# New interpretation of chiral doublet bands by a pair-truncated shell model

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## Outline of my talk

- Introduction
- Framework of the PTSM and its application to even-even and odd-mass nuclei
- New band mechanism of doubly-odd nuclei
- Summary

**In collaboration with N. Yoshinaga and K. Tanabe (Saitama university)**

# Introduction

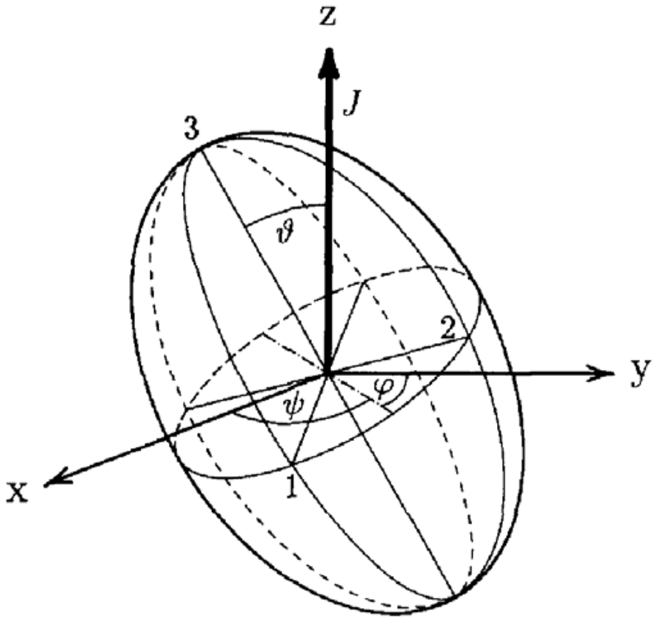
NUCLEAR

A 617 (1997)

## Tilted Axis Cranking model

Doubly odd nuclei with triaxial deformation

Orientation of axis of rotation is tiled to three axis



## Particle Rotor Model

One neutron hole and one proton particle coupled with a rigid triaxial rotor

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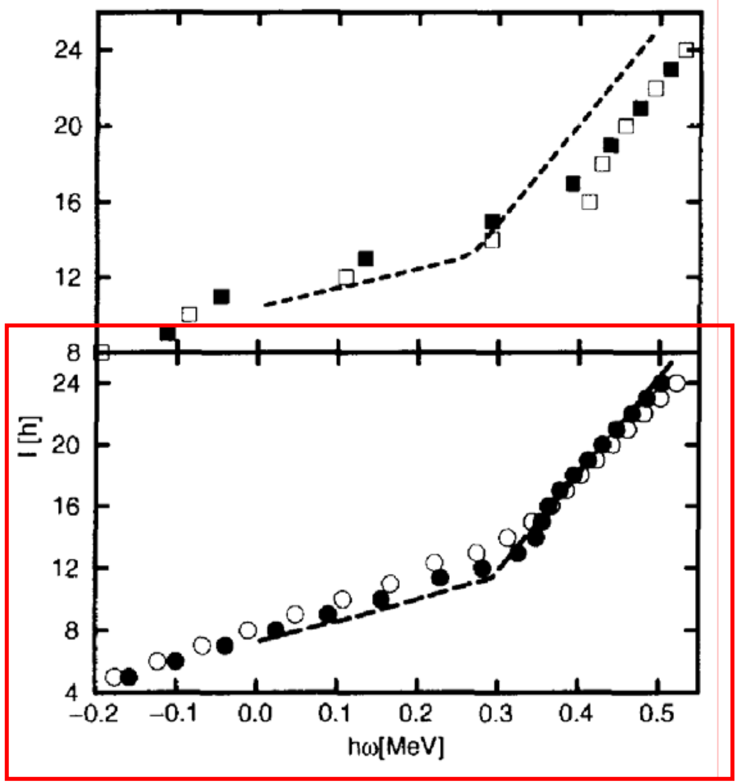


PACS: . . .
Keywords: Tilted axis cranking; Triaxiality; Chirality

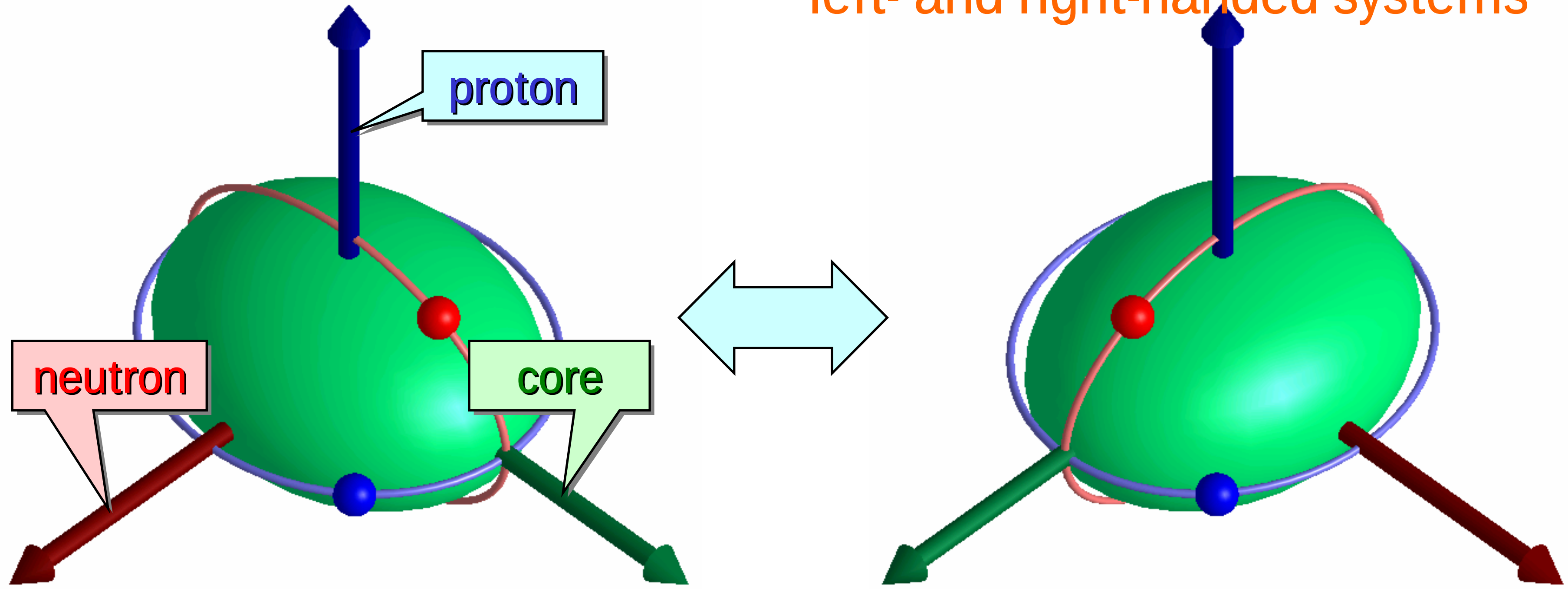
# Interpretation of chiral doublet bands

High j holes tend to align with long axis

High j particles tend to align with short axis

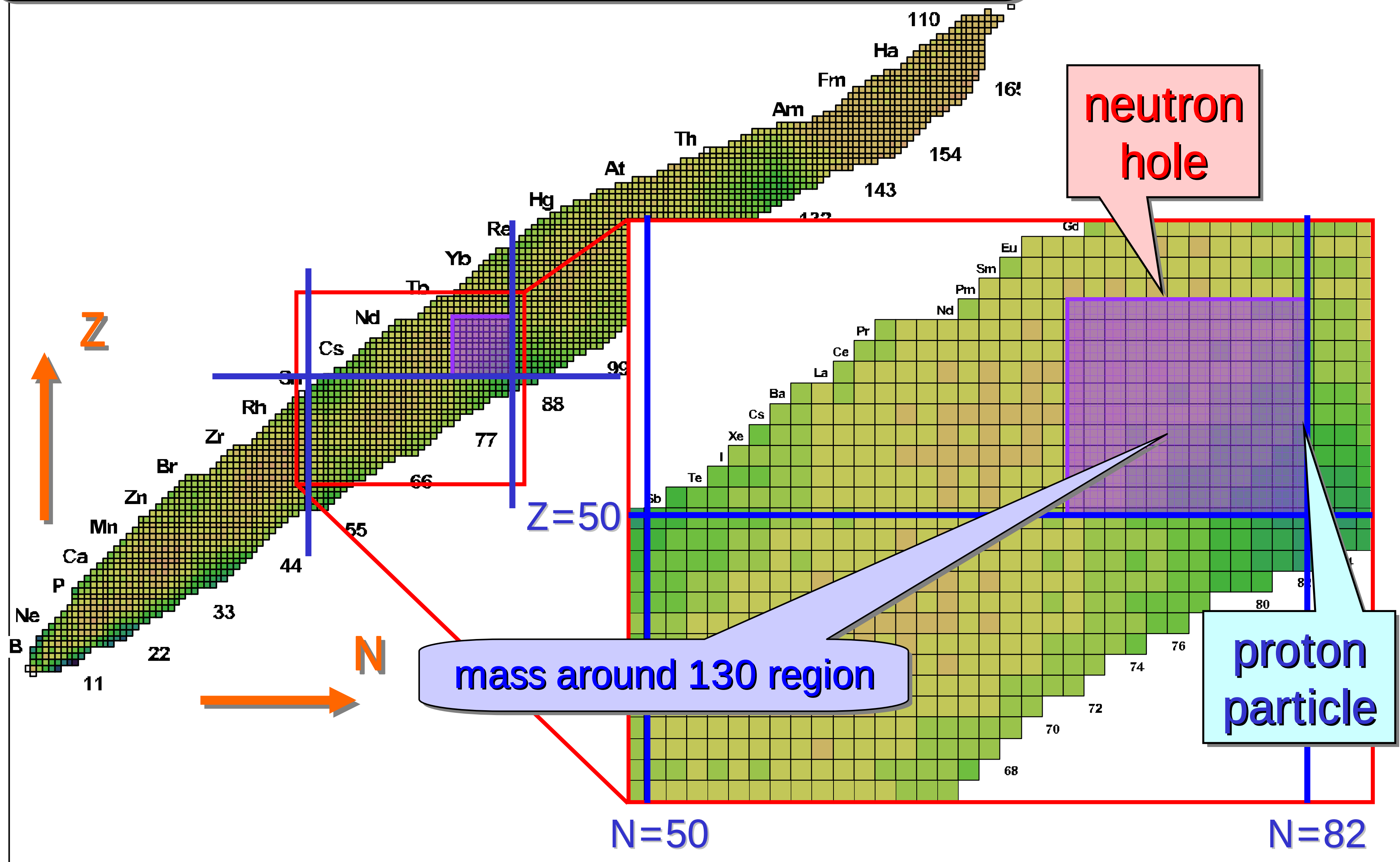
Triaxial core tend to align with intermediate axis

