9th international workshop: Quantum Phase Transitions in Nuclei and Many-body Systems

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Nuclear multiple chirality in Rh-106: a manifestation of triaxial shape coexistence

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Peking University

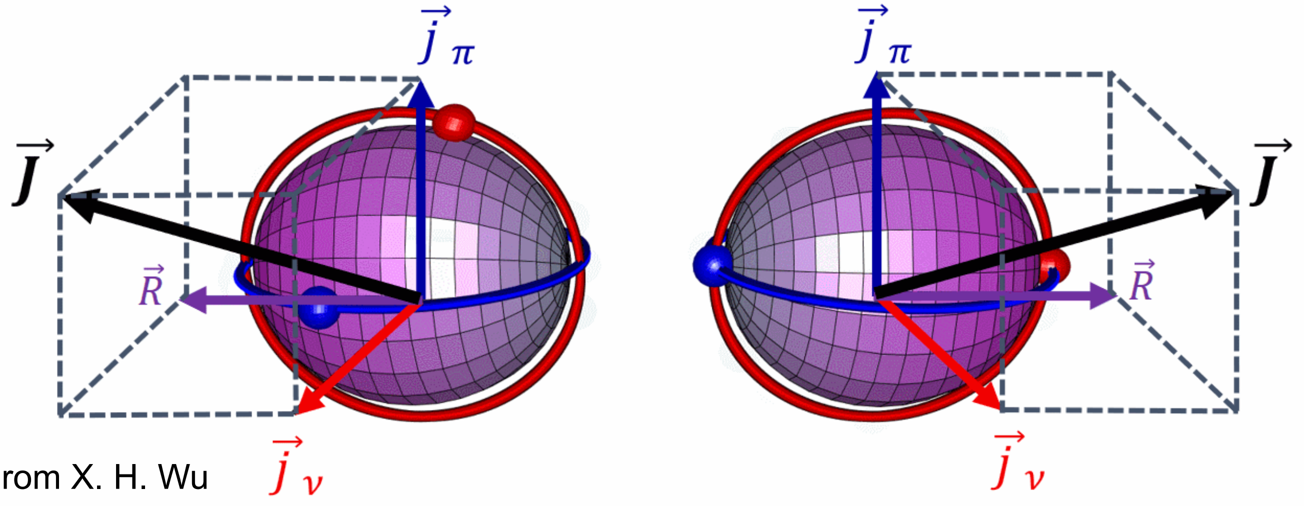
Outline

- Chirality and multiple chirality in nuclei
- Tilted axis cranking covariant DFT
- Multiple chirality in Rh-106
- Summary

Nuclear spin-chirality

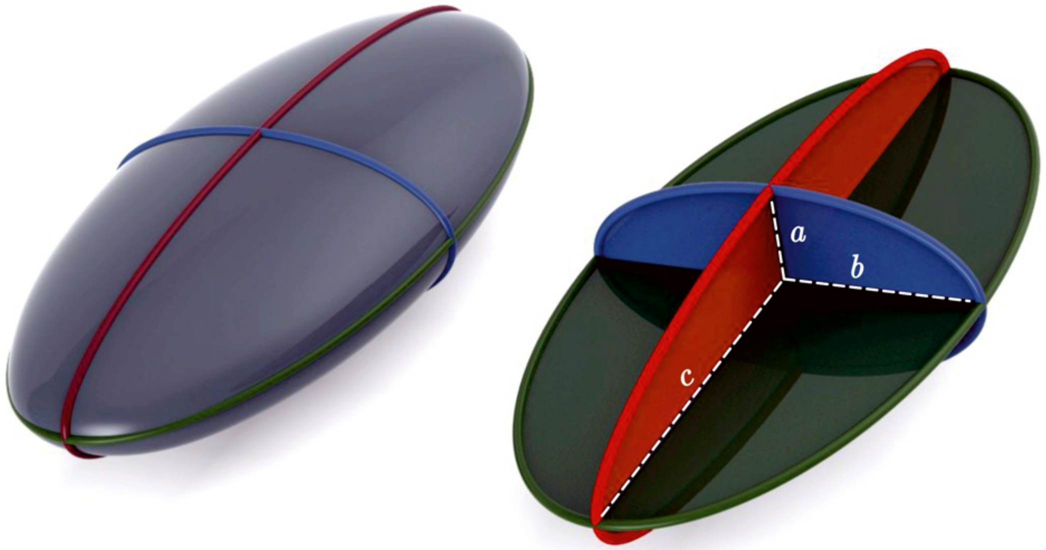
The aplanar (3D-) rotation of a triaxial nucleus could present chiral geometry.

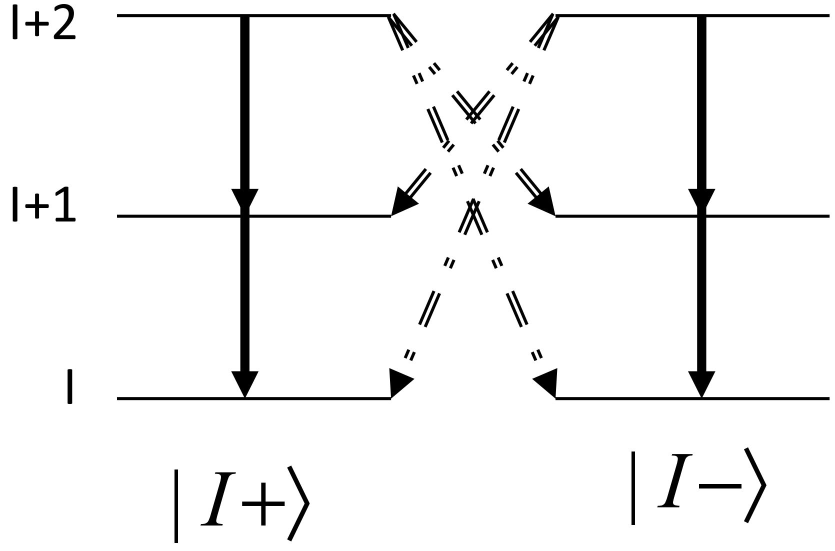
Frauendorf and Meng NPA 1997



From X. H. Wu

Left-handed $|\mathcal{L}\rangle$ Right-handed $|\mathcal{R}\rangle$





Lab. frame：

Chiral Symmetry restoration

$$|I+\rangle = \frac{1}{\sqrt{2}}(|\mathcal{L}\rangle) + |\mathcal{R}\rangle)$$

$$|I-\rangle = \frac{i}{\sqrt{2}}(|\mathcal{L}\rangle) - |\mathcal{R}\rangle)$$

Exp. signal： Two near degenerate ΔI =1 bands, called chiral doublet bands

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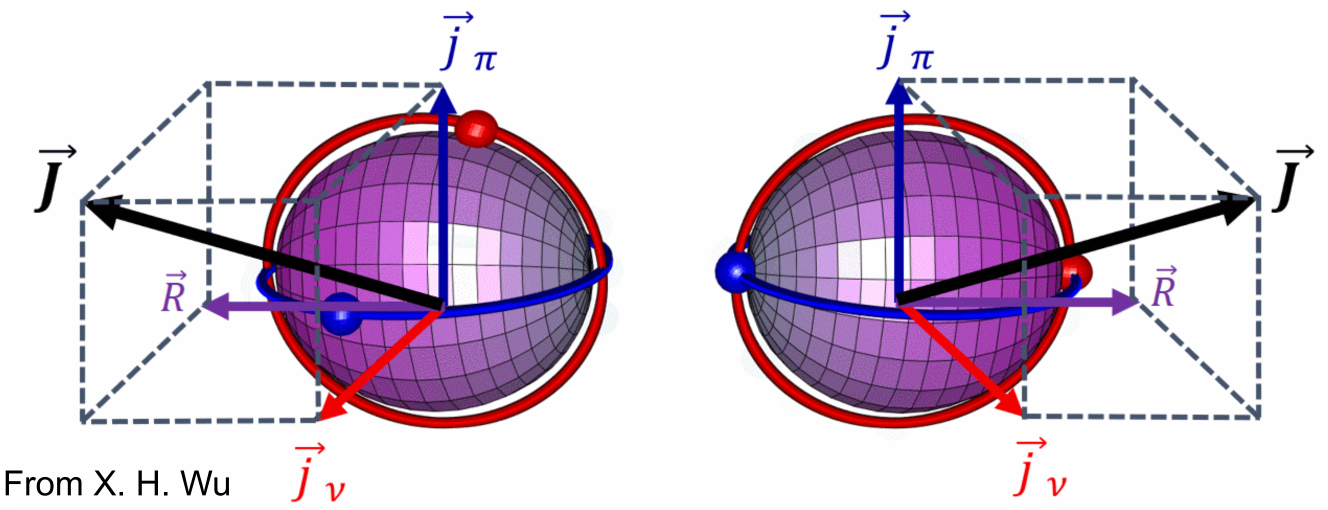


From X. H. Wu

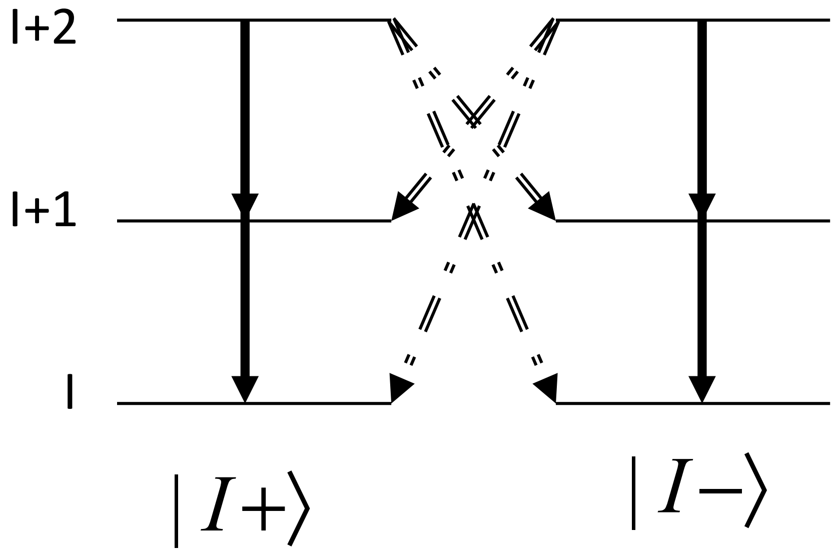
Left-handed $|\mathcal{L}\rangle$ Right-handed $|\mathcal{R}\rangle$

Intrinsic frame：

Chiral Symmetry breaking

$$\hat{\chi} = \hat{T}\hat{R}_y(\pi)$$

$$\hat{\chi}\,|\mathcal{L}\rangle = |\mathcal{R}\rangle \qquad \hat{\chi}\,|\mathcal{R}\rangle = |\mathcal{L}\rangle$$



