北京大學
PEKING UNIVERSITY

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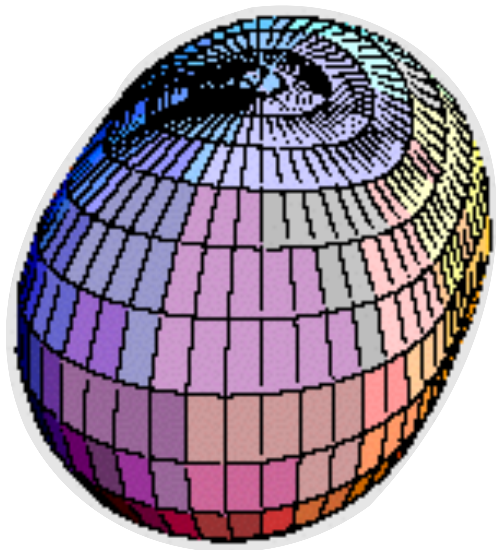
Antimagnetic rotation in nuclei: A microscopic description

Pengwei Zhao

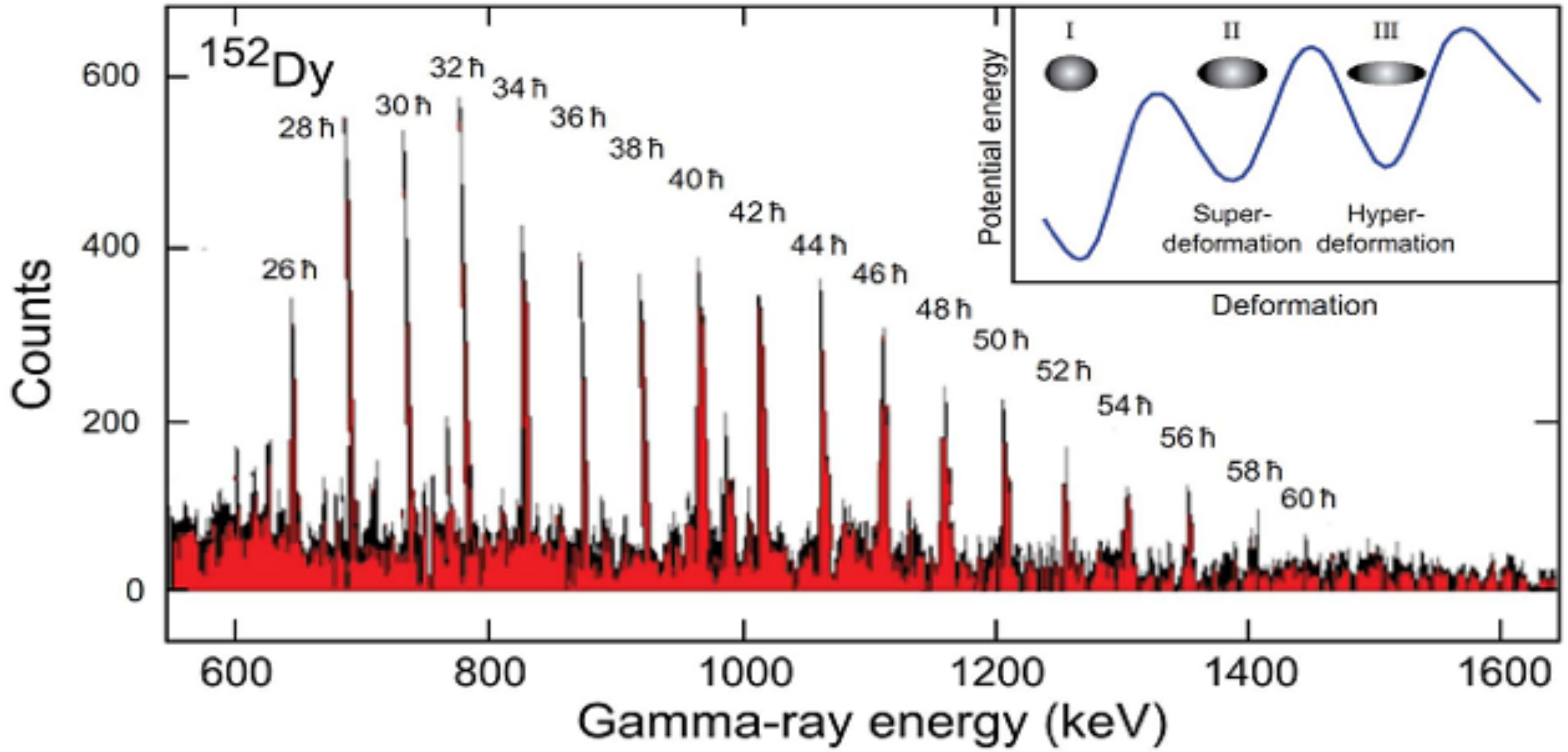
School of Physics, Peking University

Rotation bands in nuclei

- Substantial quadrupole deformation
- Strong electric quadrupole (E2) transitions
- Rotational bands with $\Delta I = 2$
- Coherent collective rotation of many nucleons