⇨ Three angular momenta construct left- and right-handed systems



Two nearly degenerate $\Delta I=1$ bands of the same parity originate from these systems

# Candidates for chiral doublet bands



neutron hole

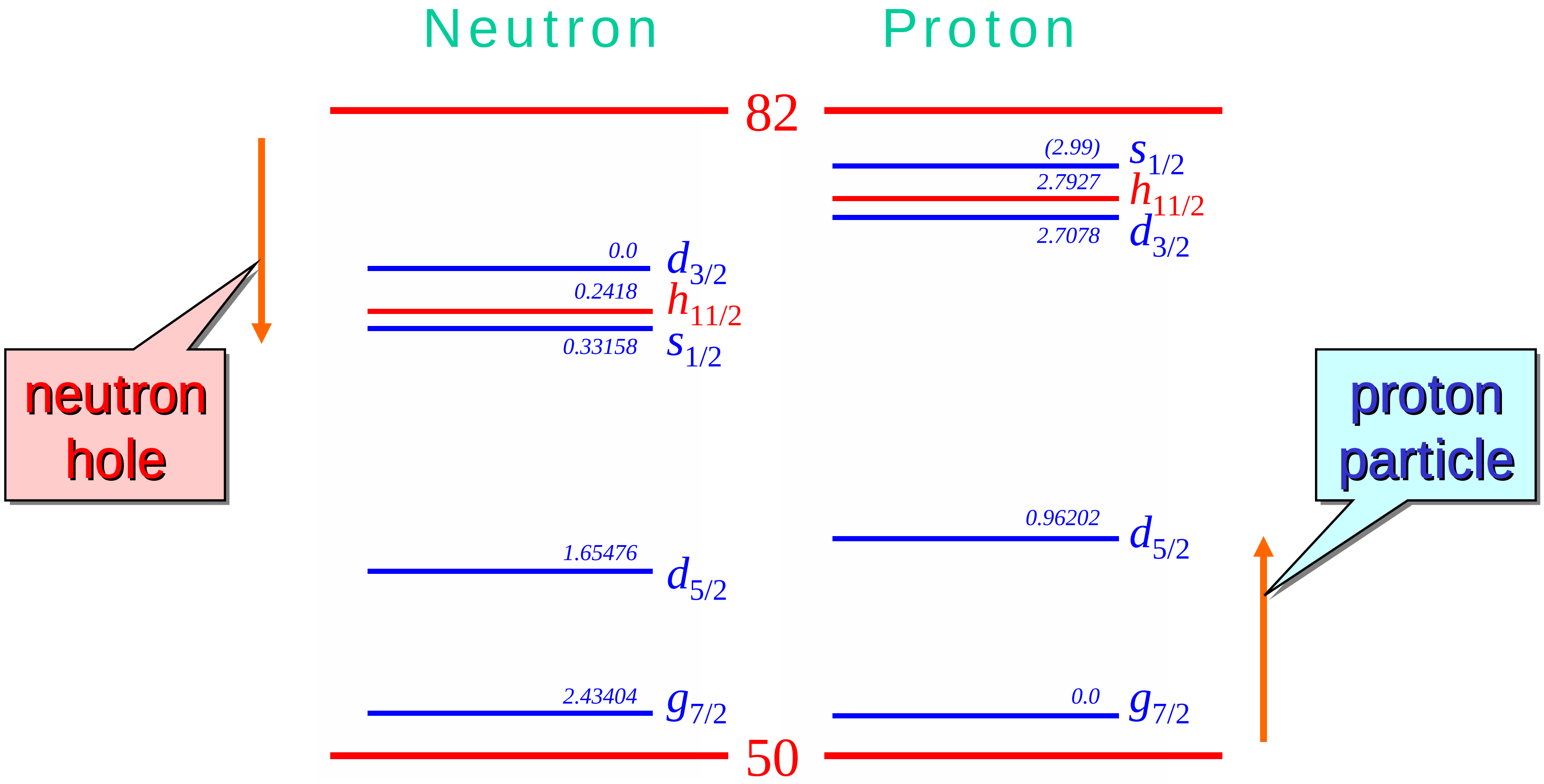
proton particle

mass around 130 region

The A~130 nuclei have several valence protons outside the closed shell Z=50 and several neutron holes with respect to the closed shell N=82.

# Single particle orbitals

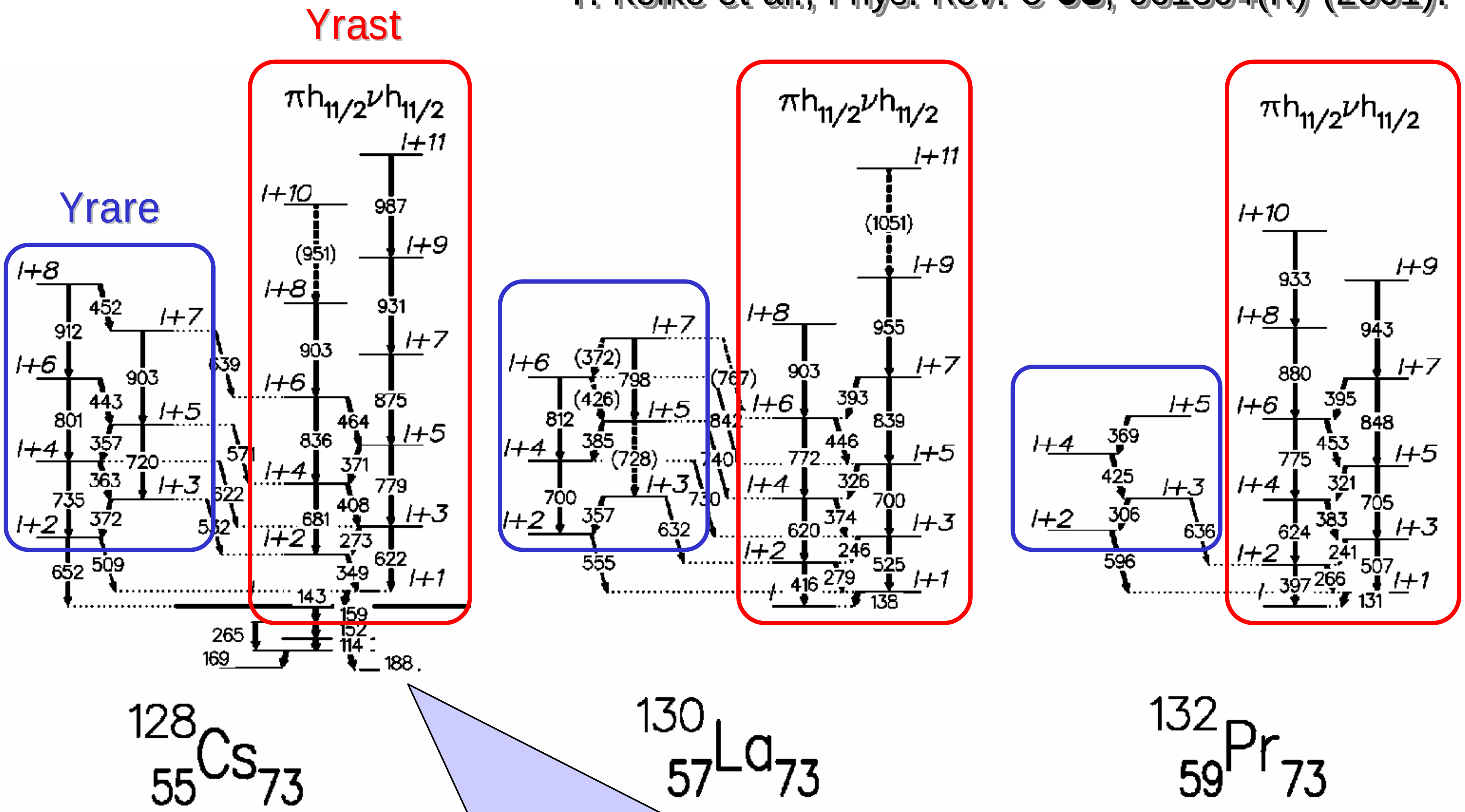
The single particle (hole) energies for proton (neutron)



The $0h_{11/2}$ orbital plays a Important role in the description of the chiral doublet bands.

# Experiment of doubly-odd nuclei

T. Koike et al., Phys. Rev. C **63**, 061304(R) (2001).



⊿I =1 bands have been found in many doubly-odd nuclei with mass around 130.

