Post-K priority issue 9
"Elucidation of the Fundamental Laws and Evolution of the Universe"

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Shell-model study in A～130 nuclei and chiral doublet of ^{128}Cs

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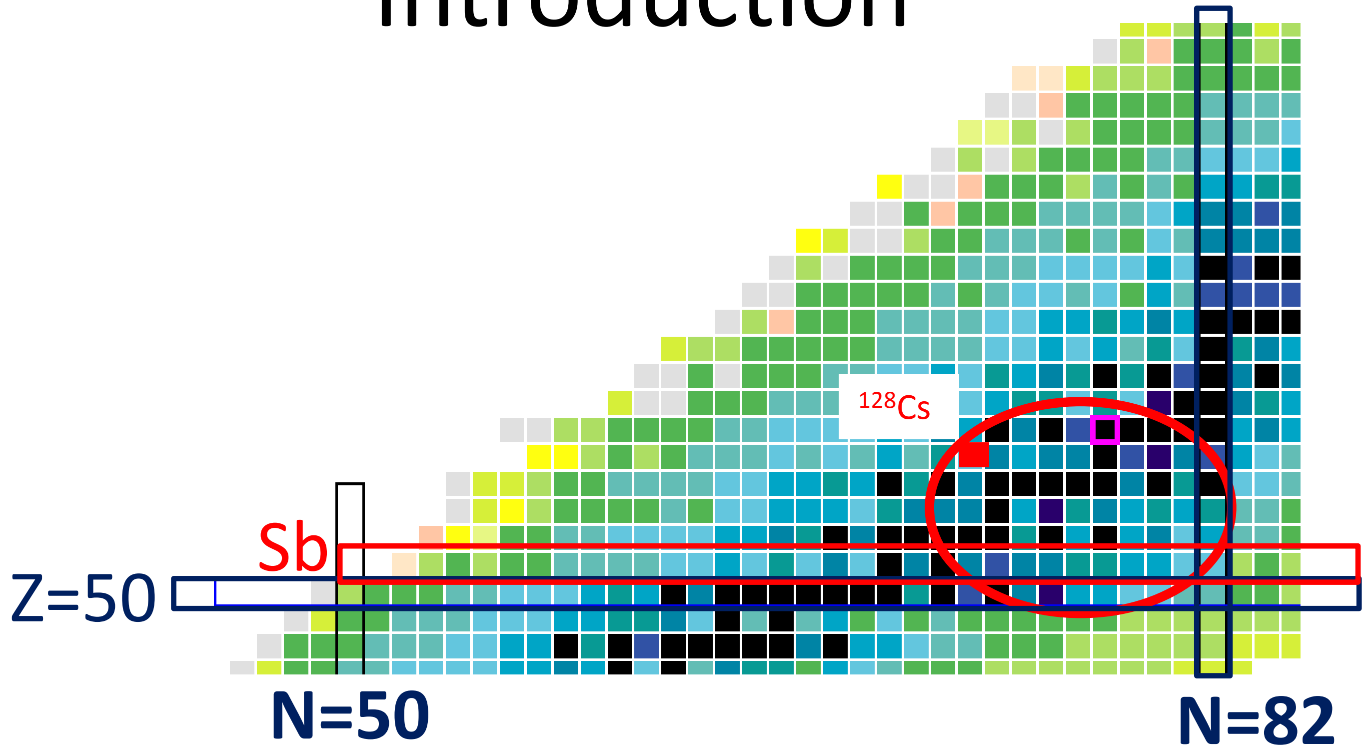
Outline

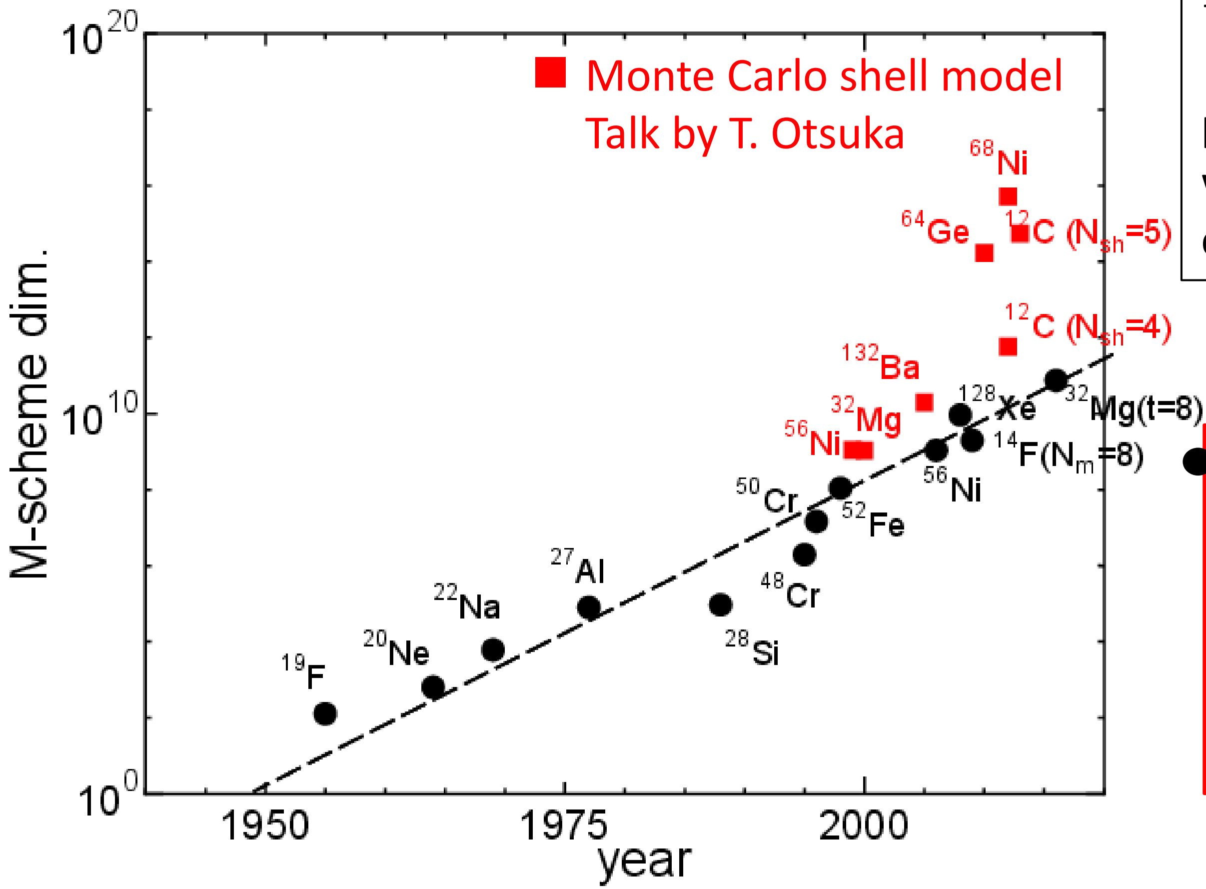
- Introduction : Large scale shell model (LSSM) calculations in A~130 region
- Shell evolution of Sb isotopes
- High-spin states in the LSSM: ^{136}Ba, ^{135}La
- ^{128}Cs as a candidate for chiral doublet band

Introduction



- Shell-model study is a challenge in this region due to huge configuration space
- Exotic phenomena emerge such as triaxial deformation, chiral bands, isomers, etc.

Developments of shell-model calculations



^{128}Cs ~ 7.6 x 10^{10} dim.

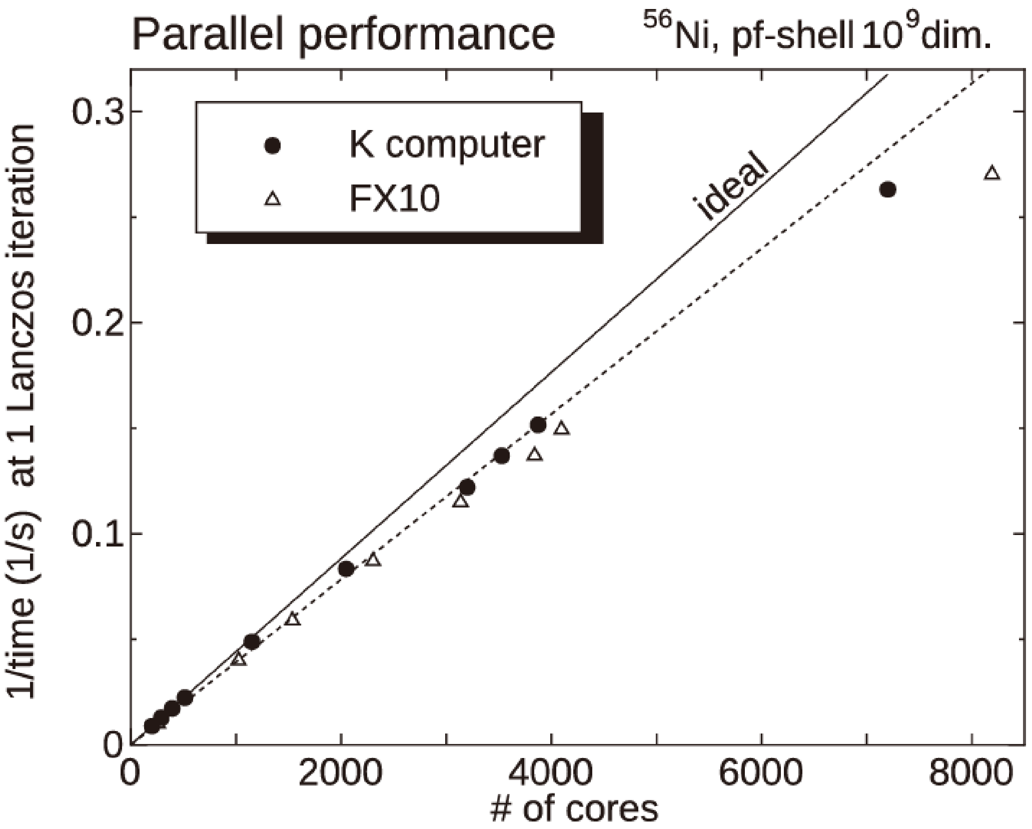
particle-hole truncation would deteriorate collective property

● **Shell model calculations with direct diagonalization (Lanczos method)**

current limit ~ 10^{11} dim.

