model calculation in the 50 ≤ *N*(*Z*) ≤ 82 space
  - *n*-*n* interaction: semi-empirical SNBG3 by Honma et al. (good fit including 3^-)
  - *p*-*n* interaction: V_{MU} with a scaling factor 0.84 for the central (binding energy)

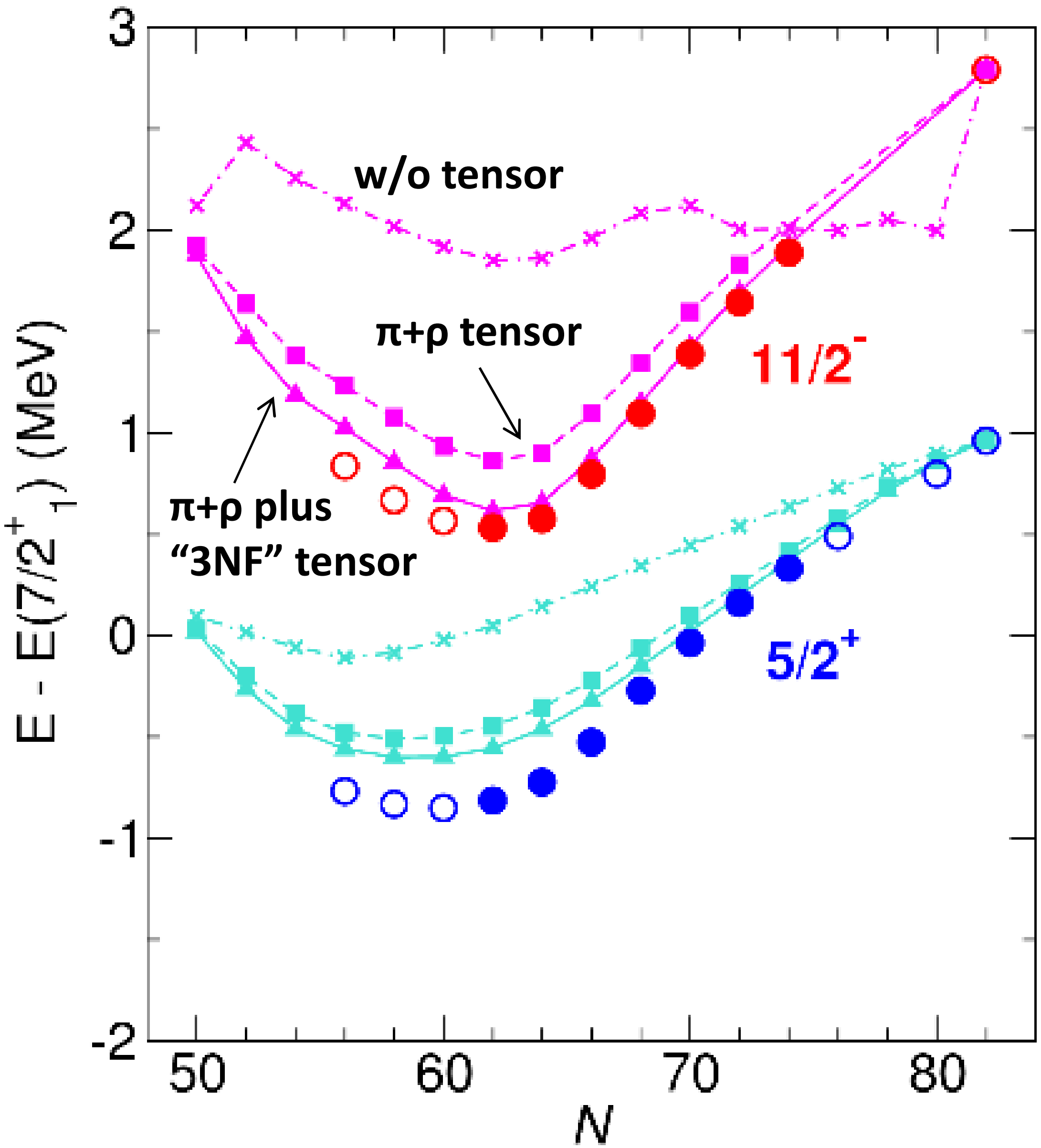




Y. Utsuno *et al.*, in preparation

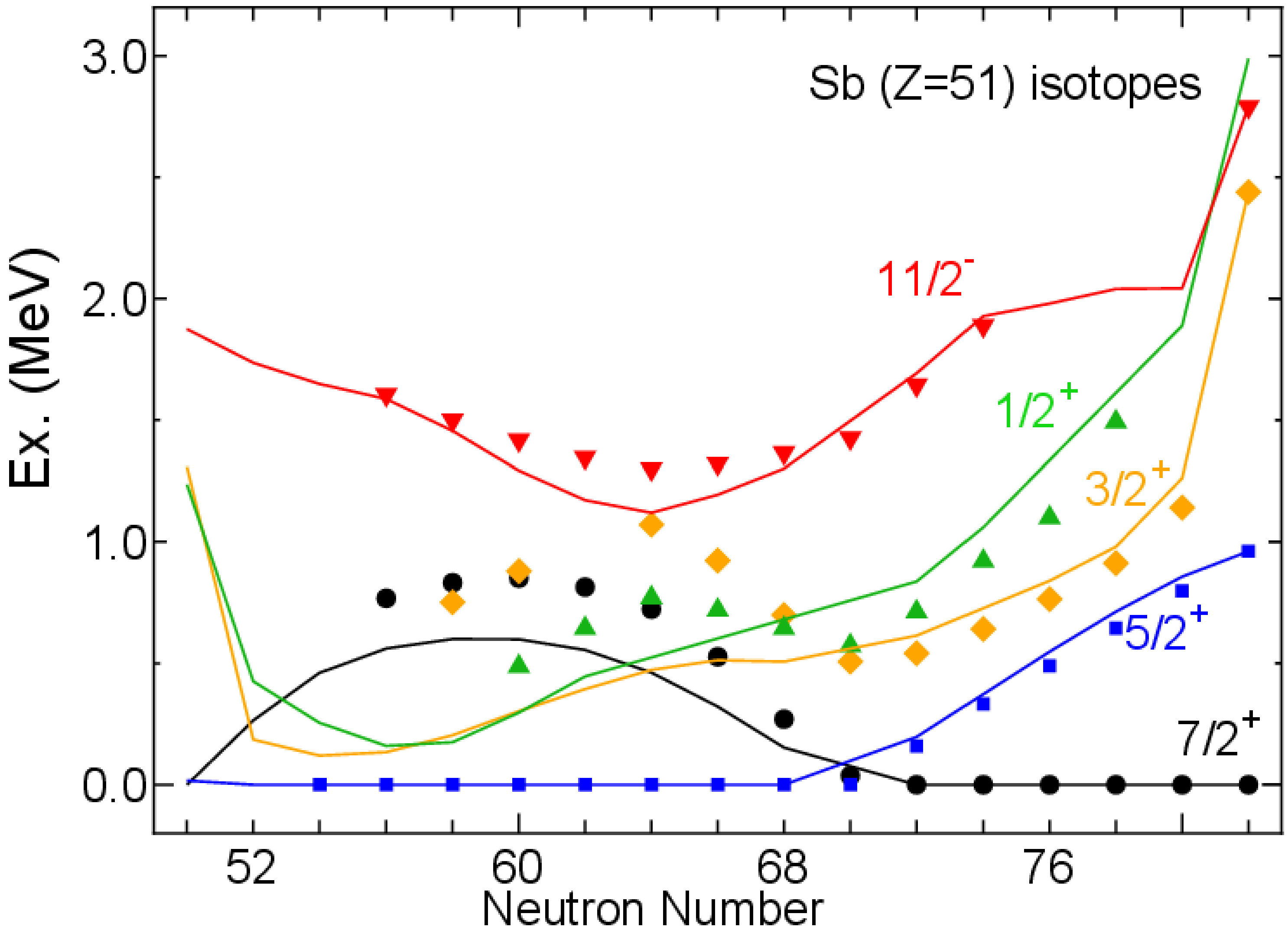
Importance of the tensor force

- Without tensor
  - $11/2^- \approx 2$ MeV
- 3NF effect
  - enhances effective *T*=0 tensor force (Kohno, 2013).
  - Almost perfect agreement with experiment