# Experiment of doubly-odd nuclei

D. J. Hartley et al,
Phys. Rev. C **64**, 031304(R) (2001).

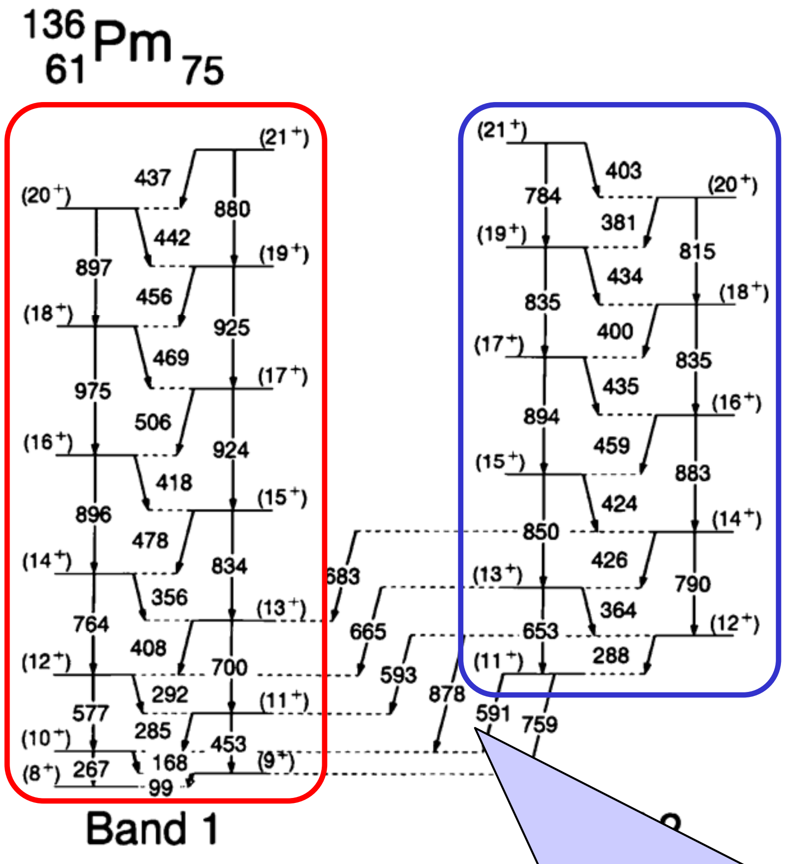


FIG. 1. Partial level scheme of $^{136}$Pm deduc

**⊿I =1 bands have been found in many doubly-odd nuclei with mass around 130.**

## Studies for A~130 nuclei

K. Starosta et al.,
Phys. Rev. Lett. **86**, 971 (2001).

A. A. Hecht et al.,
Phys. Rev. C **63**, 051302(R) (2001).

R. A. Bark et al.,
Nucl. Phys. **A691**, 577 (2001).

K. Starosta et al.,
Phys. Rev. C **65**, 044328 (2002).

T. Koike et al.,
Phys. Rev. C **67**, 044319 (2003).

G. Rainovski et al.,
Phys. Rev. C **68**, 024318 (2003).

A. A. Hecht et al.,
Phys. Rev. C **68**, 054310 (2003).

S. Zhu et al.,
Phys. Rev. Lett. **91**, 132501 (2003).

# Tilted axis cranking model

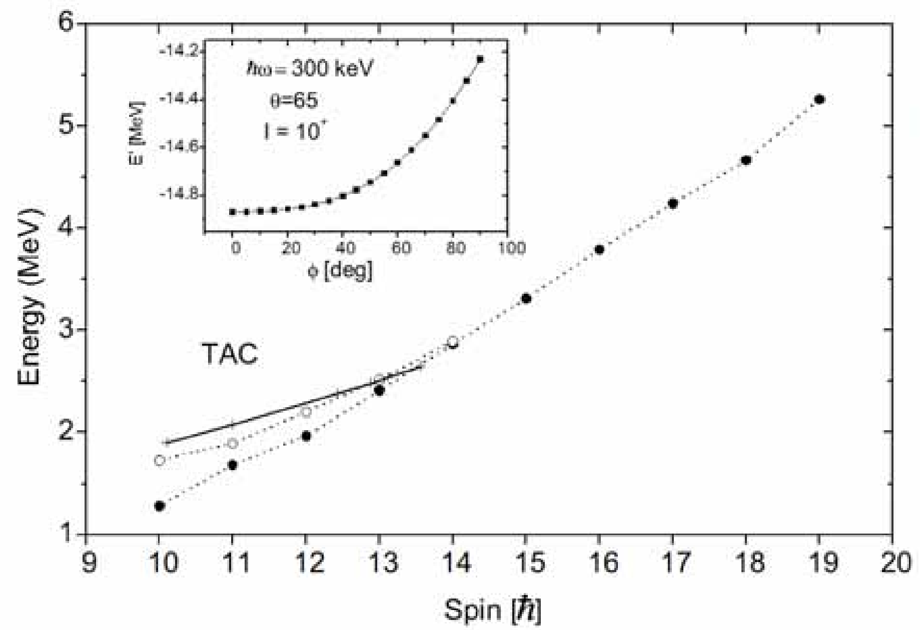
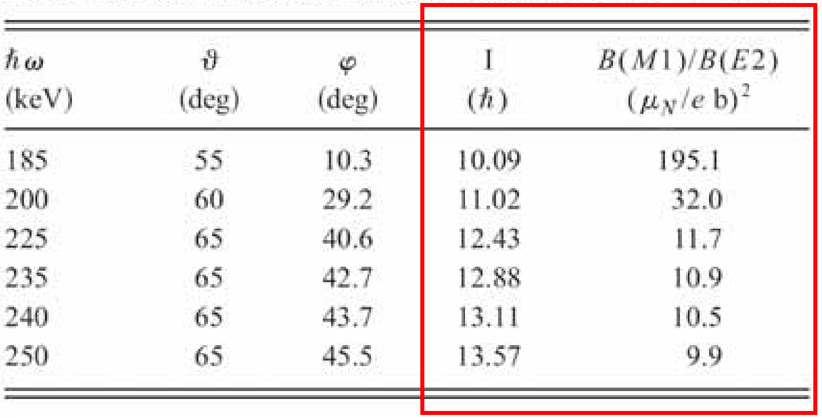


FIG. 3. Experimental energies vs spin for band 2 (filled symbols) and band 3 (open symbols) in $^{132}$Cs (cf. Fig. 2). The 3D TAC energies for the chiral $\pi h_{11/2} \otimes \nu h_{11/2}$ solution with no pairing included in $^{132}$Cs are shown by the solid line. The inset presents the dependence of the total routhian on the tilt angle $\varphi$ when the pairing is included in the calculations.

G. Rainovski et al.,
Phys. Rev. C **68**, 024318 (2003).

TABLE II. The results of 3D TAC calculations with no pairing included for the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration in $^{132}$Cs. The deformation parameters used were $\varepsilon_2 = 0.161$, $\varepsilon_4 = 0.003$, and $\gamma = 36°$. These were obtained as self-consistence values at $\hbar\omega = 185$ keV.



| $\hbar\omega$ (keV) | $\vartheta$ (deg) | $\varphi$ (deg) | I ($\hbar$) | $B(M1)/B(E2)$ $(\mu_N/e\,\text{b})^2$ |
|---|---|---|---|---|
| 185 | 55 | 10.3 | 10.09 | 195.1 |
| 200 | 60 | 29.2 | 11.02 | 32.0 |
| 225 | 65 | 40.6 | 12.43 | 11.7 |
| 235 | 65 | 42.7 | 12.88 | 10.9 |
| 240 | 65 | 43.7 | 13.11 | 10.5 |
| 250 | 65 | 45.5 | 13.57 | 9.9 |

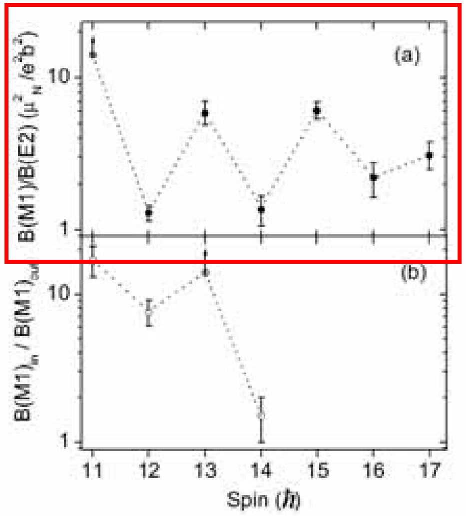


FIG. 4. (a) Measured $B(M1;I\rightarrow I-1)/B(E2;I\rightarrow I-2)$ ratios for band 2 in $^{132}$Cs. (b) Measured $B(M1;I\rightarrow I-1)_{in}/B(M1;I\rightarrow I-1)_{out}$ ratios for band 3 in $^{132}$Cs. The lines are drawn to guide the eye.

# Rigid triaxial rotor + two quasi-particles

- Particle rotor model
- Phenomenological core-particle-hole coupling model

even-even core

⇨ Rigid triaxial rotor

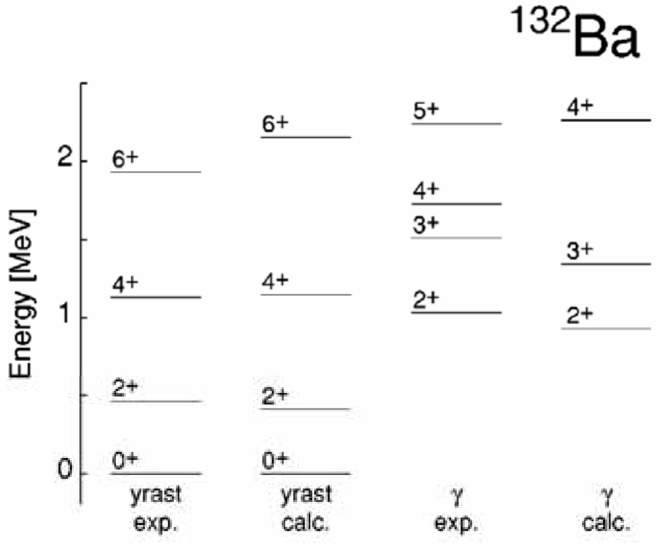


FIG. 4. Comparisons between energies of excited states in the yrast and $\gamma$ bands in $^{130}$Ba and $^{132}$Ba with those calculated for a rigid triaxial rotor. See Table II for the model parameters. The experimental data are taken from Refs. [29] and [30] for $^{130}$Ba and $^{132}$Ba, respectively.

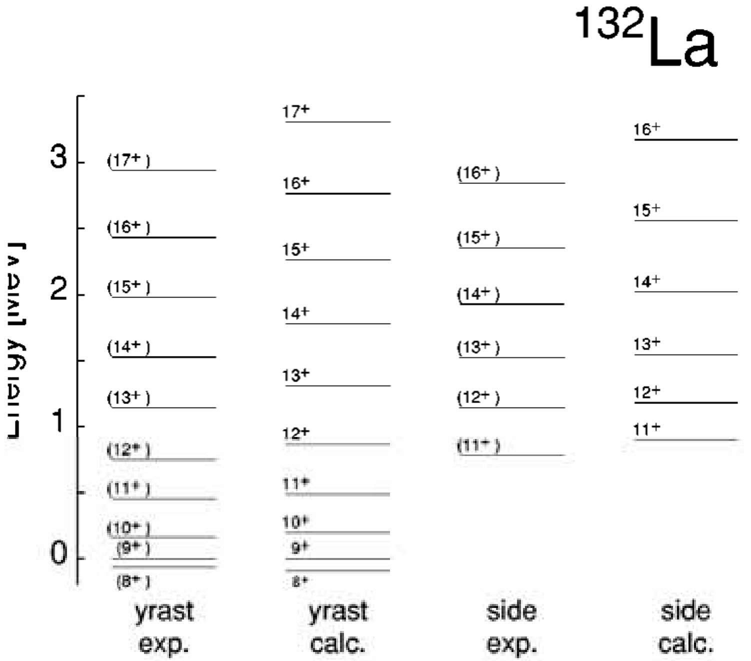


FIG. 7. Comparison between energies of excited states in the artner band in $^{132}$La with those calculated for $\pi h_{11/2}\nu^{-1}h_{11/2}$ article-hole coupling with a rigid triaxial rotor (see Table II for the model parameters). Theoretical states are shown only when the cor- sponding experimental states are known.