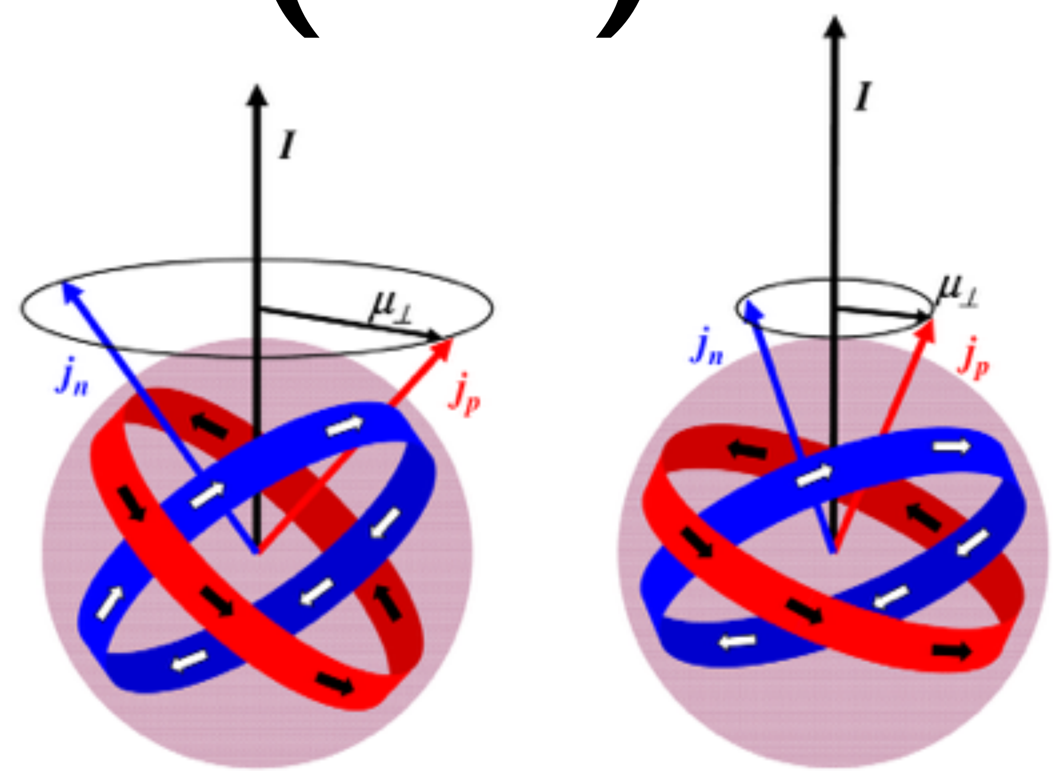
Bohr PR1951

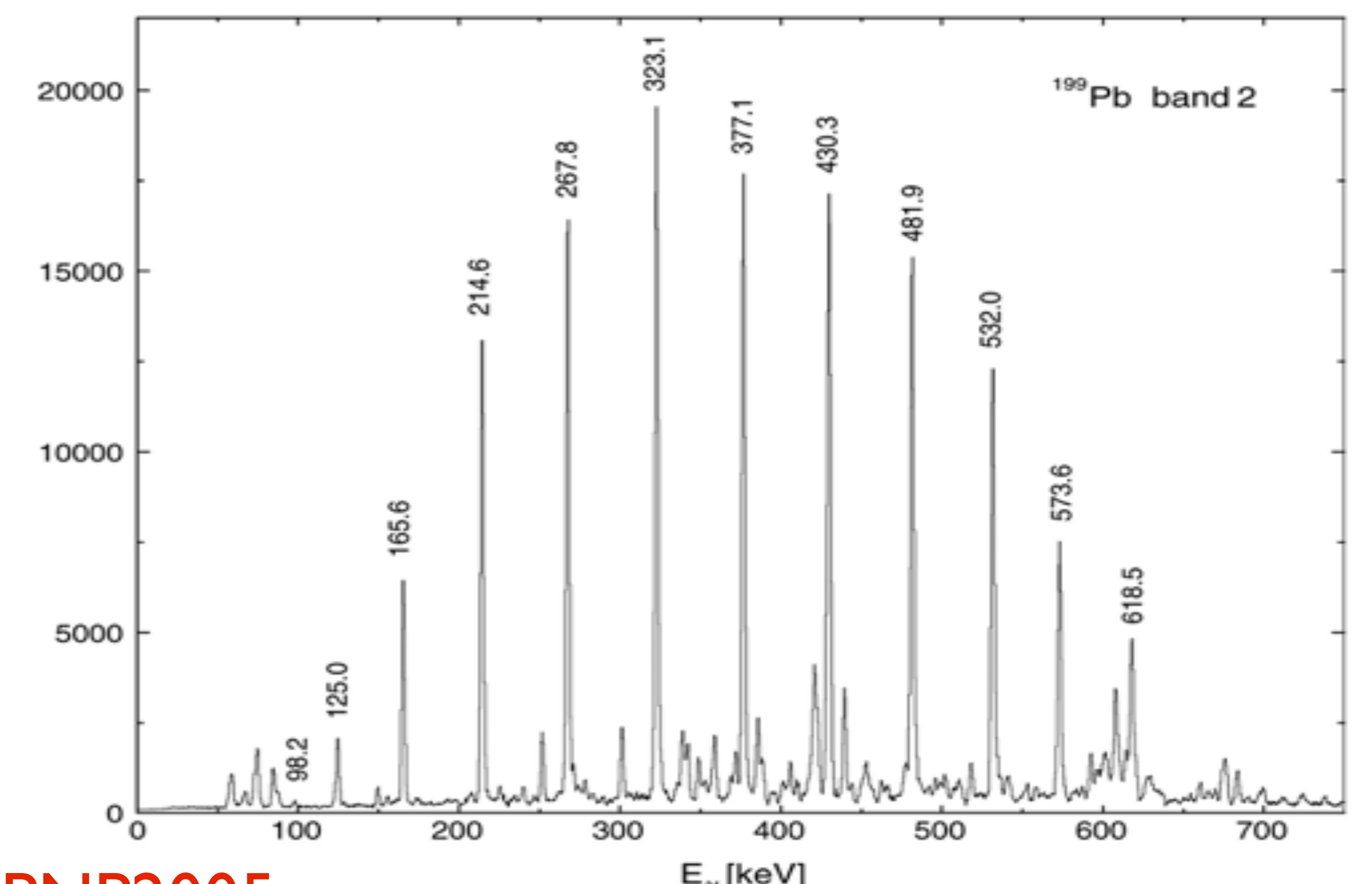


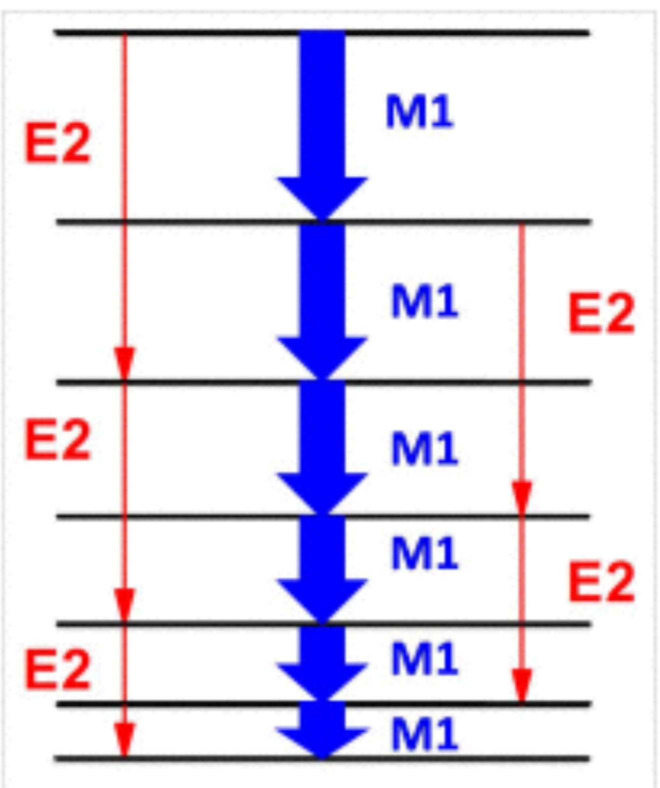
Twin PRL1986

Magnetic Rotation (MR)

- near-spherical or weakly deformed nuclei
- strong M1 and very weak E2 transitions
- rotational bands with $\Delta I = 1$
- shears mechanism



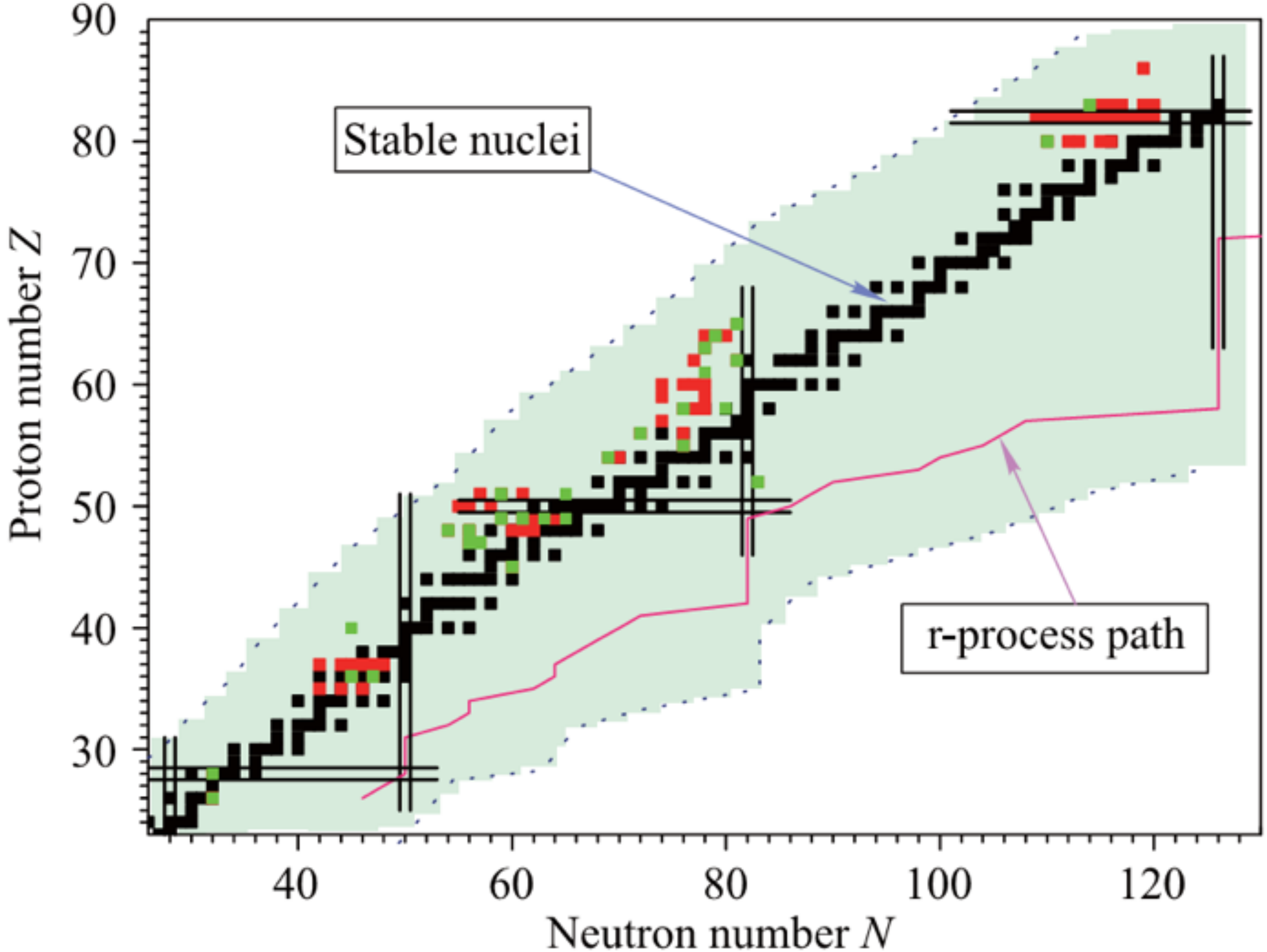




Hübel PPNP2005

Experiment: MR

Magnetic rotation: 85 nuclei

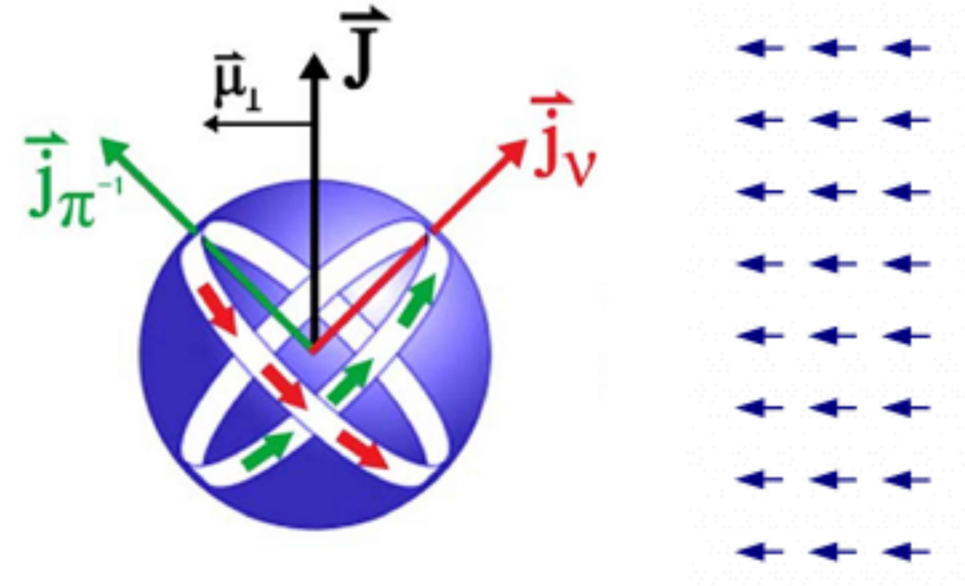


Meng, Peng, Zhang, PWZ, Front. Phys. 8, 55 (2013)

Antimagnetic Rotation (AMR)