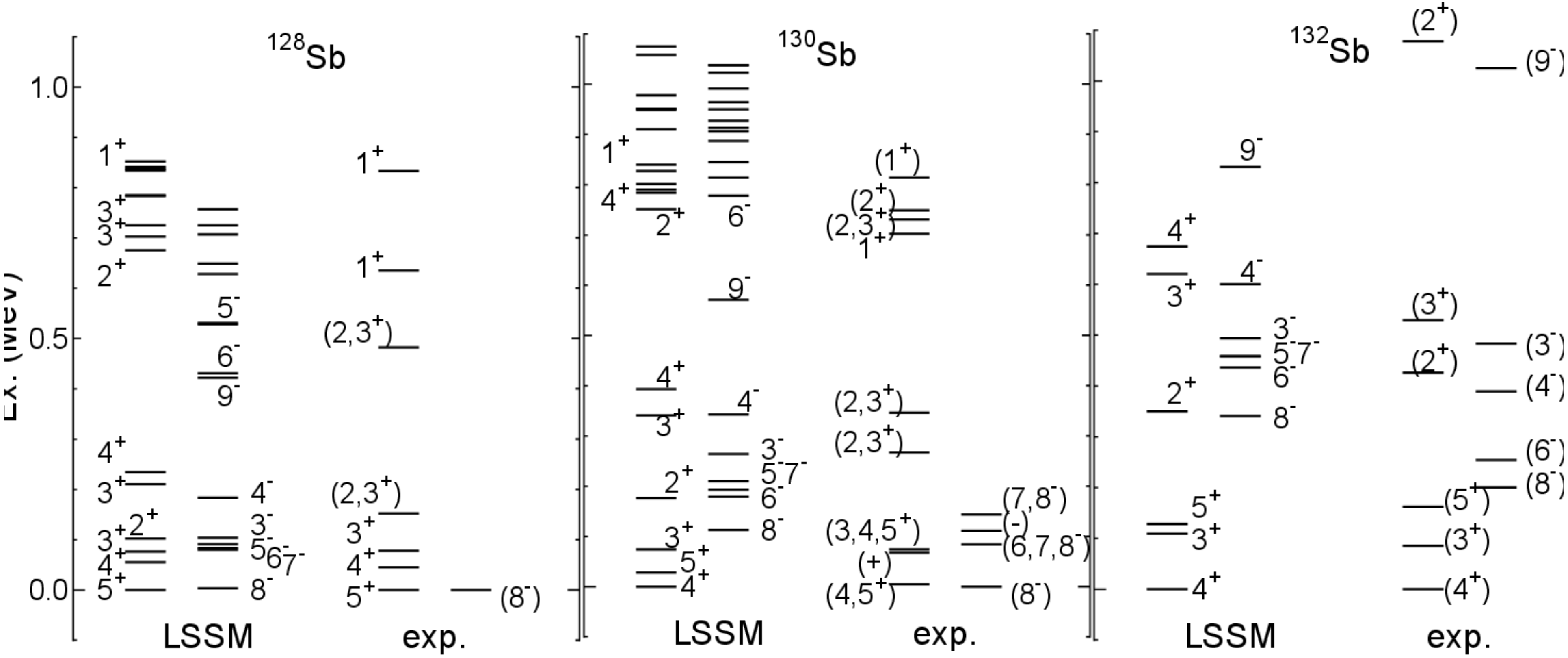


Sb isotopes

Excitation energies



Sb isotopes (odd-odd nuclei)



Reasonable description of low-lying states

valid proton-neutron interaction (VMU)

Microscopic effective int.

SN100PN interaction

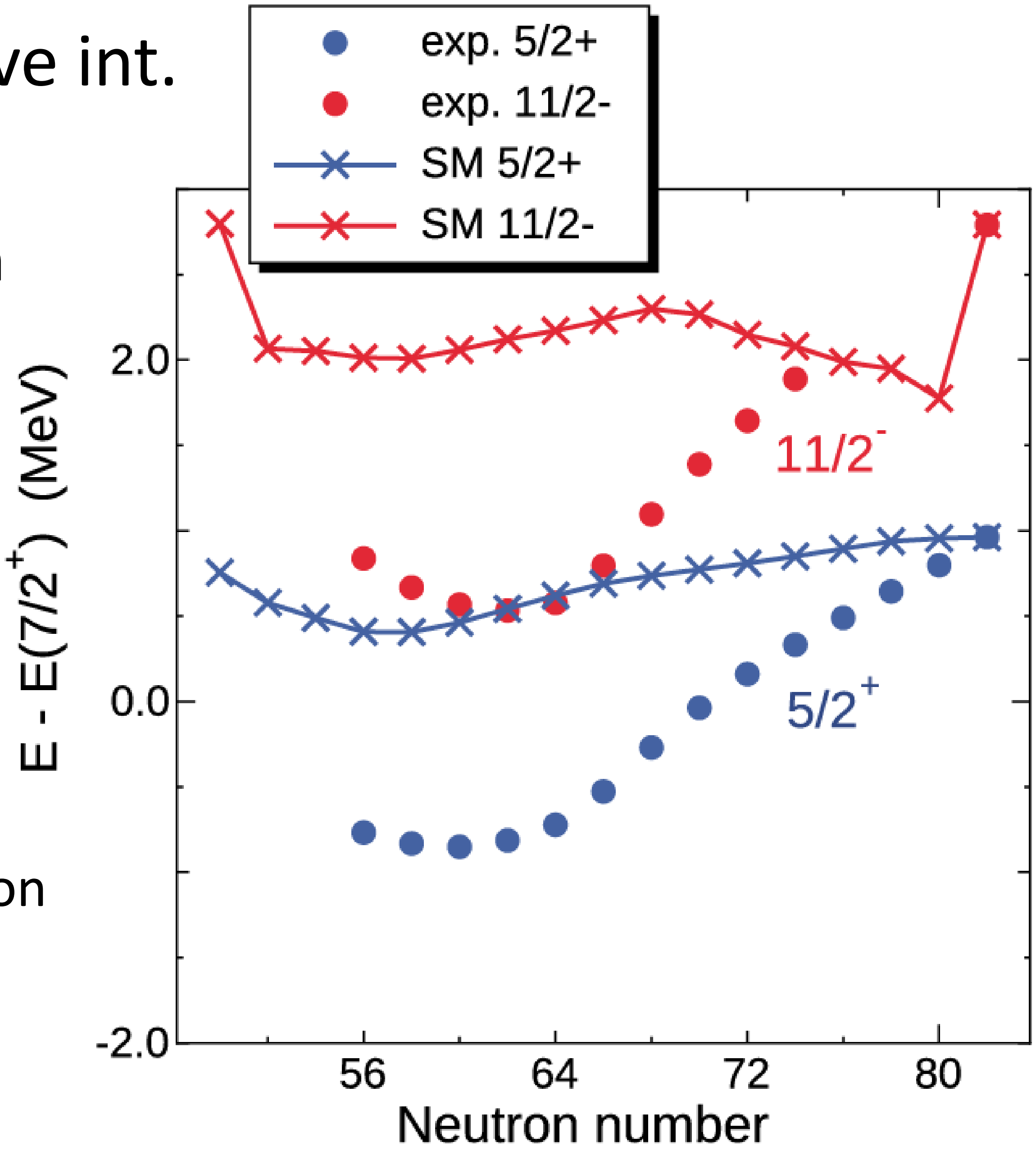
CD-Bonn + G-matrix

+ 3rd order Q-box

successful description for even-even nuclei around ^{132}Sn

... failed in the description of Sb isotopes.

What happens?