K. Starosta et al.,
Phys. Rev. C **65**, 044328 (2002).

# Interacting boson fermion-fermion model

even-even core ⇨ IBM

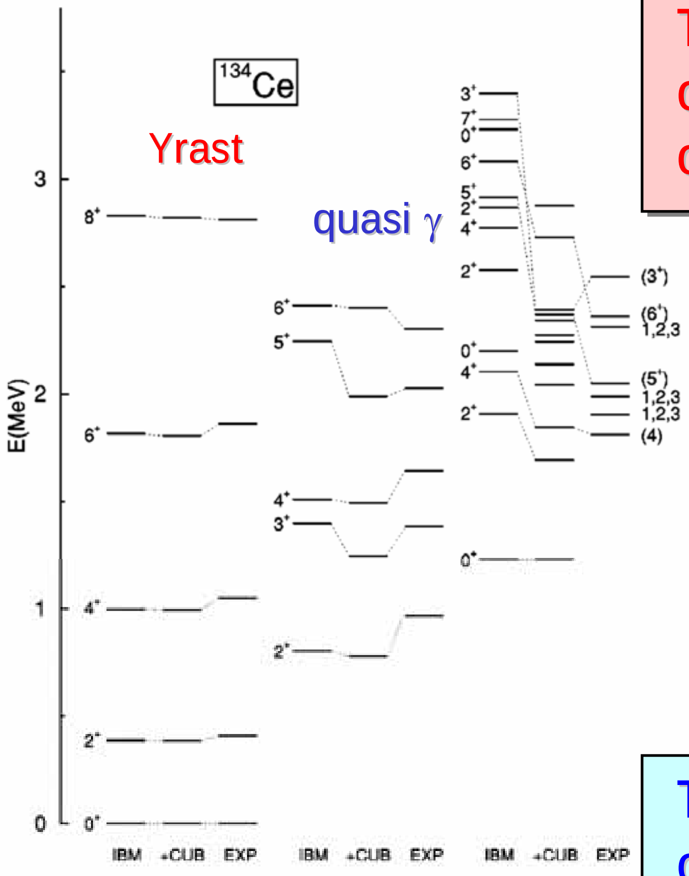
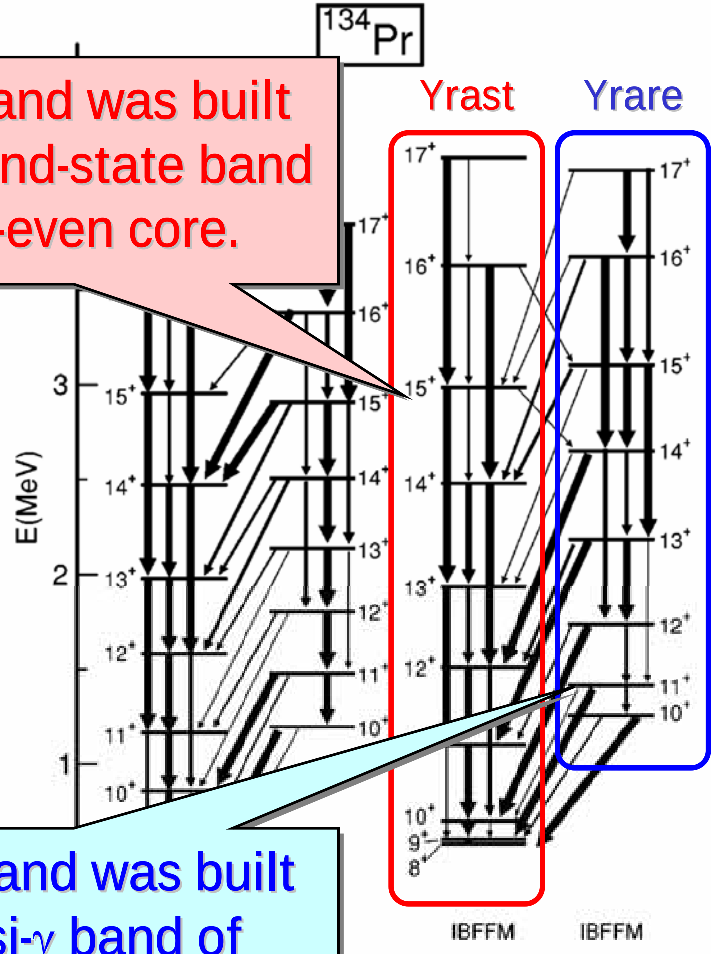


FIG. 1. IBM spectra of $^{134}$Ce shown in comparison with experimental positive-parity levels (right columns). The leve the left columns correspond to the IBM calculation with $\Theta_3$= the Hamiltonian (1), i.e., the term that induces triaxial deformation is not included. The nucleus is γ soft. The middle columns present the ground-state band, the γ band, and levels belonging to higher structures, calculated with $\Theta_3$=0.025 MeV. The cubic term in the Hamiltonian induces a stable triaxial deformation.

The yrast band was built on the ground-state band of the even-even core.



The yrare band was built on the quasi-γ band of the even-even core.

xperimental doublet of nearly de- $^{134}$Pr with the lowest two bands calculated in the IBFFM. The calculation includes the triaxial deformation of the core nucleus. The thickness of the arrows that denote transitions corresponds to the relative γ intensity in each branch.

S. Brant et al., Phys. Rev. C **69**, 017304 (2004).

# Experiment

⊿ I =1 doublet bands have been observed.

- Mass A~130 : Odd-mass and doubly-odd nuclei
- Mass A~100 : Odd-mass and doubly-odd nuclei
- Mass A~190 : Doubly-odd nuclei

# Theory

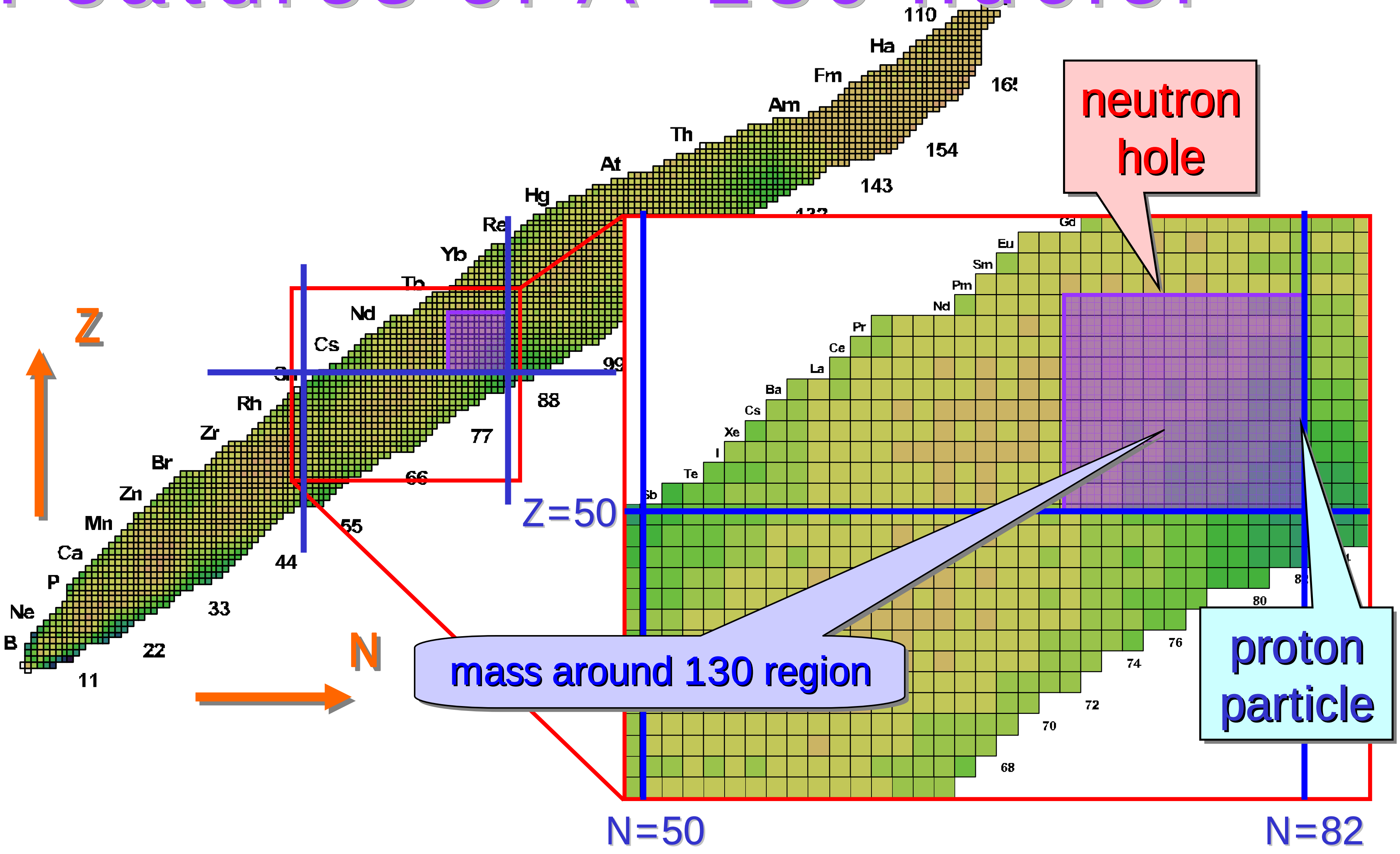
- Tilted axis cranking model

  ⇨ Support the chiral doublet bands
- Particle rotor model
- Phenomenological core-particle-hole coupling model