- MCSM: awkward in high-spin states
- Developments of Lanczos shell-model code is required:
  ANTOINE, NuSHELL, BigStick, KSHELL, ...

KSHELL code for the LSSM calculations



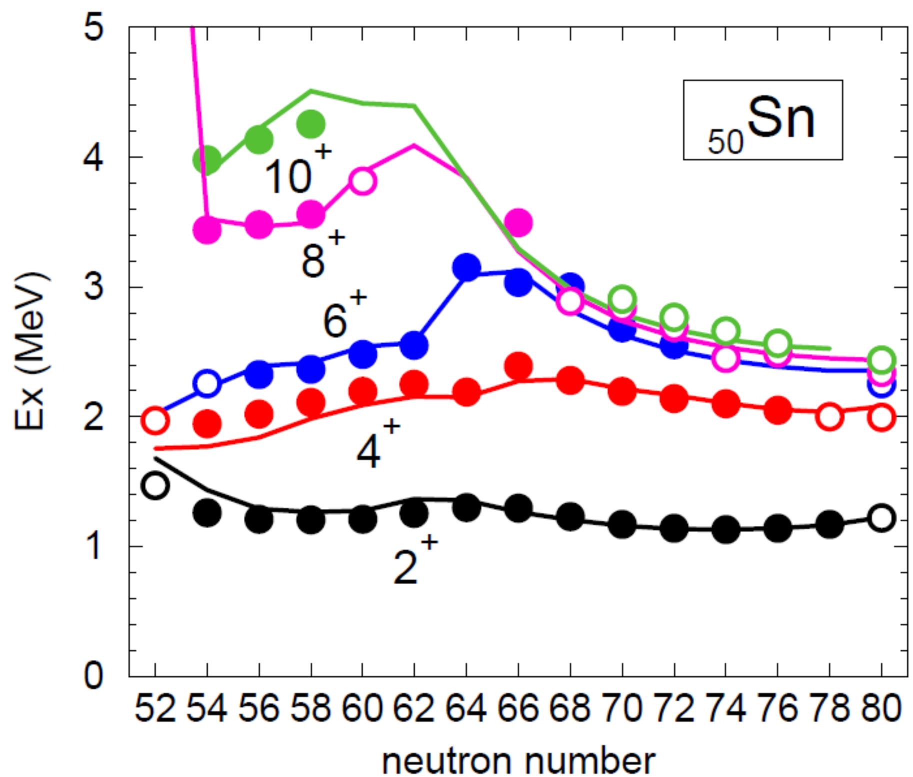
- ^{128}Cs calc. demands eigenvalue problem of 7.6 x 10^{10} dimension.
  => parallel computation
- *M*-scheme + "on the fly" computation of Hamiltonian matrix elements, code was written from scratch for OpenMP+MPI hybrid parallel
- KSHELL code is available on the web !

^{56}Ni in pf-shell One Lanczos iteration:: 25 min. (16cores) ➡ 3.8 sec. (7200cores)

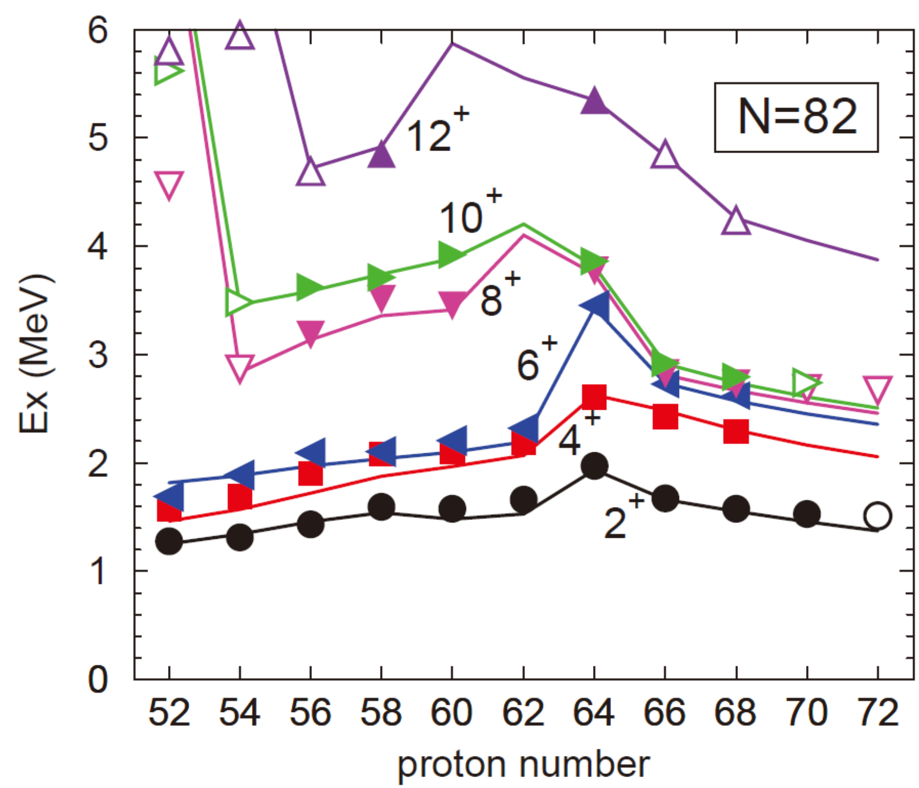
We obtained ^{56}Ni ground state energy (10^9 dim) in 135 seconds

Large scale shell model (LSSM) calculations for A～130 nuclei

- Model space : 50 < Z,N < 82 $0g_{7/2}, 1d_{5/2}, 1d_{3/2}, 2s_{1/2}, 0h_{11/2}$
- Interaction : SNBG3 for νν, N82GYM for ππ, fitted for Z=50 and N=82 semi magic nuclei



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

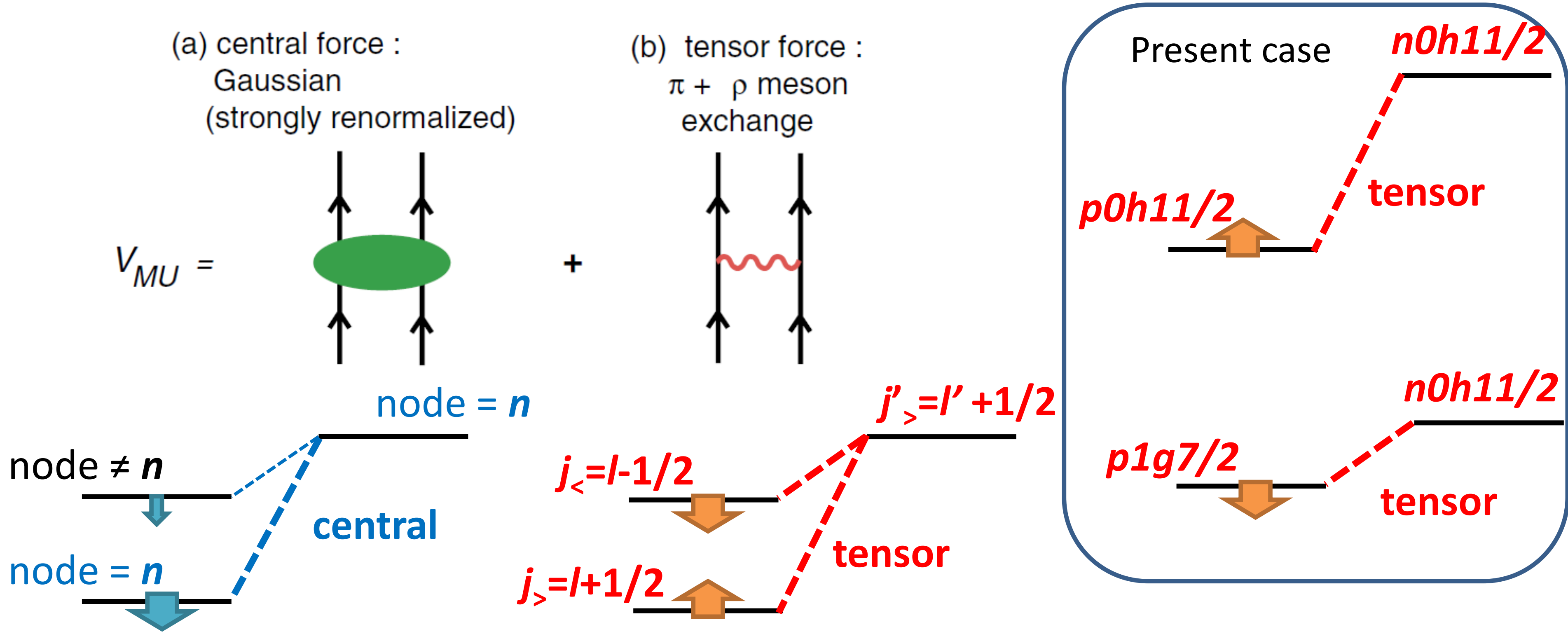


M. Honma et al., RIKEN Accel. Prog. Rep. (2016).

Monopole-based universal interaction V_{MU} for $\pi\nu$ interaction

Ref. T. Otsuka *et al.*, Phys. Rev. Lett. 104, 012501 (2010).