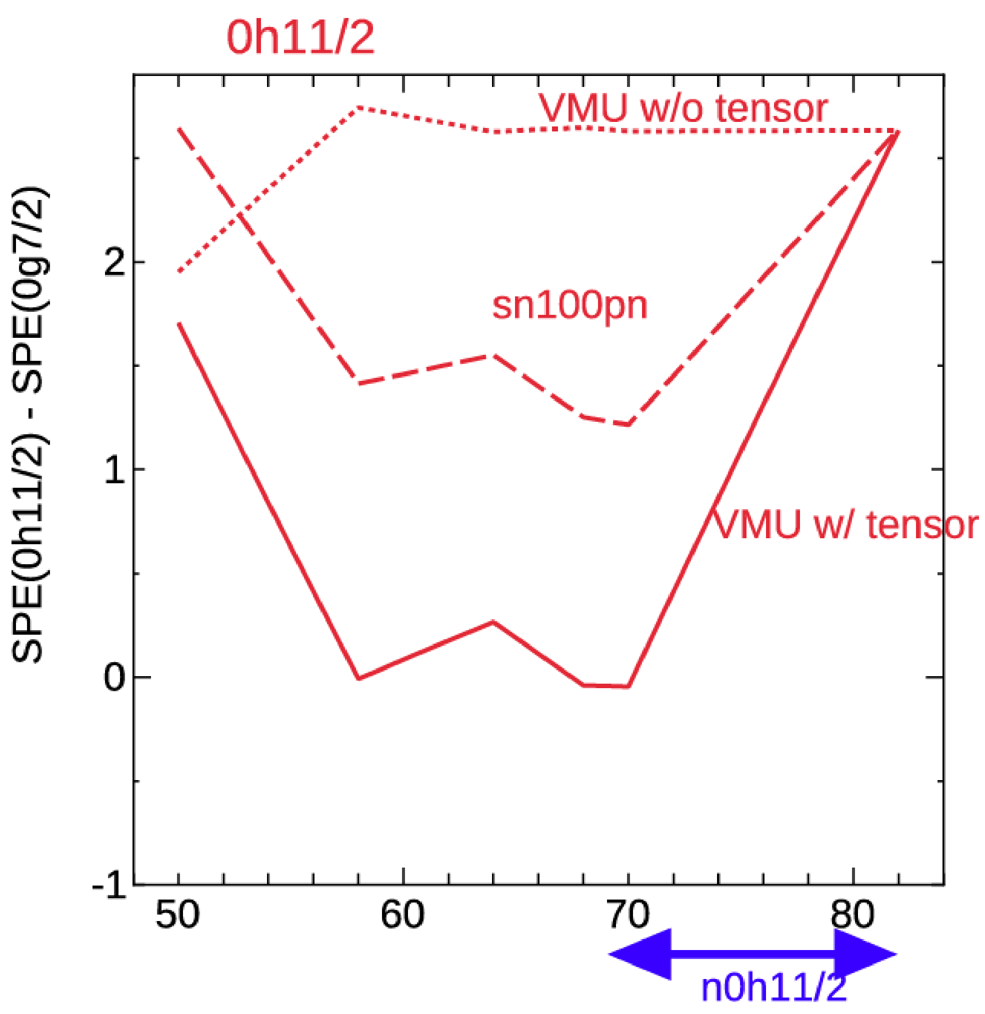


SN100PN: Ref. B. A. Brown et al., Phys. Rev. C 71, 044317 (2005)

Effective SPEs of Sb isotopes

- Although SN100PN includes tensor force, the shift of single-particle energy is half of the VMU with bare pi+rho tensor force
- Proton-neutron monopole interaction has a problem

$$H^{(m)} = \sum_{ij} V_{ij}^{(m)} n_i n_j$$



This gradient
V(n0h11/2-p0h11/2) – V(n0h11/2-p0g7/2)

Monopole part of the effective interaction and many-body perturbation theory (MBPT)

	VMU	$V_{low\text{-}k}$	SN100PN (KK 3rd)	KK 2nd order	EKK 2nd order	EKK large space
n0h11/2-p0h11/2	-0.34	-0.27	-0.31	-0.30	-0.08	-0.38
n0h11/2-p0g7/2	-0.58	-0.48	-0.43	-0.48	-0.43	-0.60
diff	0.23	0.21	0.12	0.18	0.35	0.23
	w/o MBPT		w/ MBPT			
			50 < Z, N < 82, 0g9/2 inert core			0g9/2 active

VMU ... VMU interaction (pi+rho tensor)
$V_{low\text{-}k}$ ... N3LO + $V_{low\text{-}k}$ w/o perturbation
SN100PN ... CD-Bonn + KK 3rd order by Brown, Jensen
KK 2nd order ... $V_{low\text{-}k}$ + Krenciglowa-Kuo (EKK) method 2nd order
EKK 2nd order ... $V_{low\text{-}k}$ + Extended Krenciglowa-Kuo (EKK) method 2nd order
EKK large space ... EKK 2nd order in pf+sdg+h11/2+f7/2+p3/2

"renormalization persistency" for *ls*-closed core

KK, EKK by N. Tsunoda

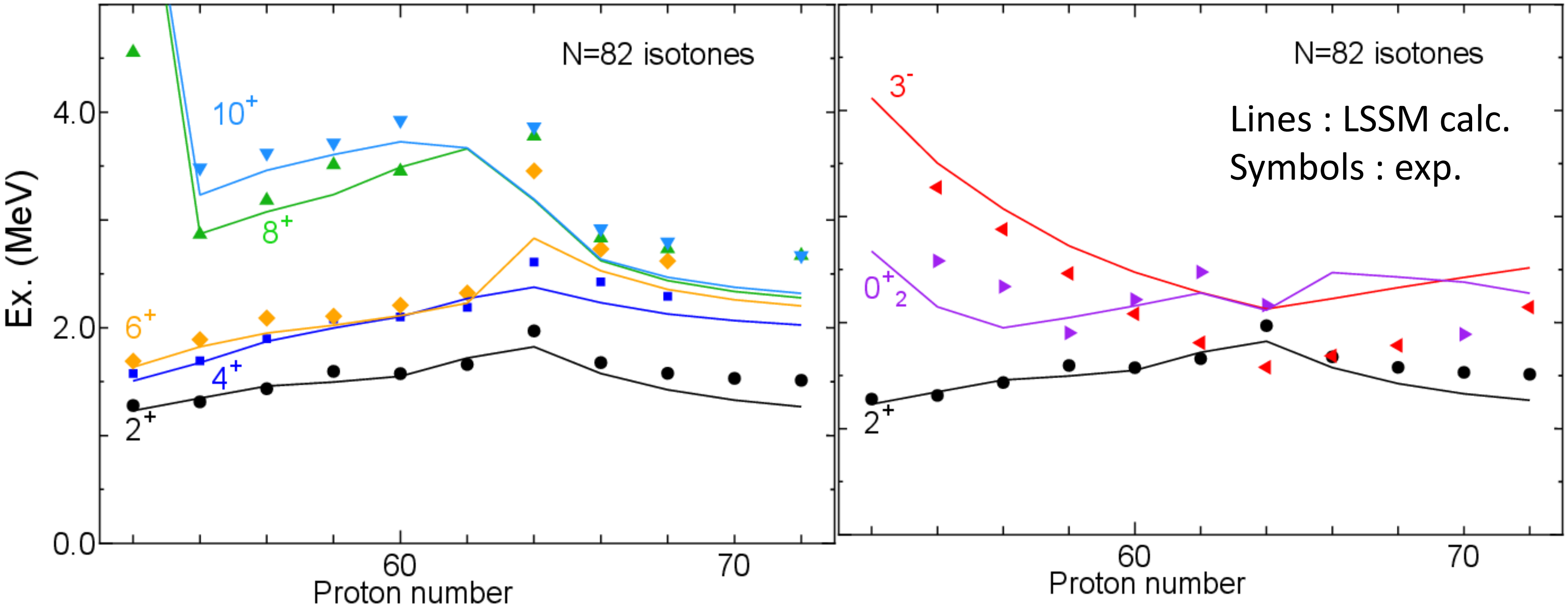
EKK large space is close to VMU with bare tensor force.