  One neutron hole and one proton particle
  coupled with a rigid triaxial rotor

  ⇨ Support the chiral doublet bands
- Interacting boson fermion-fermion model

# Features of A~130 nuclei



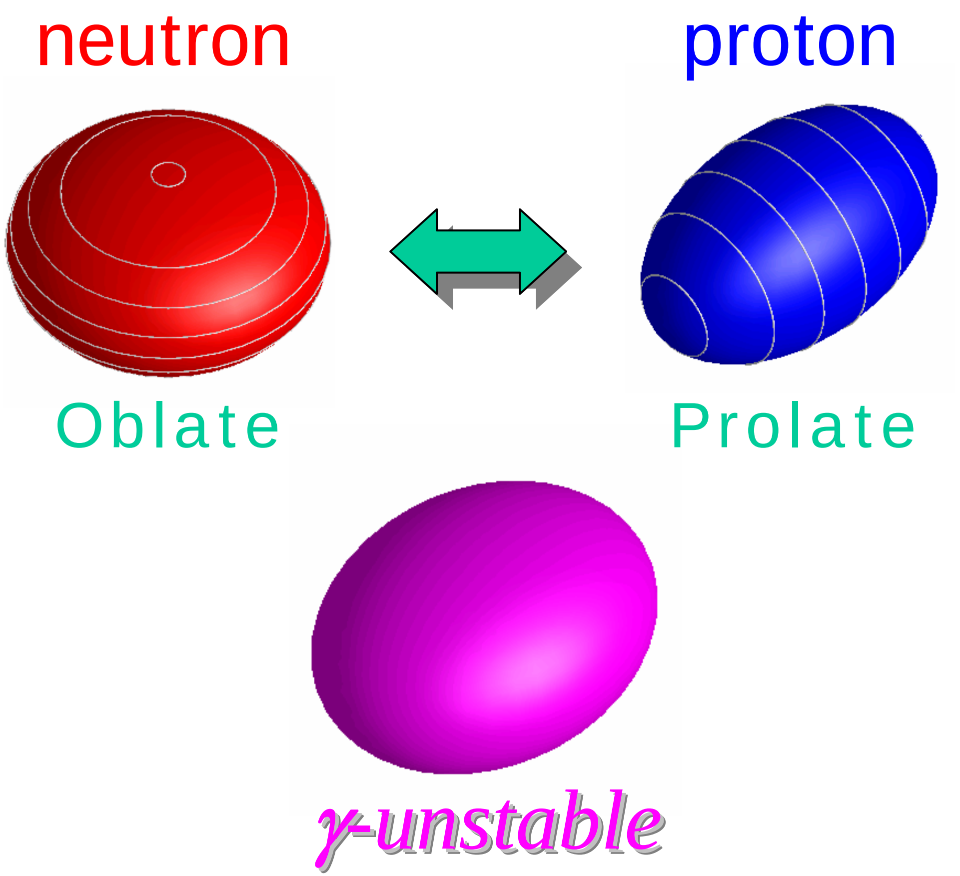
neutron hole

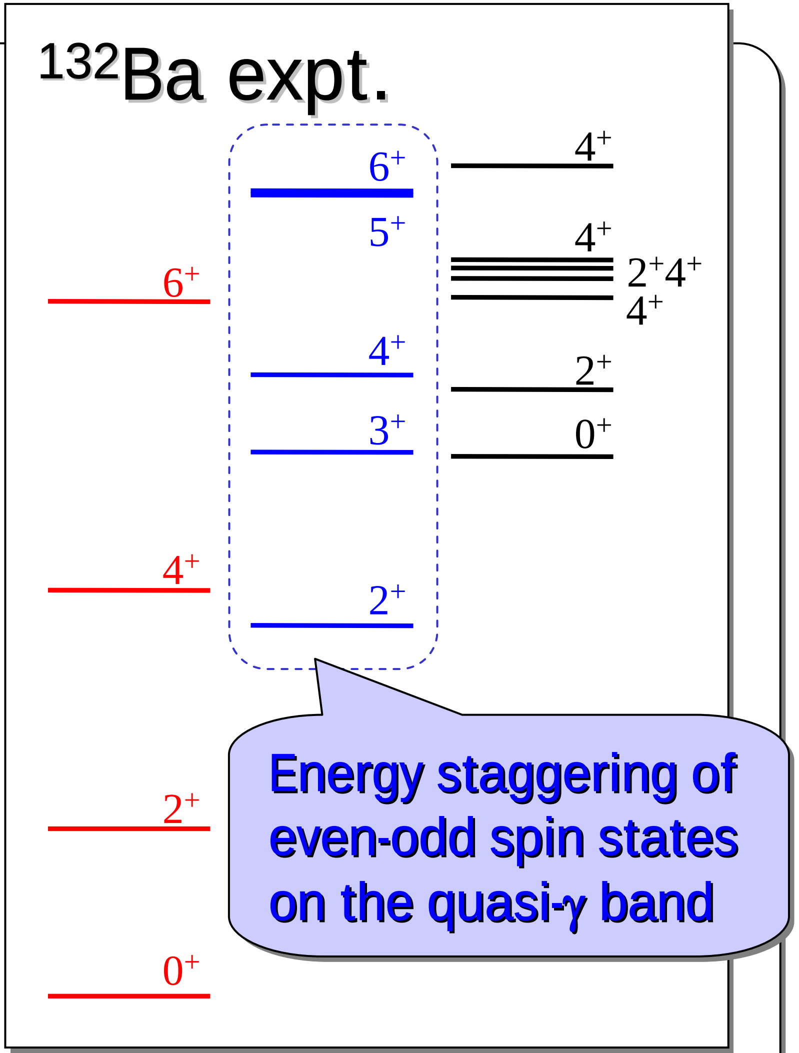
mass around 130 region

proton particle

The A~130 nuclei have several valence protons outside the closed shell Z=50 and several neutron holes with respect to the closed shell N=82.

# Low-lying collective states




$^{132}$Ba expt.

Energy staggering of even-odd spin states on the quasi-γ band

- Mean field theories are not applicable.
- Exact shell model calculations are not possible.

⇨ **Pair-truncated Shell Model**

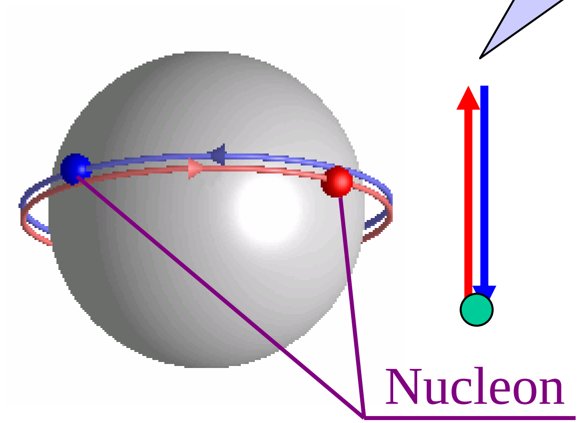
# Pair truncated shell model

## SD-pair states

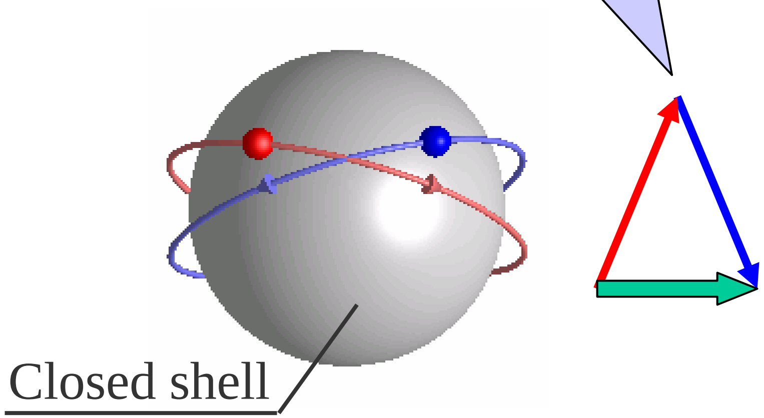
Angular momentum 0

Angular momentum 2

### S-pair



### D-pair



$$S^\dagger = \sum_j \alpha_j A_0^{\dagger(0)}(jj)$$

$$D_M^\dagger = \sum_{j_1 j_2} \beta_{j_1 j_2} A_M^{\dagger(2)}(j_1 j_2)$$

$$\left( A_M^{\dagger(J)}(j_1 j_2) = \sum_{m_1 m_2} (j_1 m_1 j_2 m_2 | JM)\, c_{j_1 m_1}^\dagger c_{j_2 m_2}^\dagger = \left[ c_{j_1}^\dagger c_{j_2}^\dagger \right]_M^{(J)} \right)$$

### SD-pair state

$$(S^\dagger)^{n_s} (D^\dagger)^{n_d} \left| - \right\rangle = \left| S^{n_s} D^{n_d} J \right\rangle$$

# Odd system

SD-pair state $\left| S^{n_s} D^{n_d} I \right\rangle$

One nucleon is included to the SD-pair states

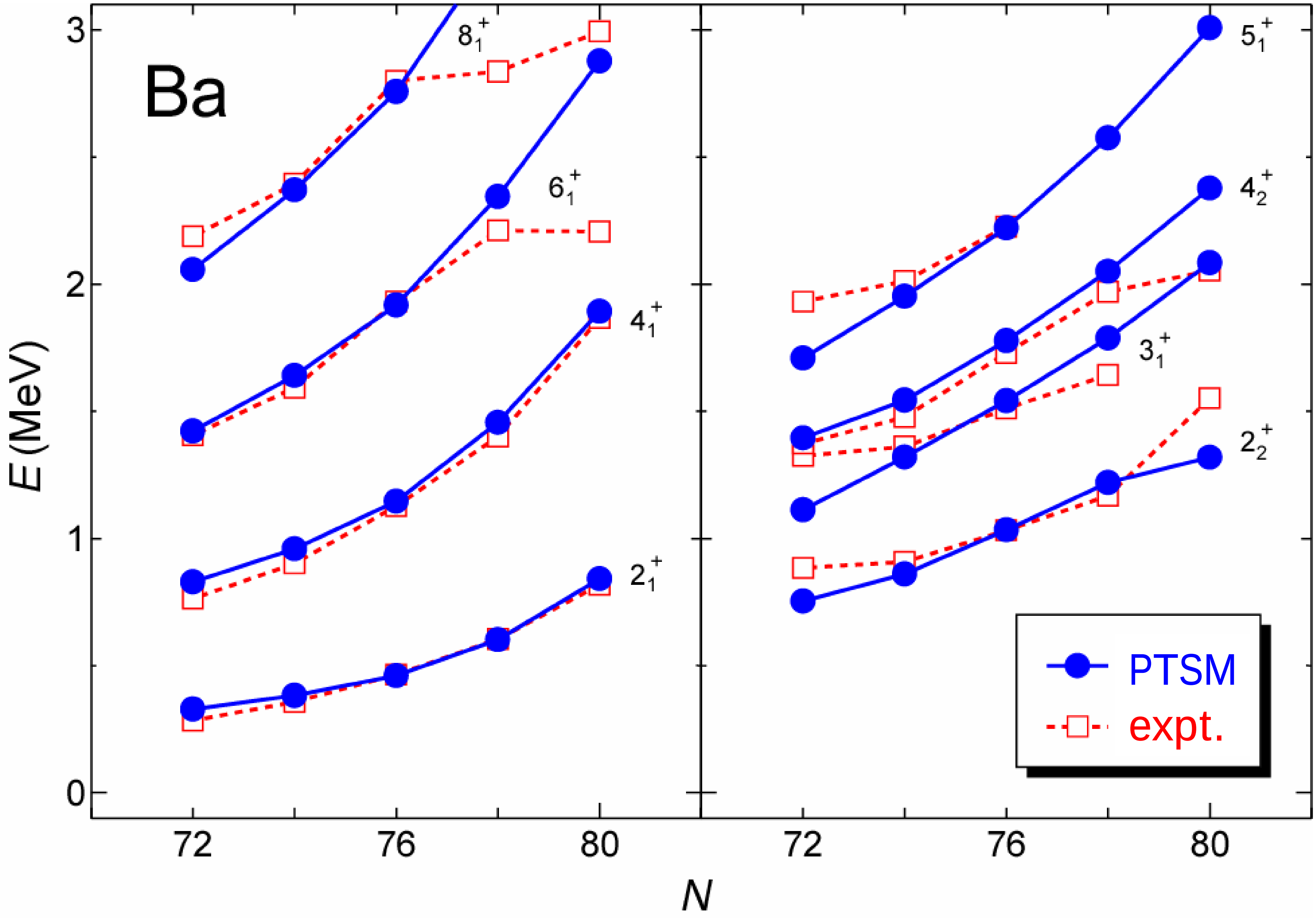
SD-pair+1 particle state

$$c_j^{\dagger} \left| S^{n_s} D^{n_d} I' \right\rangle = \left| j\, S^{n_s} D^{n_d} I \right\rangle$$