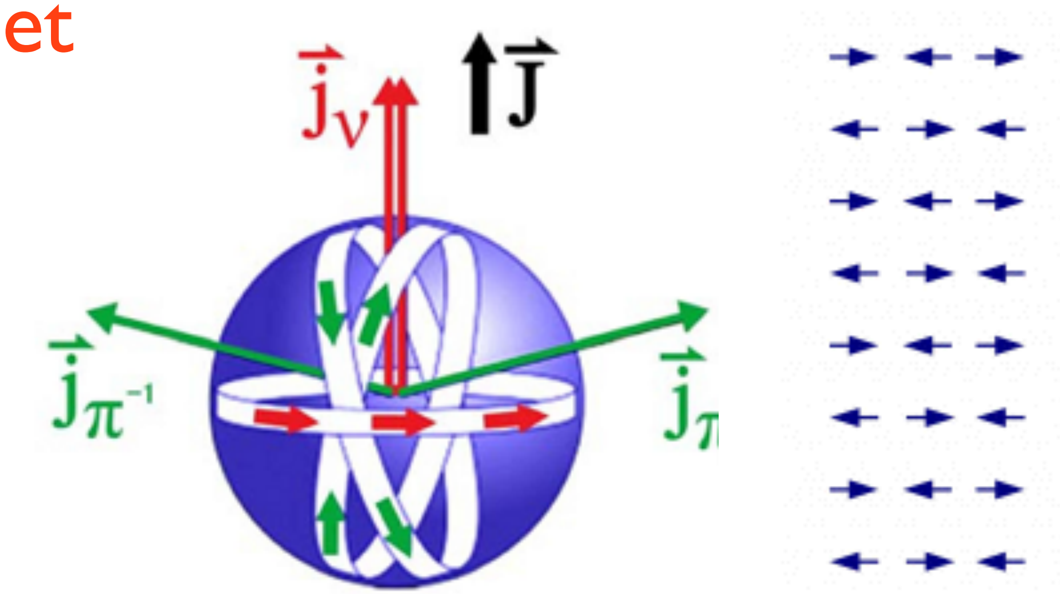
Magnetic rotation ⟺ Ferromagnet

- ✓ rotational bands with $\Delta I = 1$
- ✓ near spherical nuclei; weak E2 transitions
- ✓ strong M1 transitions
- ✓ B(M1) decrease with spin
- ✓ shears mechanism



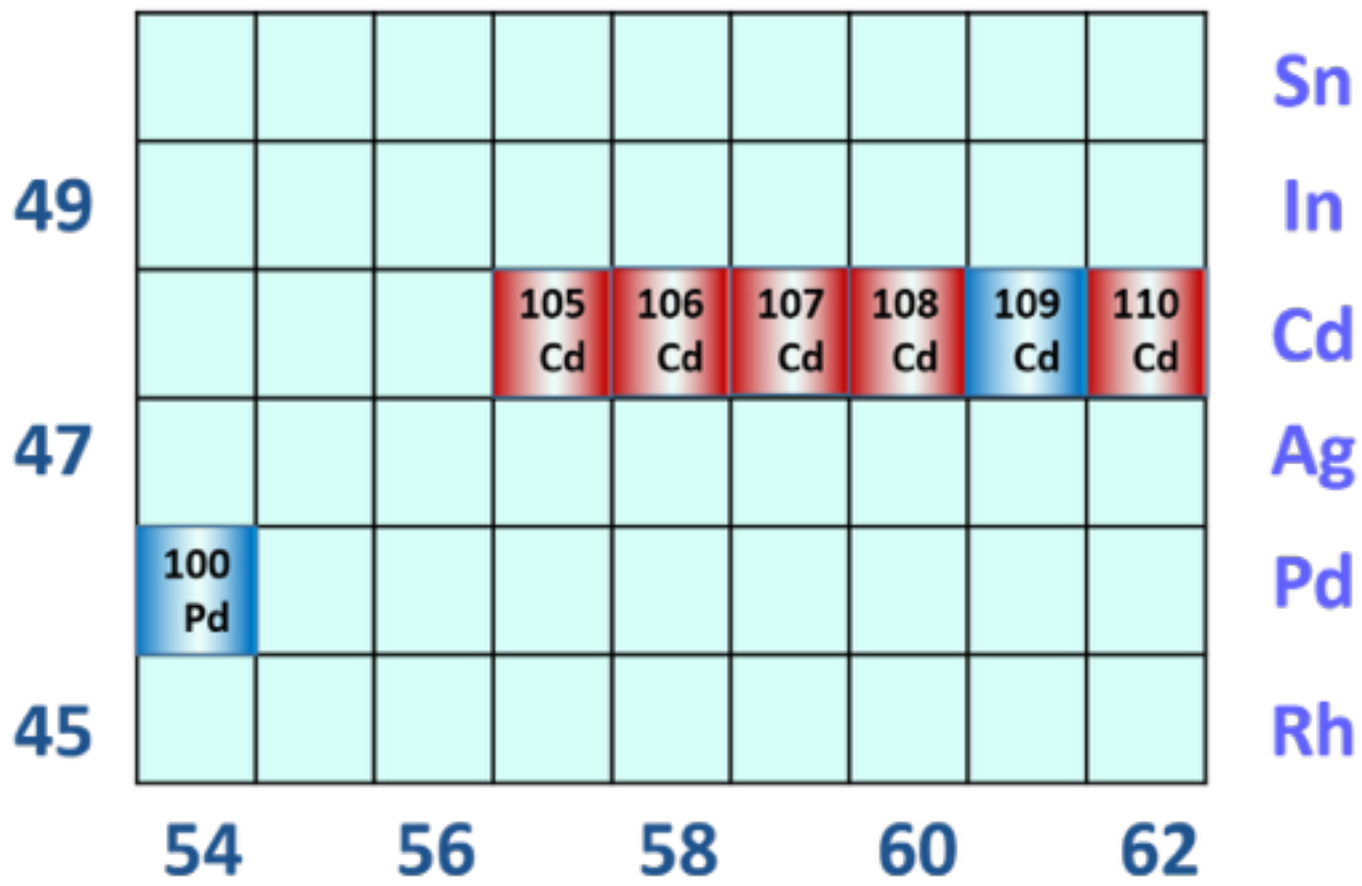
Antimagnetic rotation ⟺ Antiferromagnet

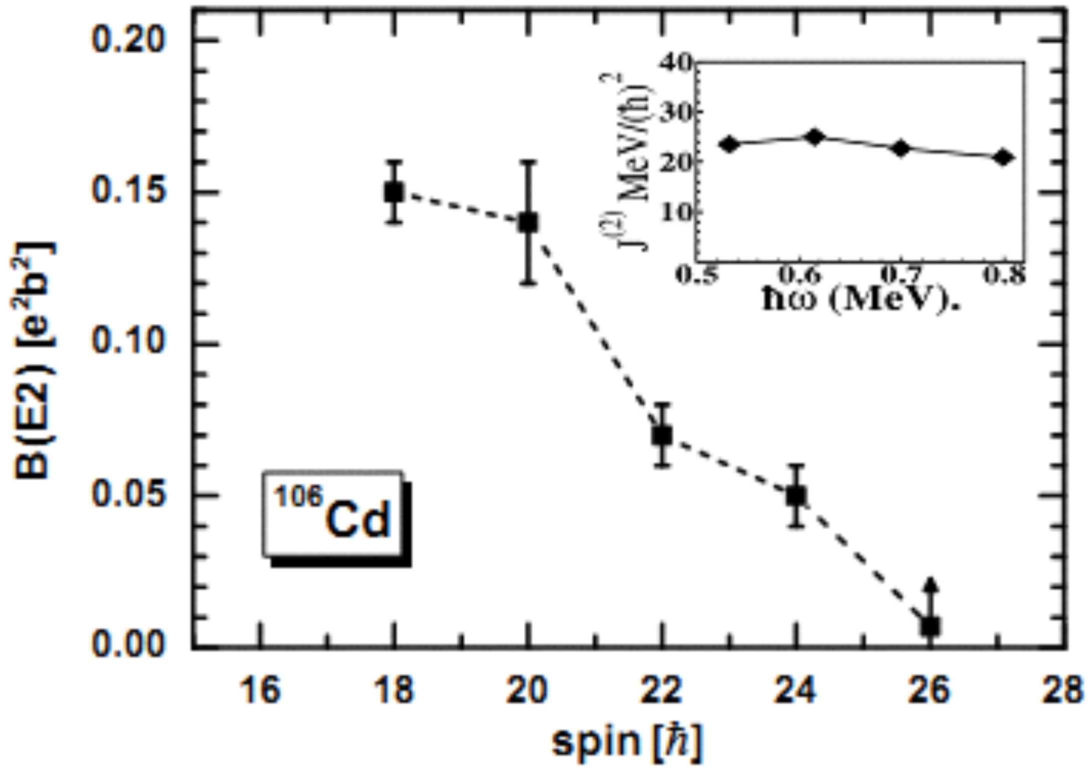
- ✓ rotational bands with $\Delta I = 2$
- ✓ near spherical nuclei; weak E2 transitions
- ✓ no M1 transitions
- ✓ B(E2) decrease with spin
- ✓ two "shears-like" mechanism

