YIPQS Long-term workshop

Computational Advances in Nuclear and Hadron Physics

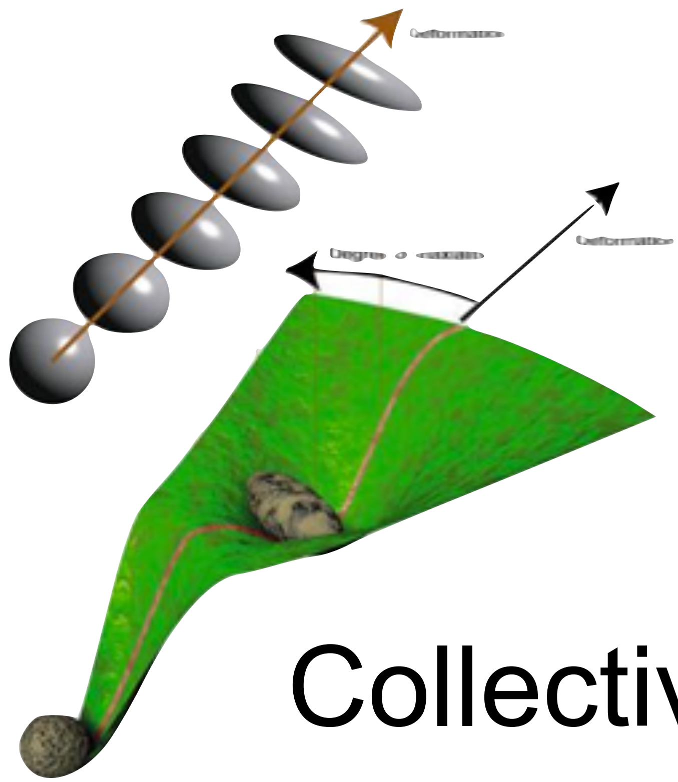
(CANHP 2015)