- Central and tensor forces

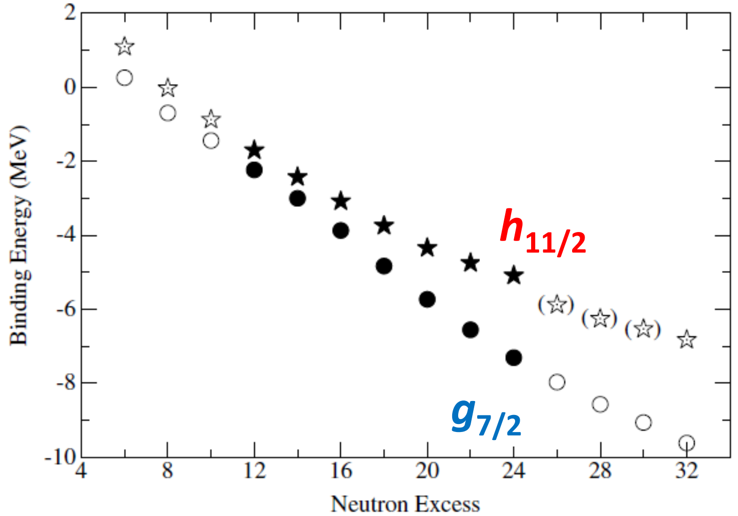


We adopt V_{MU} interaction for $\pi-\nu$ channel

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

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



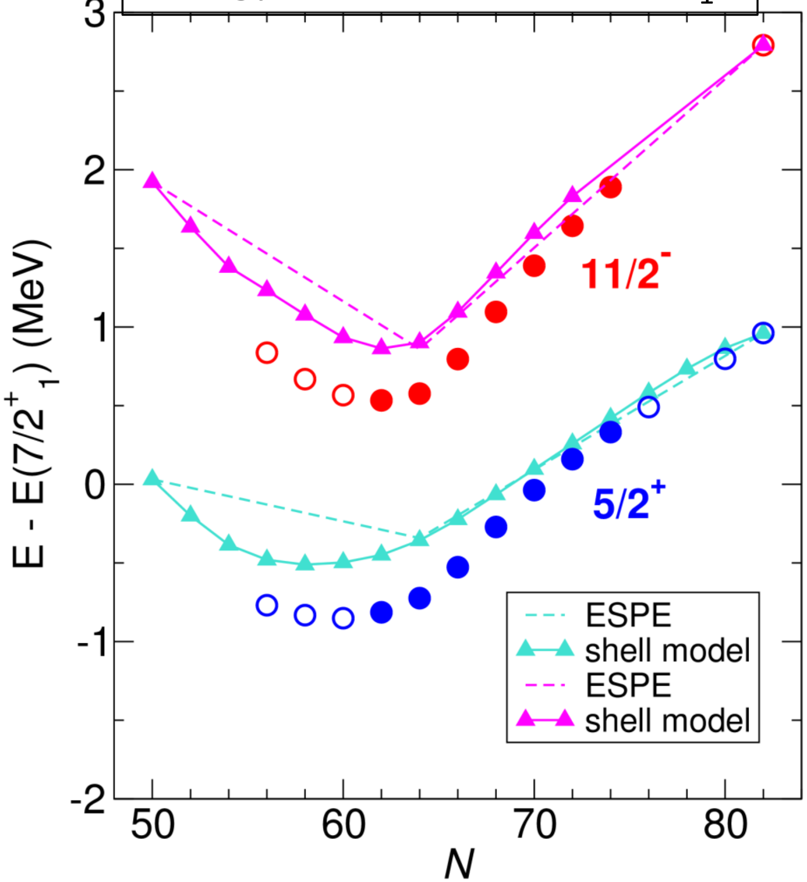
J. P. Schiffer et al., Phys. Rev. Lett. 92, 162501 (2004).

Sb (Z=51) isotopes

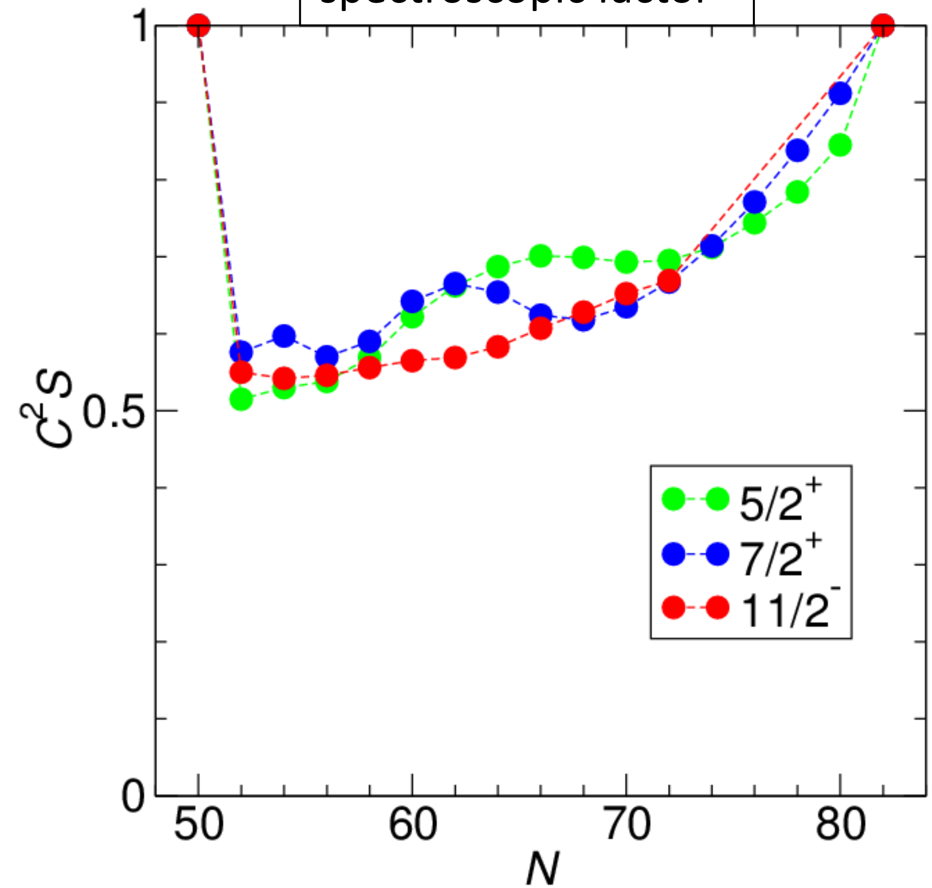
Y. Utsuno *et al.*, in preparation

- 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)

Energy levels relative to $7/2^+_1$

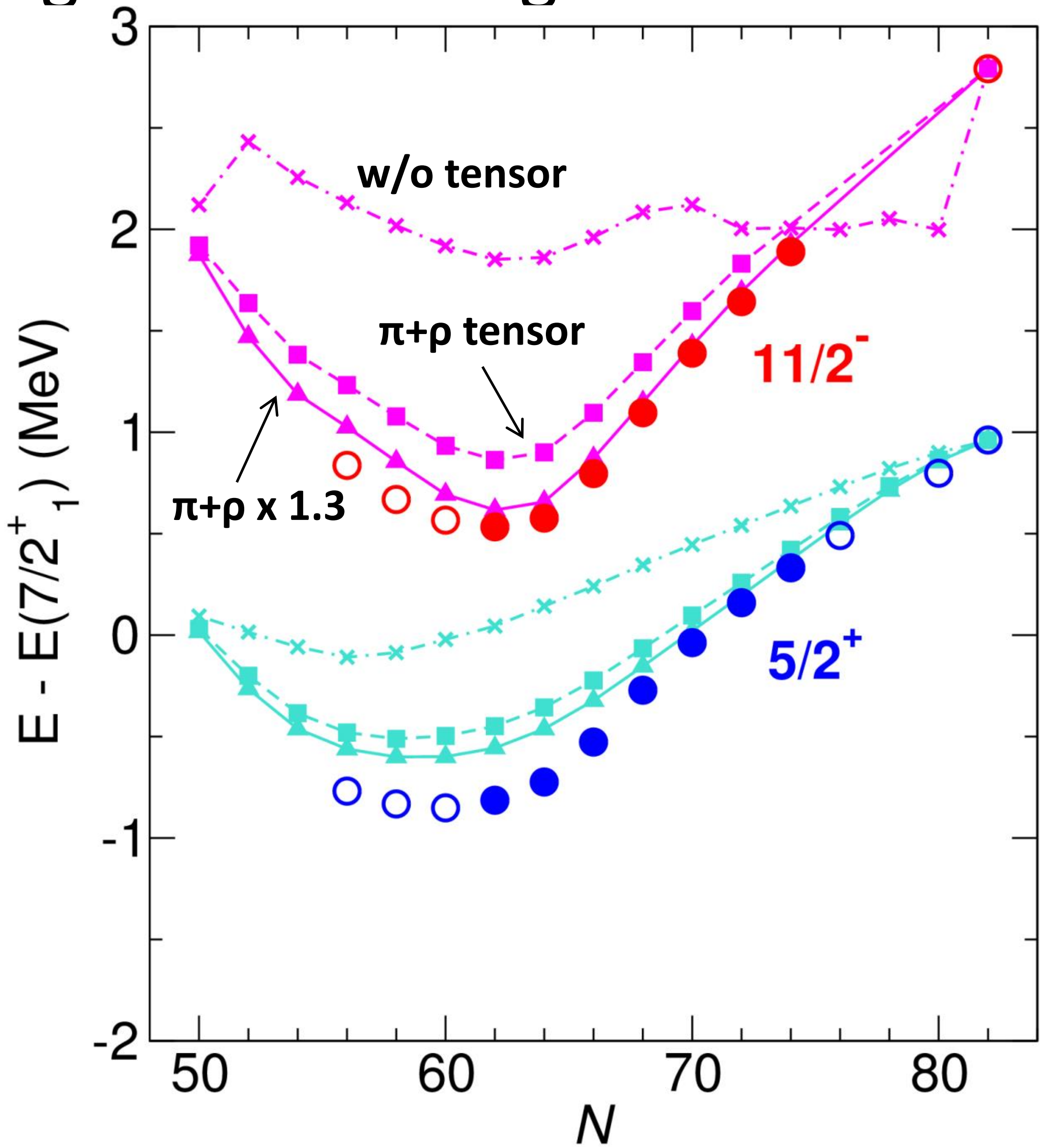


spectroscopic factor



Shell evolution driven by the tensor force and configuration mixing

- Without tensor
  - $11/2^- \approx 2$ MeV
- Tensor effect + configuration mixing
  - Good agreement with experiment
  - almost perfect agreement if the tensor force is enhanced by a factor 1.3