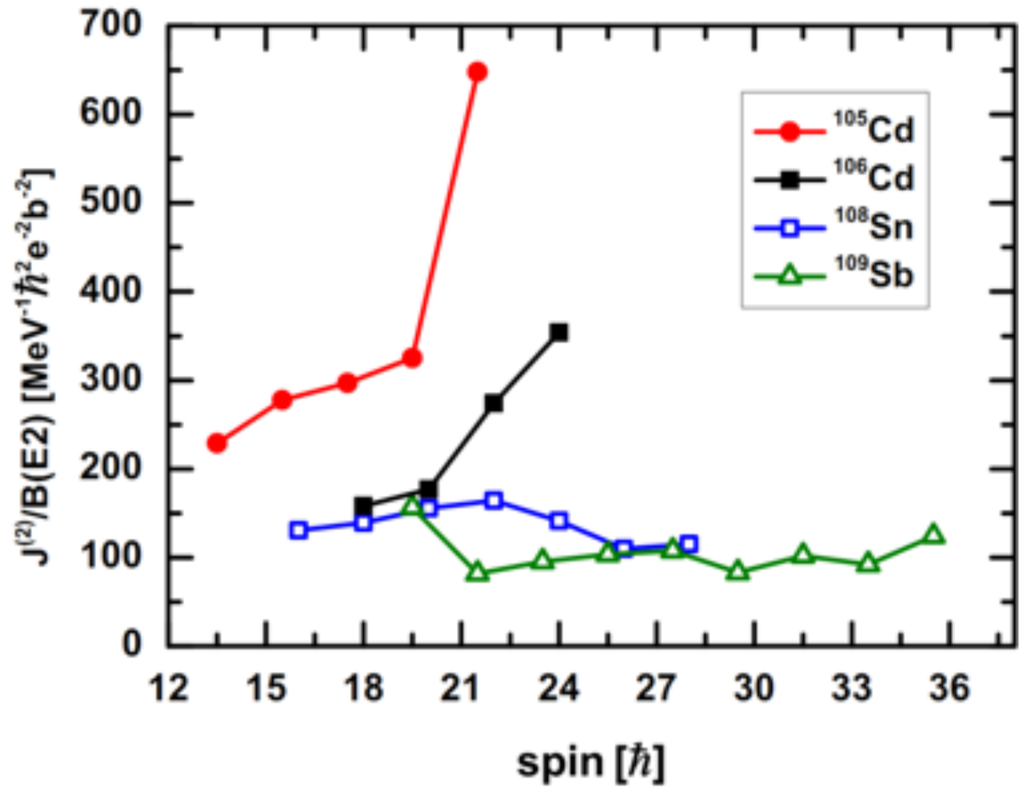


Experiment: AMR

A~100







Small B(E2)
Decrease tendency

Large J(2)/B(E2)
Increase tendency

Simons PRL2003; Simons PRC2005

Theory

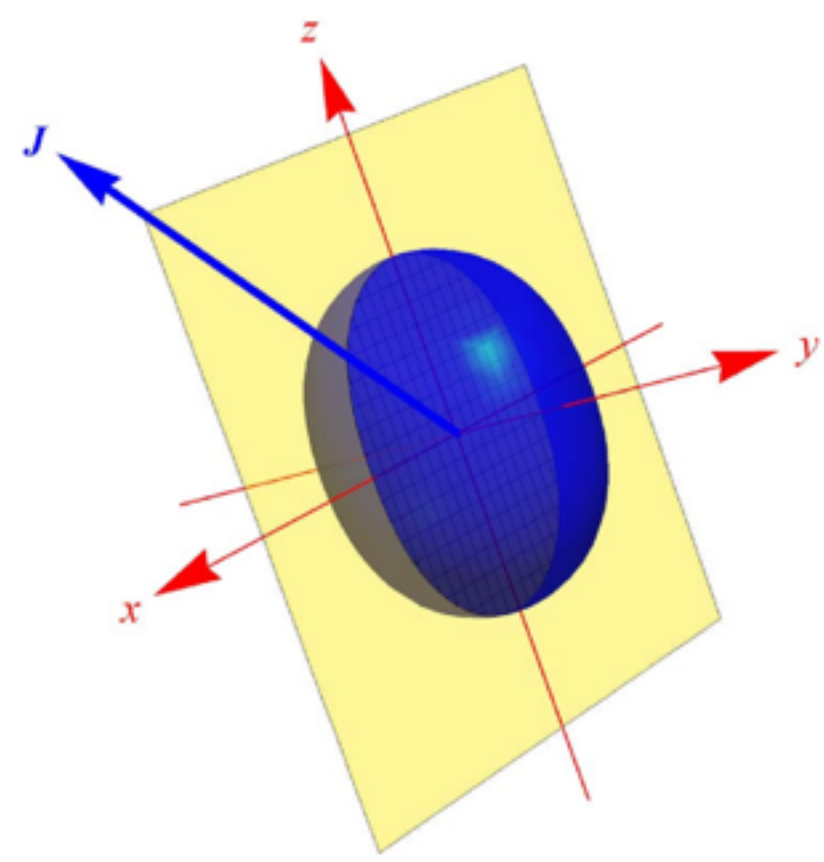
✓Semiclassical particle plus rotor model Clark ARNPS2000

simple geometry for the energies and transition probabilities

✓Pairing-plus-quadrupole tilted axis cranking (TAC) model

a schematic Hamiltonian Frauendorf NPA1993; Frauendorf NPA2000

A fully self-consistent microscopic investigation?



DFT: Cranking version

- **TAC based on Covariant Density Functional Theory**

  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)***

- **TAC based on Skyrme Density Functional Theory**

  3-D Cranking: ***Olbratowski, Dobaczewski, Dudek, Płóciennik, PRL 93, 052501(2004)***

  2-D Cranking: ***Olbratowski, Dobaczewski, Dudek, Rzaca-Urban, Marcinkowska, Lieder, APPB 33, 389(2002)***

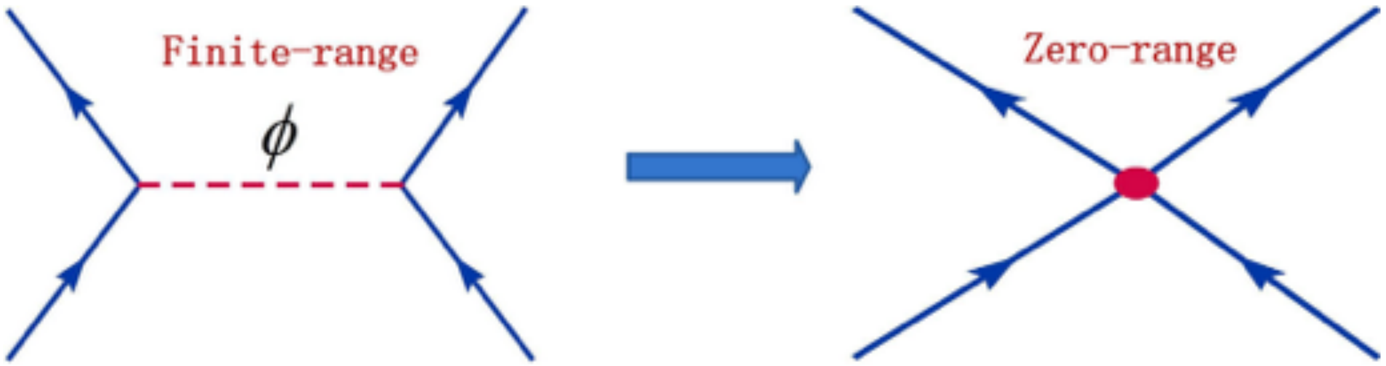
Fully self-consistent microscopic investigations

- fully taken into account polarization effects
- self-consistently treated the nuclear currents
- without any adjustable parameters for rotational excitations

Tilted axis cranking CDFT

General Lagrangian density

$$
\begin{aligned}
L =& \bar{\psi}(i\gamma_\mu \partial^\mu - m)\psi \\
& -\frac{1}{2}\alpha_S(\bar{\psi}\psi)(\bar{\psi}\psi) - \frac{1}{2}\alpha_V(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi) \\
& -\frac{1}{2}\alpha_{TV}(\bar{\psi}\vec{\tau}\gamma_\mu\psi)(\bar{\psi}\vec{\tau}\gamma^\mu\psi) - \frac{1}{3}\beta_S(\bar{\psi}\psi)^3 - \frac{1}{4}\gamma_S(\bar{\psi}\psi)^4 \\
& -\frac{1}{4}\gamma_V[(\bar{\psi}\gamma_\mu\psi)(\bar{\psi}\gamma^\mu\psi)]^2 - \frac{1}{2}\delta_S\partial_\nu(\bar{\psi}\psi)\partial^\nu(\bar{\psi}\psi) - \frac{1}{2}\delta_V\partial_\nu(\bar{\psi}\gamma_\mu\psi)\partial^\nu(\bar{\psi}\gamma^\mu\psi) - \frac{1}{2}\delta_{TV}\partial_\nu(\bar{\psi}\vec{\tau}\gamma_\mu\psi)\partial^\nu(\bar{\psi}\vec{\tau}\gamma_\mu\psi) \\
& -e\frac{1-\tau_3}{2}\bar{\psi}\gamma^\mu\psi A_\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}
\end{aligned}
$$

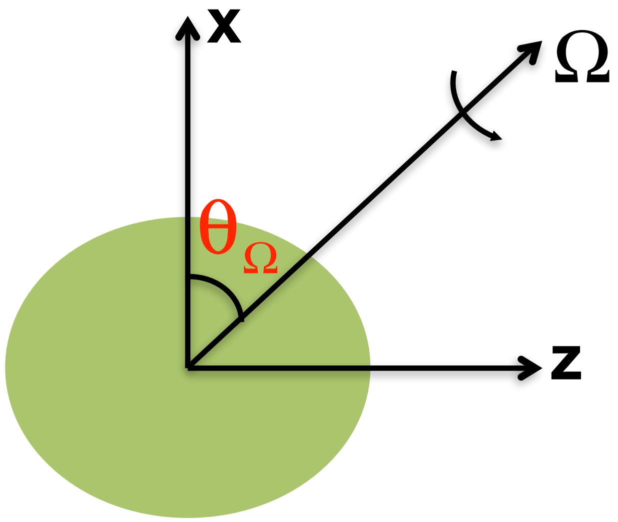


$$\frac{-g_\phi^2}{-\nabla^2 + m_\phi^2} \qquad \frac{-g_\phi^2}{m_\phi^2} + \frac{-g_\phi^2}{m_\phi^4}\nabla^2$$

Transformed to the frame rotating with the uniform velocity

$$\Omega = (\Omega_x, 0, \Omega_z) = (\Omega\cos\theta_\Omega, 0, \Omega\sin\theta_\Omega)$$

$$x^\alpha = \begin{pmatrix} t \\ \mathbf{x} \end{pmatrix} \rightarrow \tilde{x}^\alpha = \begin{pmatrix} \tilde{t} \\ \tilde{\mathbf{x}} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & \mathbf{R} \end{pmatrix}\begin{pmatrix} t \\ \mathbf{x} \end{pmatrix}$$



Koepf NPA1989; Kaneko PLB1993; Madokoro PRC1997

Equation of motion

Dirac equation

$$\begin{pmatrix} m+S+V-\Omega\cdot J & \sigma(p-\mathbf{V}) \\ \sigma(p-\mathbf{V}) & -m-S+V-\Omega\cdot J \end{pmatrix}\begin{pmatrix} f \\ g \end{pmatrix}=\varepsilon\begin{pmatrix} f \\ g \end{pmatrix}$$