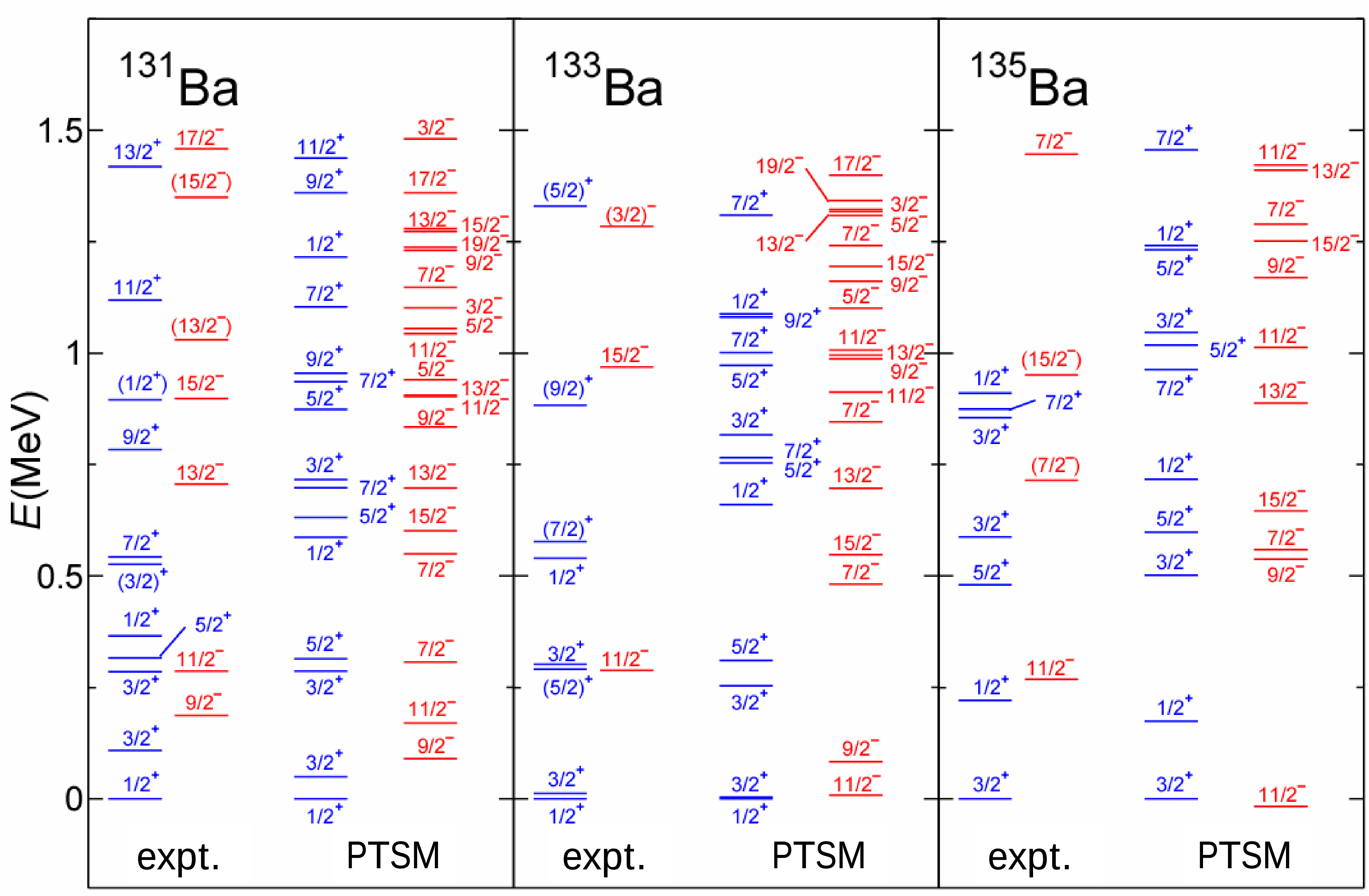
Basis state of even-even, odd-mass and doubly-odd nuclei

$$\left| \Phi(I) \right\rangle = \left[ \begin{pmatrix} \left| S_{\nu}^{n_s} D_{\nu}^{n_d} I_{\nu} \right\rangle \\ \left| j_{\nu}\, S_{\nu}^{n_s} D_{\nu}^{n_d} I_{\nu} \right\rangle \end{pmatrix} \otimes \begin{pmatrix} \left| S_{\pi}^{n_s} D_{\pi}^{n_d} I_{\pi} \right\rangle \\ \left| j_{\pi}\, S_{\pi}^{n_s} D_{\pi}^{n_d} I_{\pi} \right\rangle \end{pmatrix} \right]^{(I)}$$

In the PTSM, the shell-model basis is restricted to the SD subspace with angular momentum zero (S) and two (D) collective pairs.

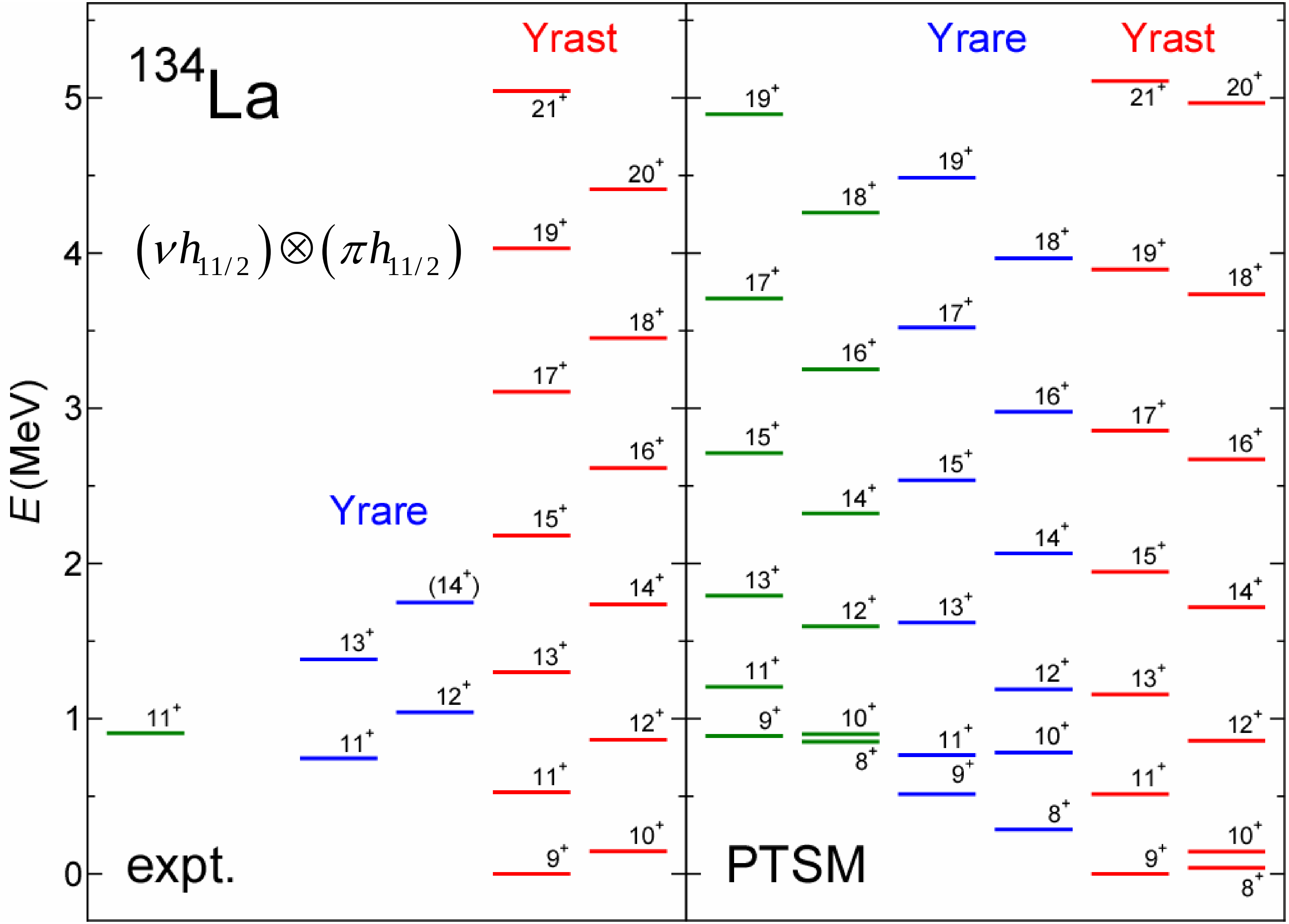


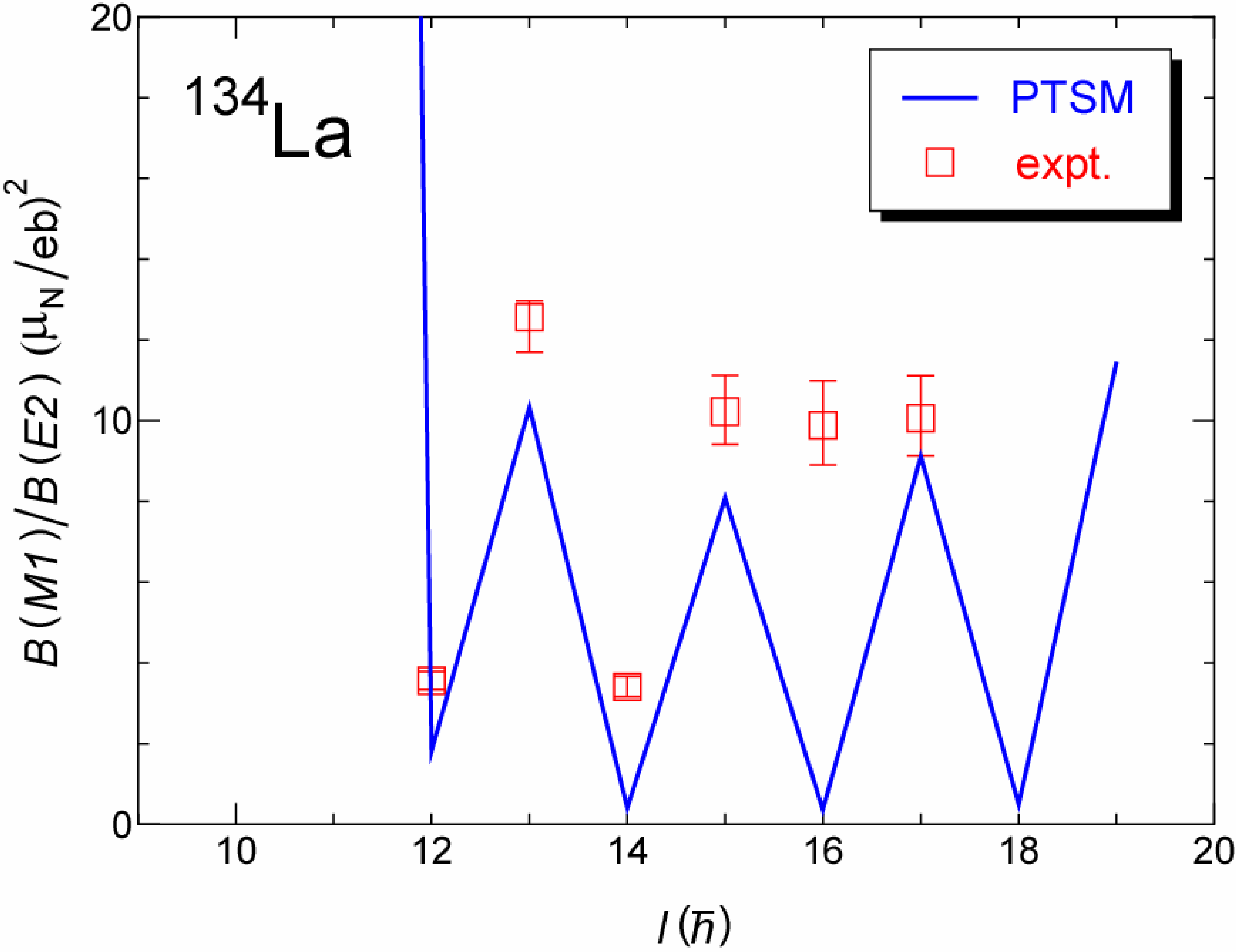
N. Yoshinaga and K. Higashiyama, Phys. Rev. C 69, 054309 (2004).