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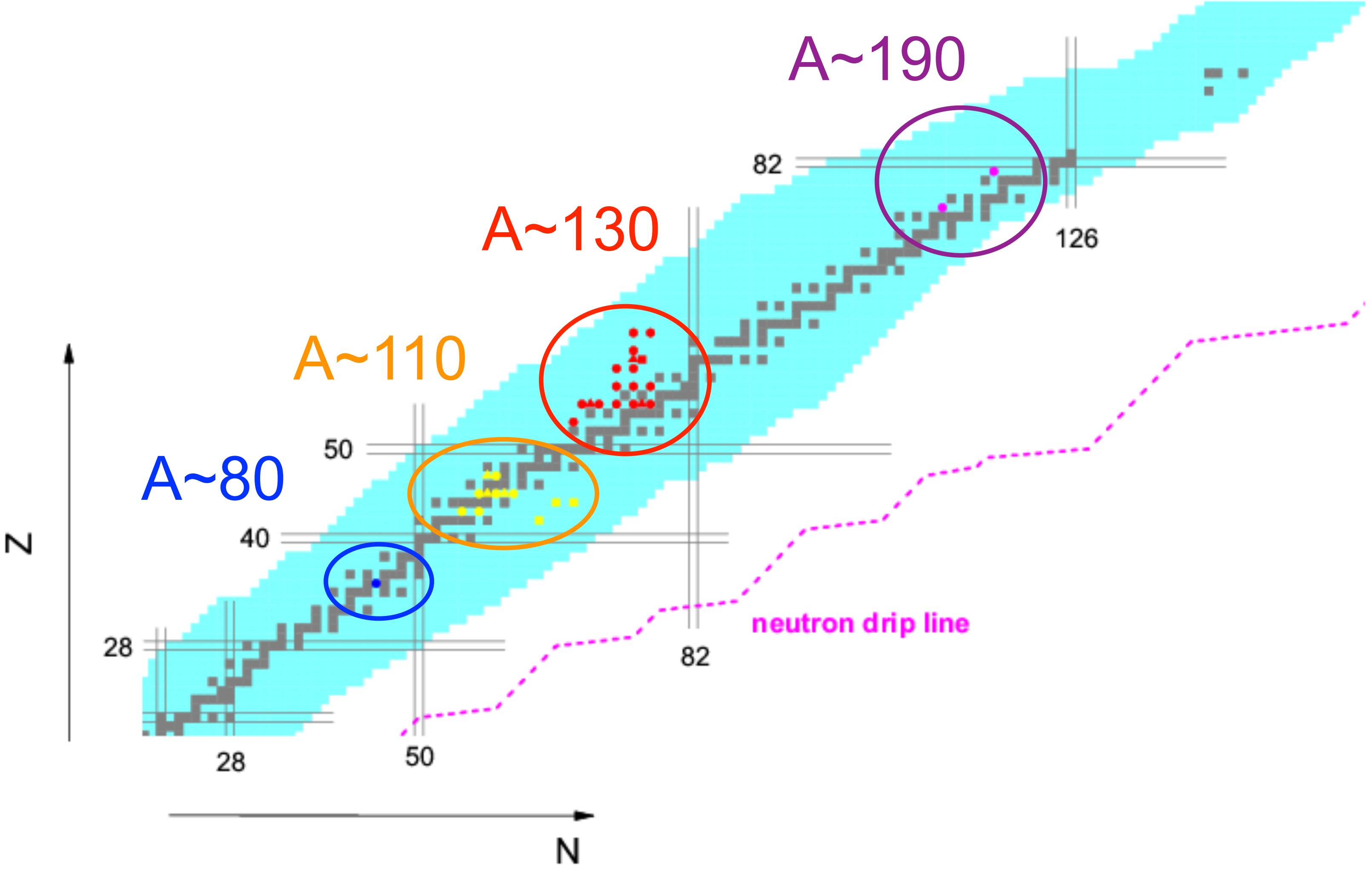
Exp. signal： Two near degenerate ΔI =1 bands, called chiral doublet bands

Observed chiral nuclei

More than 45 candidate chiral nuclei have been reported in the A~80, 100, 130, and 190 mass regions, so far.

Xiong and Wang arXiv:1804.04437



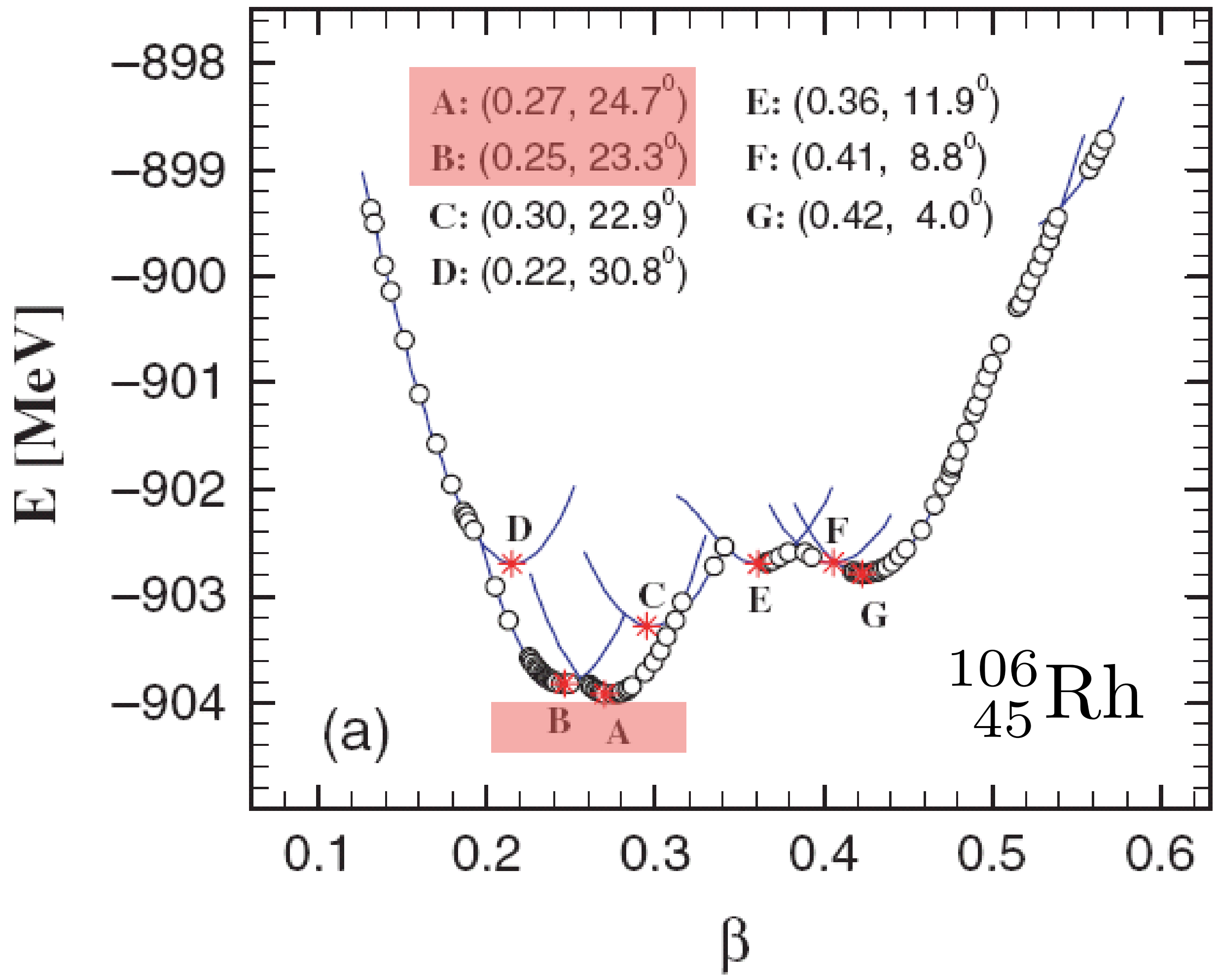
Multiple spin-chirality? a manifestation of **Triaxial Shape Coexistence**

having more than one pair of chiral bands in a single nucleus ?

Predictions of multiple spin-chirality

Covariant DFT on a static mean field: no cranking

Meng, Peng, Zhang, Zhou PRC 2006



Config. A $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{1}$

Config. B $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{2}(gd)^{1}$

Two requirements of chirality:

1. strong triaxial deformation
2. high-j particle(s) and hole(s)

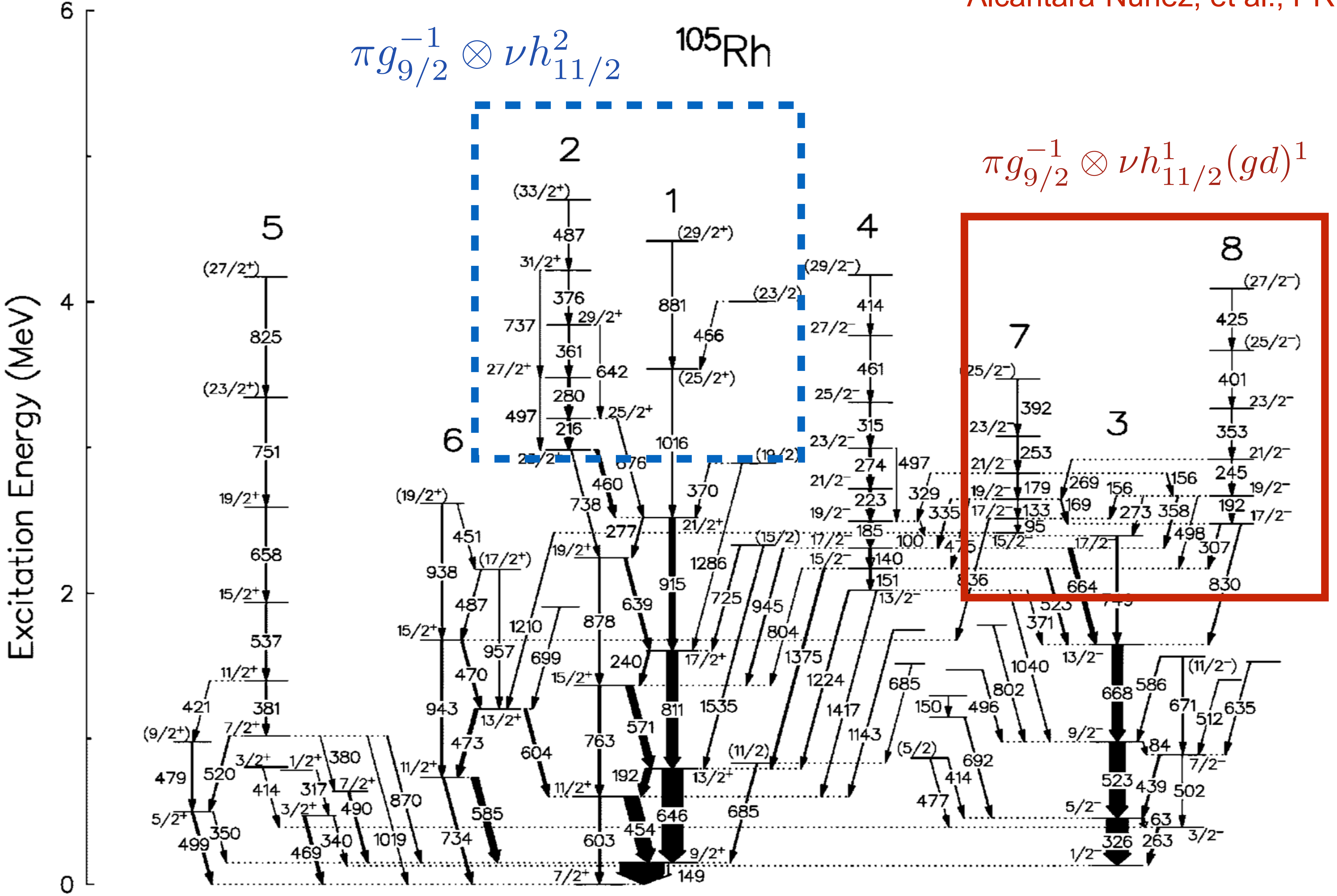
A possible multi-chirality candidate

The investigation followed by:

- Prediction for other odd-odd Rh isotopes: Peng et al., PRC 2008
- Confirmed with time-odd fields included: Yao et al., PRC 2009