2nd order term with *jj*-closed core may deteriorate ?

Further investigation is required. Now, we adopt VMU for p-n interaction.

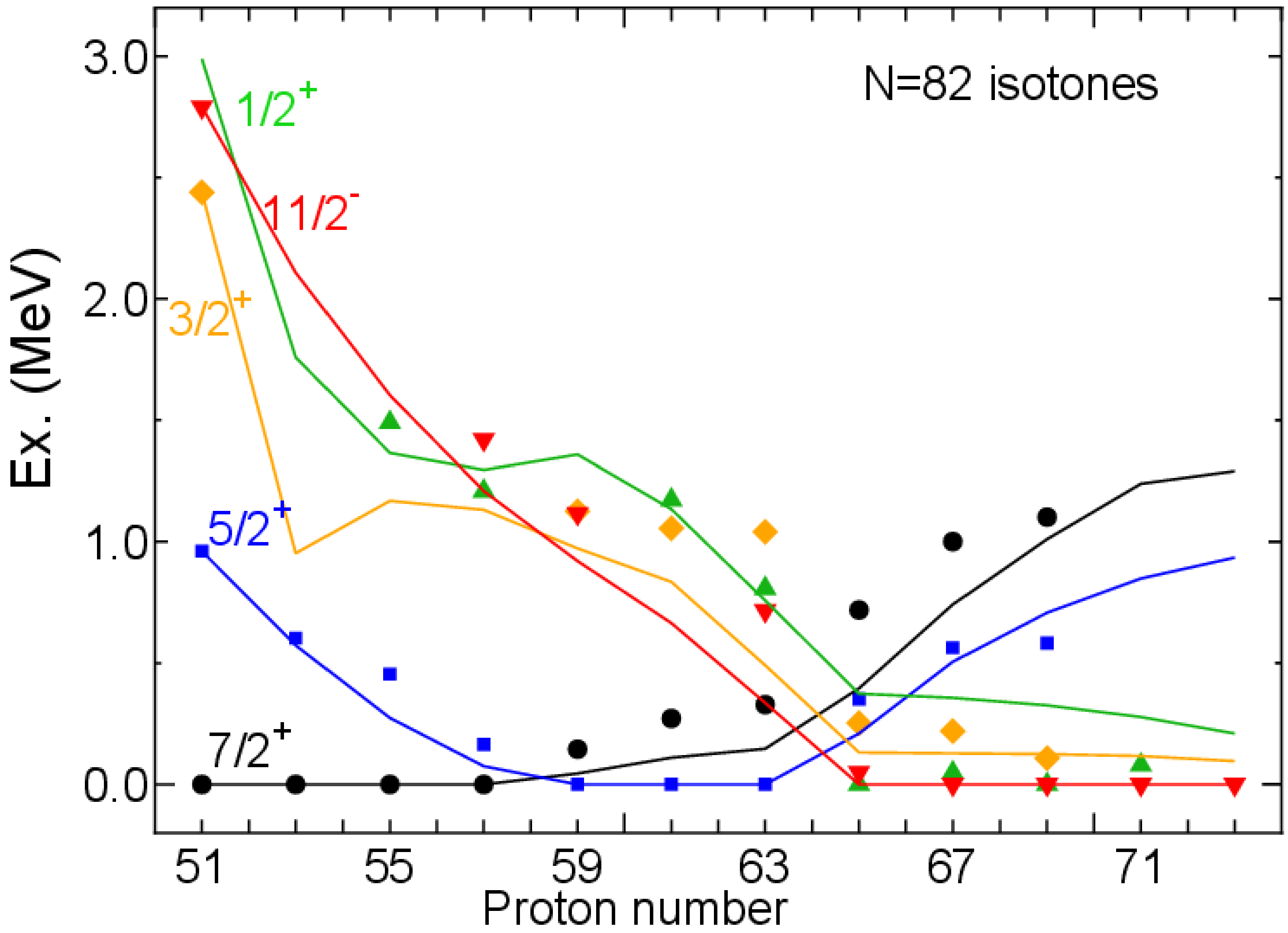
proton-proton int. for N=82 isotones

- SN100PN TBME is used for p-p TBME
  - Mass dependence of TBME, $(A/102)^{-0.3}$ is introduced
  - SN100PN (pp) + SNBG3 (nn) + VMU (pn)



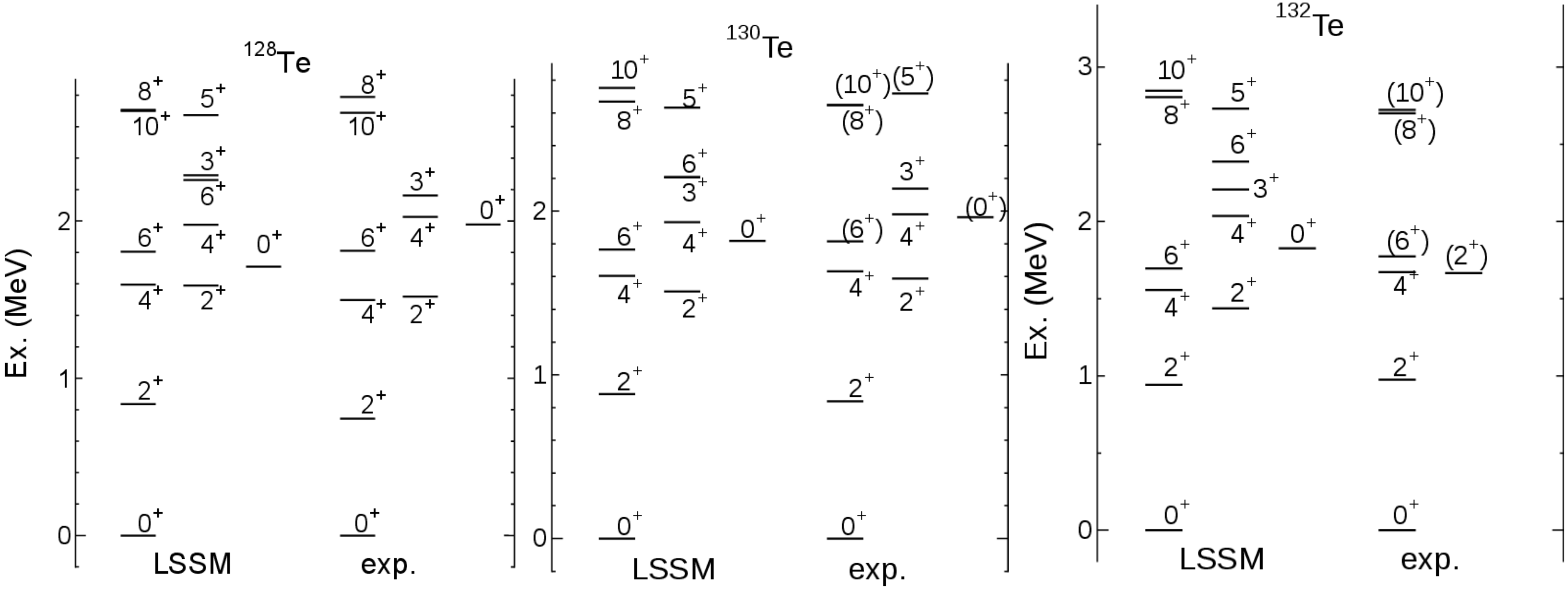
Good agreement at N=64 subshell magic (except for 3- collective states)