Relativistic description for novel rotation and exotic shape in nuclei

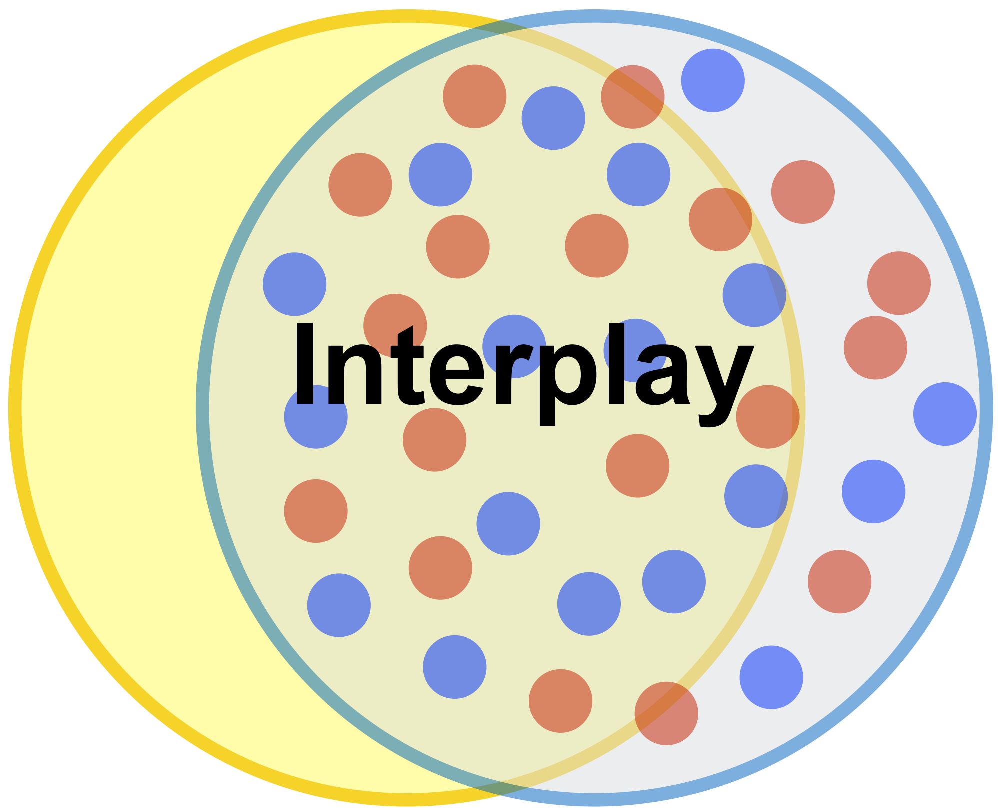
Pengwei Zhao （赵鹏巍）

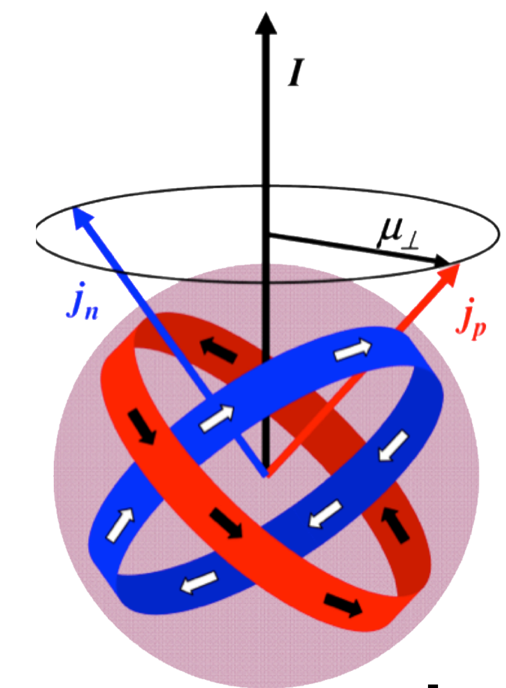
Argonne National Laboratory

Nuclear Rotation



Collectivity



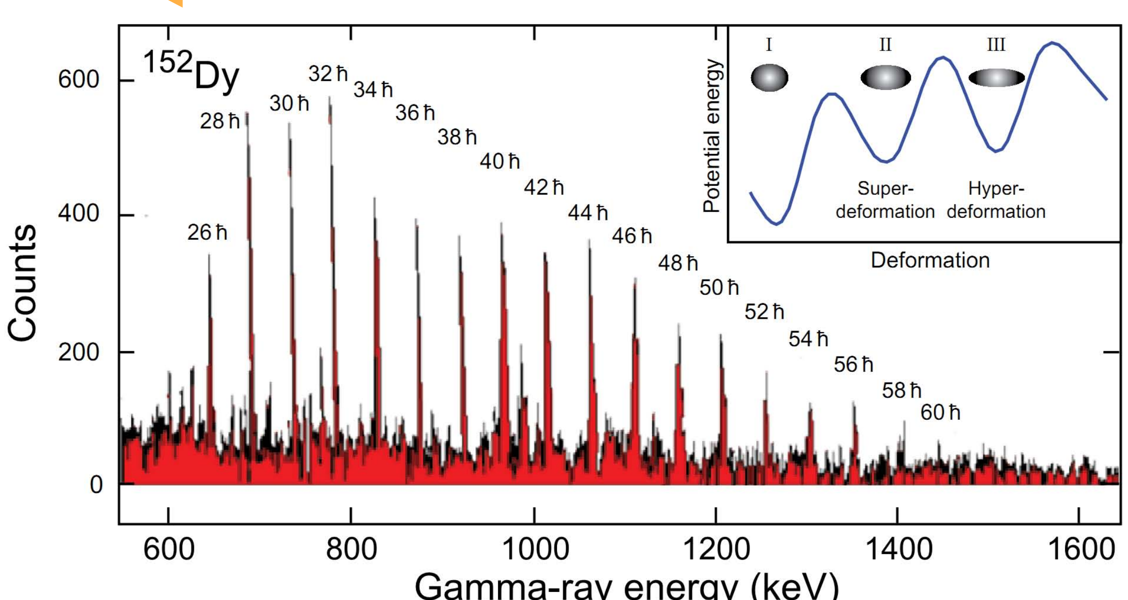


valence nucleon

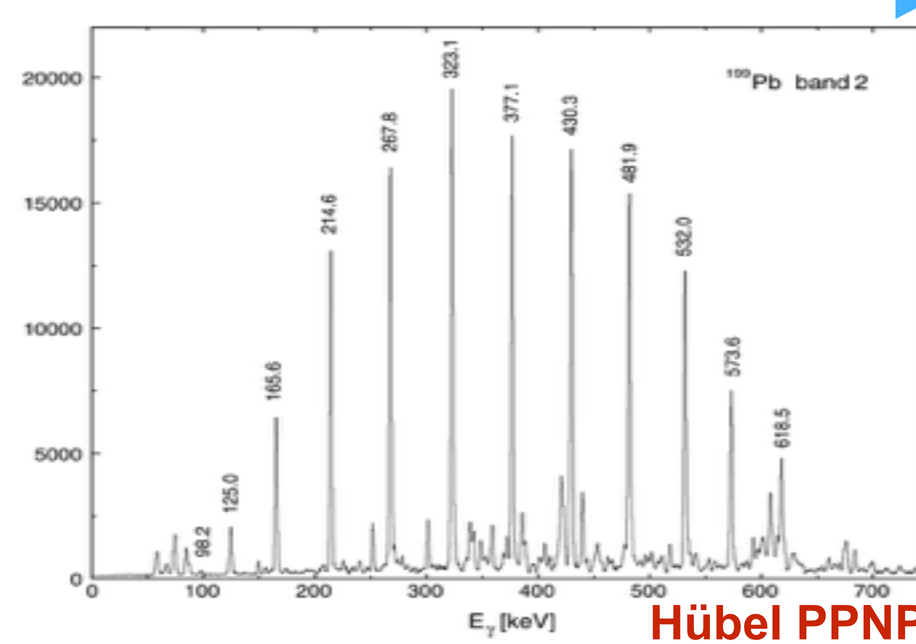