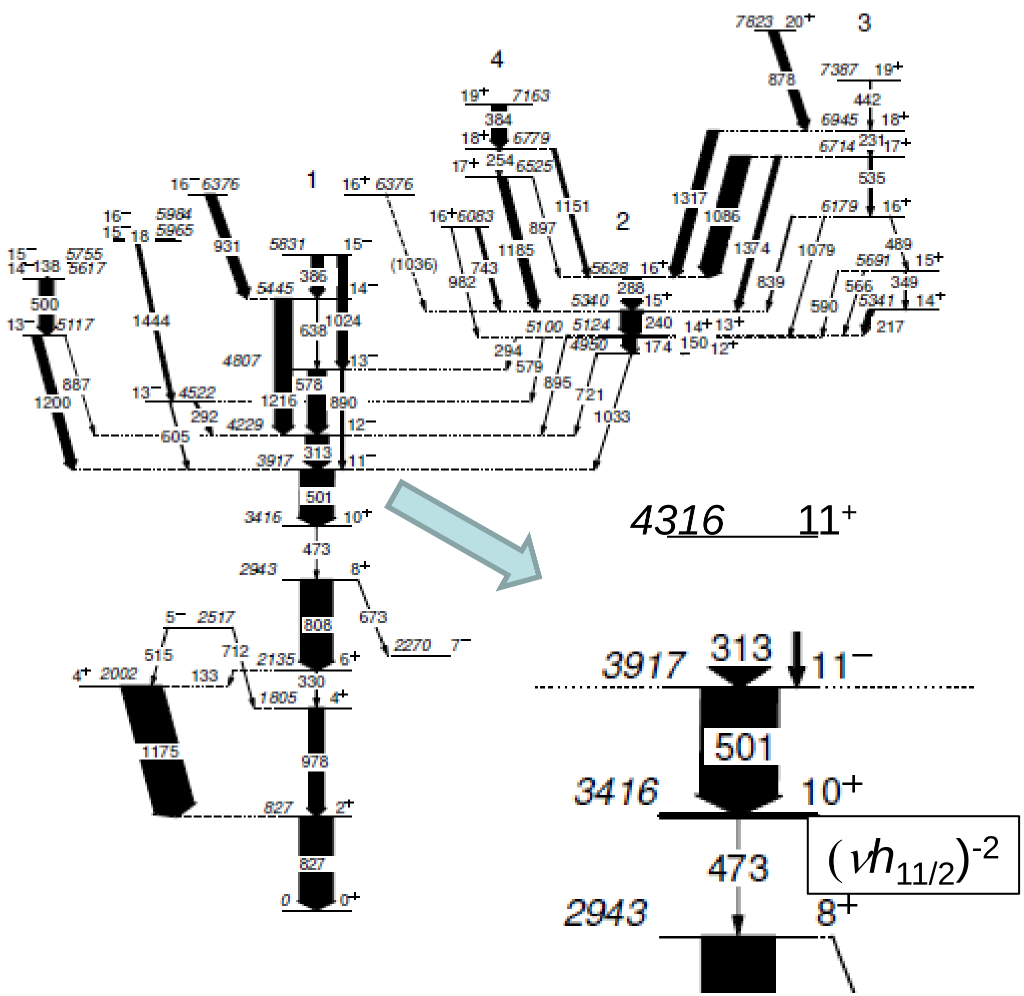


$^{136}_{56}Ba_{80}$: Exp. vs. LSSM calc.

collab. with C. Petrache *et al*.

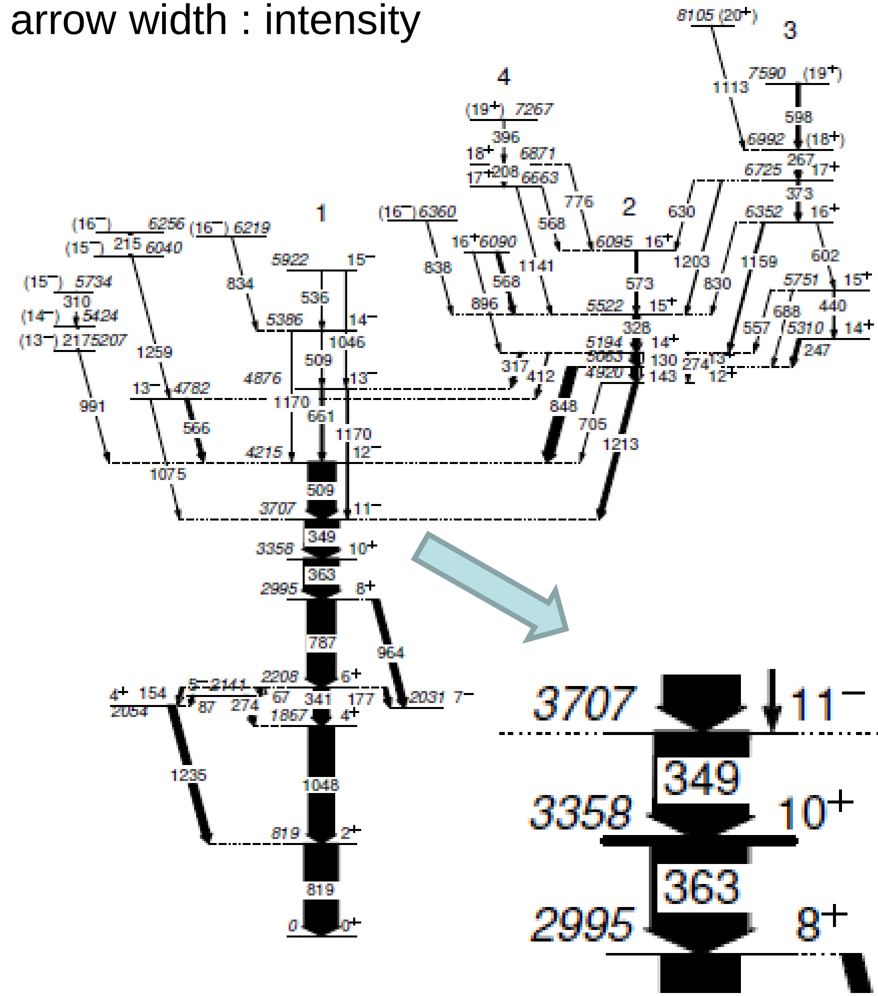
^{136}Ba - LSSM

arrow width : B(E2)