N=82 isotone, odd nuclei



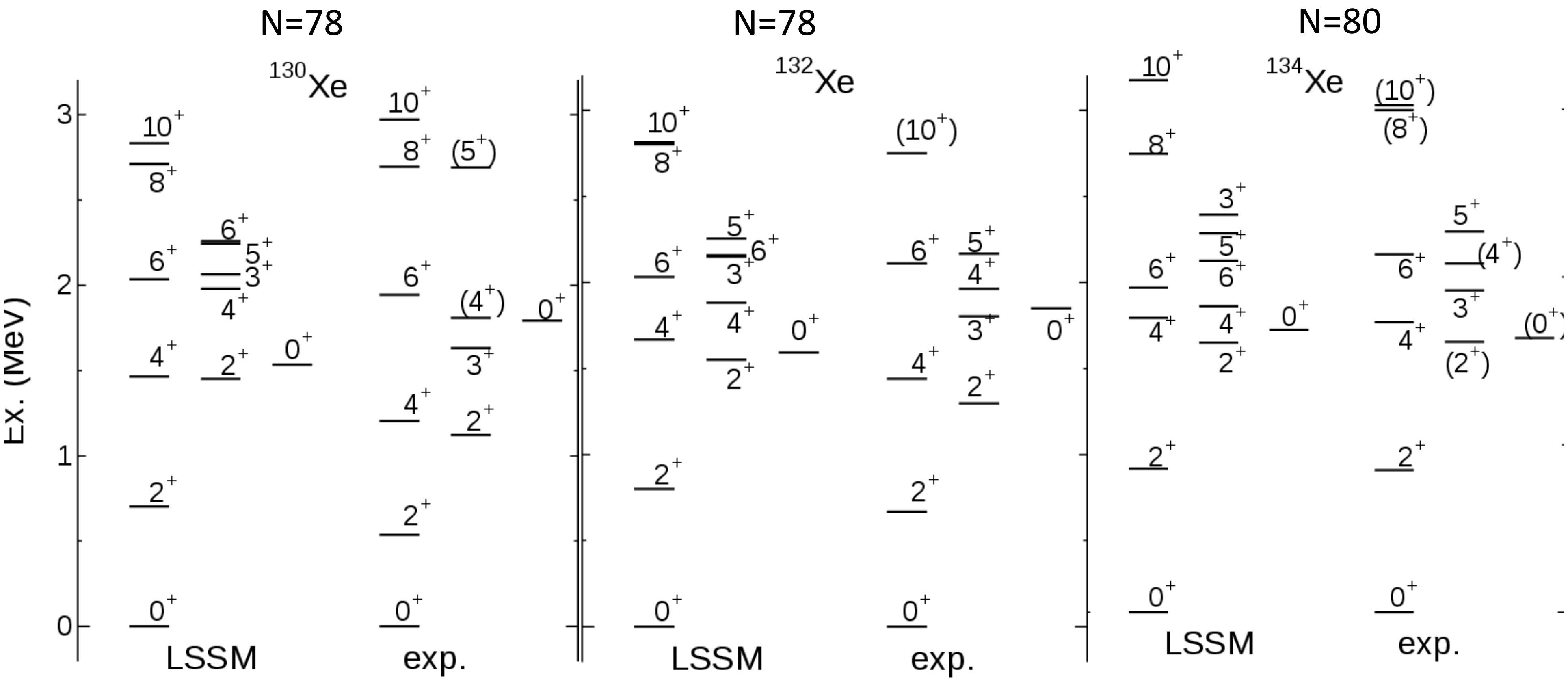
Te isotopes

N=78 N=78 N=80



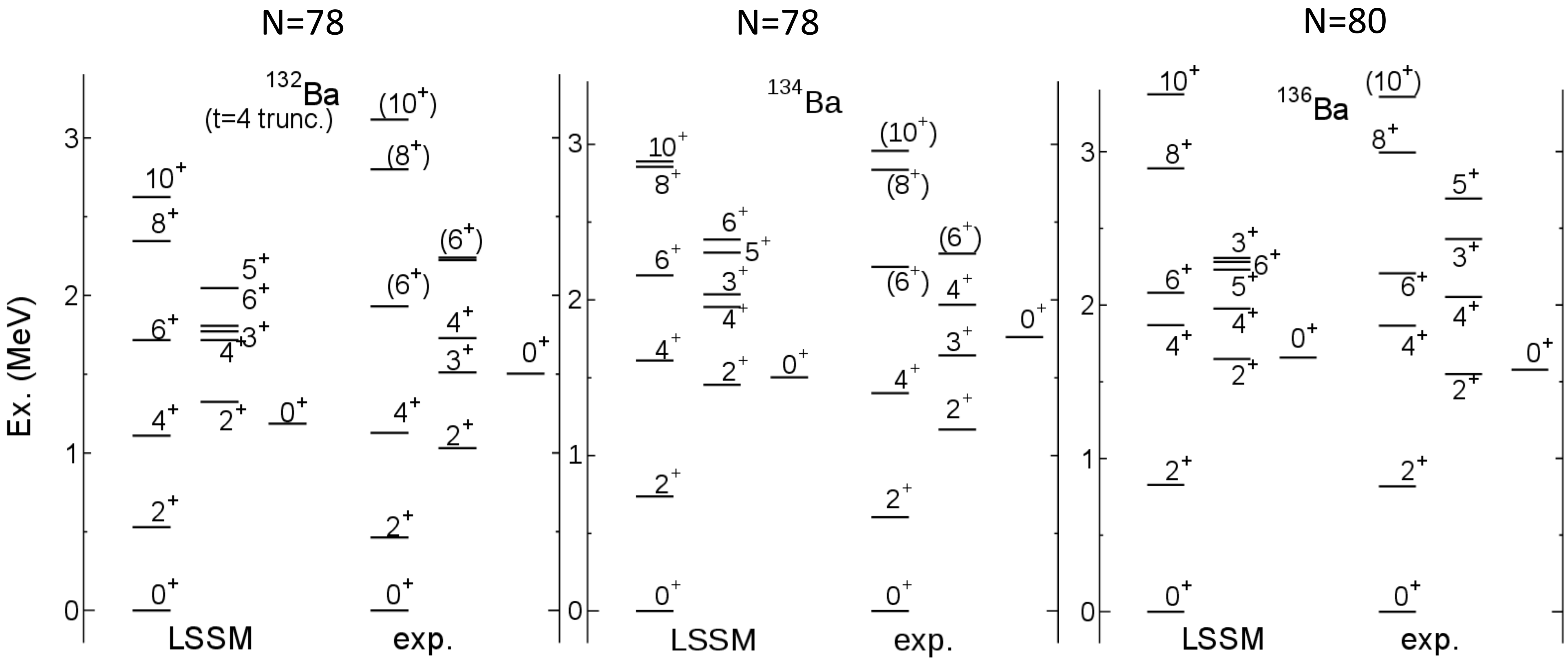
- SN100PN for pp, SNBG3 for nn, VMU for pn interactions
- Good agreements