exotic shape

novel rotation

nuclear structure under extreme conditions



Twin PRL1986

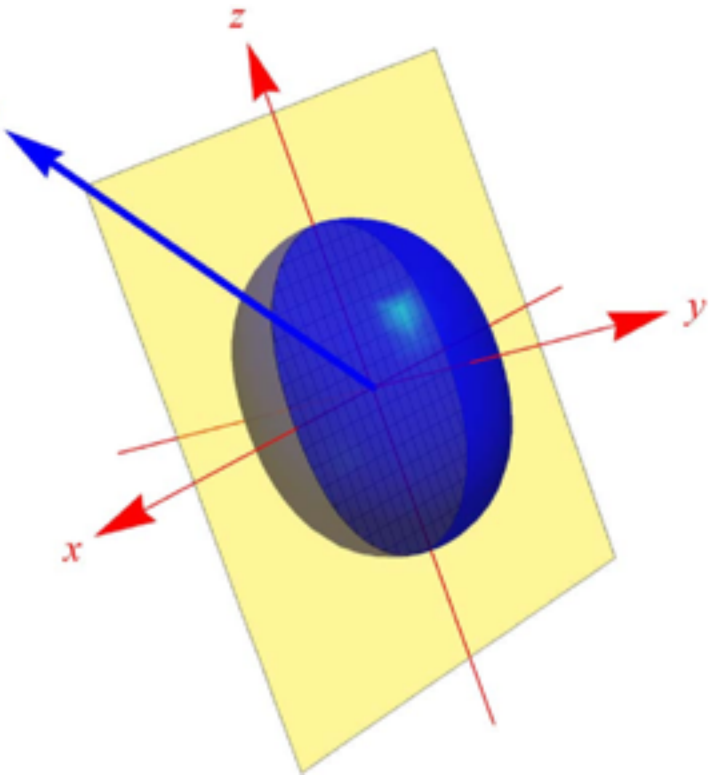


Hübel PPNP2005

Outline

- ✓ Cranking covariant density functional theory
- ✓ Novel rotation:
  magnetic and antimagnetic rotation
- ✓ Exotic shape:
  stabilization of the rod shape in C isotopes
- ✓ Summary