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

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

$$S(r)=\alpha_S\rho_S+\beta_S\rho_S^2+\gamma_S\rho_S^3+\delta_S\Delta\rho_S$$

V(r) vector potential time-like

V(r) vector potential space-like

S(r) scalar potential

Observables

Binding energy

$$E_{\text{tot}} = \sum_{k=1}^{A} \epsilon_k - \int d^3r \Big\{ \frac{1}{2}\alpha_S \rho_S^2 + \frac{1}{2}\alpha_V j_V^{\mu}(j_V)_{\mu}$$
$$+ \frac{1}{2}\alpha_{TV} j_{TV}^{\mu}(j_{TV})_{\mu} + \frac{2}{3}\beta_S \rho_S^3 + \frac{3}{4}\gamma_S \rho_S^4$$
$$+ \frac{3}{4}\gamma_V \left(j_V^{\mu}(j_V)_{\mu}\right)^2 + \frac{1}{2}\delta_S \rho_S \Delta \rho_S + \frac{1}{2}\delta_V (j_V)_{\mu} \Delta j_V^{\mu}$$
$$+ \frac{1}{2}\delta_{TV} j_{TV}^{\mu} \Delta (j_{TV})_{\mu} + \frac{1}{2} e j_p^0 A_0 \Big\} + \sum_{k=1}^{A} \langle k | \boldsymbol{\Omega} \hat{\boldsymbol{J}} | k \rangle$$
$$+ E_{\text{c.m.}}.$$

Angular momentum

$$J = \sqrt{\langle \hat{J}_x \rangle^2 + \langle \hat{J}_z \rangle^2} \equiv \sqrt{I(I+1)}.$$

Observables

Binding energy

$$E_{\text{tot}} = \sum_{k=1}^{A} \epsilon_k - \int d^3r \Big\{ \frac{1}{2}\alpha_S \rho_S^2 + \frac{1}{2}\alpha_V j_V^\mu (j_V)_\mu + \frac{1}{2}\alpha_{TV} j_{TV}^\mu (j_{TV})_\mu + \frac{2}{3}\beta_S \rho_S^3 + \frac{3}{4}\gamma_S \rho_S^4 + \frac{3}{4}\gamma_V \left(j_V^\mu (j_V)_\mu\right)^2 + \frac{1}{2}\delta_S \rho_S \Delta \rho_S + \frac{1}{2}\delta_V (j_V)_\mu \Delta j_V^\mu + \frac{1}{2}\delta_{TV} j_{TV}^\mu \Delta (j_{TV})_\mu + \frac{1}{2} e j_p^0 A_0 \Big\} + \sum_{k=1}^{A} \langle k | \boldsymbol{\Omega} \hat{\boldsymbol{J}} | k \rangle + E_{\text{c.m.}}.$$

Angular momentum

$$J = \sqrt{\langle \hat{J}_x \rangle^2 + \langle \hat{J}_z \rangle^2} \equiv \sqrt{I(I+1)}.$$

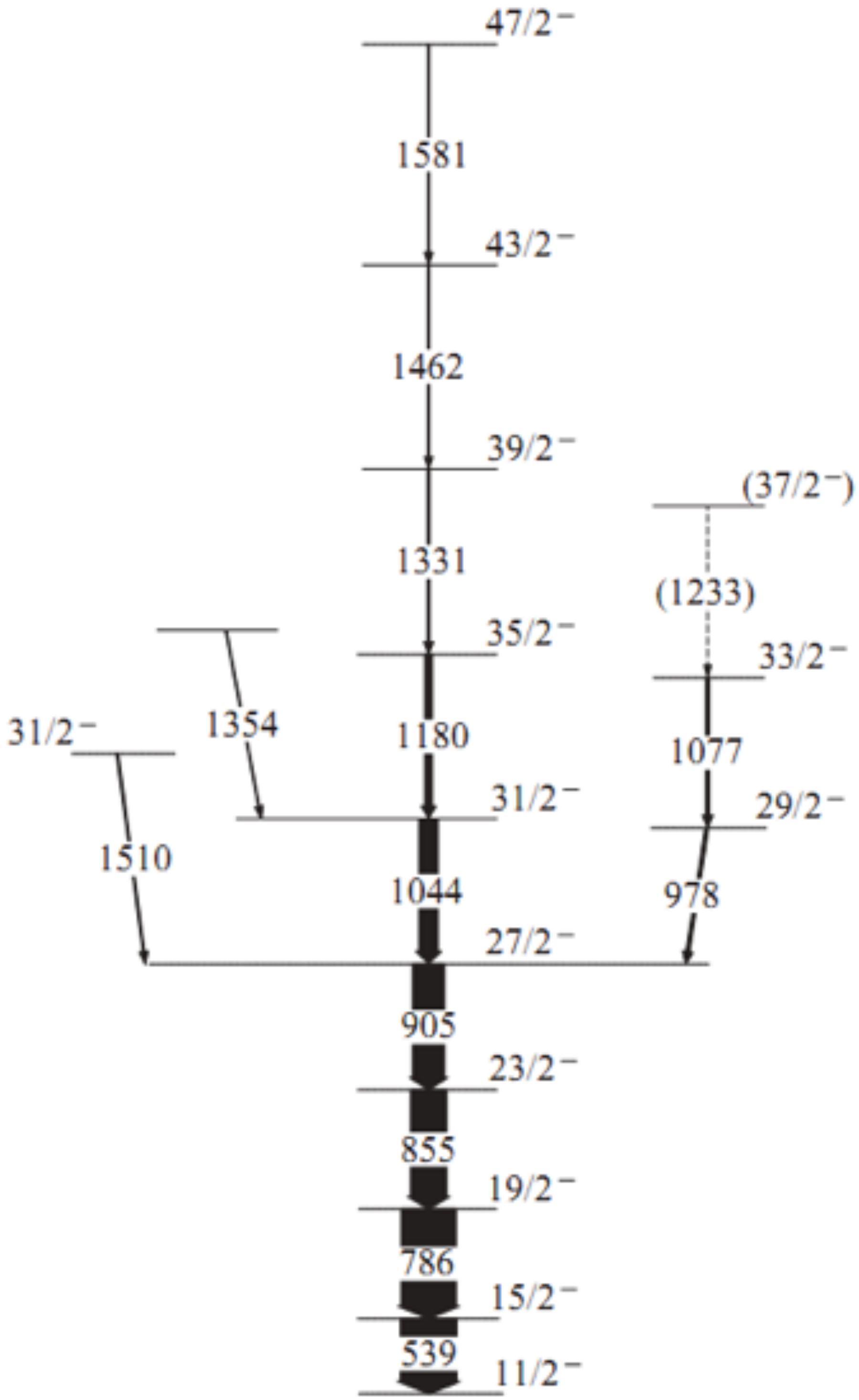
B(M1) and B(E2) transition probabilites

$$B(M1) = \frac{3}{8\pi}\mu_\perp^2 = \frac{3}{8\pi}(\mu_x \sin\theta_J - \mu_z \cos\theta_J)^2,$$

$$B(E2) = \frac{3}{8}\left[Q_{20}^p \cos^2\theta_J + \sqrt{\frac{2}{3}} Q_{22}^p (1 + \sin^2\theta_J) \right]^2.$$

AMR in ^{105}Cd

First odd-A nucleus with antimagnetic rotation



Choudhury et al, PRC 82 , 061308 (2010)