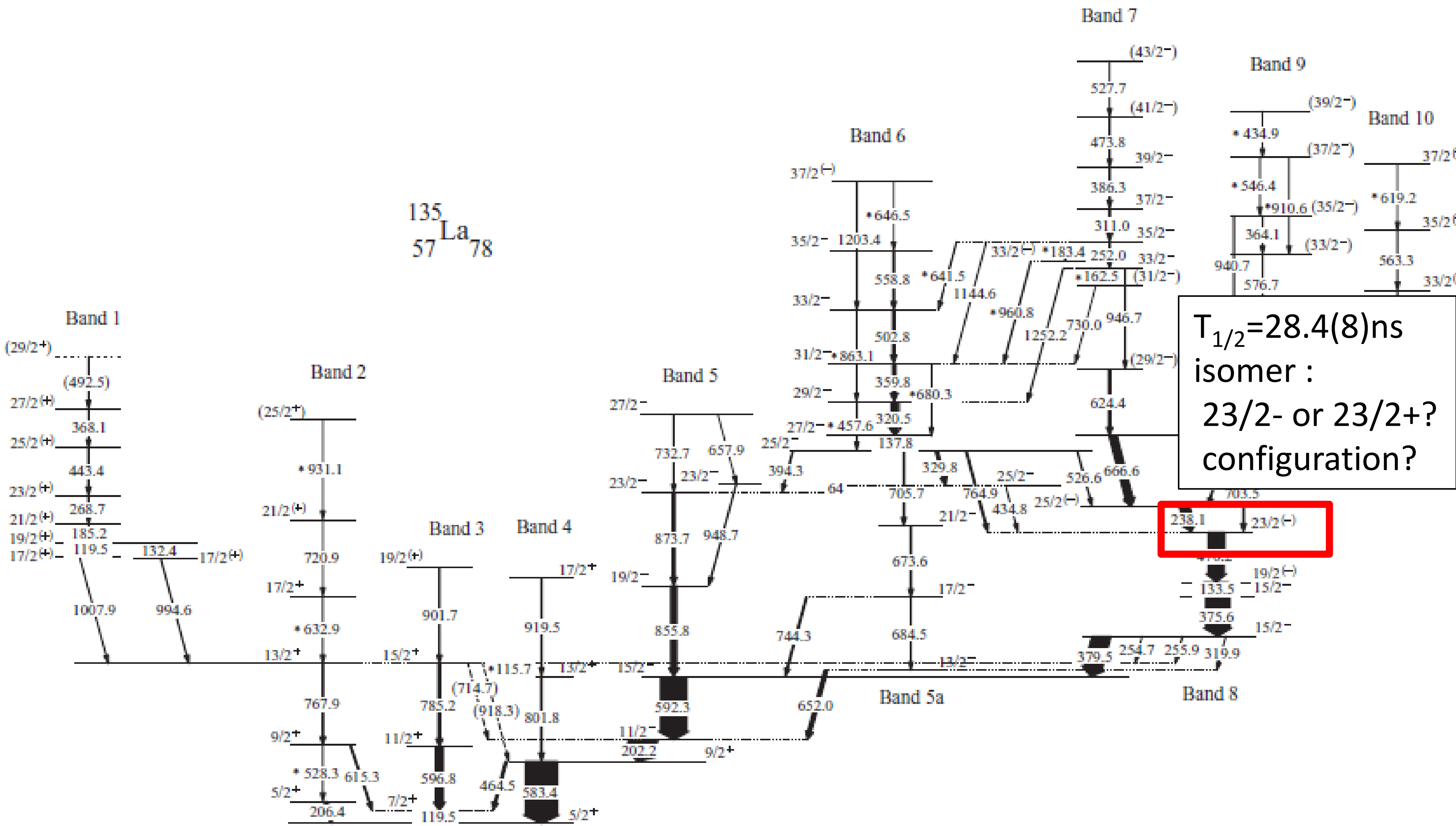


^{136}Ba - exp

arrow width : intensity



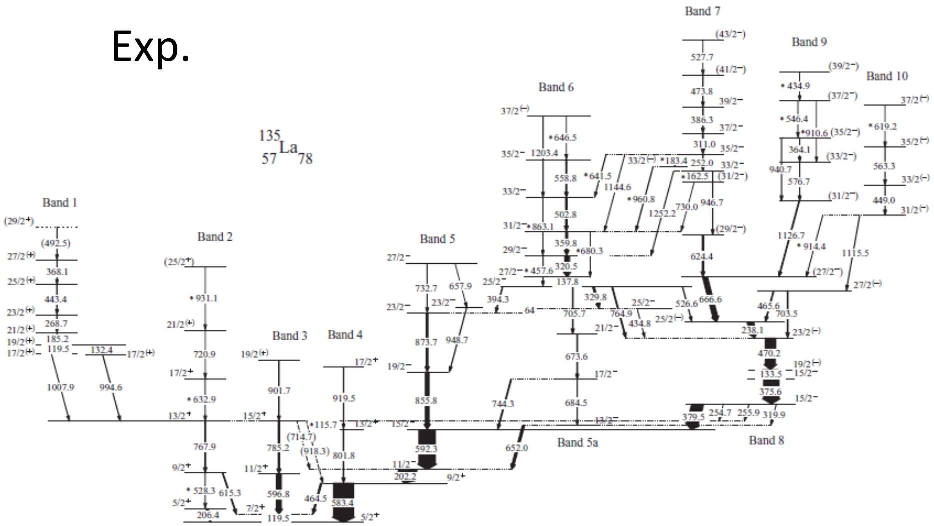
Exp. level scheme of $^{135}_{57}La_{78}$



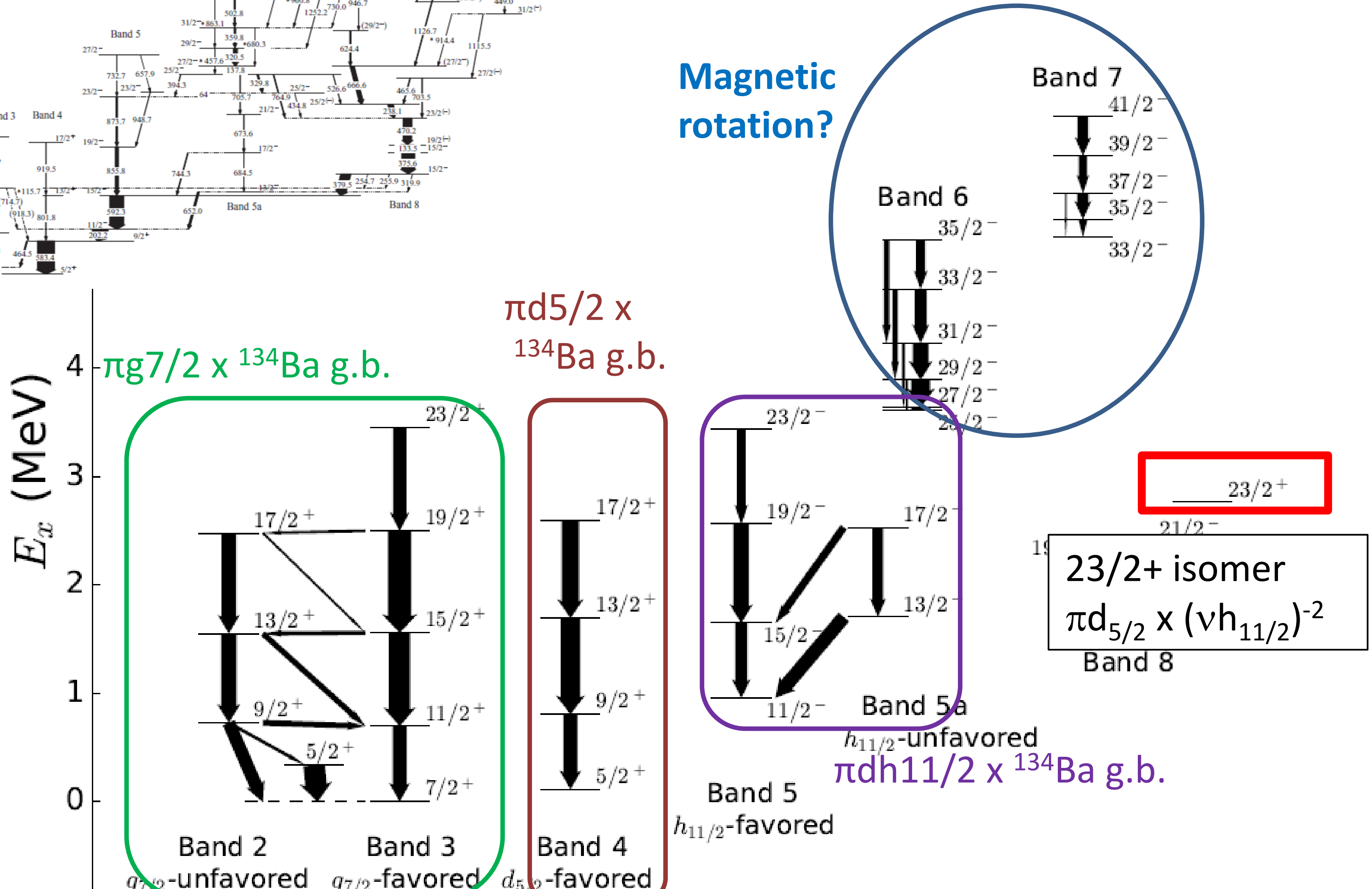
R. Garg *et al.,* PRC 87, 034317 (2013), R. Leguillion *et al.*, PRC 88, 044309 (2013)

$^{135}_{57}La_{78}$: LSSM calc. w/ R. Palit, E. Ideguchi *et al.*

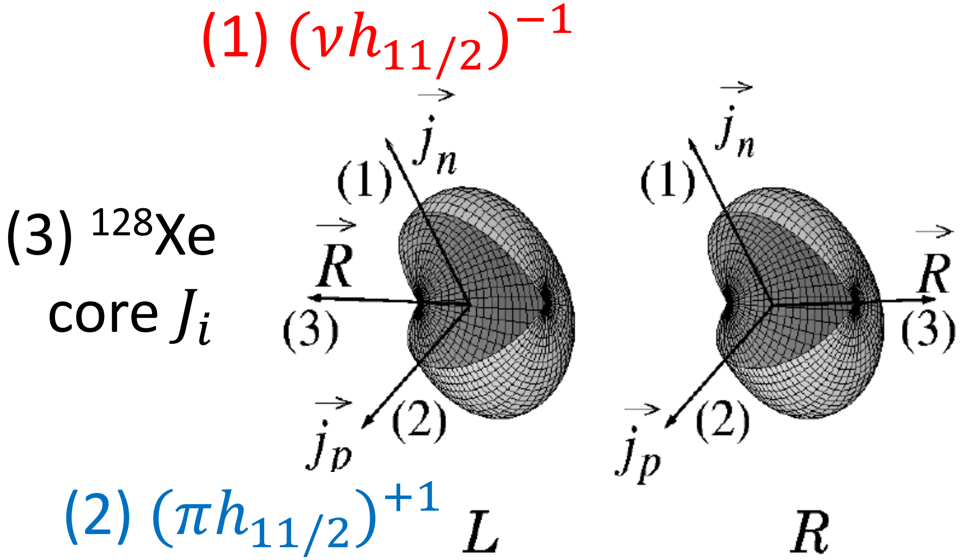
Exp.