Tilted axis cranking DFT



- **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)***

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

- **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)***

Self-consistent microscopic investigations

- fully taken into account polarization effects
- self-consistently treated the nuclear currents
- no additional parameter beyond a well-determined functional

Covariant Density Functional Theory

Elementary building blocks

$$(\bar{\psi}\mathcal{O}_\tau \Gamma \psi) \qquad \mathcal{O}_\tau \in \{1, \tau_i\} \qquad \Gamma \in \{1, \gamma_\mu, \gamma_5, \gamma_5\gamma_\mu, \sigma_{\mu\nu}\}$$

Densities and currents

Isoscalar-scalar $\rho_S(\mathbf{r}) = \sum_k^{occ} \bar{\psi}_k(\mathbf{r})\psi_k(\mathbf{r})$

Isoscalar-vector $j_\mu(\mathbf{r}) = \sum_k^{occ} \bar{\psi}_k(\mathbf{r})\gamma_\mu\psi_k(\mathbf{r})$

Isovector-scalar $\vec{\rho}_S(\mathbf{r}) = \sum_k^{occ} \bar{\psi}_k(\mathbf{r})\vec{\tau}\psi_k(\mathbf{r})$

Isovector-vector $\vec{j}_\mu(\mathbf{r}) = \sum_k^{occ} \bar{\psi}_k(\mathbf{r})\vec{\tau}\gamma_\mu\psi_k(\mathbf{r})$

Energy Density Functional

$$E_{kin} = \sum_k v_k^2 \int \bar{\psi}_k \left(-\gamma\nabla + m\right)\psi_k d\mathbf{r}$$

$$E_{2nd} = \frac{1}{2}\int (\alpha_S\rho_S^2 + \alpha_V\rho_V^2 + \alpha_{tV}\rho_{tV}^2)d\mathbf{r}$$

$$E_{hot} = \frac{1}{12}\int (4\beta_S\rho_S^3 + 3\gamma_S\rho_S^4 + 3\gamma_V\rho_V^4)d\mathbf{r}$$

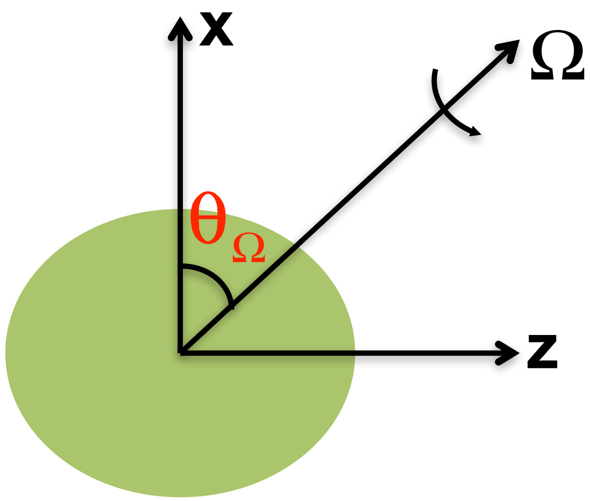
$$E_{der} = \frac{1}{2}\int (\delta_S\rho_S\triangle\rho_S + \delta_V\rho_V\triangle\rho_V + \delta_{tV}\rho_{tV}\triangle\rho_{tV})d\mathbf{r}$$

$$E_{em} = \frac{e}{2}\int j_\mu^p A^\mu d\mathbf{r}$$

Cranking Covariant Density Functional Theory

Transform to the frame rotating with a uniform velocity

$$x^{\alpha} = \begin{pmatrix} t \\ \boldsymbol{x} \end{pmatrix} \rightarrow \tilde{x}^{\mu} = \begin{pmatrix} \tilde{t} \\ \tilde{\boldsymbol{x}} \end{pmatrix} = \begin{pmatrix} 1 & \mathbf{0} \\ \mathbf{0} & R_x(t) \end{pmatrix} \begin{pmatrix} t \\ \boldsymbol{x} \end{pmatrix}$$



Rotating Density Functional

$$E_{kin} = \sum_k v_k^2 \int \bar{\psi}_k \left(-\gamma\nabla + m\right) \psi_k d\mathbf{r}$$

$$E_{2nd} = \frac{1}{2}\int (\alpha_S \rho_S^2 + \alpha_V \rho_V^2 + \alpha_{tV}\rho_{tV}^2) d\mathbf{r}$$

$$E_{hot} = \frac{1}{12}\int (4\beta_S\rho_S^3 + 3\gamma_S\rho_S^4 + 3\gamma_V\rho_V^4) d\mathbf{r}$$

$$E_{der} = \frac{1}{2}\int (\delta_S\rho_S\triangle\rho_S + \delta_V\rho_V\triangle\rho_V + \delta_{tV}\rho_{tV}\triangle\rho_{tV}) d\mathbf{r}$$

$$E_{em} = \frac{e}{2}\int j_\mu^p A^\mu d\mathbf{r}$$

Peng, Meng, Ring, Zhang, Phys. Rev. C 78, 024313 (2008).
PWZ, Zhang, Peng, Liang, Ring, Meng, Phys. Lett. B 699, 181 (2011).
PWZ, Peng, Liang, Ring, Meng, Phys. Rev. Lett. 107, 122501 (2011).
PWZ, Peng, Liang, Ring, Meng, Phys. Rev. C 85, 054310 (2012).
Meng, Peng, Zhang, PWZ, Front. Phys. 8, 55 (2013).
PWZ, Zhang, Meng, Phys. Rev. C 92, 034319 (2015).