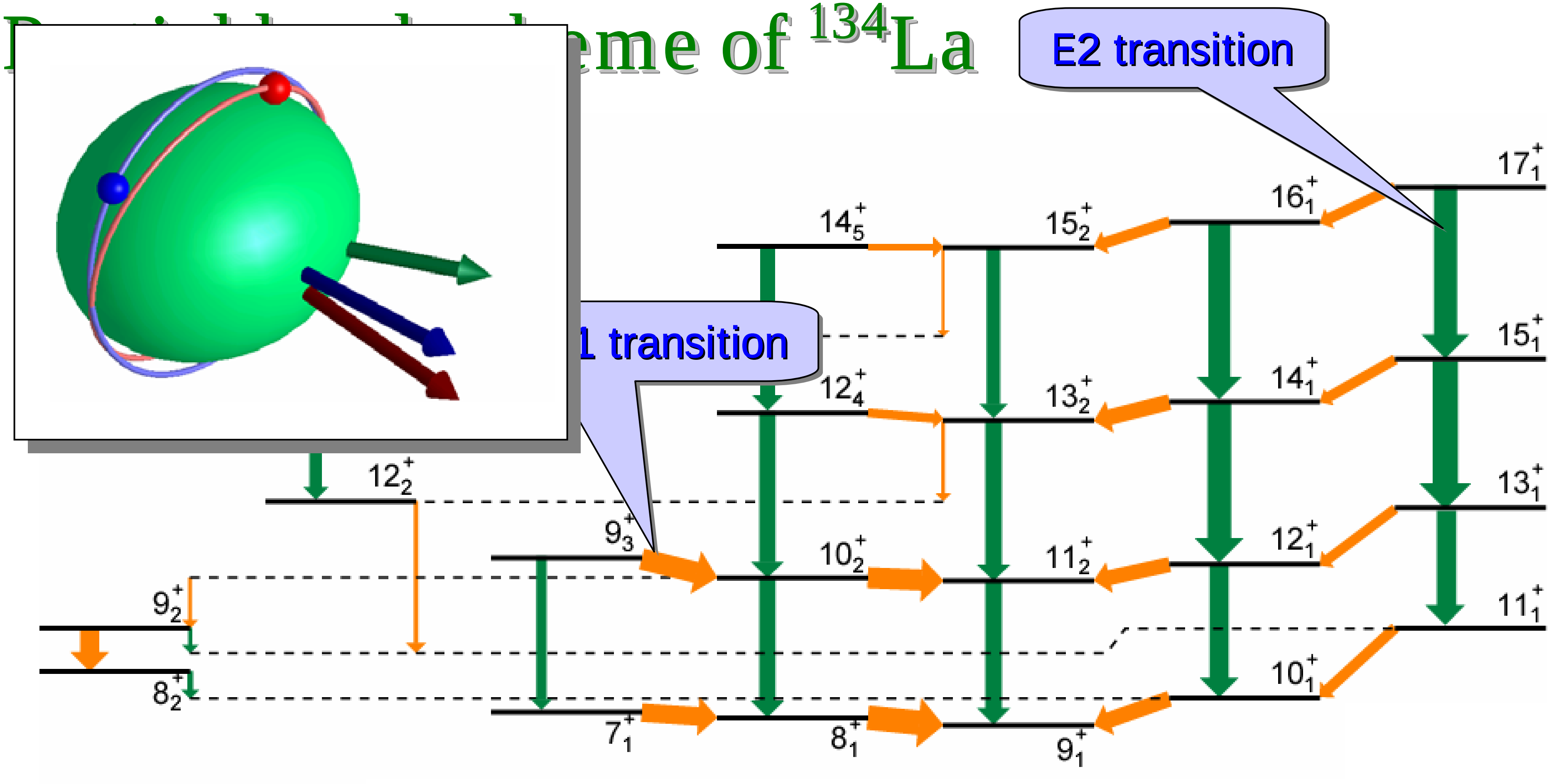
N. Yoshinaga and K. Higashiyama, Phys. Rev. C 69, 054309 (2004).

# Doubly-odd nuclei




$^{134}$La
PTSM
expt.
$B(M1)/B(E2)$ $(\mu_N/eb)^2$
$I\,(\hbar)$
0
10
20
10
12
14
16
18
20

# eme of $^{134}$La



We analyze the behavior of three angular momenta of the unpaired neutron , unpaired proton and even-even core.

# Internal structure of doublet bands

$\hat{\boldsymbol{j}}_{\tau j} \quad (\tau = \nu \text{ or } \pi)$ : angular momenta of valence nucleons in the $0h_{11/2}$ orbital

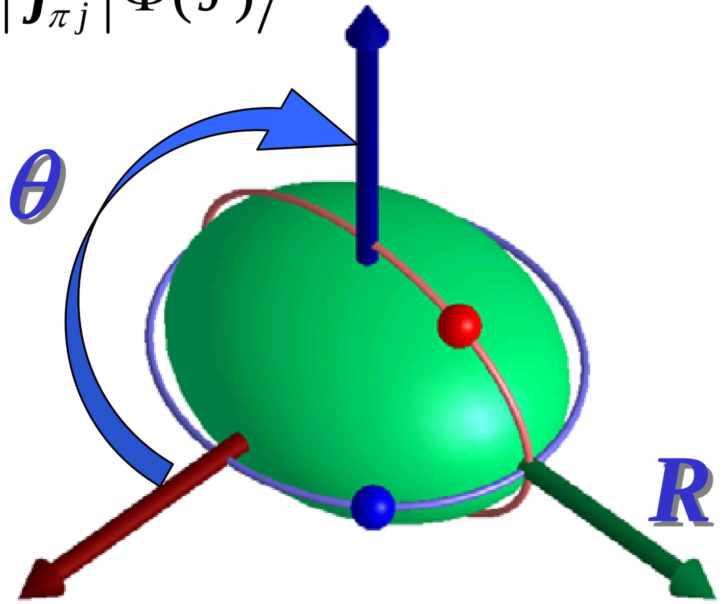
$\hat{\boldsymbol{R}} = \hat{\boldsymbol{J}} - \hat{\boldsymbol{j}}_{\nu j} - \hat{\boldsymbol{j}}_{\pi j}$ : angular momentum of the core

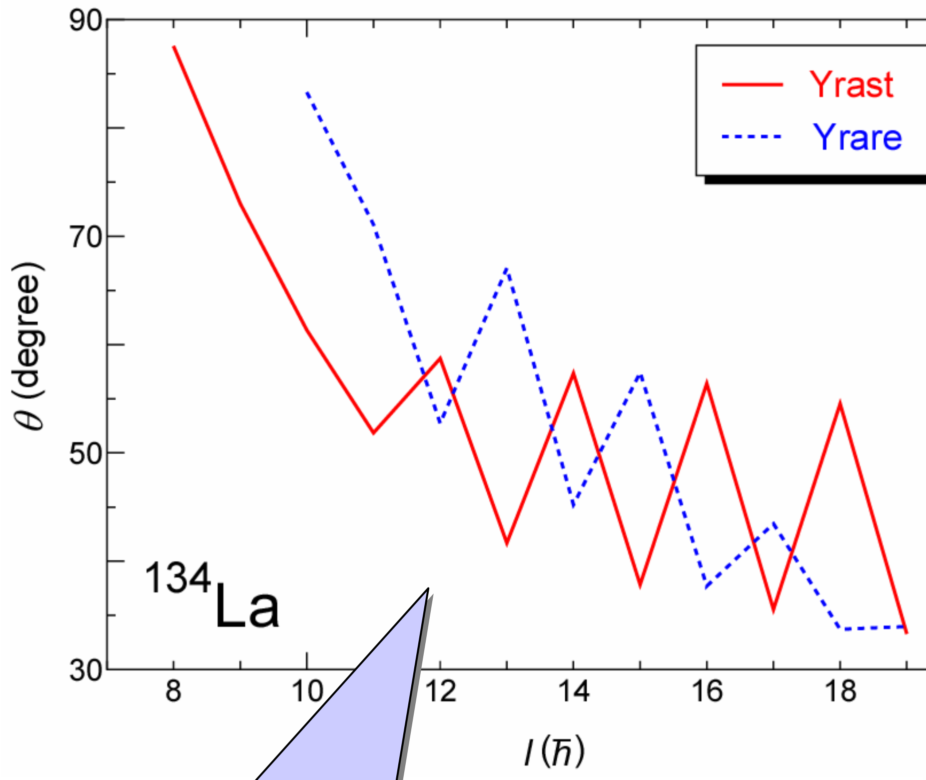
## Effective angle of two angular momenta

$$\cos\theta_{\mathbf{j}_{\nu j}\cdot\mathbf{j}_{\pi j}} = \frac{\langle\Phi(J)|\boldsymbol{j}_{\nu j}\cdot\boldsymbol{j}_{\pi j}|\Phi(J)\rangle}{\sqrt{\langle\Phi(J)|\boldsymbol{j}_{\nu j}^2|\Phi(J)\rangle\langle\Phi(J)|\boldsymbol{j}_{\pi j}^2|\Phi(J)\rangle}}$$