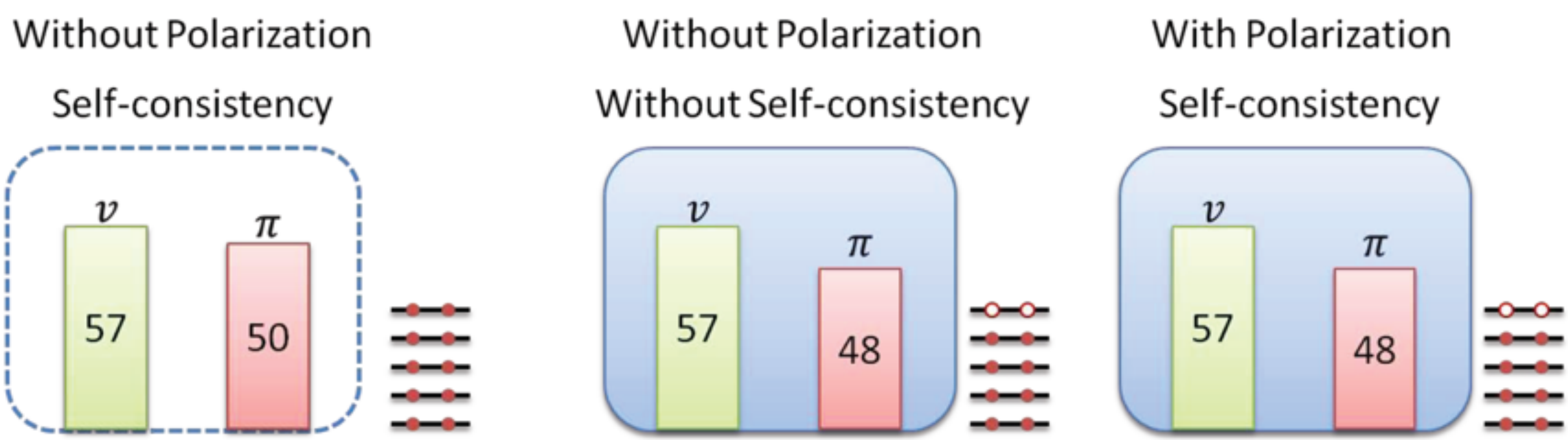
Numerical Details

✓ Harmonic oscillator shells: Nf = 10

✓ Effective interaction: PC-PK1

✓ Configurations: $\nu[h_{11/2}(g_{7/2})^2] \otimes \pi[(g_{9/2})^{-2}]$

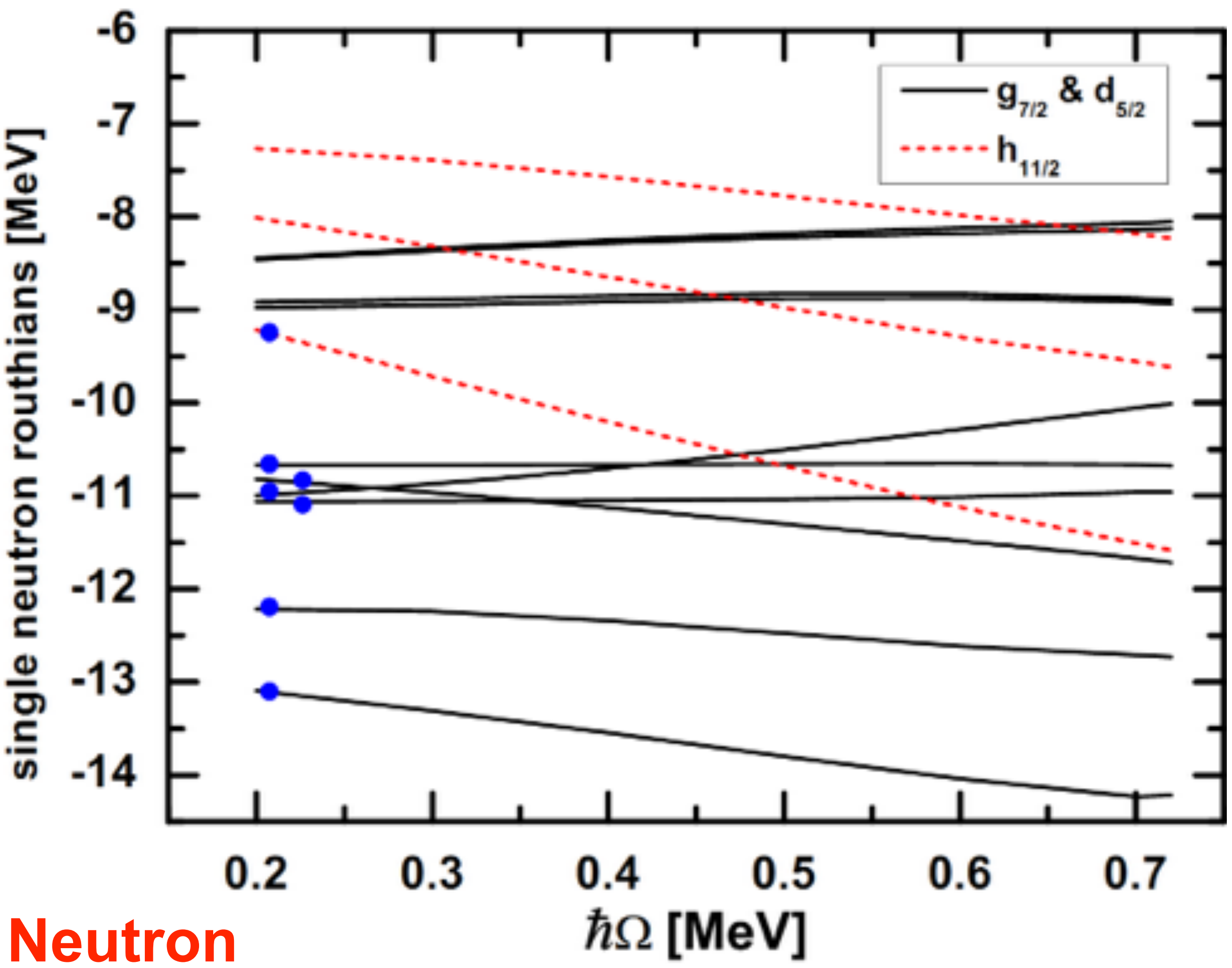
✓ Polarizations:



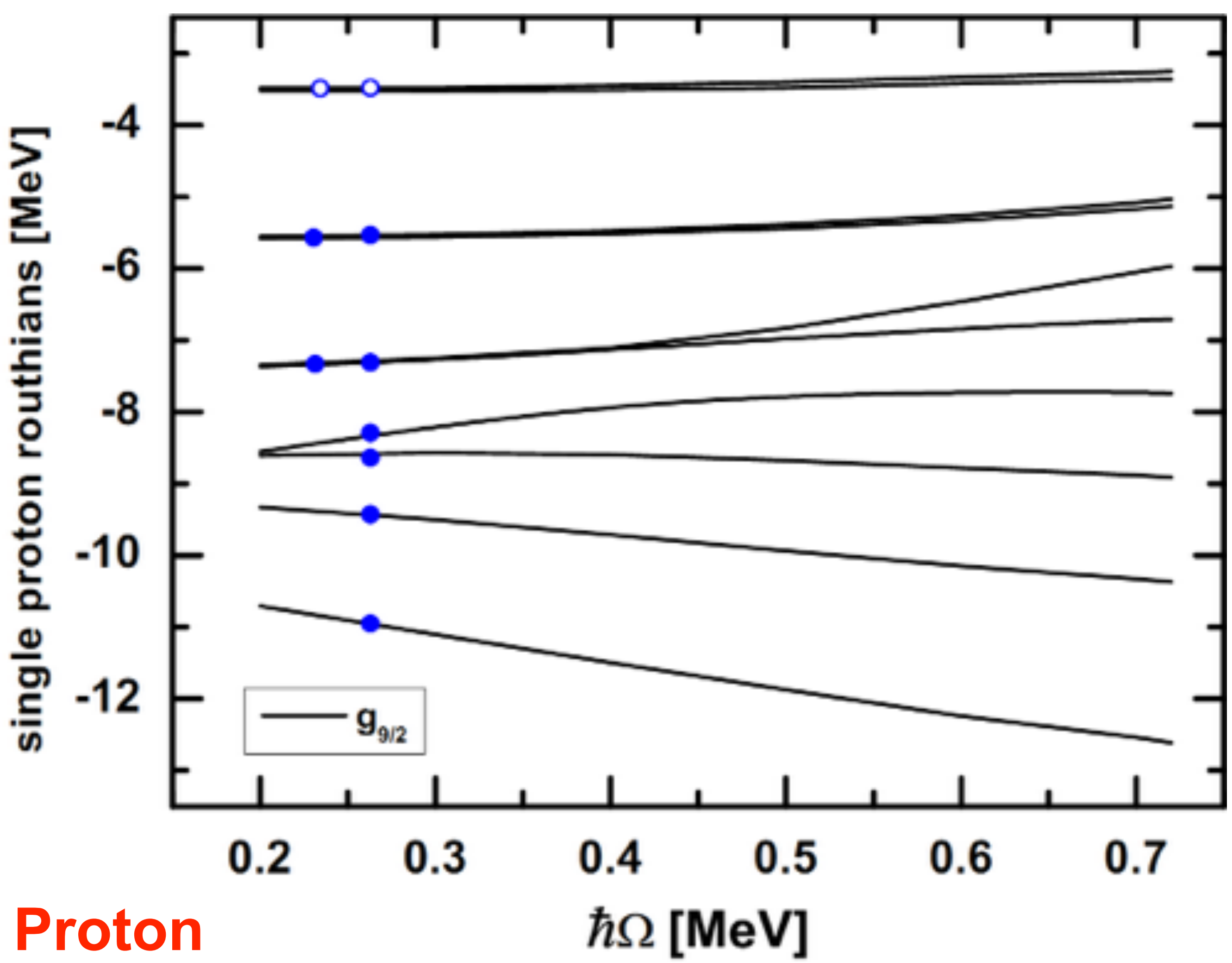
^{107}Sn ^{107}Sn + $\pi[(g_{9/2})^{-2}]$ ^{105}Cd

PWZ, Peng, Liang, Ring, Meng   PRL 107, 122501(2011)

Single particle routhians



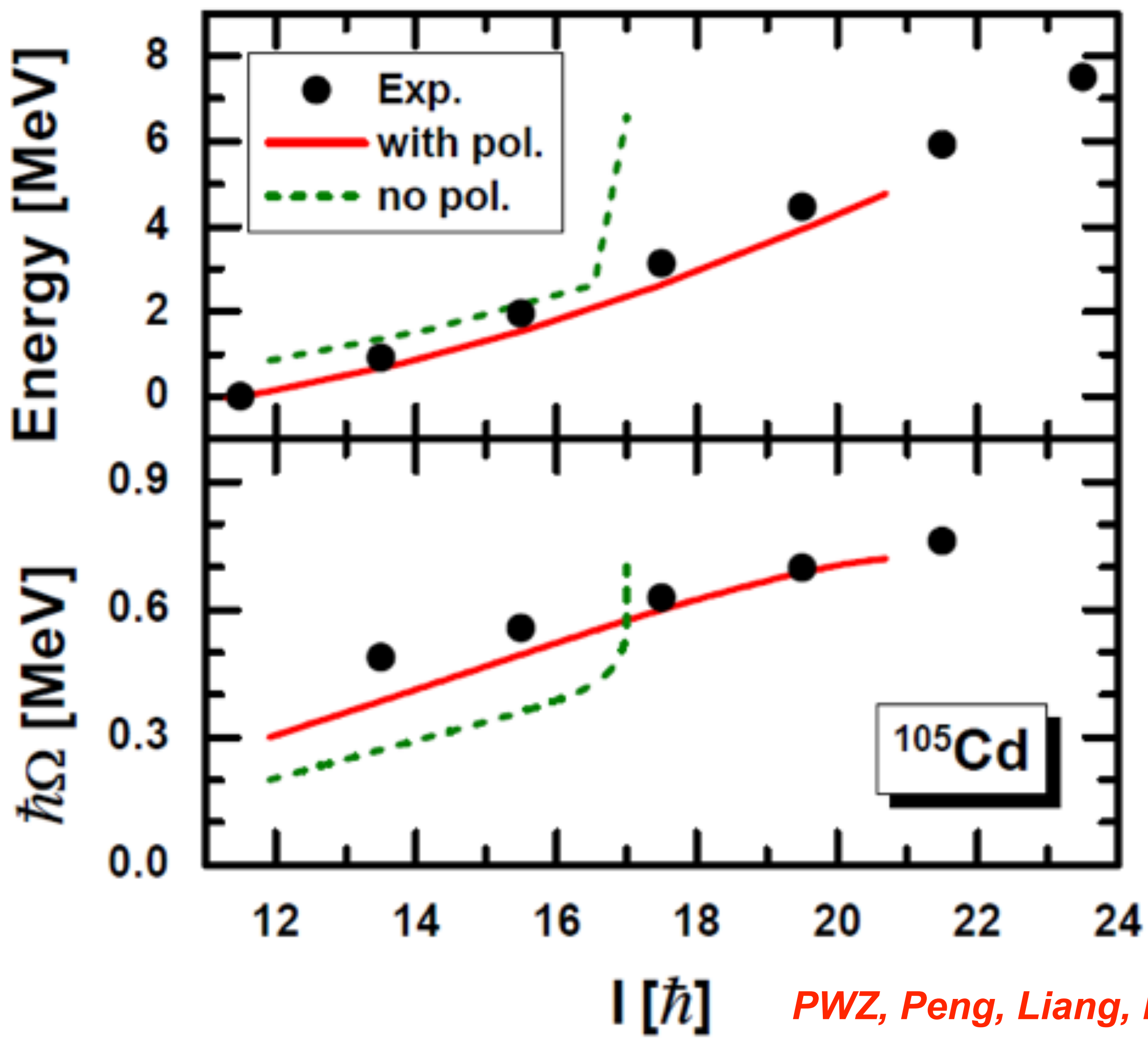
Neutron



Proton

- ✓ **Time reversal symmetry broken: energy splitting**
- ✓ **For proton, two holes in the top of $g_{9/2}$ shell**
- ✓ **For neutron, one particle in the bottom of $h_{11/2}$ shell, the other six are distributed over the (gd) shell with strong mixing**
- ✓ **This configuration is similar to $\nu[h_{11/2}(g_{7/2})^2] \otimes \pi[(g_{9/2})^{-2}]$, but not exactly**