Kohn-Sham/Dirac Equation:

Dirac equation for single nucleon

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

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

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

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

V(r) vector potential time-like

V(r) vector potential space-like

S(r) scalar potential

PWZ, Zhang, Peng, Liang, Ring, Meng, Phys. Lett. B 699, 181 (2011)

Kohn-Sham/RHB Equation: With Pairing

RHB equation for single quasi-nucleon

$$\begin{pmatrix} h_D - \lambda & \Delta \\ -\Delta^* & -h_D^* + \lambda \end{pmatrix} \begin{pmatrix} U_k \\ V_k \end{pmatrix} = E_k \begin{pmatrix} U_k \\ V_k \end{pmatrix}$$

$$h_D = \begin{pmatrix} m + S + V - \Omega \bullet J & \sigma(p - \mathbf{V}) \\ \sigma(p - \mathbf{V}) & -m - S + V - \Omega \bullet J \end{pmatrix}$$

$$\Delta_{ab} = \frac{1}{2} \sum_{cd} \langle ab | V^{pp} | cd \rangle_a \kappa_{cd}.$$

S(r) scalar potential

V(r) vector potential time-like

V(r) vector potential space-like

PWZ, Zhang, Meng, Phys. Rev. C 92, 034319 (2015)

Observables

Total energy

$$E_{\mathrm{tot}} = E_{\mathrm{kin}} + E_{\mathrm{int}} + E_{\mathrm{cou}} + E_{\mathrm{cm}} + E_{\mathrm{pair}}$$

Angular momentum

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

Quadrupole moments and magnetic moments

$$Q_{20} = \sqrt{\frac{5}{16\pi}} \langle 3z^2 - r^2 \rangle,$$

$$Q_{22} = \sqrt{\frac{15}{32\pi}} \langle x^2 - y^2 \rangle,$$

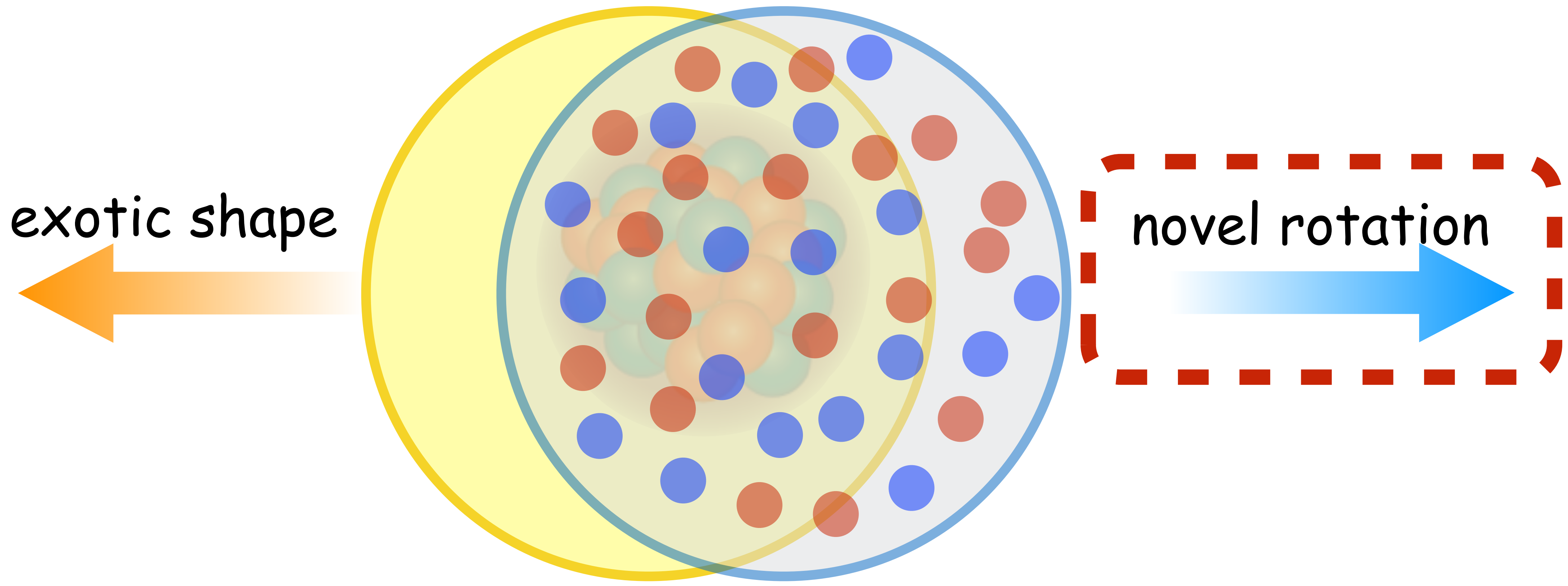
$$\boldsymbol{\mu} = \sum_{i=1}^{A} \int d^3 r \left[\frac{mc^2}{\hbar c} q \psi_i^\dagger(\boldsymbol{r}) \boldsymbol{r} \times \boldsymbol{\alpha} \psi_i(\boldsymbol{r}) + \kappa \psi_i^\dagger(\boldsymbol{r}) \beta \boldsymbol{\Sigma} \psi_i(\boldsymbol{r}) \right],$$