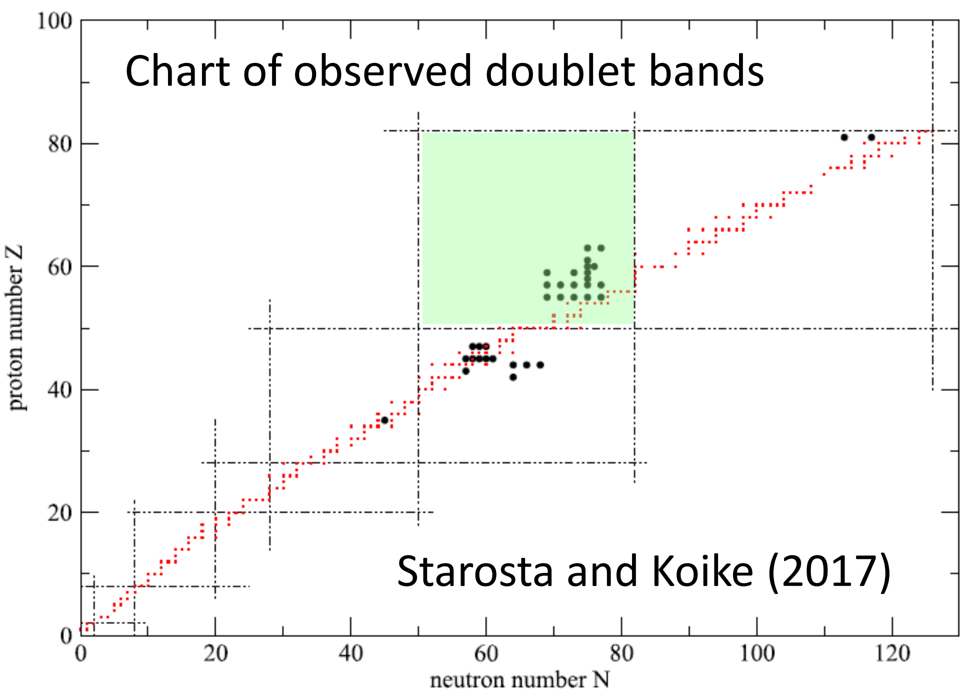


LSSM calc. , arrow width : B(E2)
3 x 10^9 M-scheme dimension



Chiral doublet bands of ^{128}Cs

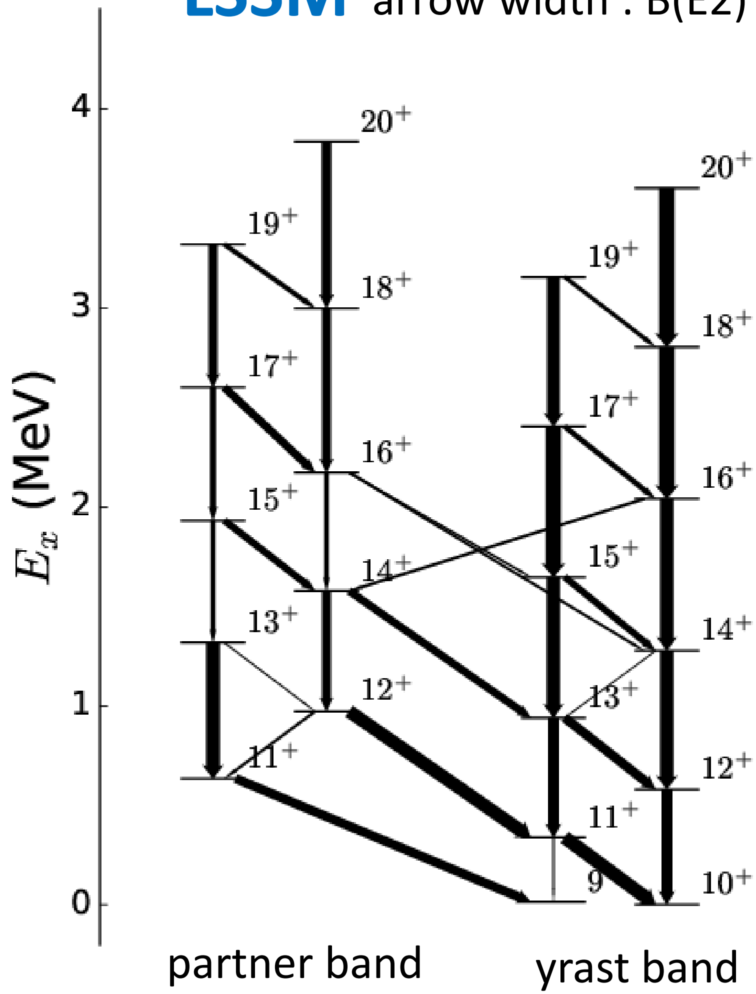




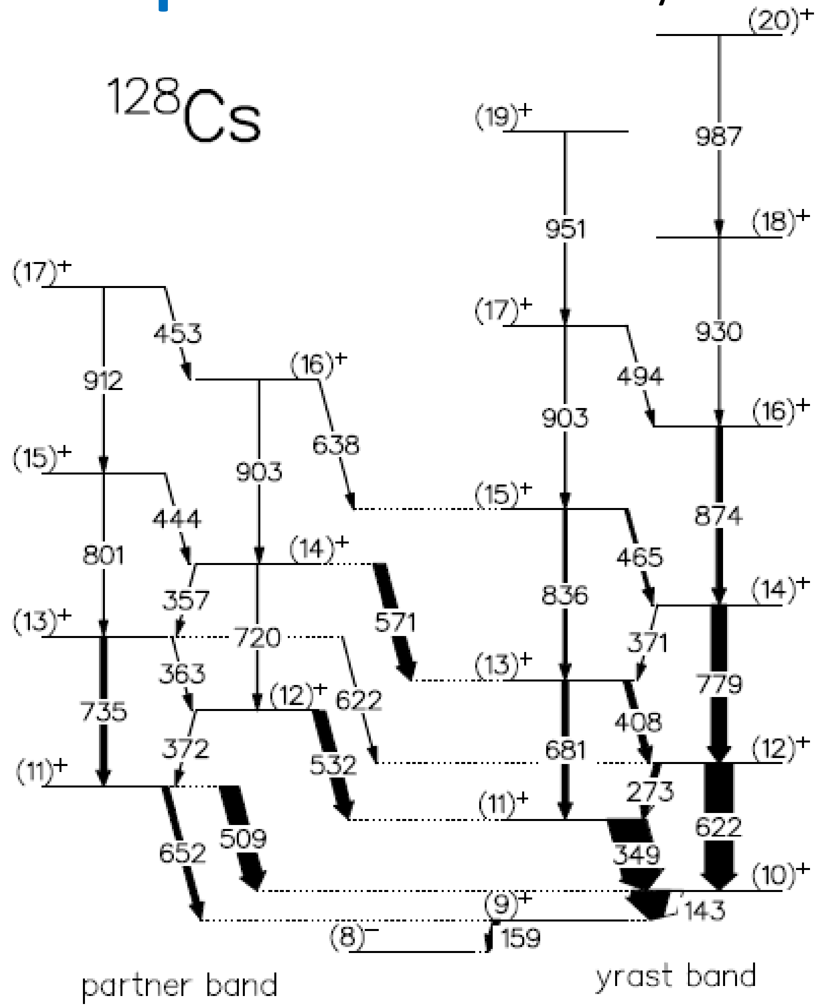
- First proposed by Frauendorf and Meng in 1997
- *A* ~ 130 region: the region of most extensive study
  - Triaxiality favored
  - $\pi(h_{11/2})^1\nu(h_{11/2})^{-1}$ config. favored
- Theoretical tools
  - Tilted axis cranking (TAC)
  - Particle-rotor model (PRM)
  - PSM, IBFFM, DFT, …
- Aim of the LSSM study for chiral bands
  - Including various degrees of freedom, e.g. γ-vibration

^{128}Cs: energy levels

LSSM arrow width : B(E2)



Exp. arrow width : intensity



$\pi(h_{11/2})^1\nu(h_{11/2})^{-1}$ configuration

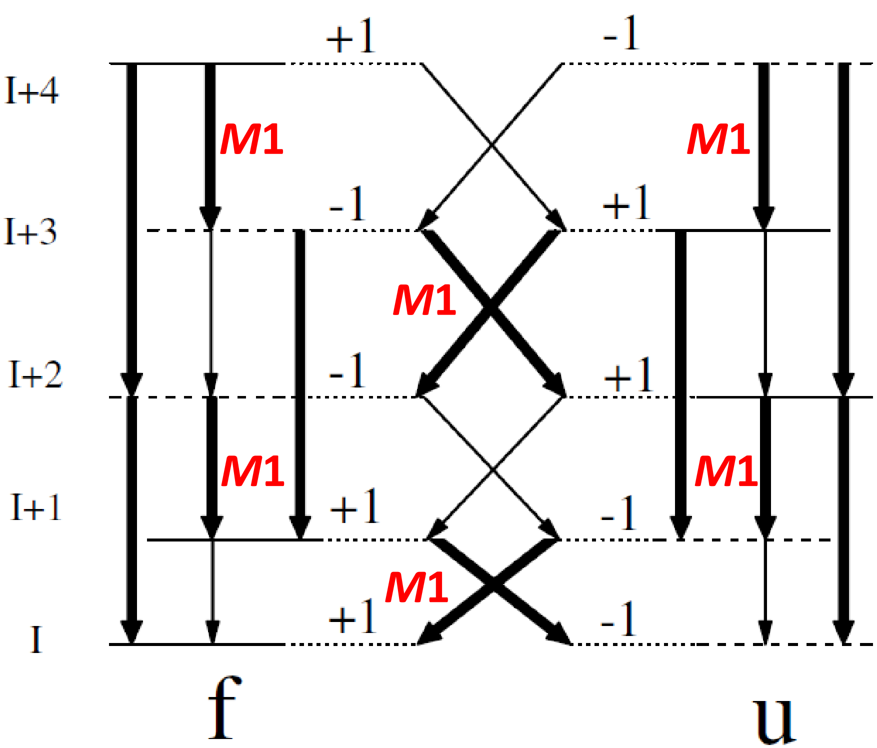
Remarkable agreement with exp.