Possible candidates in ^{105}Rh

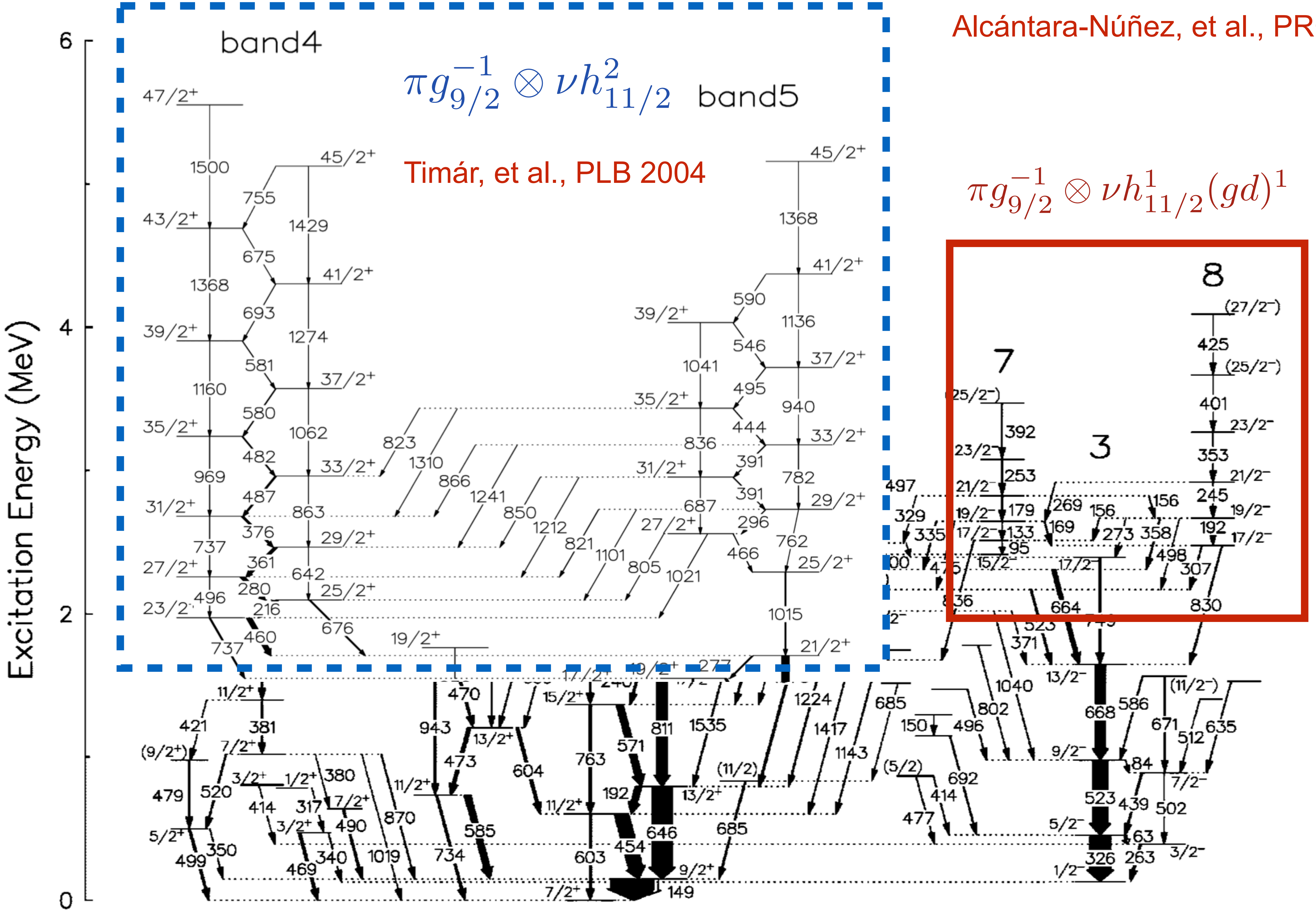
Alcántara-Núñez, et al., PRC 2004



$\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{2}$

$\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{1} (gd)^{1}$

Possible candidates in ^{105}Rh



$\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{2}$

Timár, et al., PLB 2004

Alcántara-Núñez, et al., PRC 2004

$\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{1}(gd)^{1}$

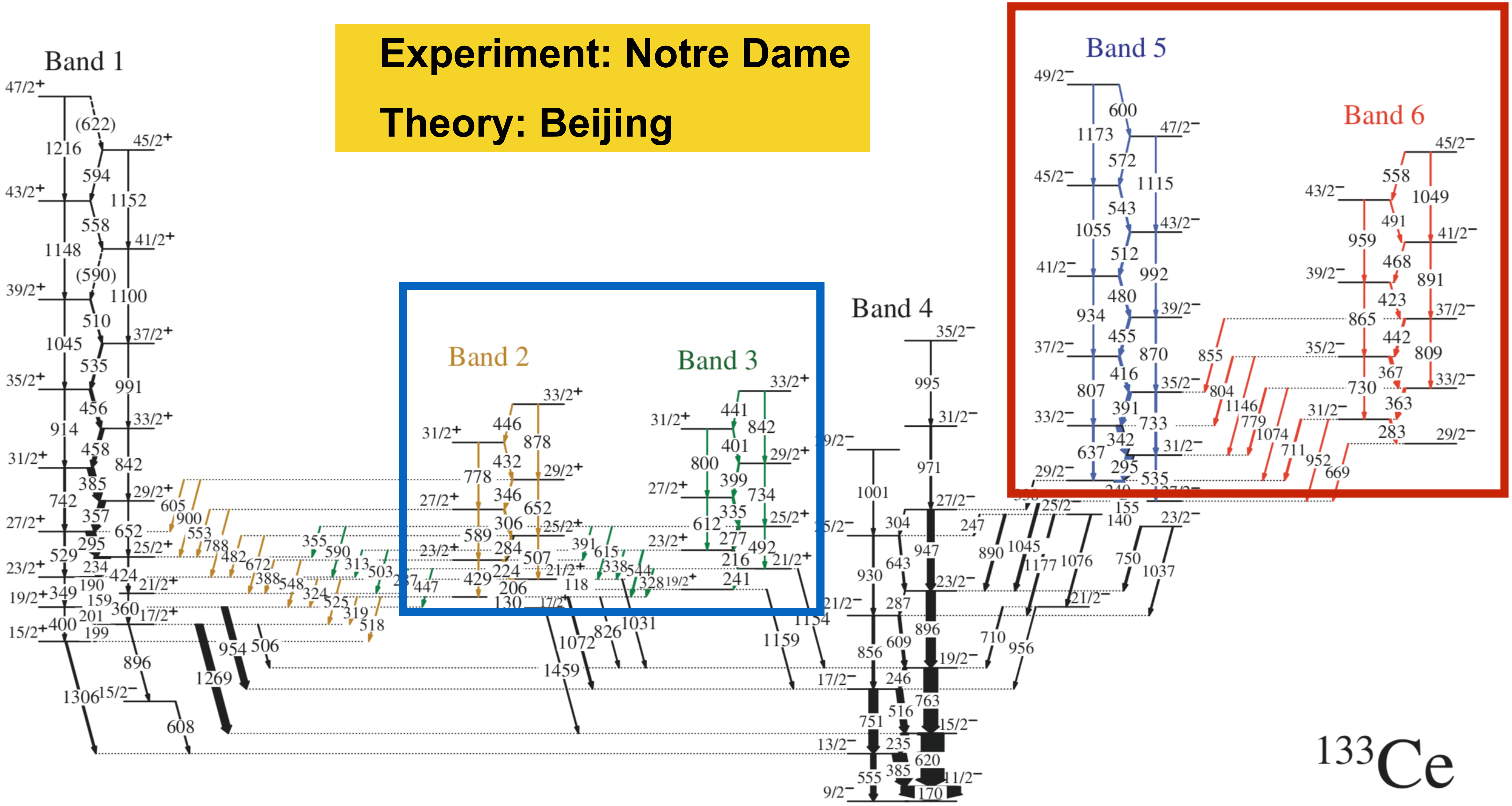
Multiple chiral doublet bands in ^{133}Ce

<u>Two distinct sets of chiral-partner bands have been identified.</u>

Ayangeakaa et al., PRL 2013

Experiment: Notre Dame

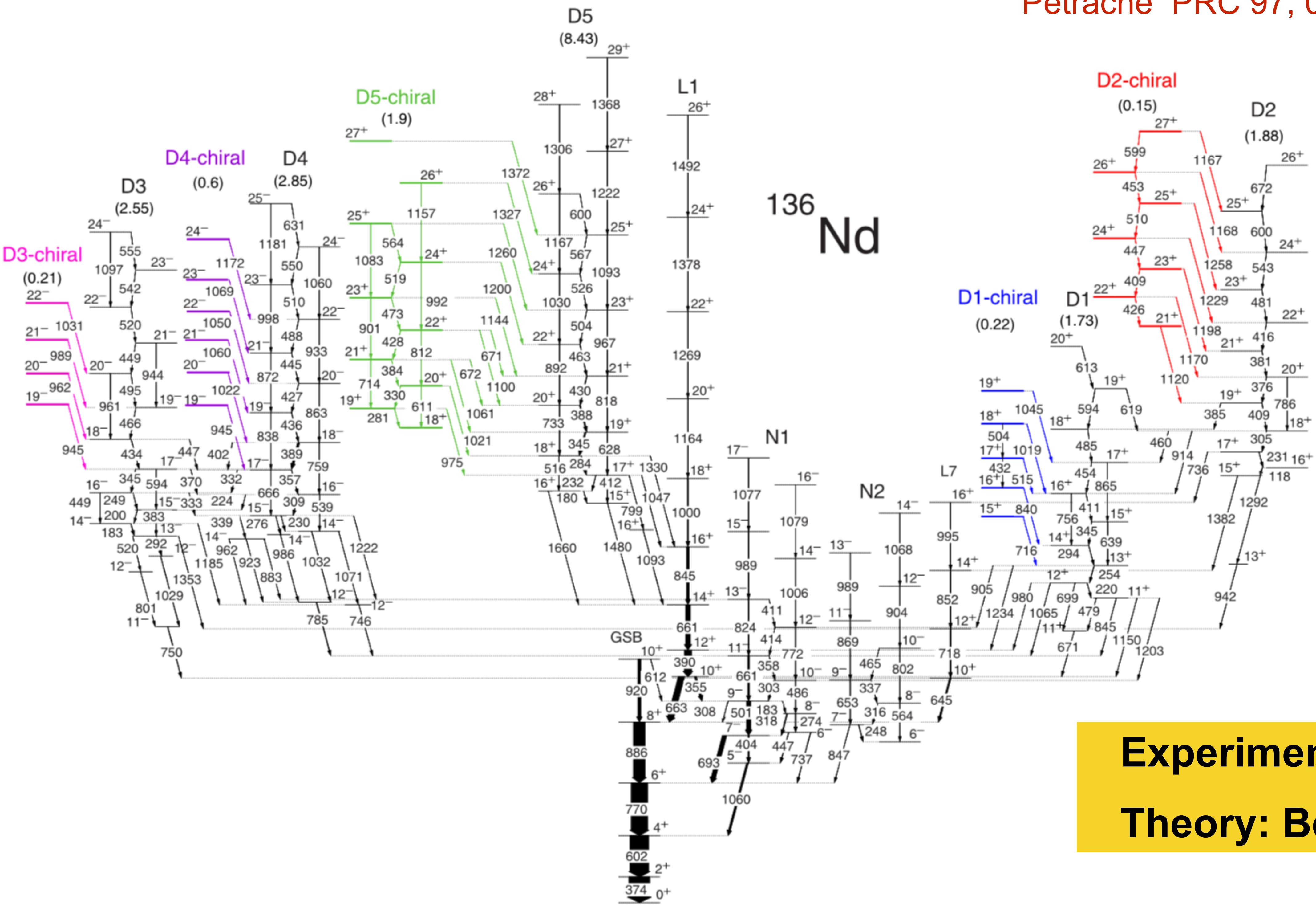
Theory: Beijing



Triaxiality can be robust against different configurations

Multiple chiral doublet bands in ^{136}Nd

Petrache PRC 97, 041304(R) (2018)