B(M1) and B(E2) transition probabilites

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

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

nuclear structure under extreme conditions

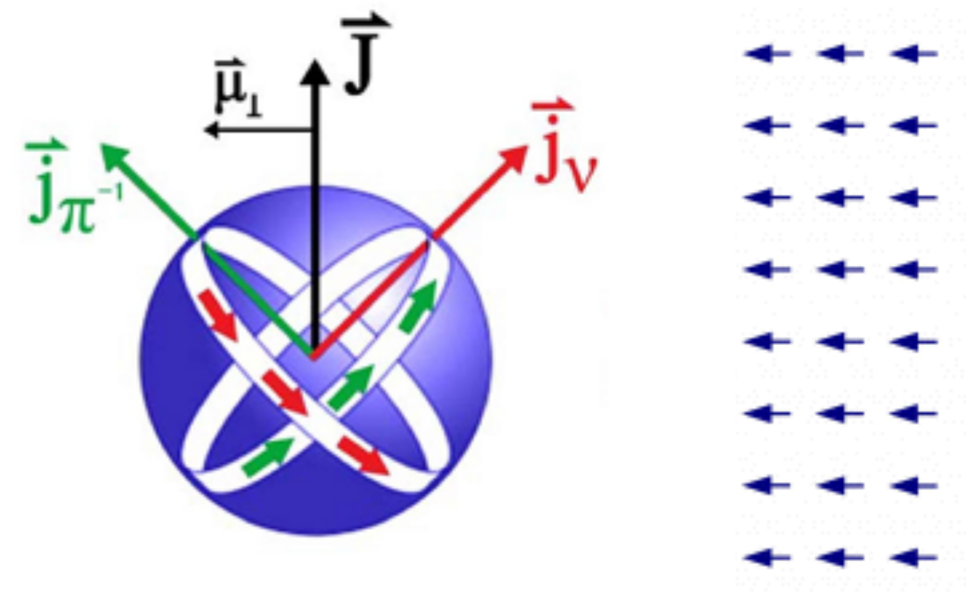


magnetic and antimagnetic rotation

Magnetic and antimagnetic rotation

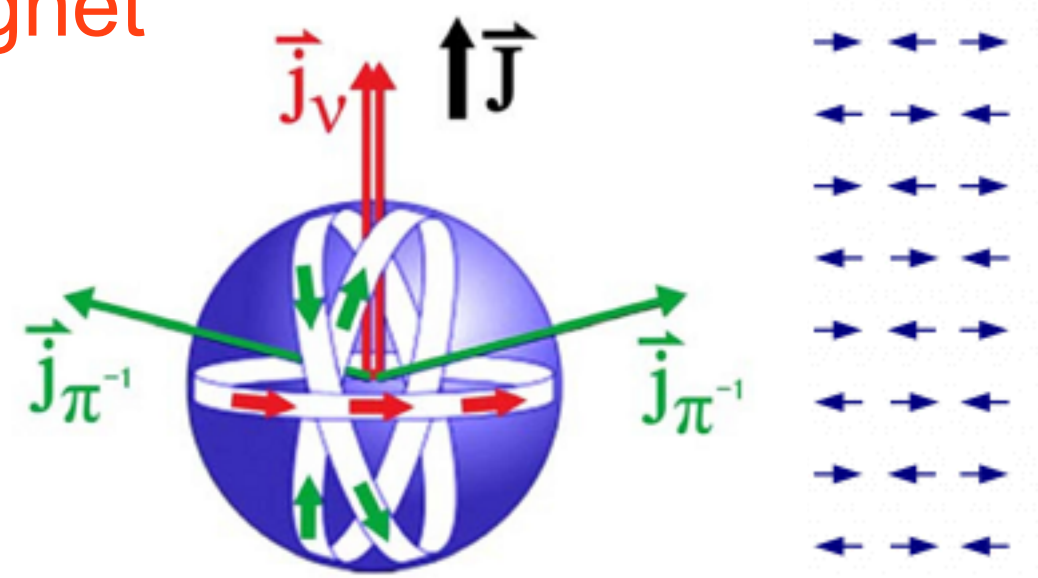
Magnetic rotation ⟺ Ferromagnet

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



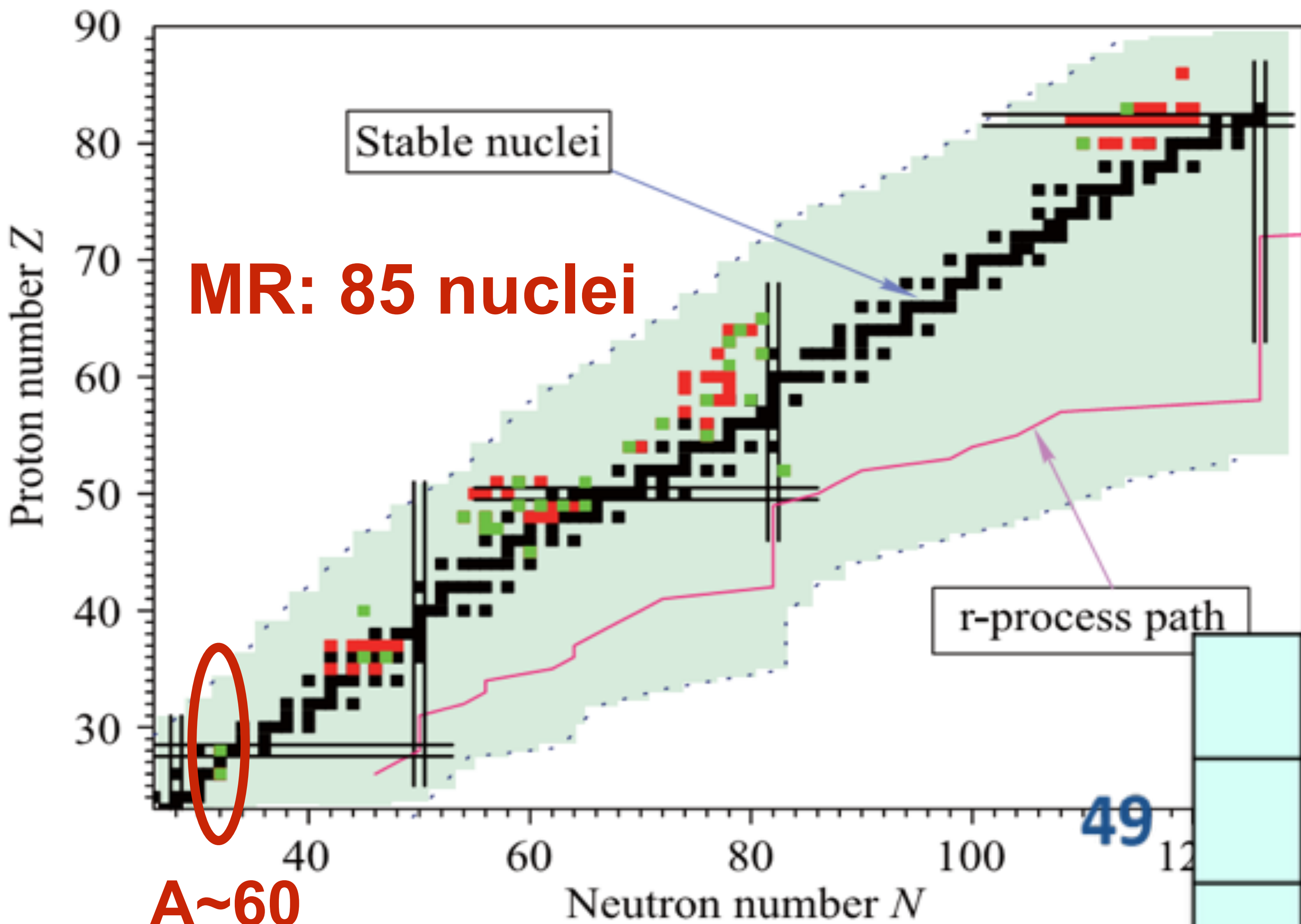
Antimagnetic rotation ⟺ Antiferromagnet

- ✓ near spherical nuclei; weak E2 transitions
- ✓ rotational bands with ΔI = 2
- ✓ no M1 transitions
- ✓ B(E2) decrease with spin
- ✓ two “shears-like” mechanism