Level spacing suppressed by ~20%

E. Grodner *et al.*, IJMPE 14, 347 (2005)

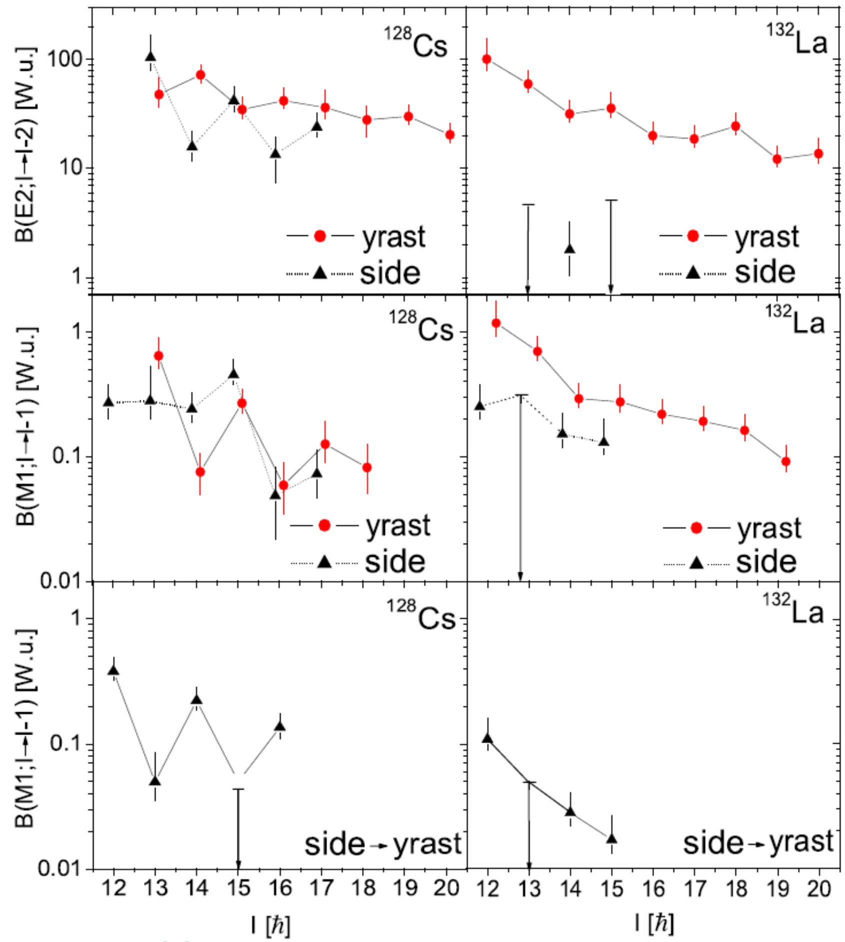
Doublet bands ≠ Chiral bands

- Selection rule
  - Symmetry consideration



T. Koike, K. Starosta, I. Hamamoto, Phys. Rev. Lett. 93, 172502 (2004).

Experiment

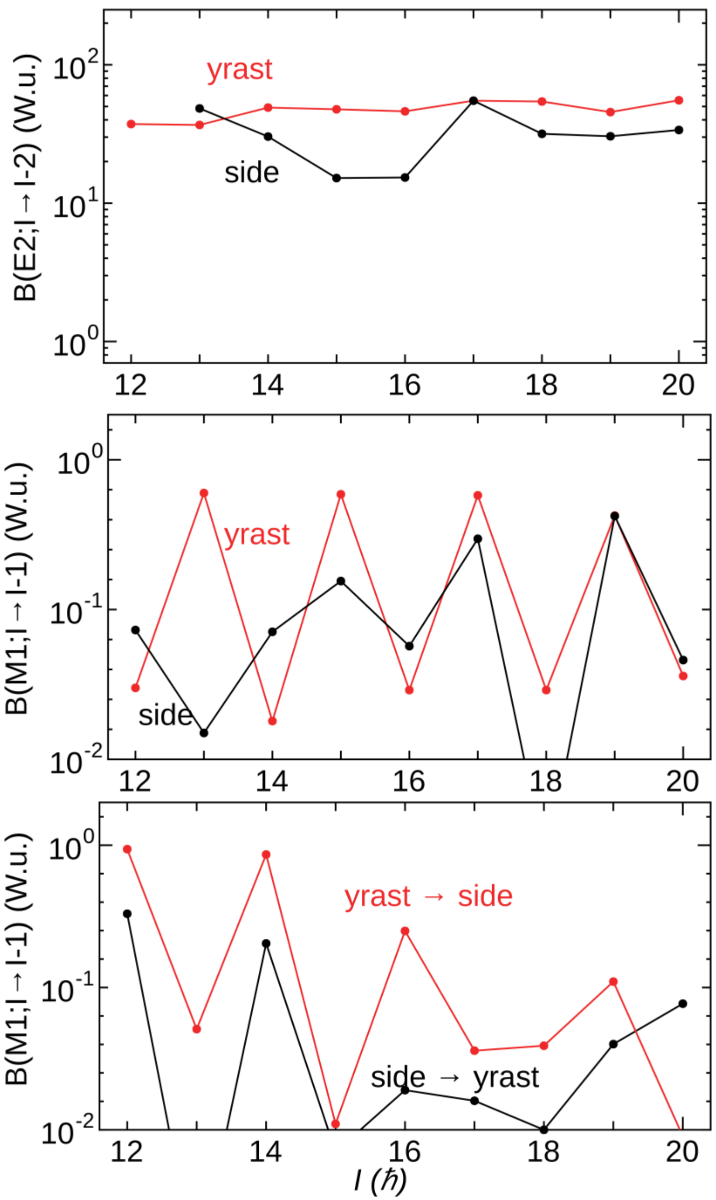


^{128}Cs: a best candidate

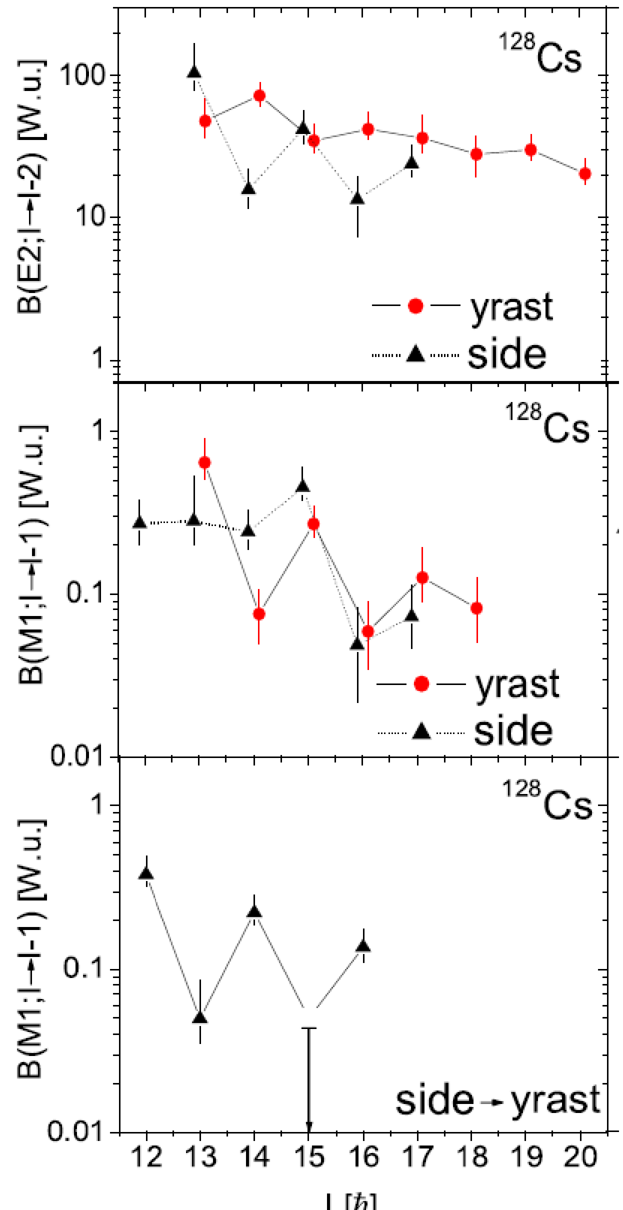
E. Grodner *et al.,*
Phys. Rev. Lett 97, 172501 (2006).

^{128}Cs: transitions

LSSM calc.

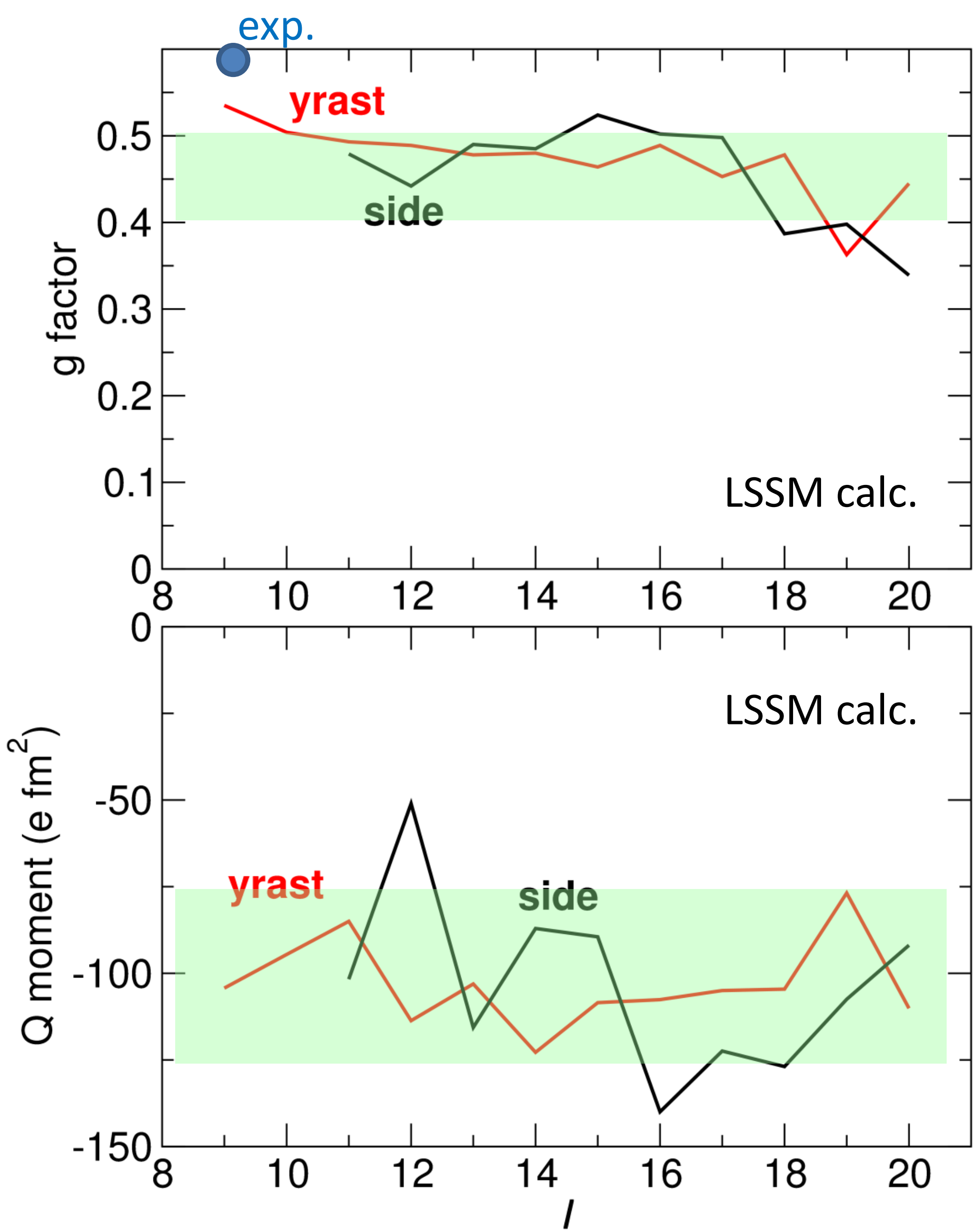


Expt. (Grodner *et al.*)