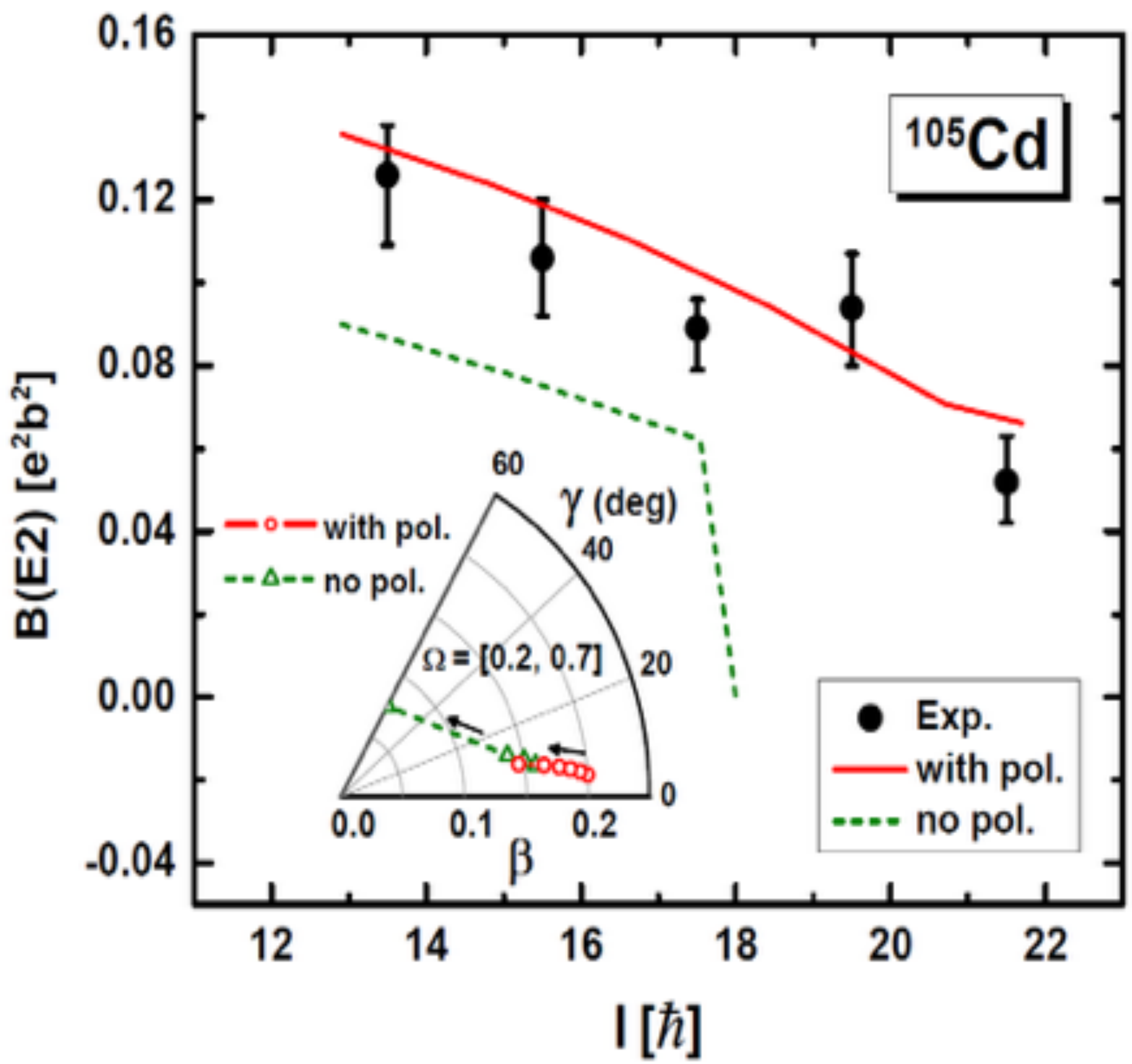
Energy and angular momentum

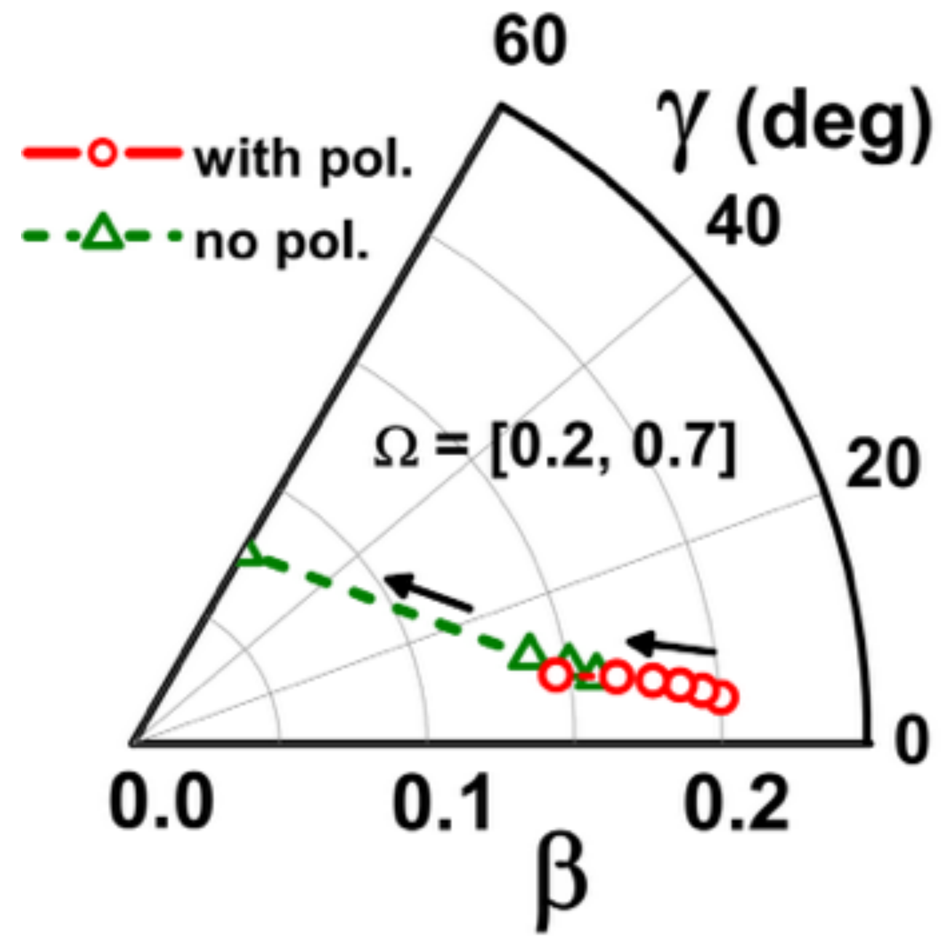


PWZ, Peng, Liang, Ring, Meng PRL 107, 122501(2011)

- ✓ The energy and total angular momentum agree well with the data.
- ✓ The spin increase linearly with frequency / nearly constant moment of inertia.
- ✓ Without polarization, a much smaller frequency is needed to reach the same angular momentum.
- ✓ Without polarization, there is a maximal angular momentum of roughly 17ħ