Frauendorf, Rev. Mod. Phys., 73 (2001) 463

Experiment: MR & AMR

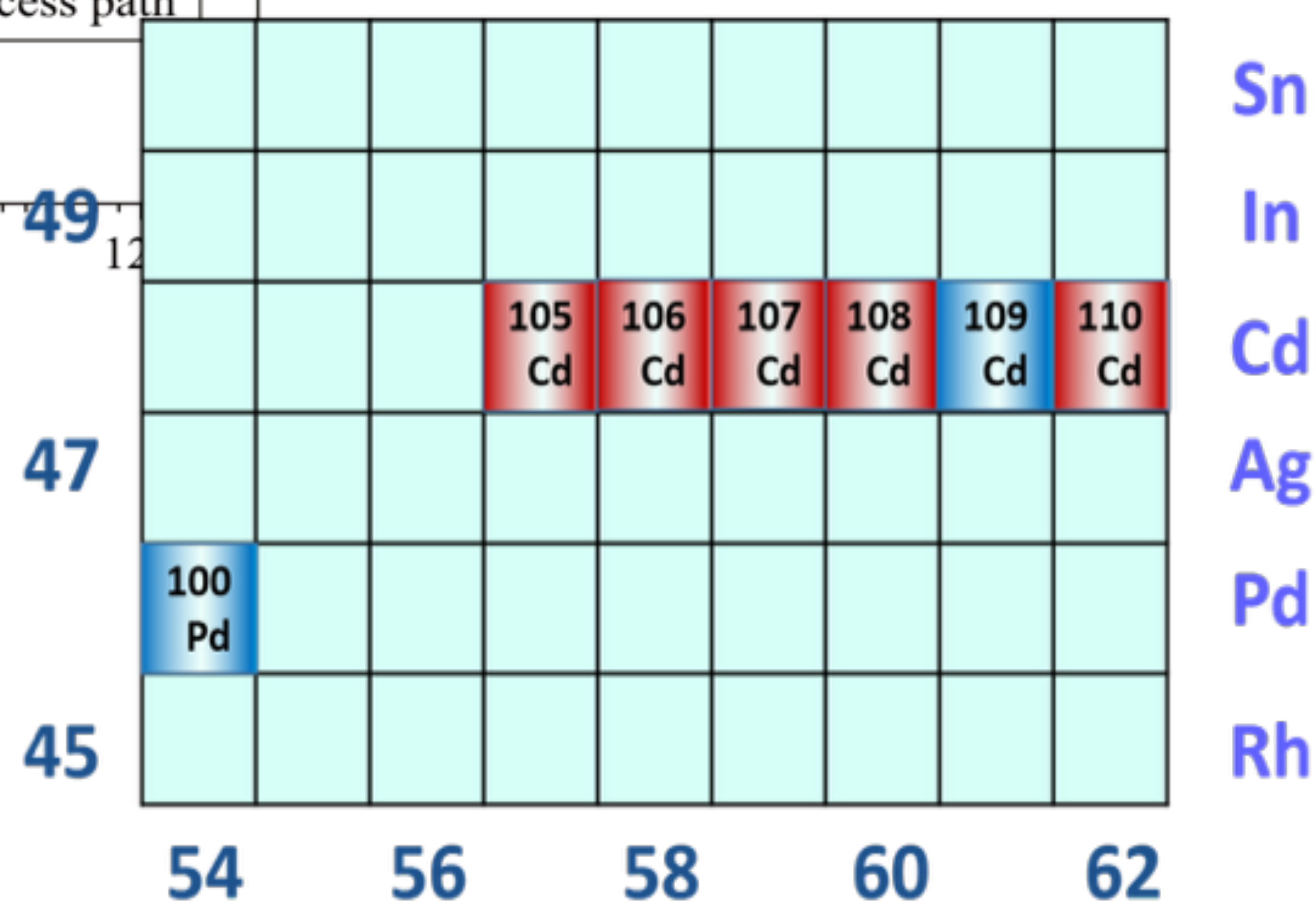


MR: 85 nuclei

A~60

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

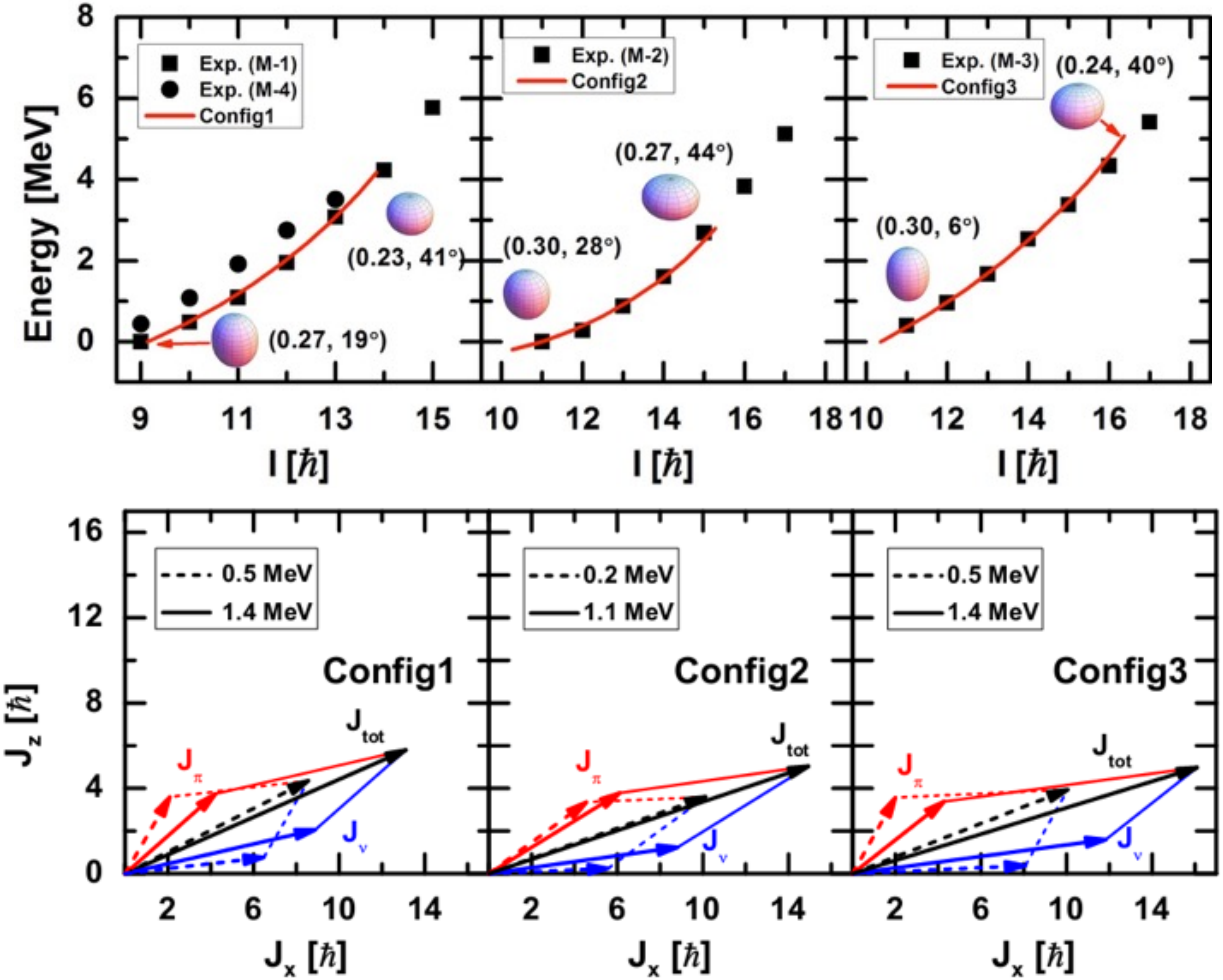
AMR A~100



AMR
A~140
Eu-143; Dy-144

Rajbanshi PLB 2015; Sugawara PRC 2009