Xe isotopes



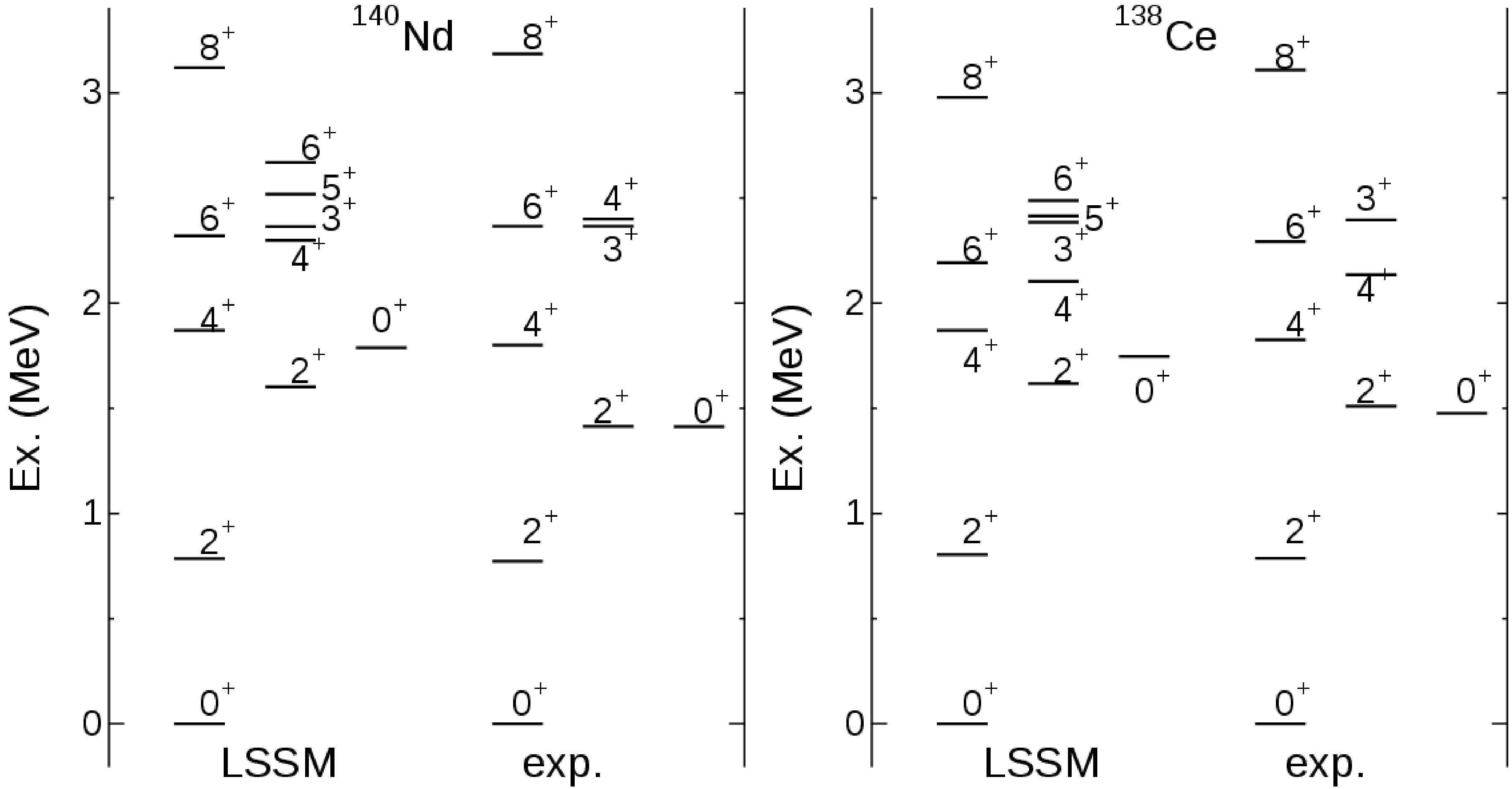
- Good agreements especially for yrast band
- problem in quasi-gamma band

Ba isotopes



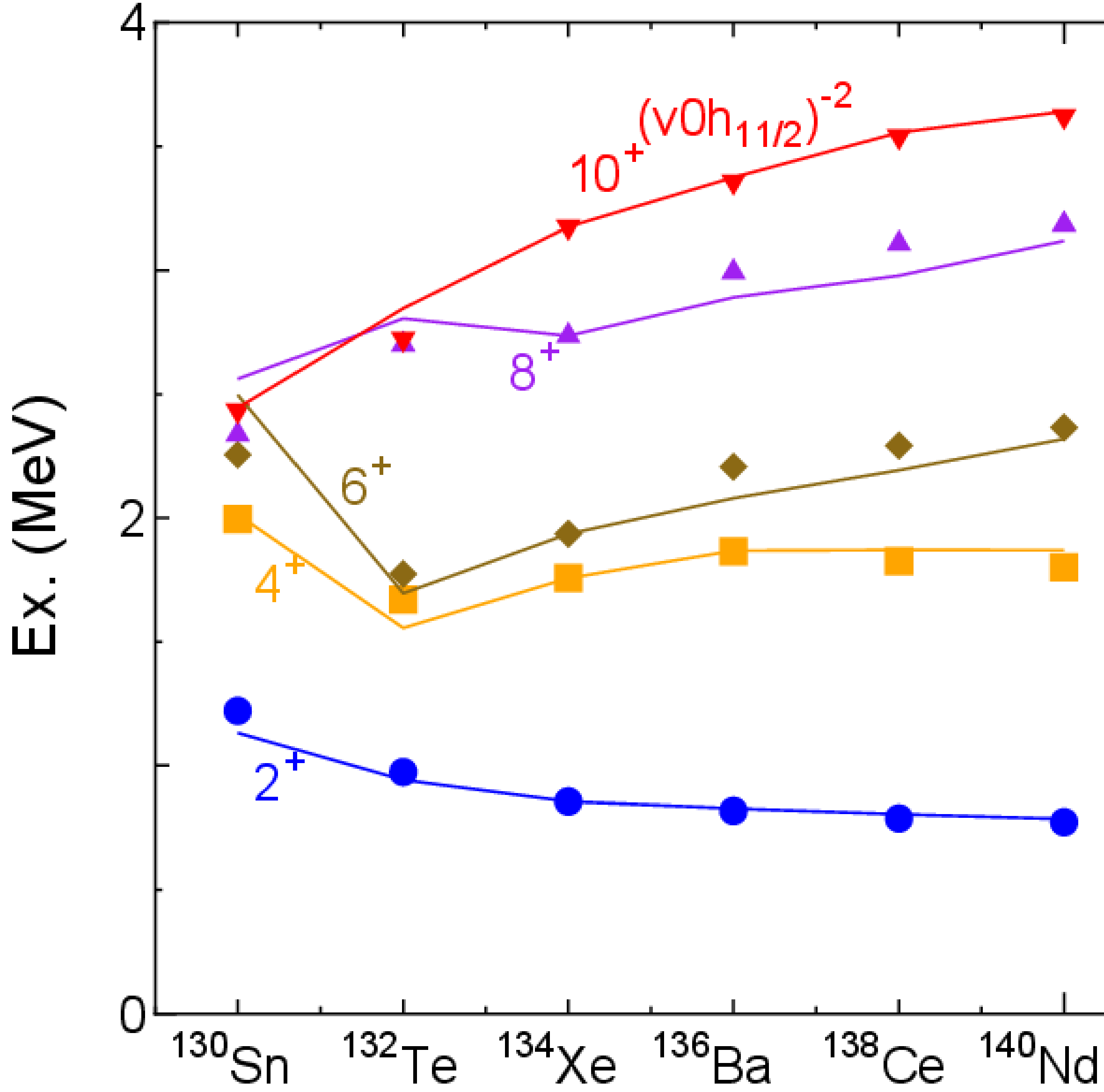
- Good agreements especially for yrast band
- problem in quasi-gamma band

Ce, Nd isotopes (N=80)