B(E2) and deformation

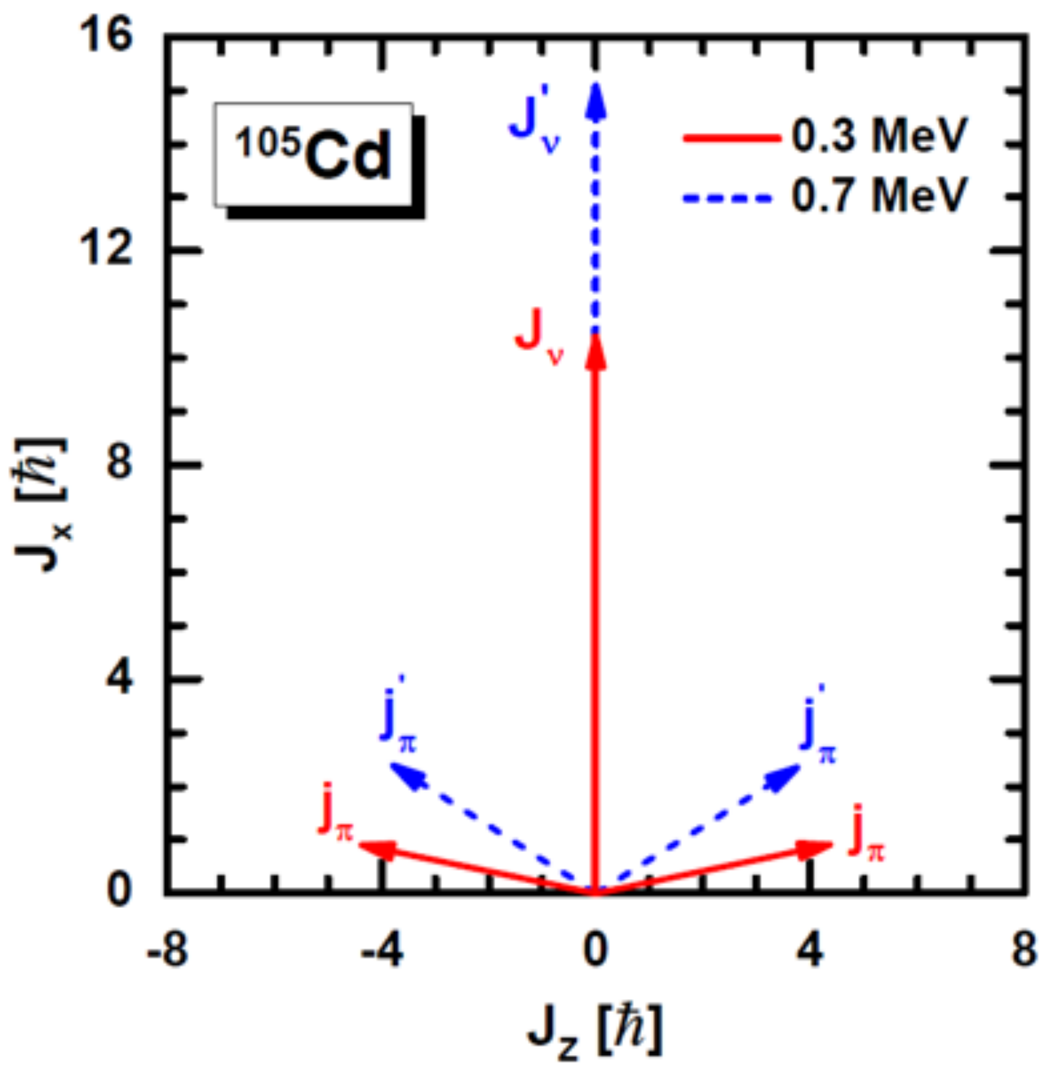


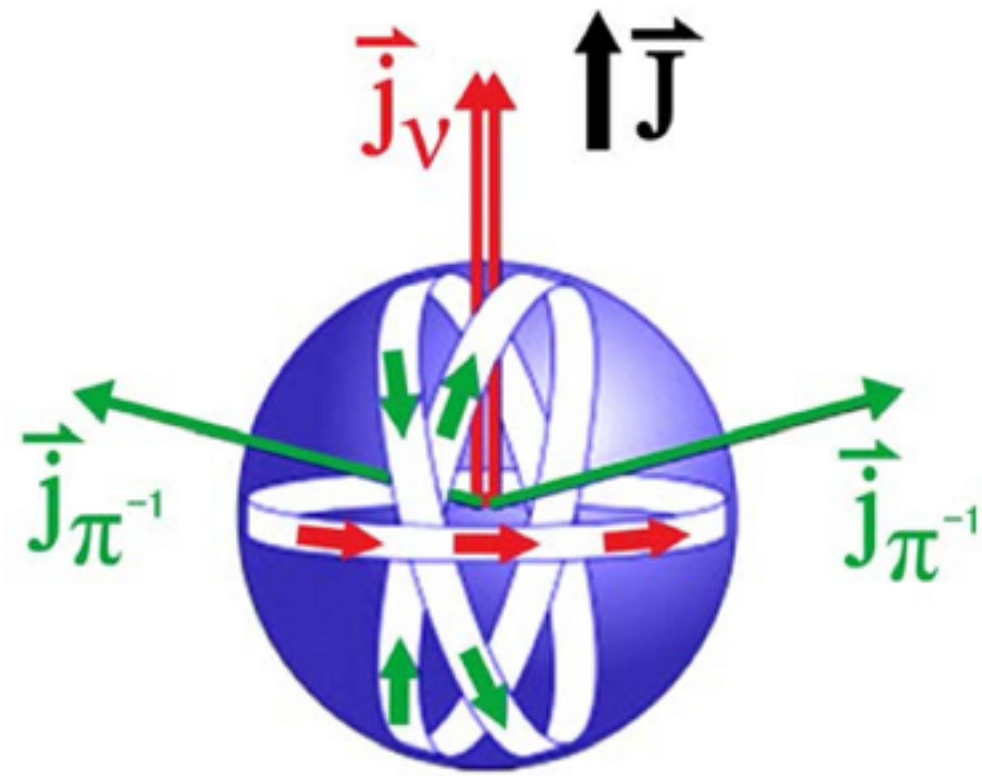


PWZ, Peng, Liang, Ring, Meng PRL 107, 122501(2011)

- ✓ The calculated B(E2) values are in excellent agreement with the data.
- ✓ The B(E2) values decrease with the increasing spin / two “shears-like” mechanism.
- ✓ Without polarization, the B(E2) values are reduced to only ~60% of the self-consistent results, and dropped to zero when the frequency $\Omega \geq 0$:5 MeV.
- ✓ It is of importance to emphasize that polarization effects play a very important role in the self-consistent microscopic description of AMR bands, especially for theE2 transitions.

Two shears mechanism





PWZ, Peng, Liang, Ring, Meng PRL 107, 122501(2011)

✓ The two proton angular momentum are pointing opposite to each other and are nearly perpendicular to the neutron angular momentum. They form the blades of the two shears.

✓ Increasing Ω, the two proton blades towards to each other and generates the total angular momentum.

Summary

- Covariant density functional theory has been extended to describe rotational excitations including MR and AMR.

- ^{105}Cd: AMR

  reproduce well the AMR pictures, E, I, and B(E2) values in a fully self-consistent microscopic way for the first time

In collaboration with

Haozhao Liang

Jie Meng

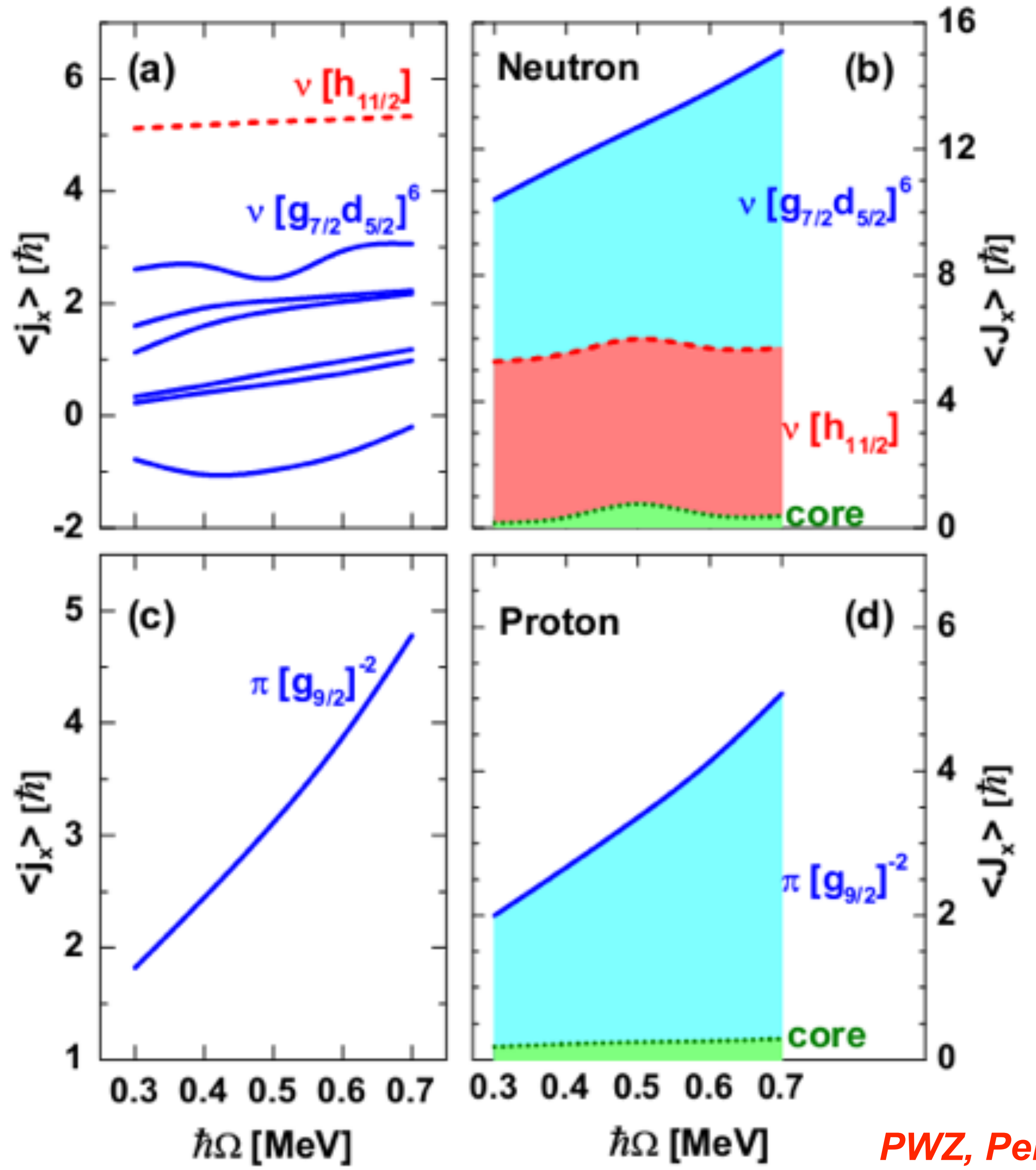
Jing Peng

Peter Ring

Shuangquan Zhang

Thank You!

Single-particle angular momentum



PWZ, Peng, Liang, Ring, Meng   PRC 85, 054310 (2012)

- ✓ For the protons, only the two holes in the $g_{9/2}$ shell contribute.
- ✓ For the neutrons, only the particles above the N= 50 shell contribute.
- ✓ Angular momentum results from the alignment of proton holes and the mixing within the neutron orbitals.
- ✓ Due to the strong mixing between neutrons, a core in the phenomenological model cannot be well defined.