## Square of core angular momentum

$$R^2 = \langle\Phi(J)|\hat{\boldsymbol{R}}^2|\Phi(J)\rangle$$

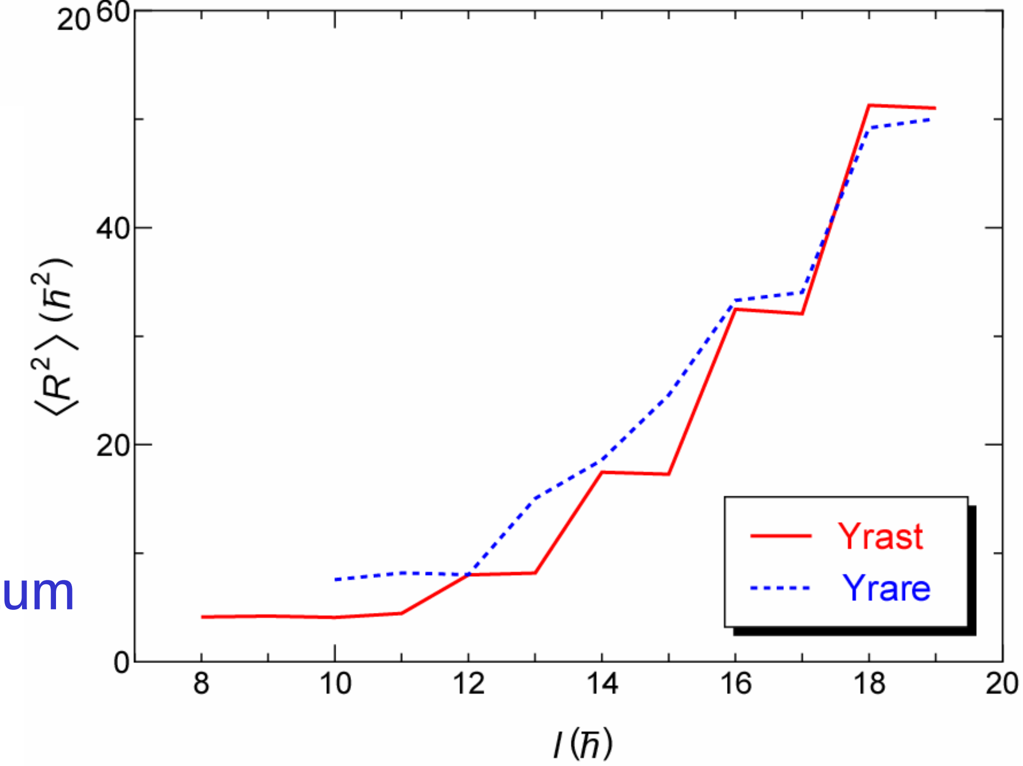




The effective angles of two angular momenta of the neutrons and protons in the $0h_{11/2}$ orbitals calculated in the PTSM.

**The effective angles never become zero because of quantum fluctuations.**

The squares of core angular momentum calculated in the PTSM.

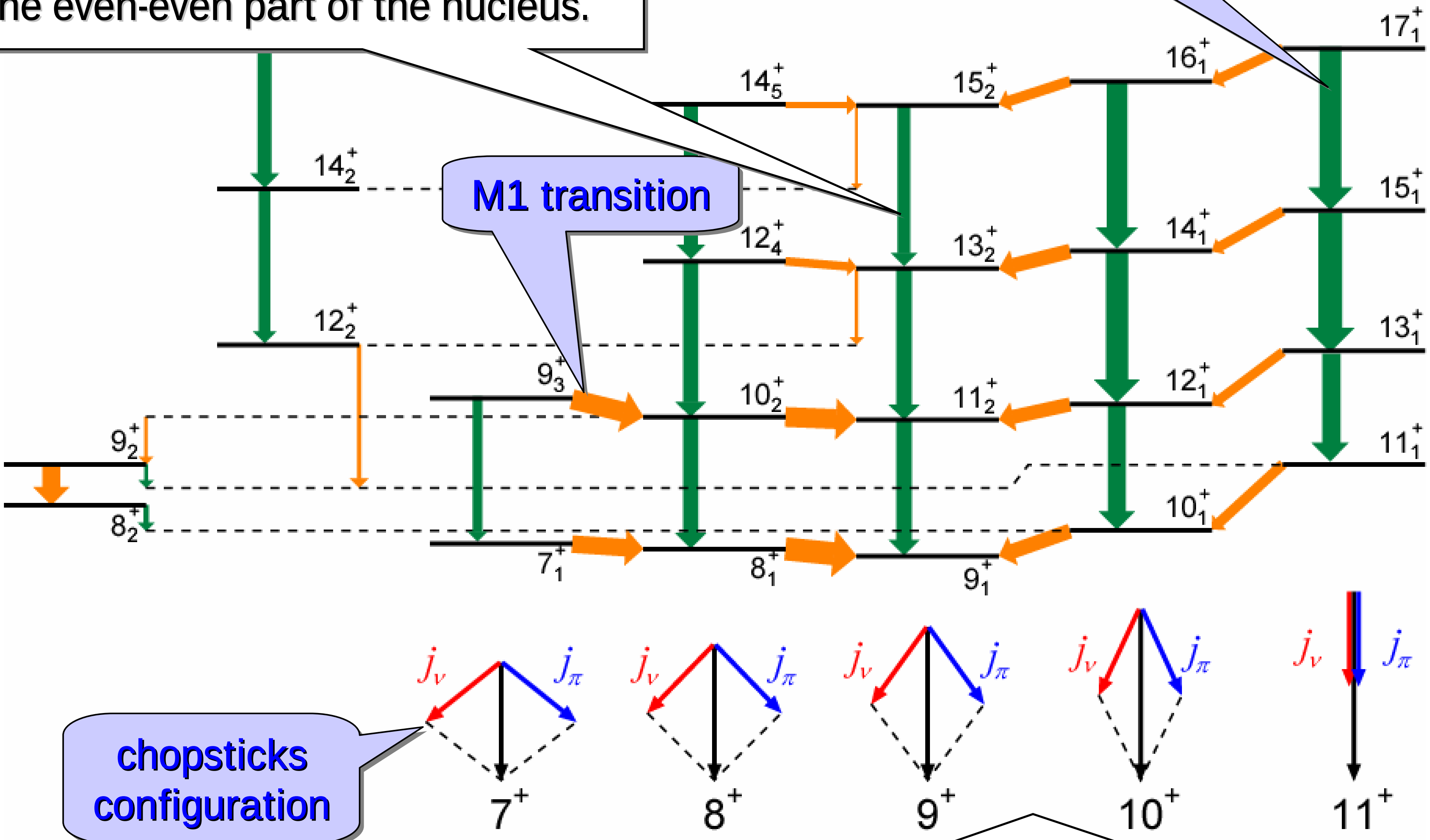


# of $^{134}$La

Each $\Delta I = 2$ E2 band arises from the quadrupole collective excitation of the even-even part of the nucleus.

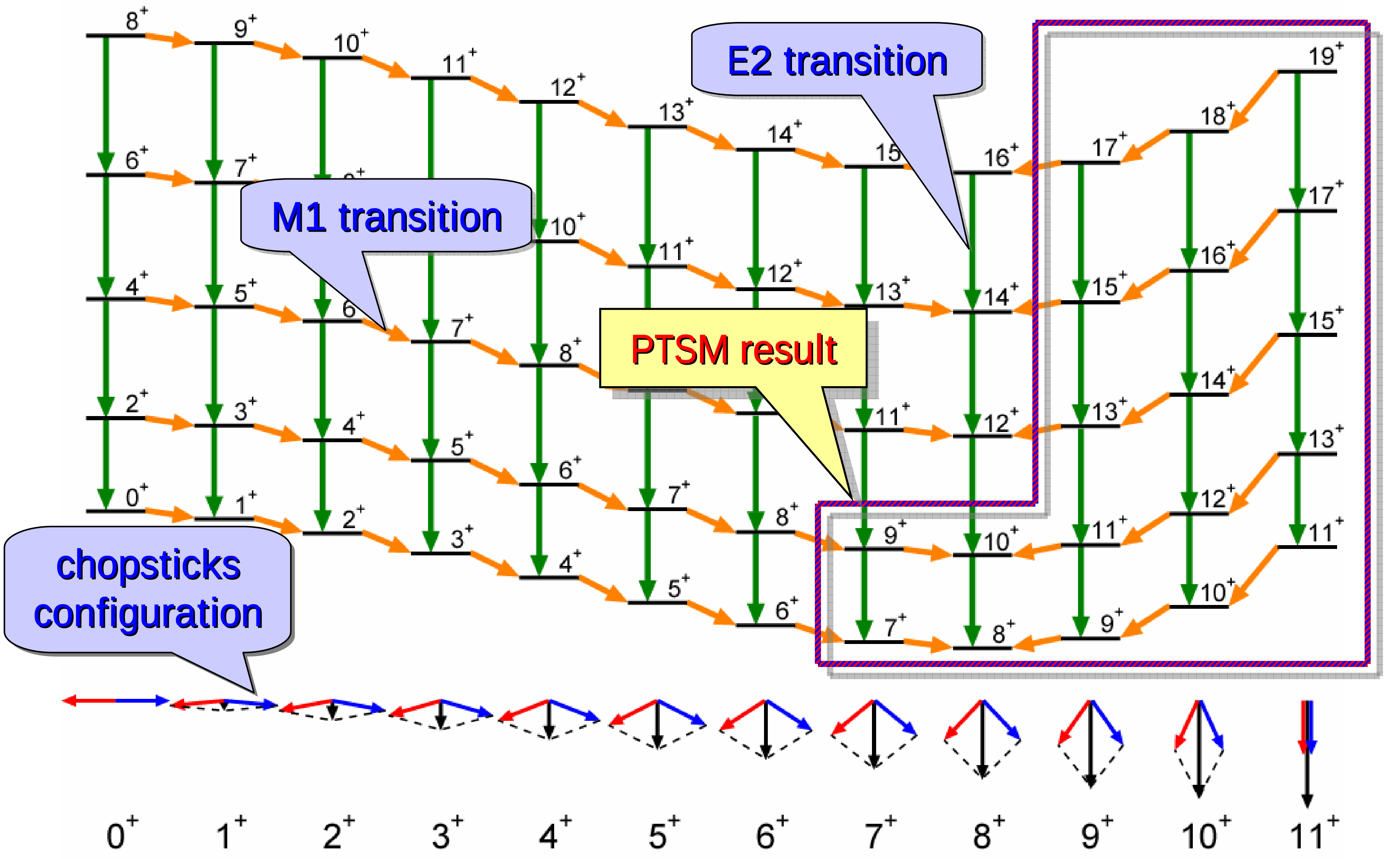
E2 transition

M1 transition



chopsticks configuration

The chopsticks motion of the unpaired neutron and unpaired proton in $0h_{11/2}$ orbitals enhances the B(M1) values to be large.



E2 transition

M1 transition

PTSM result

chopsticks configuration

The $\nu h_{11/2} \otimes \pi h_{11/2}$ bands are interpreted as arising from the chopsticks configurations of the two angular momenta of the unpaired nucleons, and the quadrupole collective excitations of the even-even core.

# Summary

## PTSM calculations were carried out for the doubly-odd nucleus $^{134}$La.

- Good agreement with experiment for both energy levels and electromagnetic transitions is obtained.
- The structure of the $\nu h_{11/2} \otimes \pi h_{11/2}$ bands is well explained by the chopsticks configurations of the unpaired nucleons, weakly coupled with the quadrupole collective excitations of the even-even part of the nucleus.

## Similar results are obtained for doubly-odd nuclei $^{130}$Cs, $^{130}$Cs and $^{132}$La.

The detailed results and their analyses are presented in

K. Higashiyama et al., Phys. Rev. C 72, 024315 (2005).