- excellent agreement except for N=80 isotones

Yrast levels of N=80 isotones



Mixed symmetry states around N=80 : experiments

$$|2_1^+\rangle \simeq Q_s\,|0_1^+\rangle = [Q_\pi + Q_\nu]\,|0_1^+\rangle$$

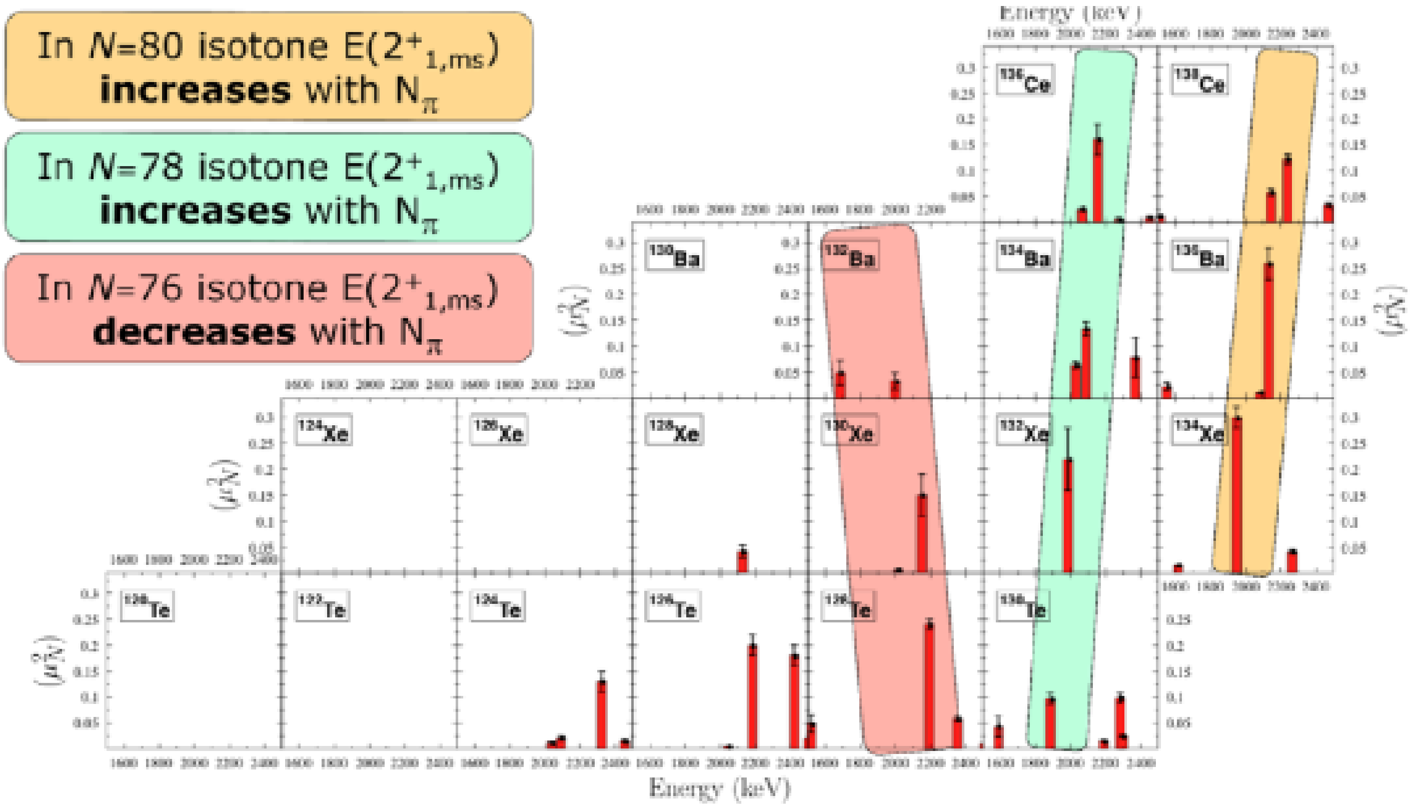
$$|2_{1,\mathrm{ms}}^+\rangle \simeq Q_m\,|0_1^+\rangle = N\left[\frac{Q_\pi}{N_\pi} - \frac{Q_\nu}{N_\nu}\right]|0_1^+\rangle$$

$B(M1; 2^+_i \rightarrow 2^+_1)$ (μ_N^2)

In N=80 isotone $E(2^+_{1,ms})$ **increases** with N_π

In N=78 isotone $E(2^+_{1,ms})$ **increases** with N_π

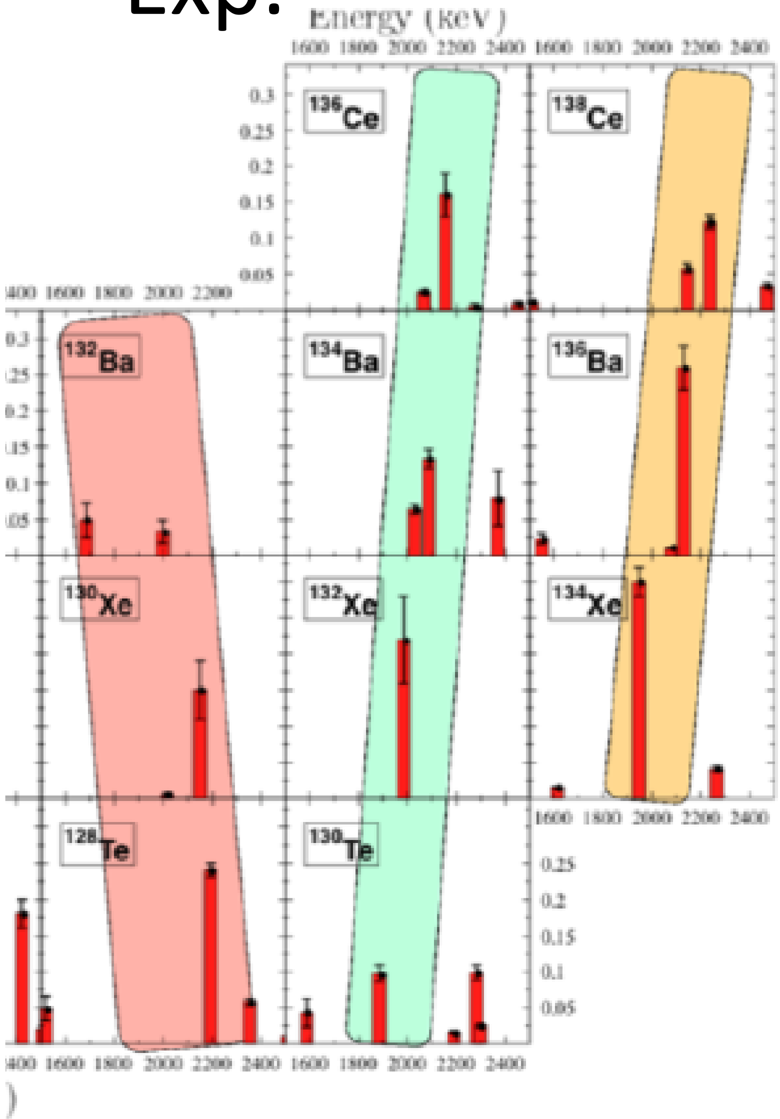
In N=76 isotone $E(2^+_{1,ms})$ **decreases** with N_π



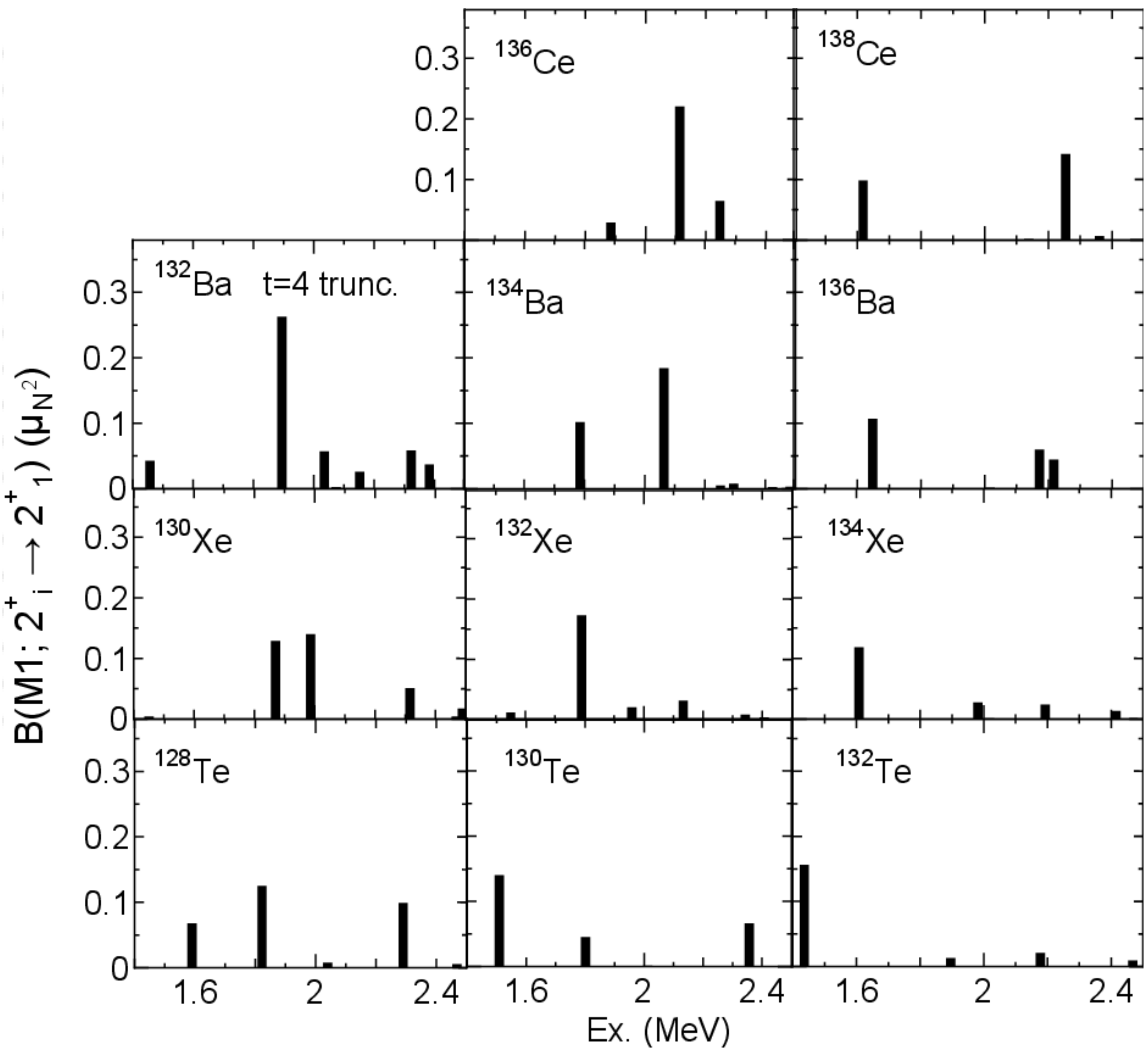
Ref. N. Pietralla *et al.*, J. Phys. Conf. Ser. 445, 012030 (2013)