Experiment: Orsay

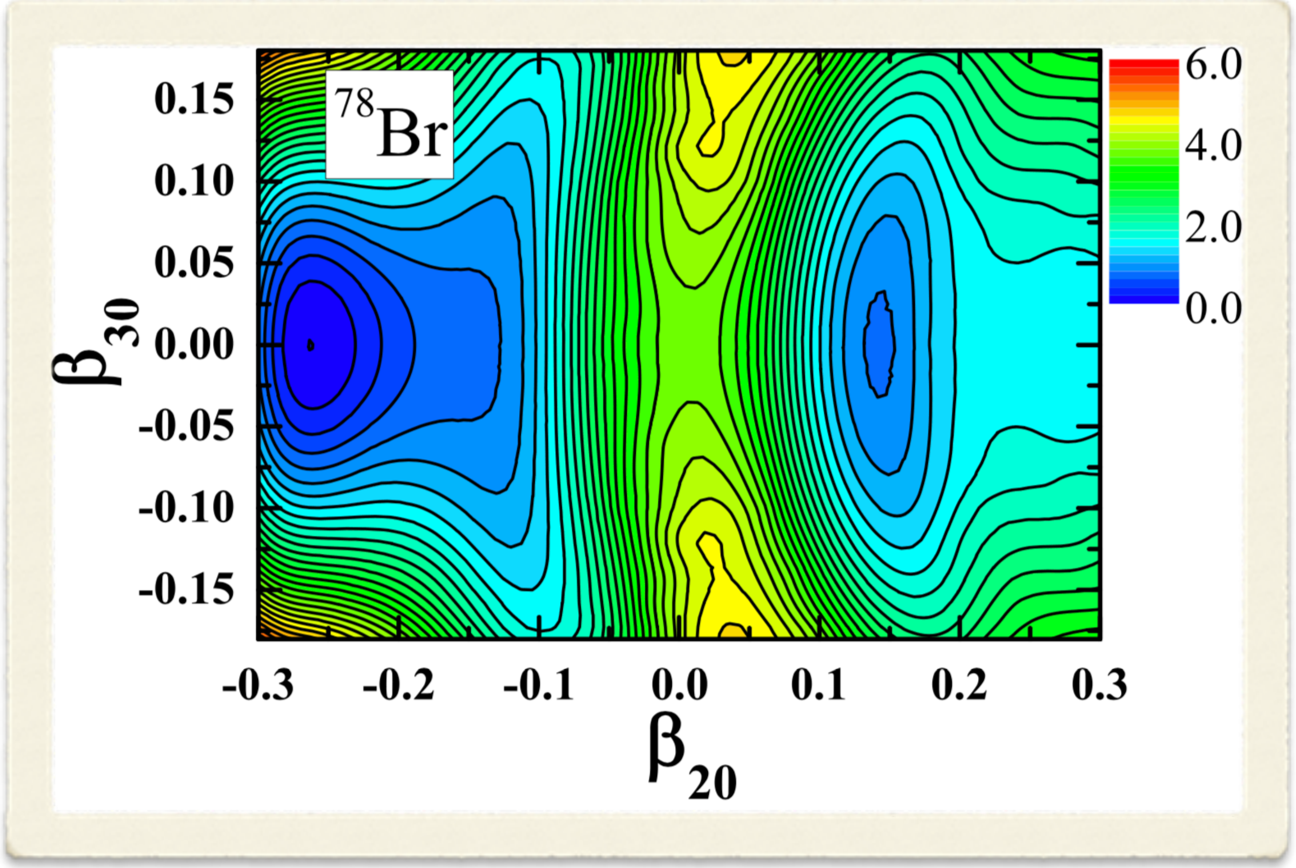
Theory: Beijing

Five candidates for chiral bands are identified

Octupole Correlations in Multiple Chiral Doublet Bands

Chiral bands in octupole soft nuclei

Liu et al, PRL 2016

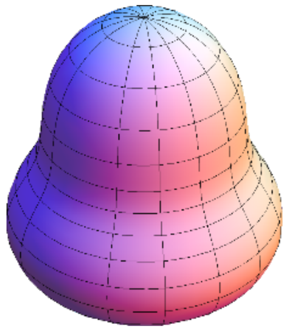


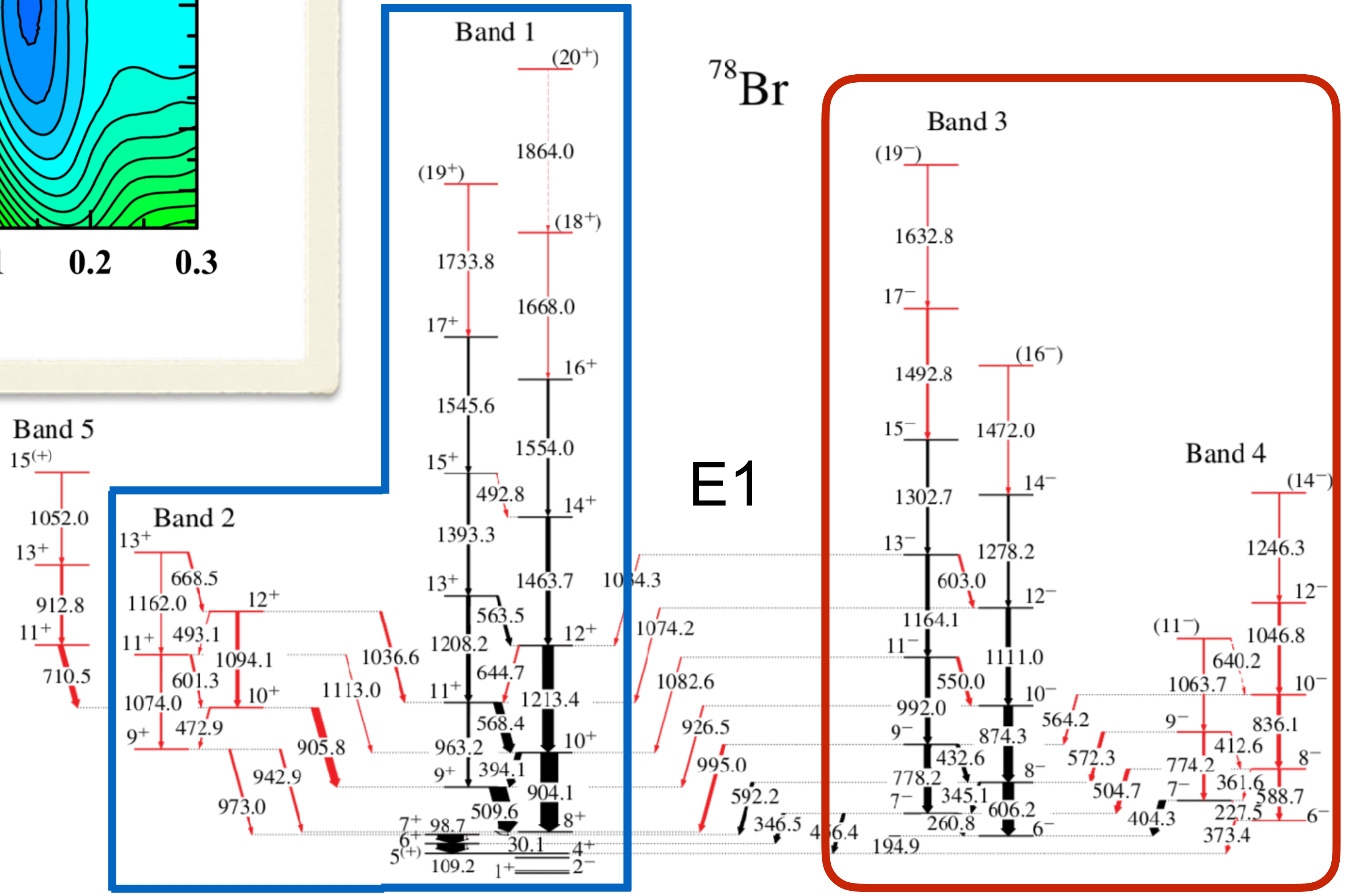
Experiment: iThemba LABS

Theory: Beijing

Multi-dimensional CDFT

Lv, Zhao, Zhou, PRC (2012)





Theoretical tools for nuclear chirality

- **Particle Core Coupling**

  (lab frame, phenomenological, quantal, with quantum tunneling)

  - **Triaxial Particle Rotor Model (TPRM)**

    Frauendorf and Meng NPA(1997); Peng et al PRC(2003); Koike et al PRL(2004), Zhang et al PRC(2007); Lawrie et al PRC (2008); Qi et al PLB(2009)
  - Core-quasiparticle coupling model Starosta et al PRC(2002); Koike et al PRC(2003)
  - Interacting Boson Fermion Fermion Model S. Brant et al PRC (2004), PRC (2008), Tonev et al PRL(2006)

- **Tilted axis cranking mean-field**

  (intrinsic frame, microscopic, semi-classical, no quantum tunneling)

  - Single-j model Frauendorf and Meng NPA(1997)
  - Hybird Woods-Saxon and Nilsson model Dimitrov et al PRL(2000)
  - Non-relativistic Skyrme DFT Olbratowski et al PRL(2004), PRC(2006)
  - **Covariant DFT** Madokoro et al PRC(2000); PWZ PLB (2017)

- **Shell-model**
  - Pair Truncated Shell Model K. Higashiyama et al, PRC(2005)
  - Projected Shell Model F. Q. Chen et al., PRC (2017)
  - Shell-model N. Shimizu' talk

TPRM for multi-chirality

Calculations based on a combination of the triaxial CDFT and the PRM

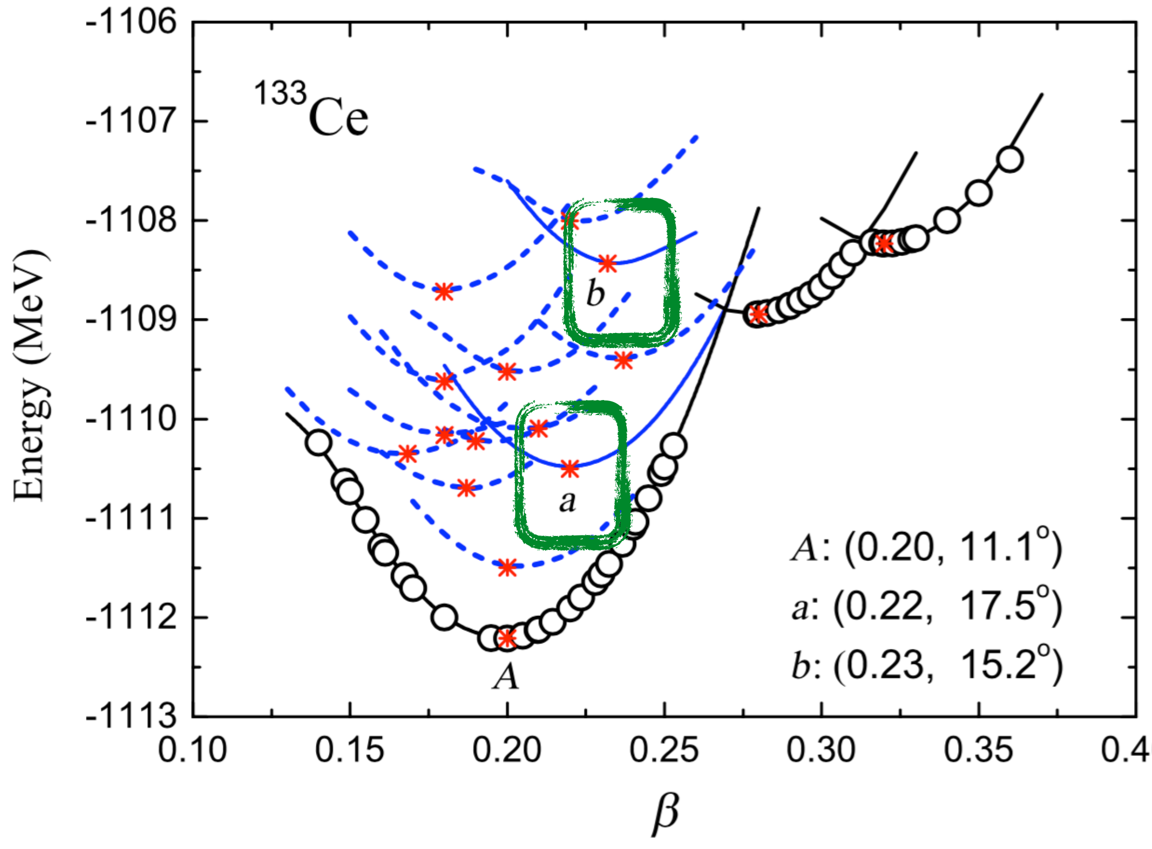
Ayangeakaa et al., PRL 2013

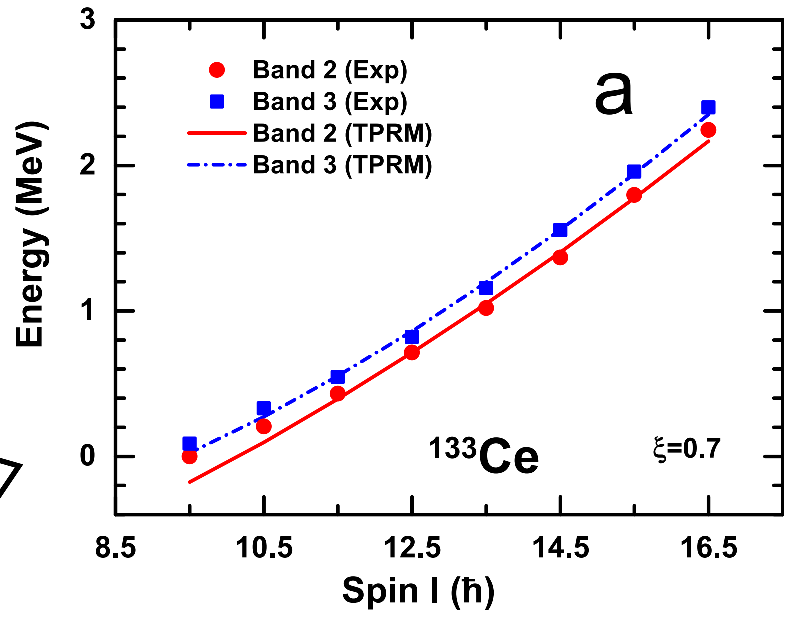
Experiment: Notre Dame

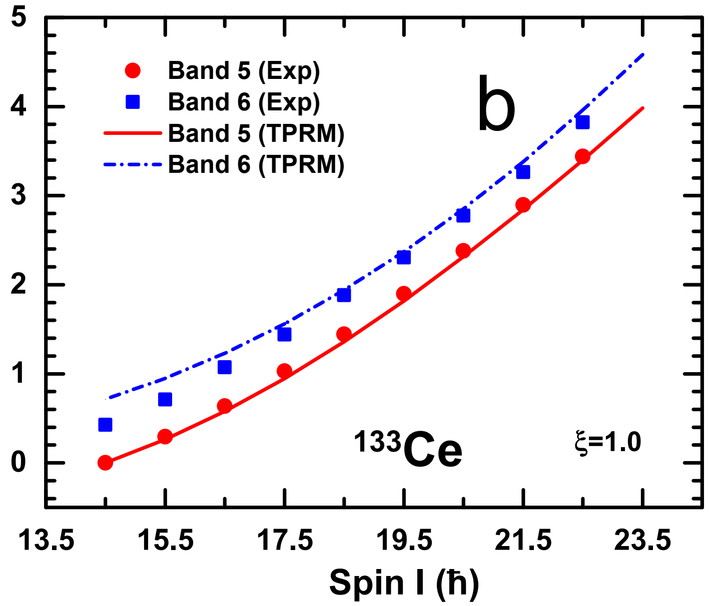
Theory: Beijing

quantal, no self-consistency

$$\text{CDFT} \xrightarrow[\text{Configurations}]{\text{Deformations}} \text{TPRM} \longrightarrow \begin{matrix}\text{Energy Spectra}\\ \text{EM transitions}\end{matrix}$$