^{128}Cs: moments

- Worth calculating to see whether the doublet bands are the partners.
- *g* factors
  - Exp. g=+0.59(1) for the 9⁺ state (Grodner 2018)
  - Similar between yrast and side
  - Nearly constant around 0.4-0.5
  - Seems consistent with chiral
- *Q* moments
  - Similar between yrast and side
  - Rather stable for yrast
  - Fluctuating by ±25% for side

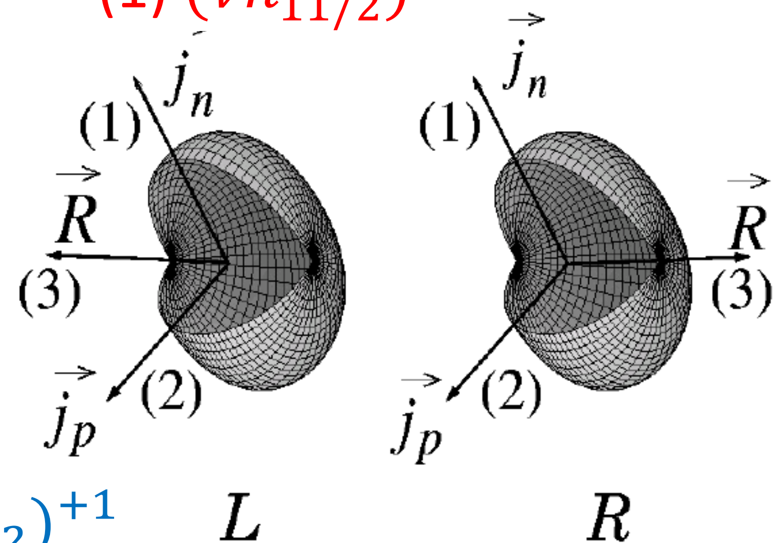


Chiral band or not ?

- To investigate the nature of the doublet bands in ^{128}Cs
  - Calculating the overlaps $\left\langle {}^{128}\mathrm{Cs}, In_1 \middle\| \left[a^{\dagger}_{\pi h11/2} \times a_{\nu h11/2}\right]^{\lambda} \middle\| {}^{128}\mathrm{Xe}, Rn_2 \right\rangle$, where In_1 and Rn_2 denote the states of ^{128}Cs and ^{128}Xe, respectively, and λ stands for the coupling of a proton particle and a neutron hole.
  - If $\overrightarrow{j_p}$ and $\overrightarrow{j_n}$ are orthogonal, λ of large overlaps should be $\sqrt{2} \times \frac{11}{2} \sim 8$.

(1) $(\nu h_{11/2})^{-1}$

(3) ^{128}Xe core J_i

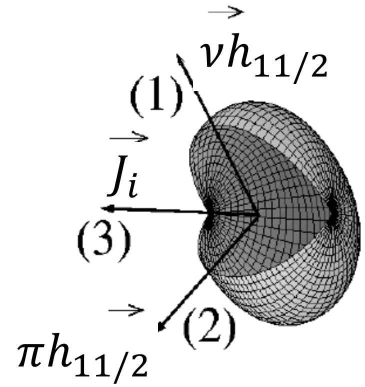


(2) $(\pi h_{11/2})^{+1}$

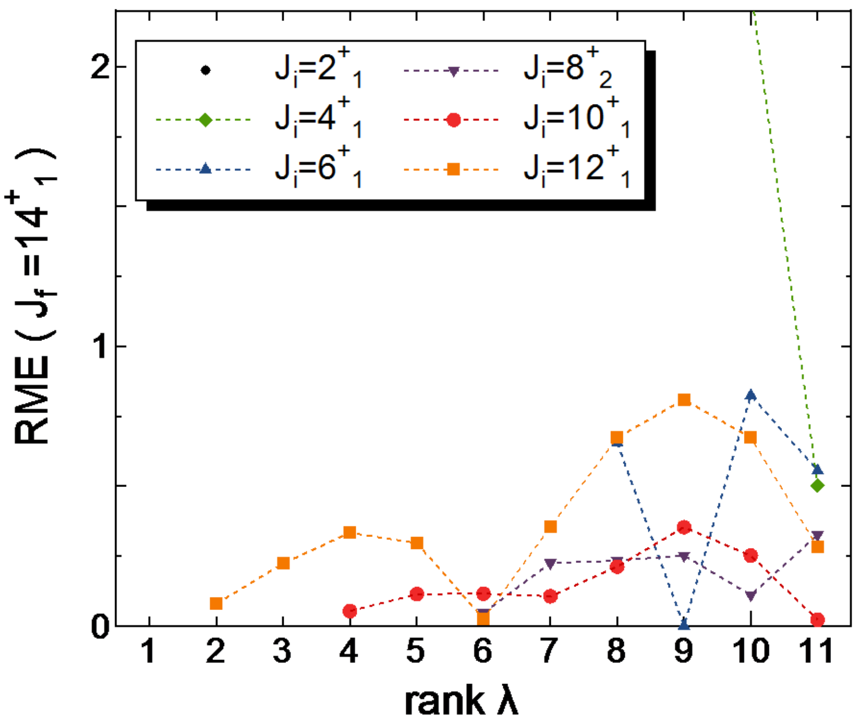
One-body reduced matrix element between ^{128}Cs and ^{128}Xe

- analogy to Two-Nucleon Amplitude
- OBRME for the $J_f = 14^+$ states of ^{128}Cs

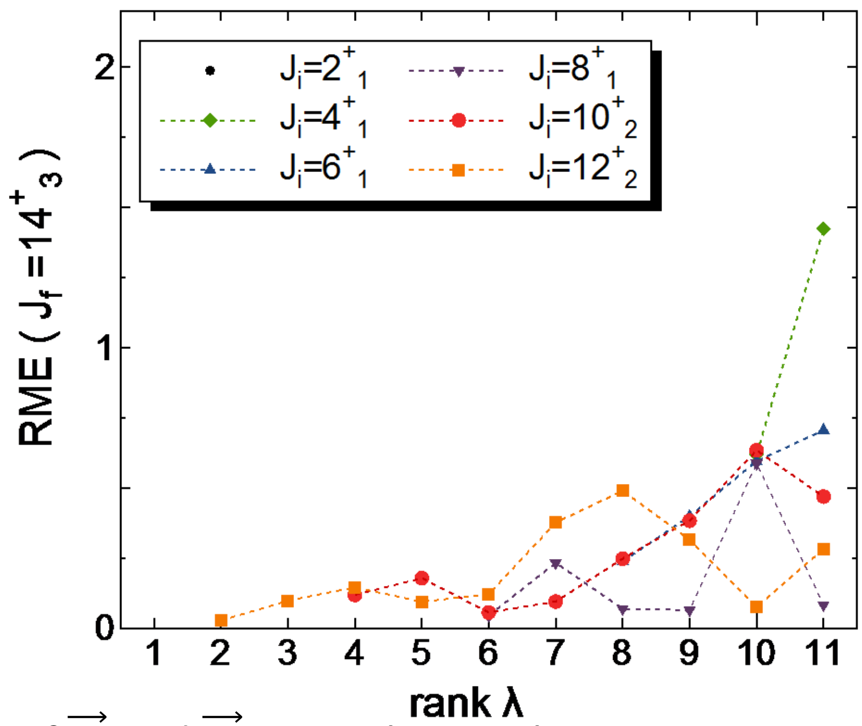
$$\langle ^{128}\mathrm{Cs}; J_f n_f || [c^{\dagger}_{\pi h11/2} \otimes c_{\nu h11/2}]^{(\lambda)} || ^{128}\mathrm{Xe}; J_i n_i \rangle$$



^{128}Cs 14$^+$ yrast state



^{128}Cs 14$^+$ chiral partner



c.f. $\lambda = \sqrt{2} \times \frac{11}{2} \sim 8$ If $\vec{j_p}$ and $\vec{j_n}$ are orthogonal.

Further investigations are ongoing.

Summary

- A~130 mass nuclei is interesting for triaxial deformation are described by the LSSM calculations
  - shell-model code developments : 10^{11} M-scheme dimension is feasible

- Shell evolution of Sb isotopes : driven by tensor force with a certain configuration mixing

- High-spin states of ^{134}Ba and ^{135}La are well understood by the LSSM calc. including collective states

- ^{128}Cs as a candidate of chiral doublet bands :
  - Fully correlated LSSM successfully reproduces the experimental behaviors
  - ^{128}Xe core plus $\pi h_{11/2}^{+1}$ $\nu h_{11/2}^{-1}$ configuration while further investigations are required to confirm the chiral doublet bands