Mixed symmetry states in N=80 isotones

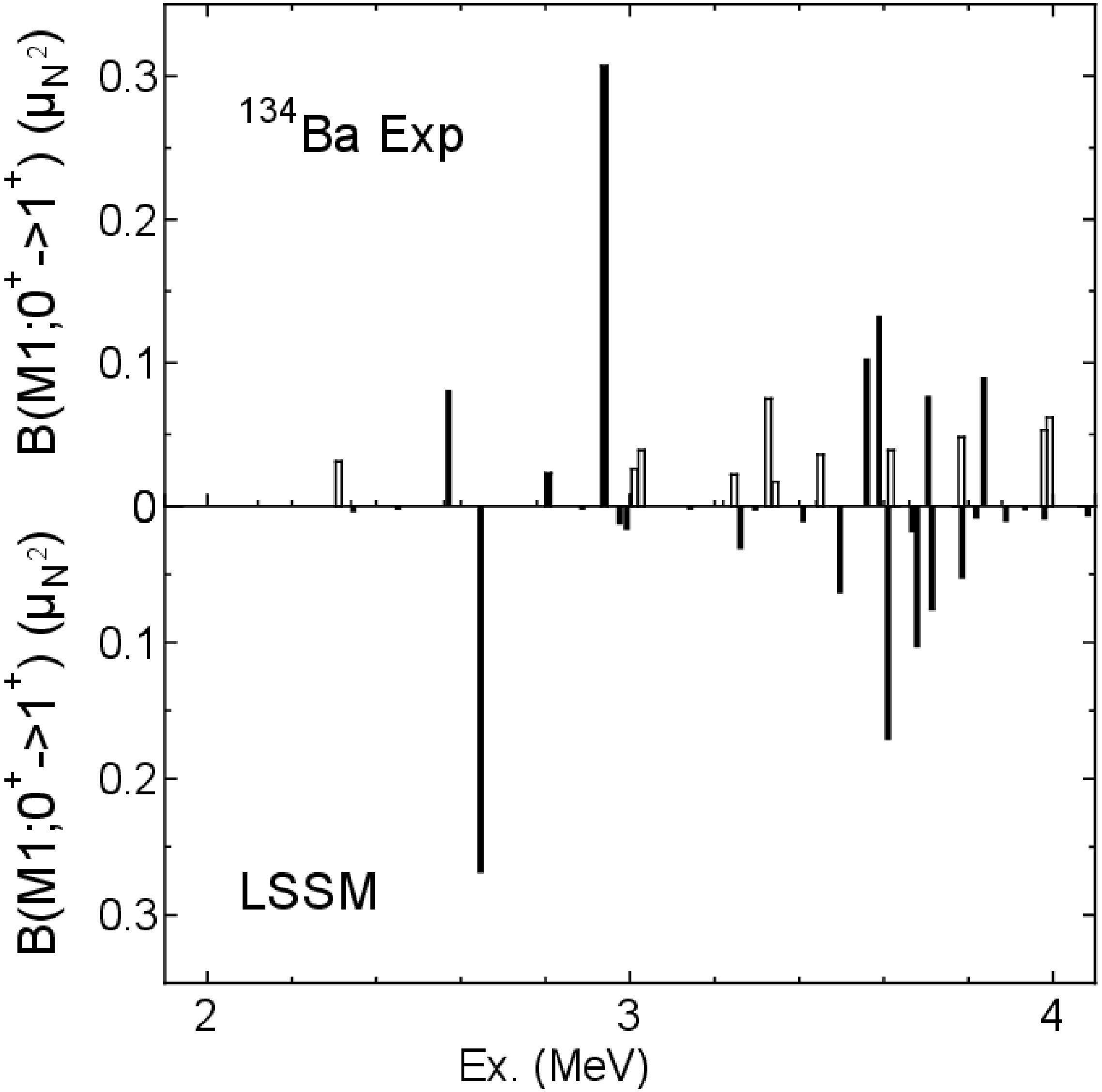
Exp.



LSSM spin quenching 0.7

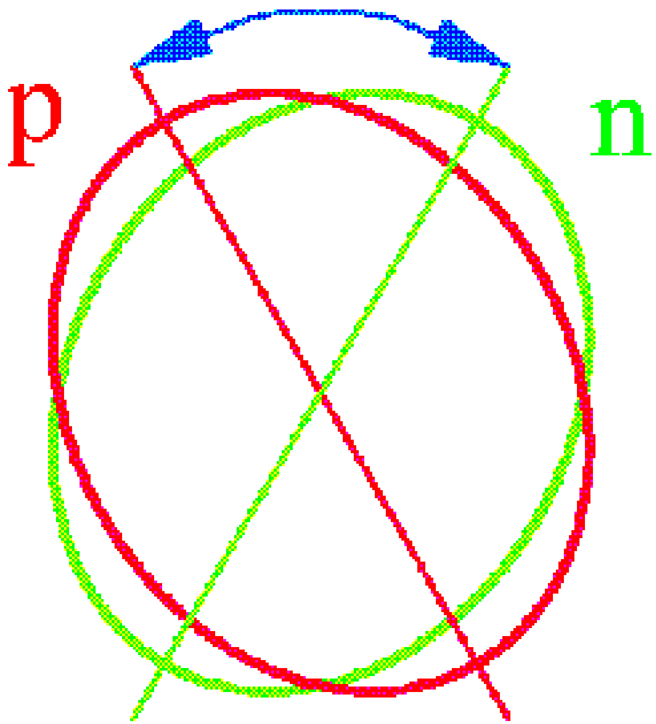


M1 excitation of ^{134}Ba



Solid bar : B(M1)
Open bar : M1/E1 not identified

Scissors mode



Exp. H. Maser et al., PRC 54 2129R (1995)

Summary

- Nuclei around N=80 are investigated in LSSM and MCSM
- P+QQ interaction successful for triaxially deformed states
- Construct realistic effective interaction towards unified description of 50<N,Z<82 region
  - Sb isotopes and shell evolution by tensor force
  - discuss mixed symmetry states, scissors mode in LSSM
  - in preparation for MCSM calc.