TAC for multi-chirality

Calculations based on the tilted axis cranking CDFT and beyond…

An on going project …

TAC-CDFT

Deformations
Configurations
Energy Spectra
EM transitions

Beyond the rotating mean-field

2D Collective Hamiltonian

Self-consistent

Quantum fluctuations

TAC for multi-chirality

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2D Collective Hamiltonian

Self-consistent

In the present talk

PWZ, PLB 773, 1 (2017)

Quantum fluctuations

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TAC-CDFT

Deformations

Configurations

Energy Spectra

EM transitions

Self-consistent

In the present talk

PWZ, PLB 773, 1 (2017)

Beyond the rotating mean-field

2D Collective Hamiltonian

Quantum fluctuations

available based on a single j model

Chen, Zhang, PWZ, Jolos, Meng,
PRC 87, 024314 (2013)

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Tilted axis cranking CDFT

The cranking mean-field model has been very successful for rotations

Meson exchange version:

3-D Cranking: *Madokoro, Meng, Matsuzaki, Yamaji, PRC 62, 061301 (2000)*

2-D Cranking: *Peng, Meng, Ring, Zhang, PRC 78, 024313 (2008)*

Point-coupling version:

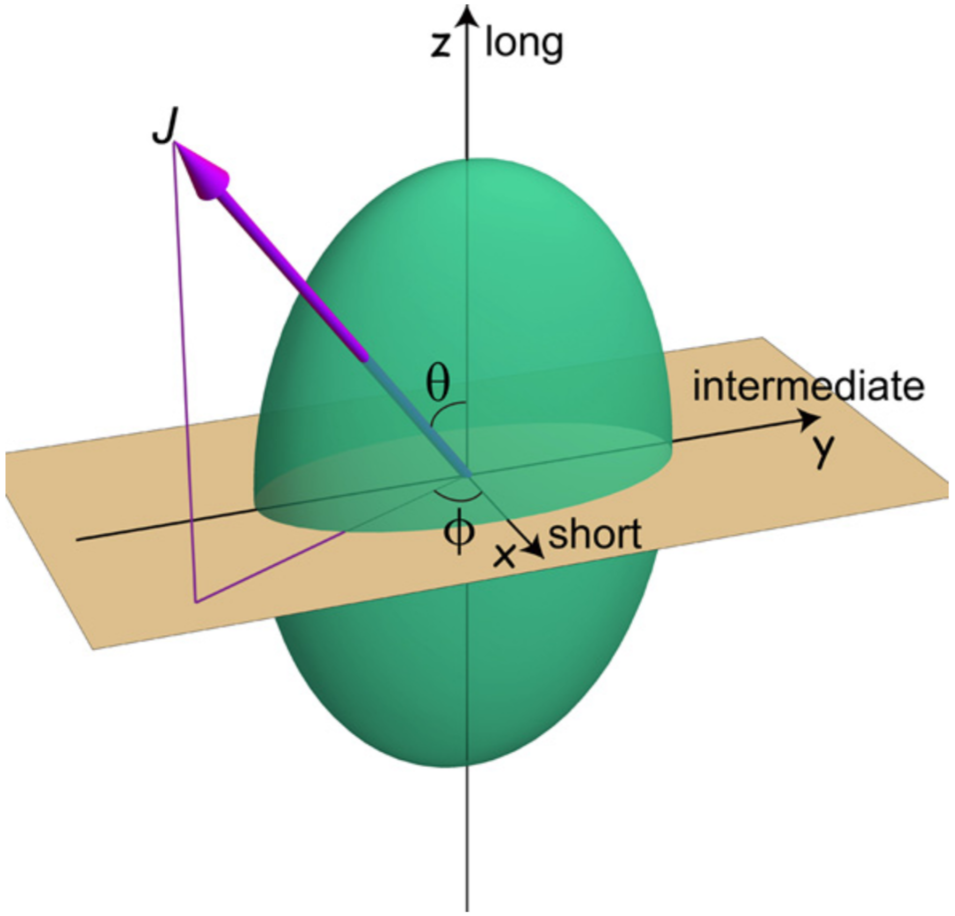
Simple and more suitable for systematic investigations

2-D Cranking: *PWZ, Zhang, Peng, Liang, Ring, Meng, PLB 699, 181 (2011)*

2-D Cranking + Pairing: *PWZ, Zhang, Meng, PRC 92, 034319 (2015)*

3-D Cranking: *PWZ, PLB 773, 1 (2017)*

3-D Cranking + Pairing: *PWZ, in preparation*



Self-consistent and microscopic investigations

- full account of polarization effects
- self-consistent treatment of the nuclear currents
- no additional parameter beyond a well-determined functional

Cranking Relativistic Kohn-Sham Equation

Dirac Equation

$$\begin{pmatrix} m + V + S - \boldsymbol{\omega}\cdot\boldsymbol{J} & \boldsymbol{\sigma}\cdot\boldsymbol{p} - \boldsymbol{\sigma}\cdot\boldsymbol{V} \\ \boldsymbol{\sigma}\cdot\boldsymbol{p} - \boldsymbol{\sigma}\cdot\boldsymbol{V} & -m + V - S - \boldsymbol{\omega}\cdot\boldsymbol{J} \end{pmatrix} \begin{pmatrix} f \\ g \end{pmatrix} = \varepsilon \begin{pmatrix} f \\ g \end{pmatrix}$$

$$S(\boldsymbol{r}) = \alpha_S \rho_S + \beta_V \rho_S^2 + \gamma_V \rho_S^3 + \delta_S \Delta \rho_S$$

$$V(\boldsymbol{r}) = \alpha_V \rho_V + \gamma_V \rho_V^3 + \delta_V \Delta \rho_V + \tau_3 \alpha_{TV} \rho_{TV} + \tau_3 \delta_{TV} \Delta \rho_{TV} + e\frac{1-\tau_3}{2} A$$

$$\boldsymbol{V}(\boldsymbol{r}) = \alpha_V \boldsymbol{j}_V + \gamma_V \boldsymbol{j}_V^3 + \delta_V \Delta \boldsymbol{j}_V + \tau_3 \alpha_{TV} \boldsymbol{j}_{TV} + \tau_3 \delta_{TV} \Delta \boldsymbol{j}_{TV} + e\frac{1-\tau_3}{2} \boldsymbol{A}$$

Consistent treatment for time-odd fields from nuclear currents

PWZ, Zhang, Peng, Liang, Ring, Meng, PLB 699, 181 (2011)

Cranking Relativistic Kohn-Sham Equation

Dirac Equation

Coriolis term   Time-odd mean fields

$$\begin{pmatrix} m + V + S - \boldsymbol{\omega}\cdot\boldsymbol{J} & \boldsymbol{\sigma}\cdot\boldsymbol{p} - \boldsymbol{\sigma}\cdot\boldsymbol{V} \\ \boldsymbol{\sigma}\cdot\boldsymbol{p} - \boldsymbol{\sigma}\cdot\boldsymbol{V} & -m + V - S - \boldsymbol{\omega}\cdot\boldsymbol{J} \end{pmatrix} \begin{pmatrix} f \\ g \end{pmatrix} = \varepsilon \begin{pmatrix} f \\ g \end{pmatrix}$$

$$S(\boldsymbol{r}) = \alpha_S \rho_S + \beta_V \rho_S^2 + \gamma_V \rho_S^3 + \delta_S \Delta\rho_S$$

$$V(\boldsymbol{r}) = \alpha_V \rho_V + \gamma_V \rho_V^3 + \delta_V \Delta\rho_V + \tau_3 \alpha_{TV} \rho_{TV} + \tau_3 \delta_{TV} \Delta\rho_{TV} + e\frac{1-\tau_3}{2} A$$

$$\boldsymbol{V}(\boldsymbol{r}) = \alpha_V \boldsymbol{j}_V + \gamma_V \boldsymbol{j}_V^3 + \delta_V \Delta\boldsymbol{j}_V + \tau_3 \alpha_{TV} \boldsymbol{j}_{TV} + \tau_3 \delta_{TV} \Delta\boldsymbol{j}_{TV} + e\frac{1-\tau_3}{2} \boldsymbol{A}$$

Consistent treatment for time-odd fields from nuclear currents

PWZ, Zhang, Peng, Liang, Ring, Meng, PLB 699, 181 (2011)

Cranking Relativistic Kohn-Sham Equation

Dirac Equation

Coriolis term

Time-odd mean fields

$$\begin{pmatrix} m+V+S-\boldsymbol{\omega}\cdot\boldsymbol{J} & \boldsymbol{\sigma}\cdot\boldsymbol{p}-\boldsymbol{\sigma}\cdot\boldsymbol{V} \\ \boldsymbol{\sigma}\cdot\boldsymbol{p}-\boldsymbol{\sigma}\cdot\boldsymbol{V} & -m+V-S-\boldsymbol{\omega}\cdot\boldsymbol{J} \end{pmatrix}\begin{pmatrix} f \\ g \end{pmatrix}=\varepsilon\begin{pmatrix} f \\ g \end{pmatrix}$$

$$S(\boldsymbol{r})=\alpha_S\rho_S+\beta_V\rho_S^2+\gamma_V\rho_S^3+\delta_S\Delta\rho_S$$

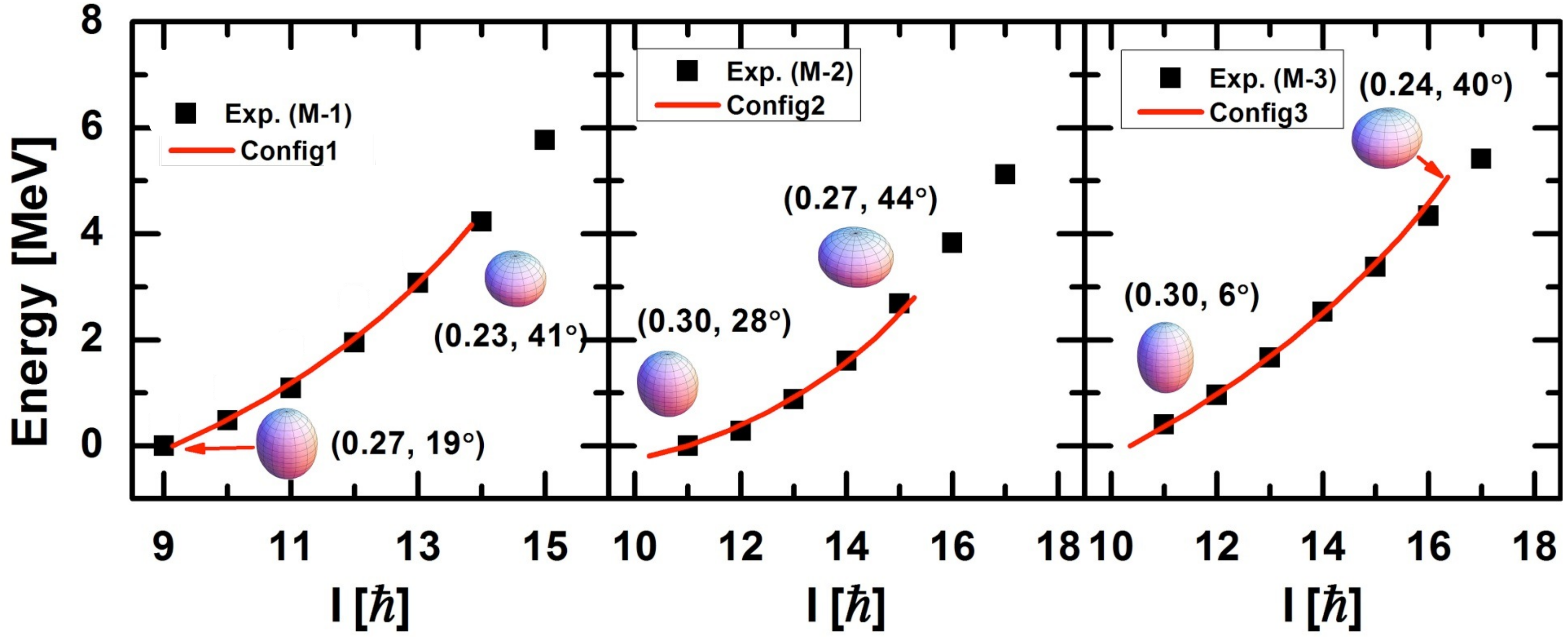
$$V(\boldsymbol{r})=\alpha_V\rho_V+\gamma_V\rho_V^3+\delta_V\Delta\rho_V+\tau_3\alpha_{TV}\rho_{TV}+\tau_3\delta_{TV}\Delta\rho_{TV}+e\frac{1-\tau_3}{2}A$$

$$\boldsymbol{V}(\boldsymbol{r})=\alpha_V\boldsymbol{j}_V+\gamma_V\boldsymbol{j}_V^3+\delta_V\Delta\boldsymbol{j}_V+\tau_3\alpha_{TV}\boldsymbol{j}_{TV}+\tau_3\delta_{TV}\Delta\boldsymbol{j}_{TV}+e\frac{1-\tau_3}{2}\boldsymbol{A}$$

Consistent treatment for time-odd fields from nuclear currents

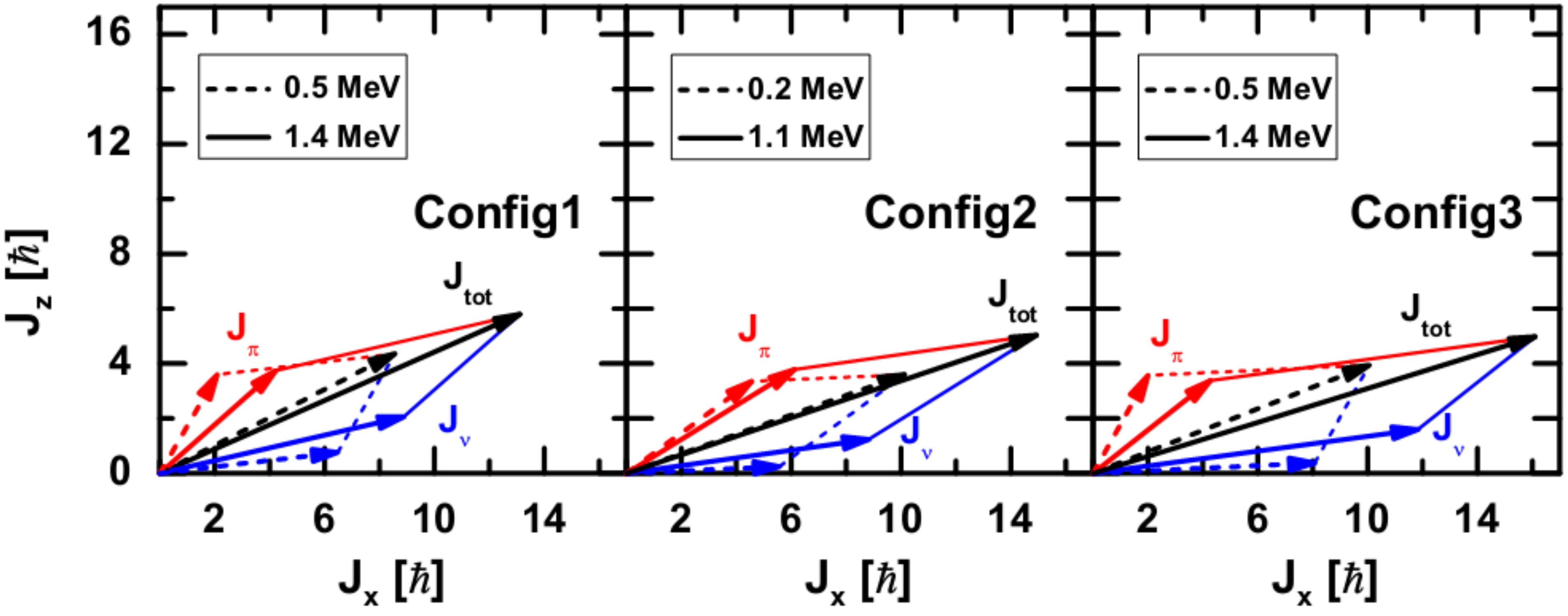
PWZ, Zhang, Peng, Liang, Ring, Meng, PLB 699, 181 (2011)

Magnetic Rotation in ^{60}Ni



Energy Spectra

Shape evolution



Shears mechanism

PWZ, Zhang, Peng, Liang, Ring, Meng, PLB 699, 181 (2011)

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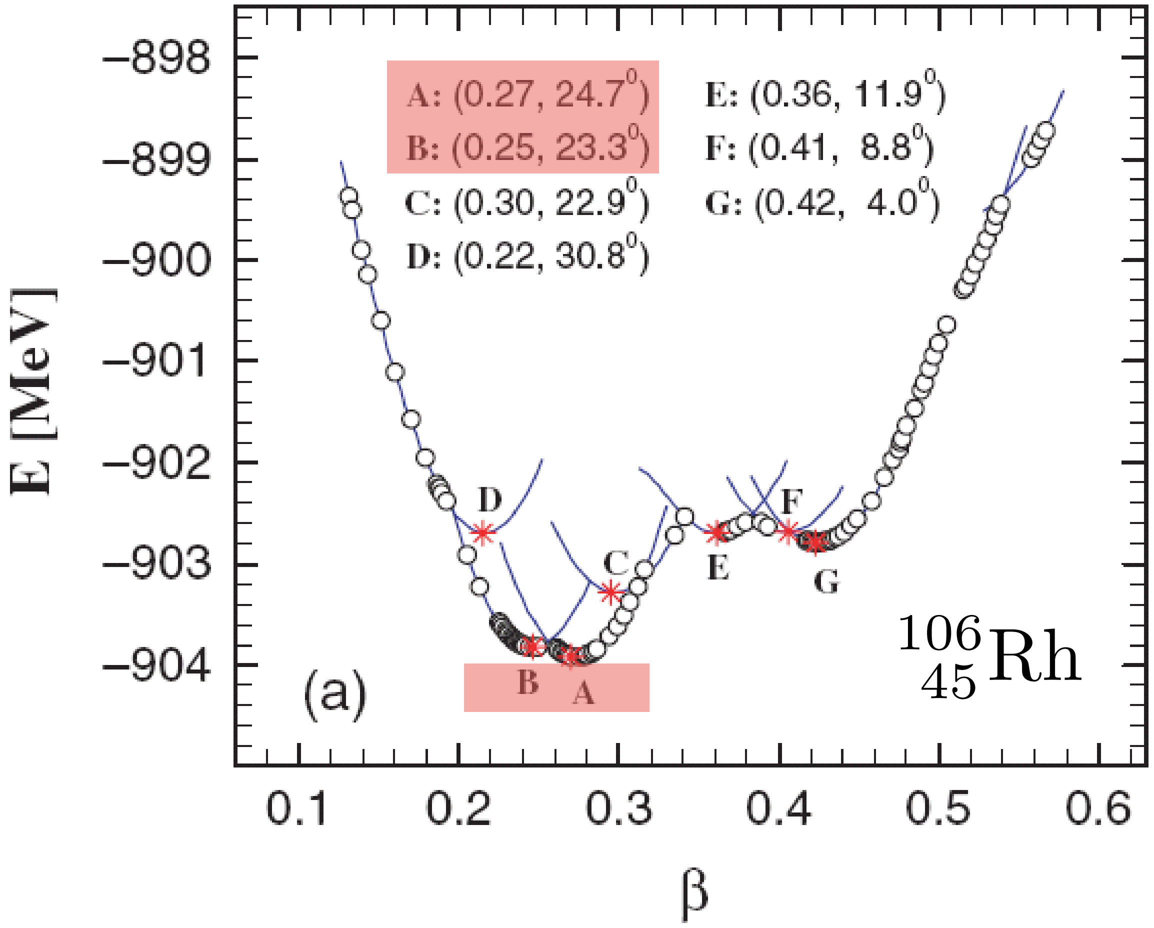
Configurations

Config. A $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{1}$

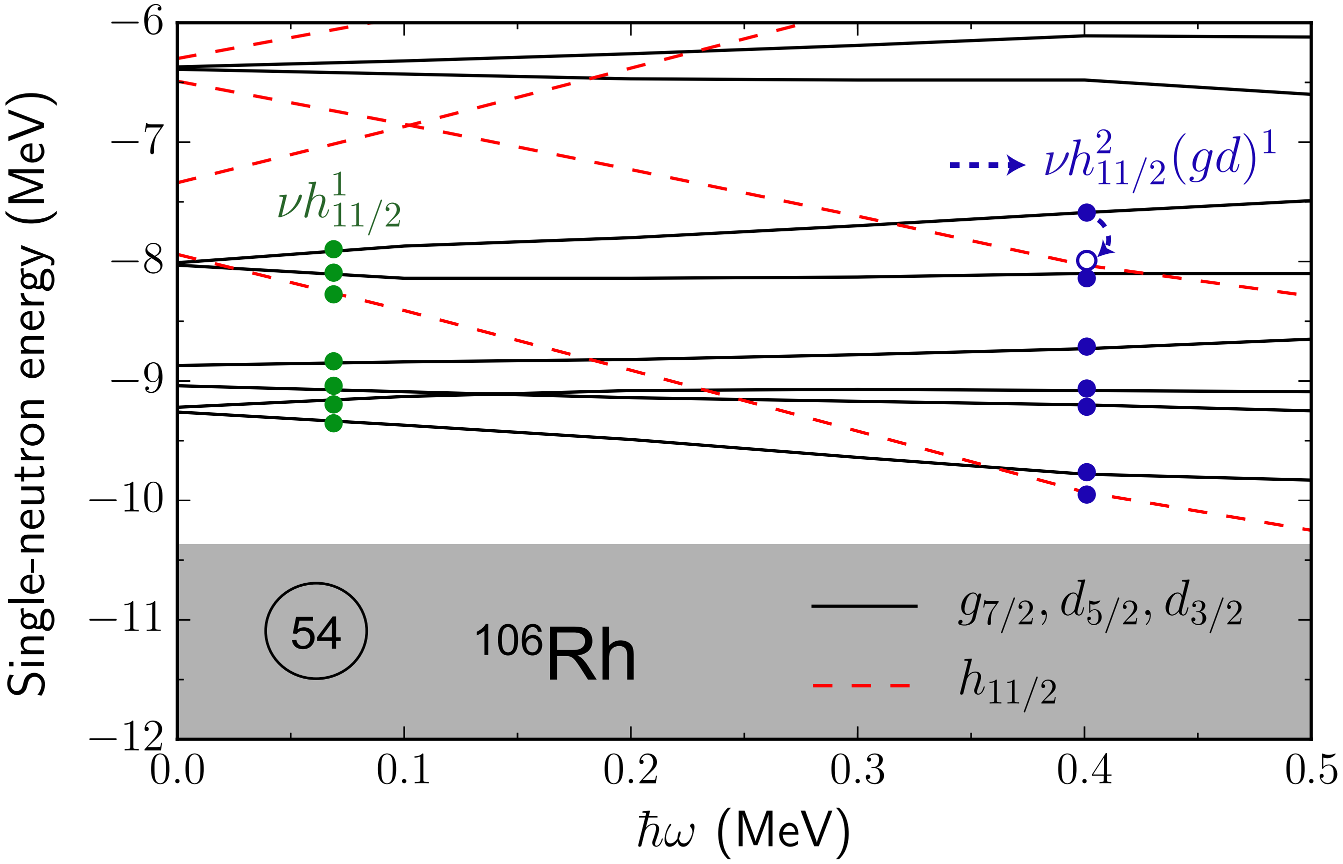
Config. B $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{2} (gd)^{1}$

CDFT: no cranking



Meng, Peng, Zhang, Zhou PRC 2006

With cranking

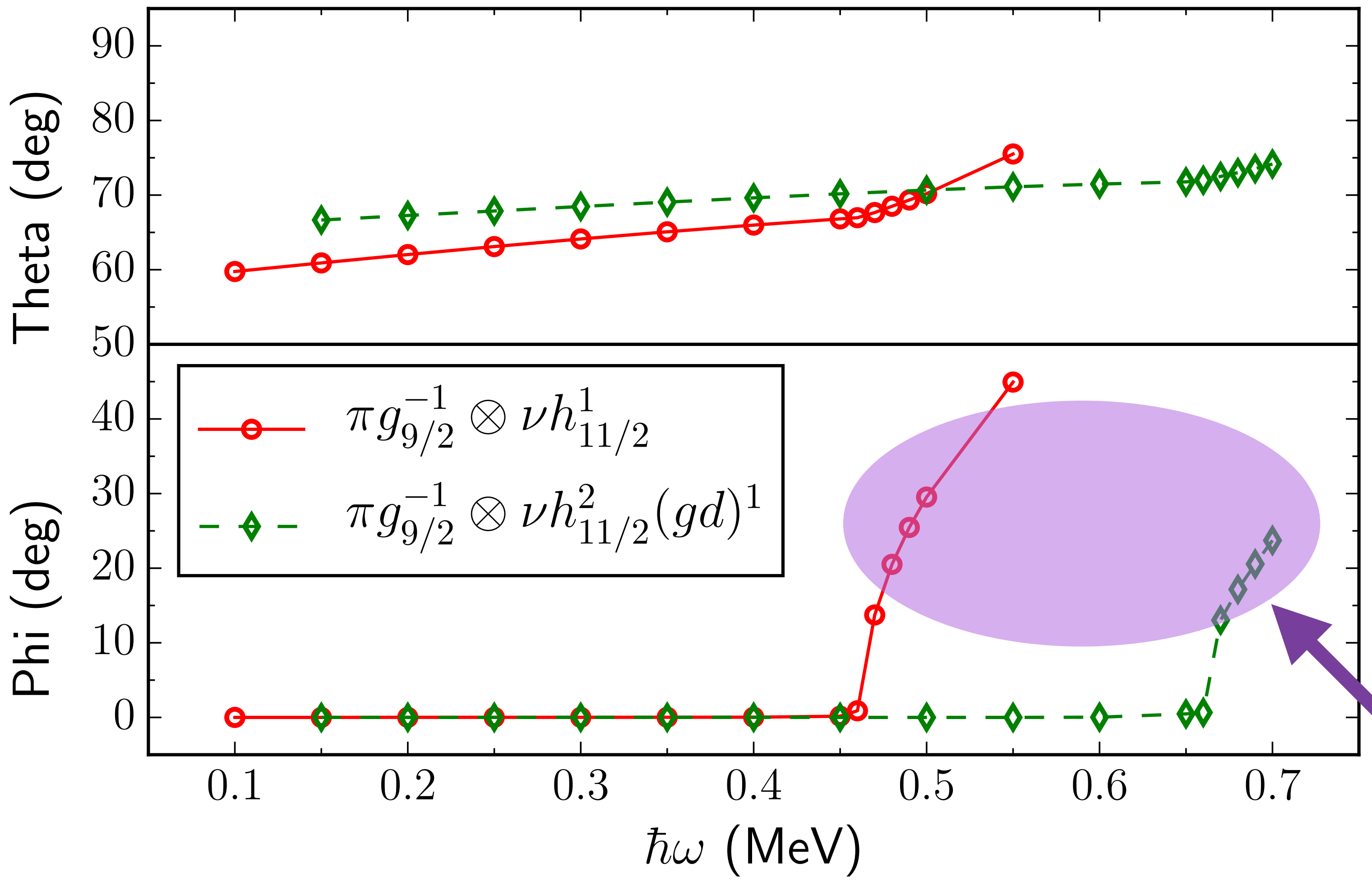


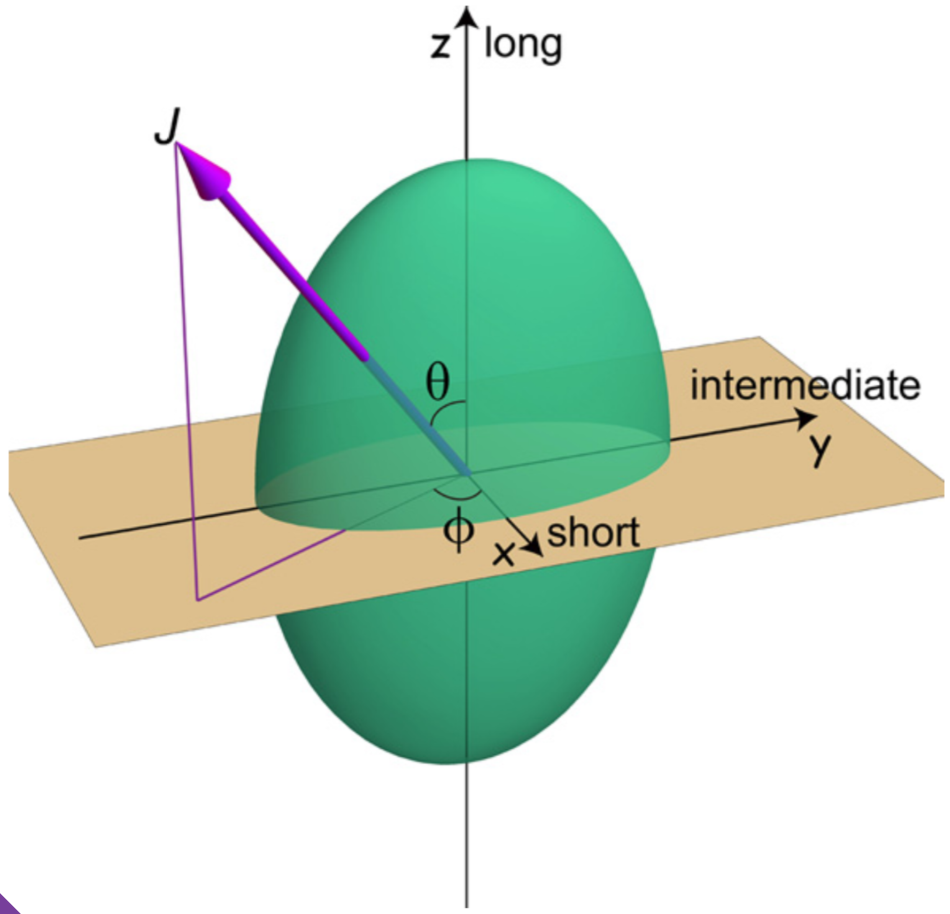
PWZ PLB 773 (2017) 1-5

Aplanar rotation in Rh-106

PWZ PLB 773 (2017) 1-5

Rotational Angles (Theta, Phi)





Chiral geometry appears!

Critical frequency in nuclear chiral rotation

Olbratowski PRL 2004

The 1st pair of chiral bands

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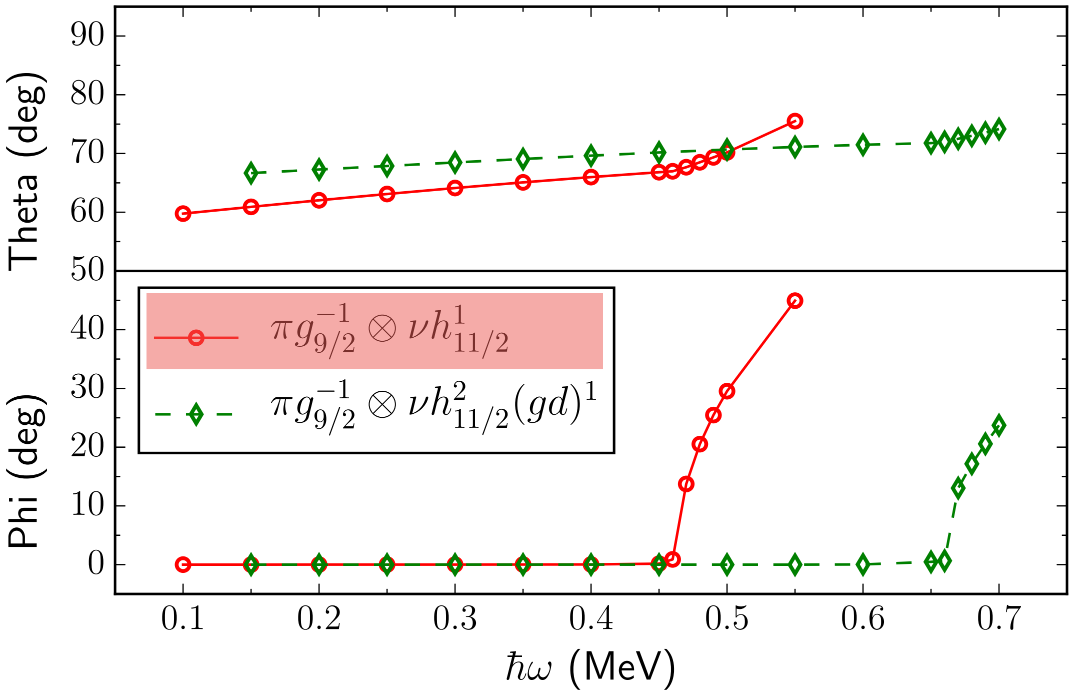
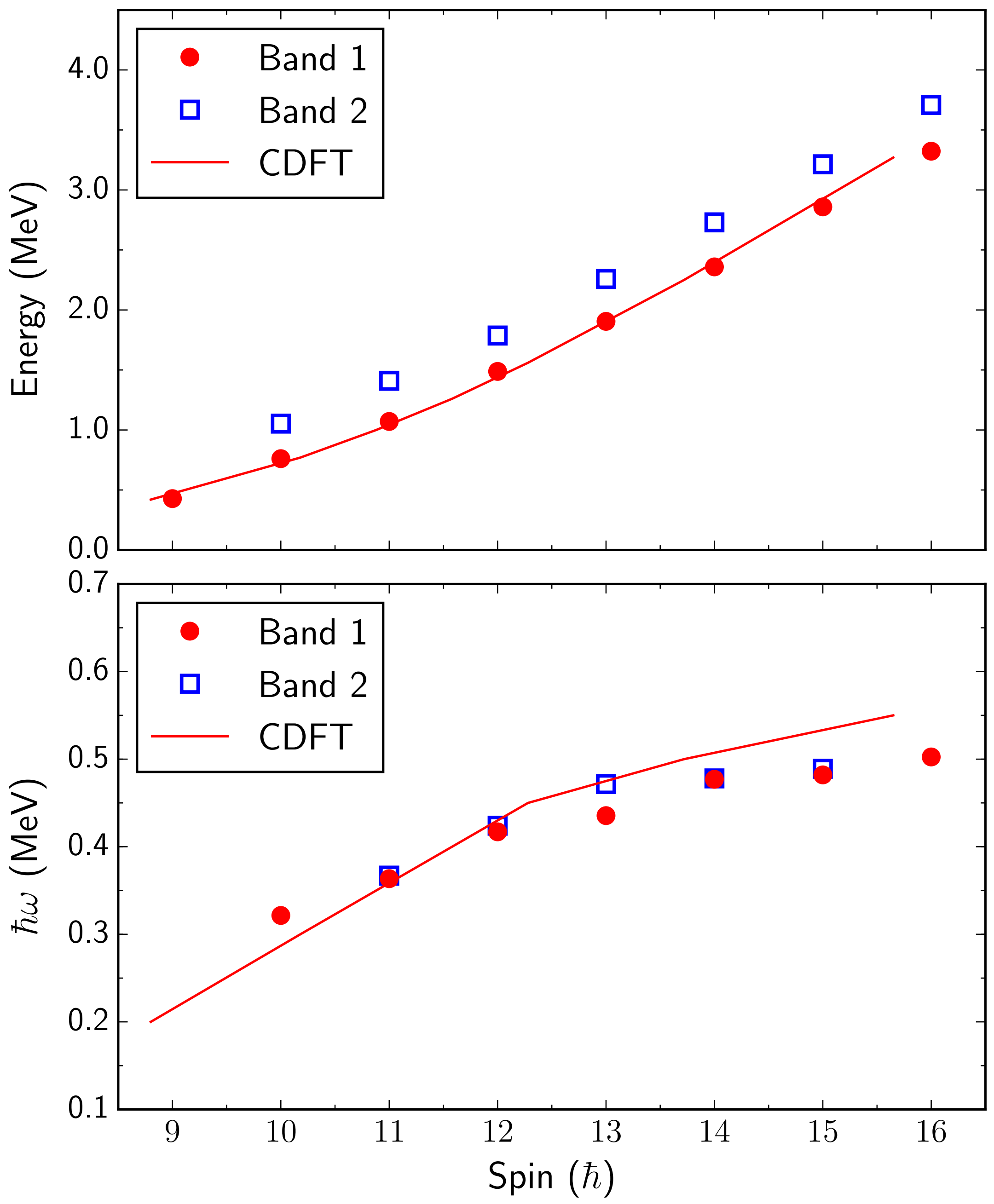
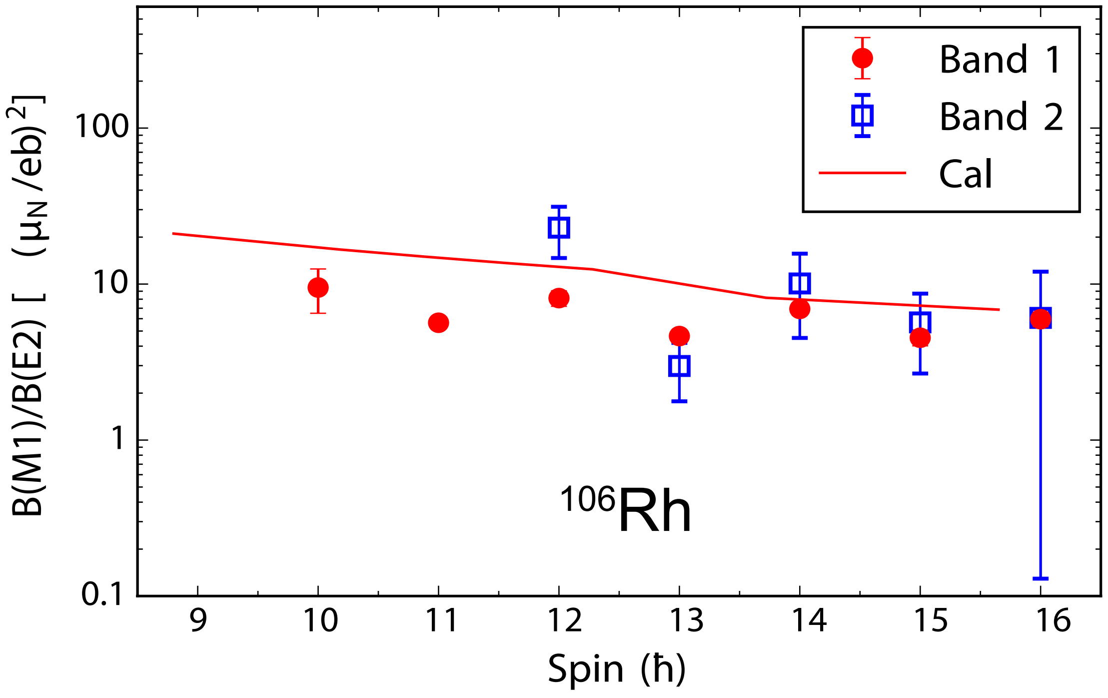


Good agreement with the data !

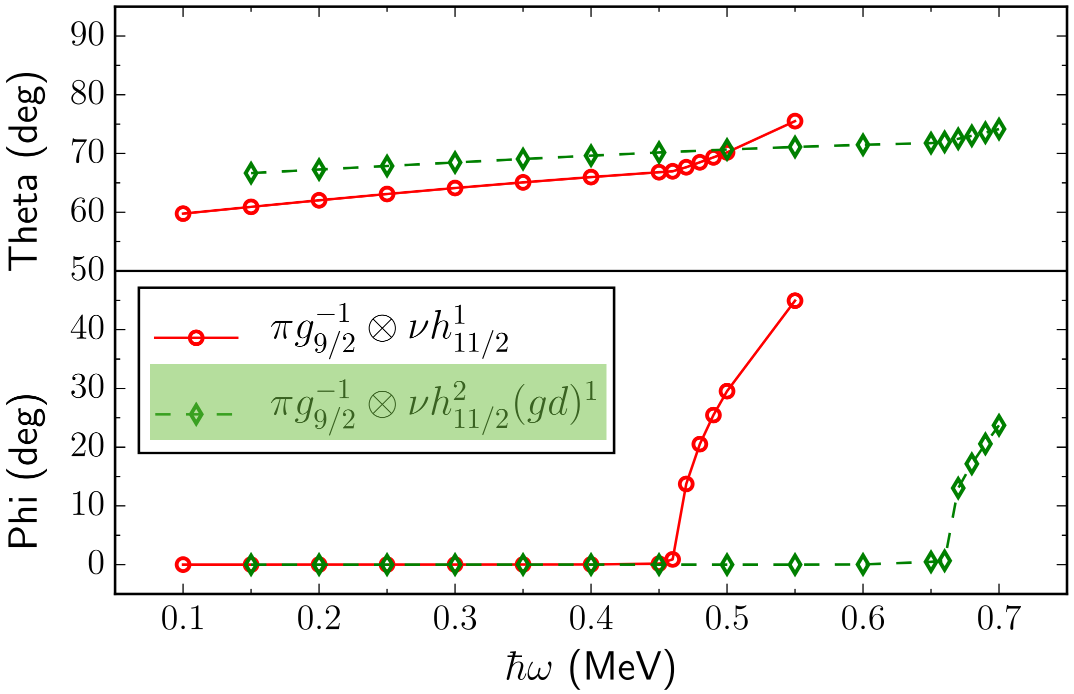




Data from Joshi et al., PLB 595 (2004) 135

The 2nd pair of chiral bands?

PWZ PLB 773 (2017) 1-5



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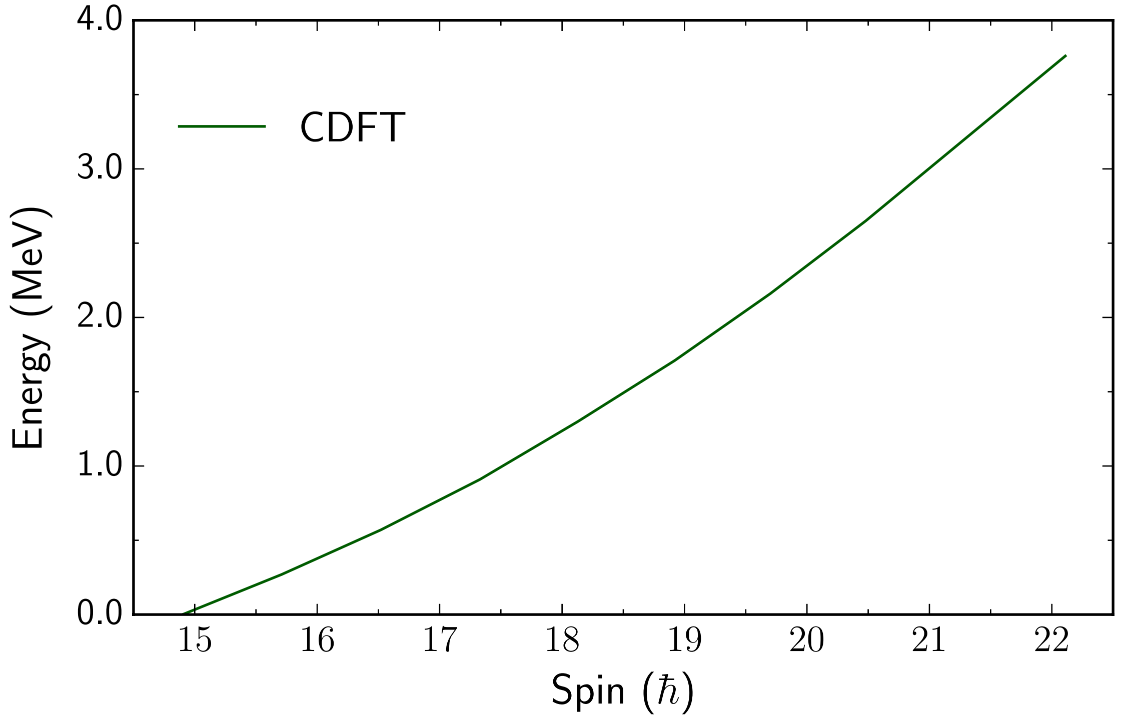

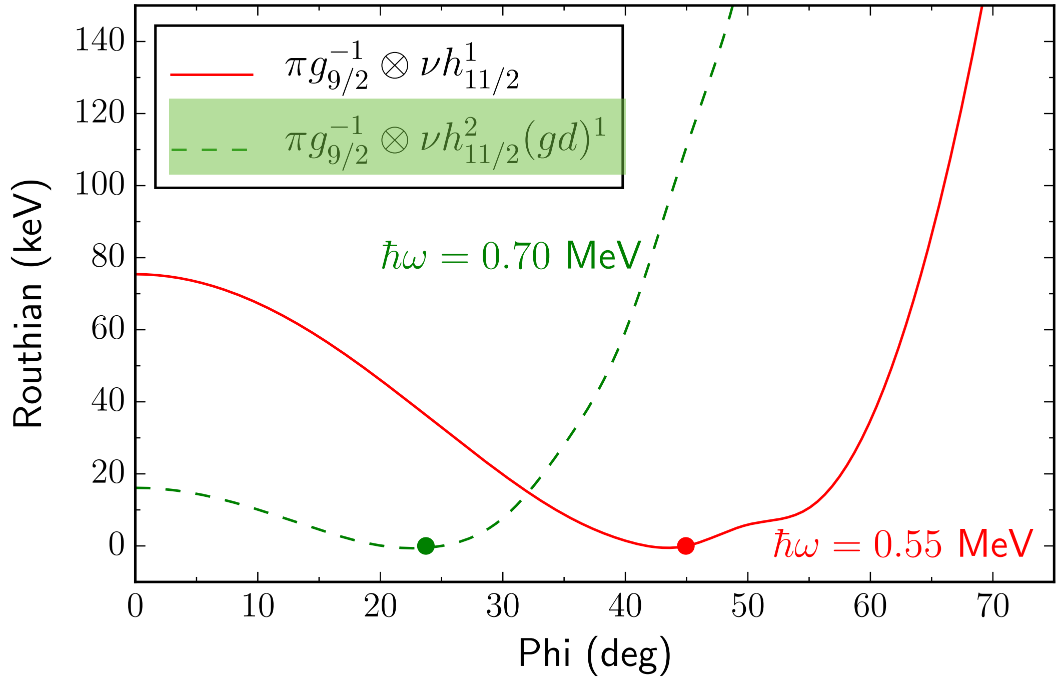

The tunneling between the left and the right-handed sectors could be substantial.

A strong degeneracy of the chiral twin bands is not expected.

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Summary

Covariant density functional theory has been extended for describing nuclear multiple chirality.

- The first DFT description of the multiple chiral bands has been presented.
- Two distinct sets of chiral solutions have been uncovered in the nucleus ^{106}Rh, and a transition between planar and chiral rotation has been found for both configurations.
- The calculated energy spectrum and B(M1)/B(E2) ratios for the negative-parity band are in good agreement with the corresponding experimental data.
- Experiments on the other predicted positive-parity chiral bands are welcome, and a strong degeneracy is not expected due to the soft Routhians.

Collaborations

Beijing
Qibo Chen
Jie Meng
Shuangquan Zhang

Munich
Peter Ring

Notre Dame
Umesh Garg

…

and many other experimentalists…

Thank you for your attention!