MR in ^{60}Ni

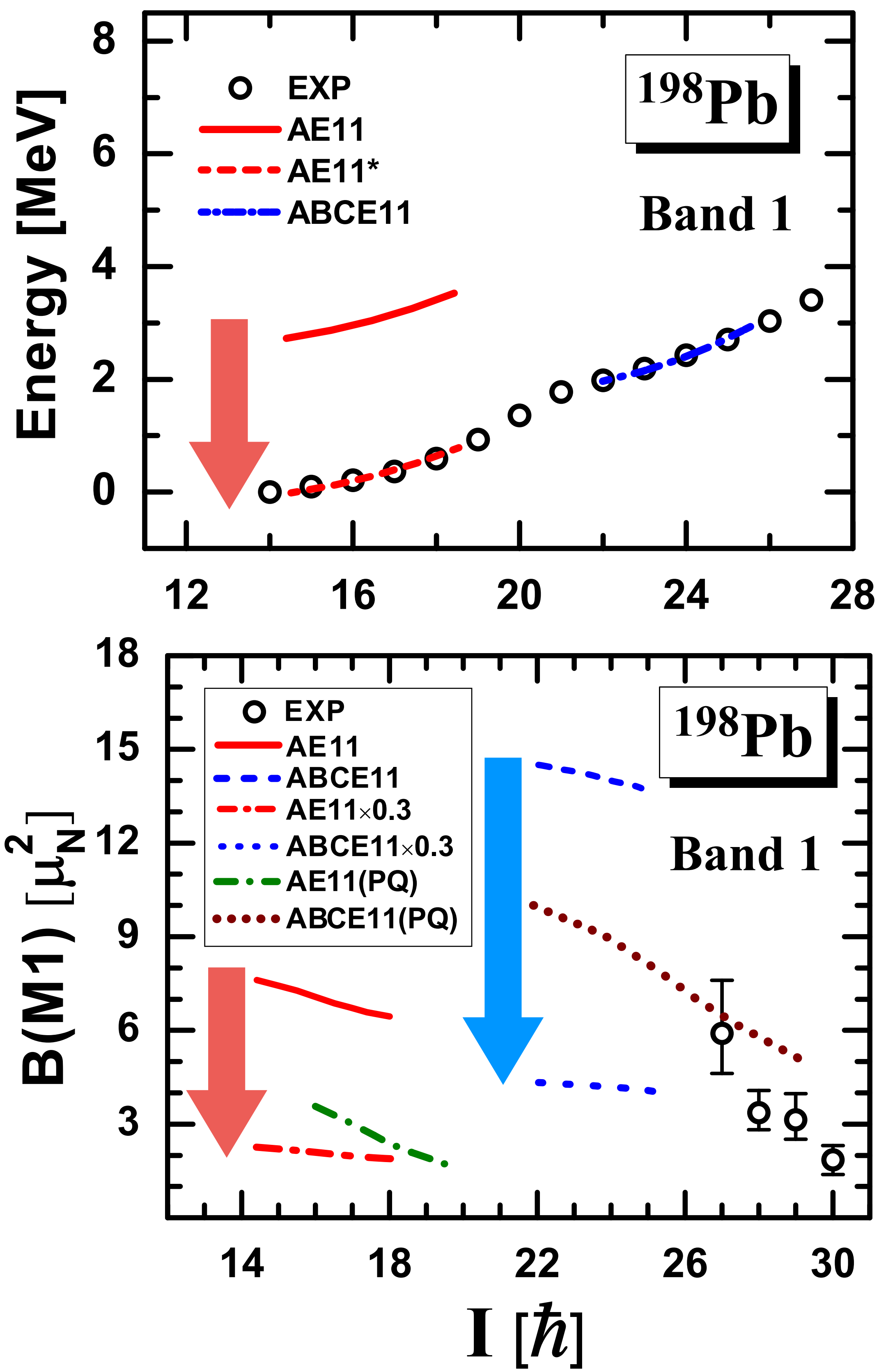


Energy & Deformation

Shears mechanism

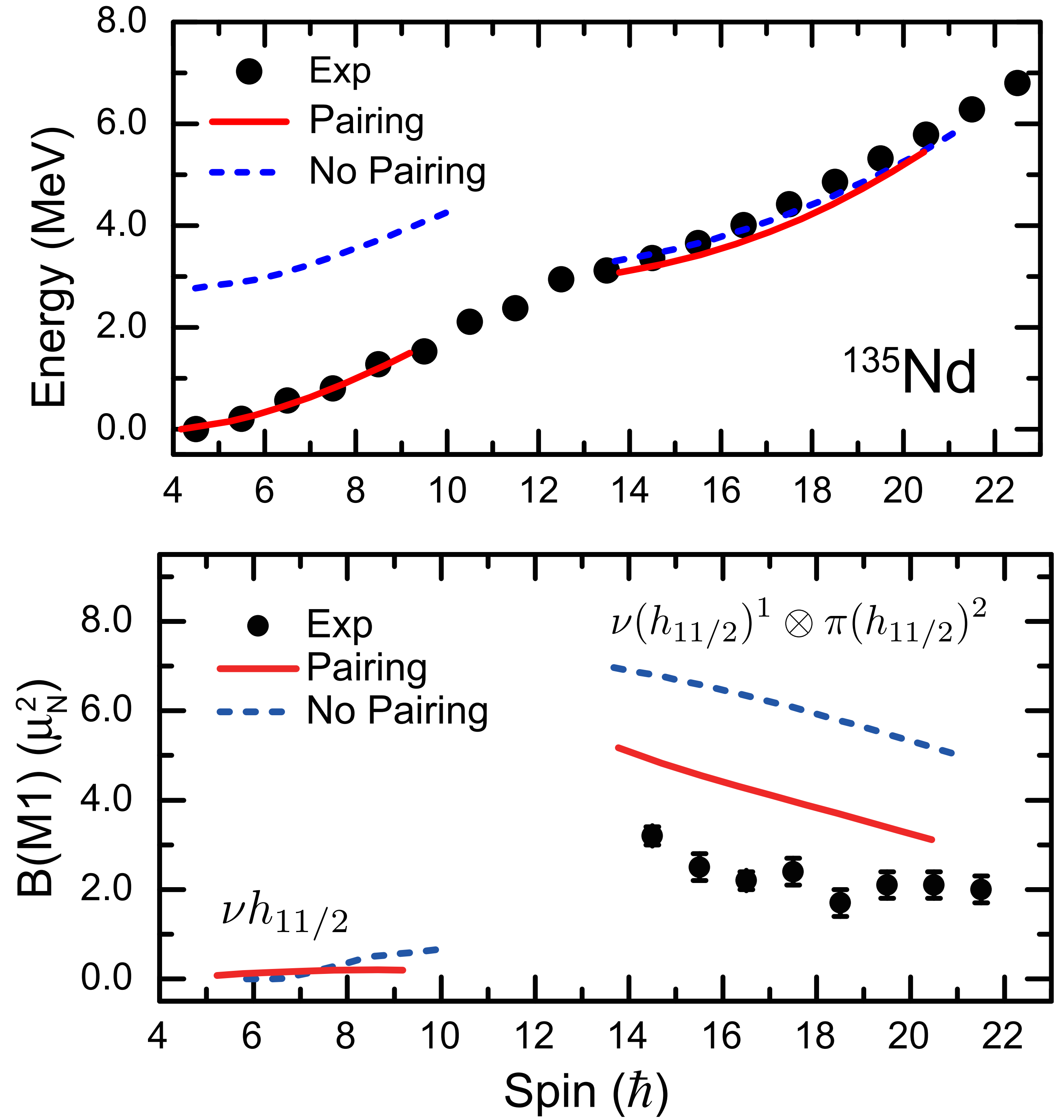
PWZ, Zhang, Peng, Liang, Ring, Meng, PLB 699, 181 (2011)

MR in ^{198}Pb



Yu, PWZ, Zhang, Ring, Meng PRC 85 (2012) 024318

Pairing Effects ^{135}Nd

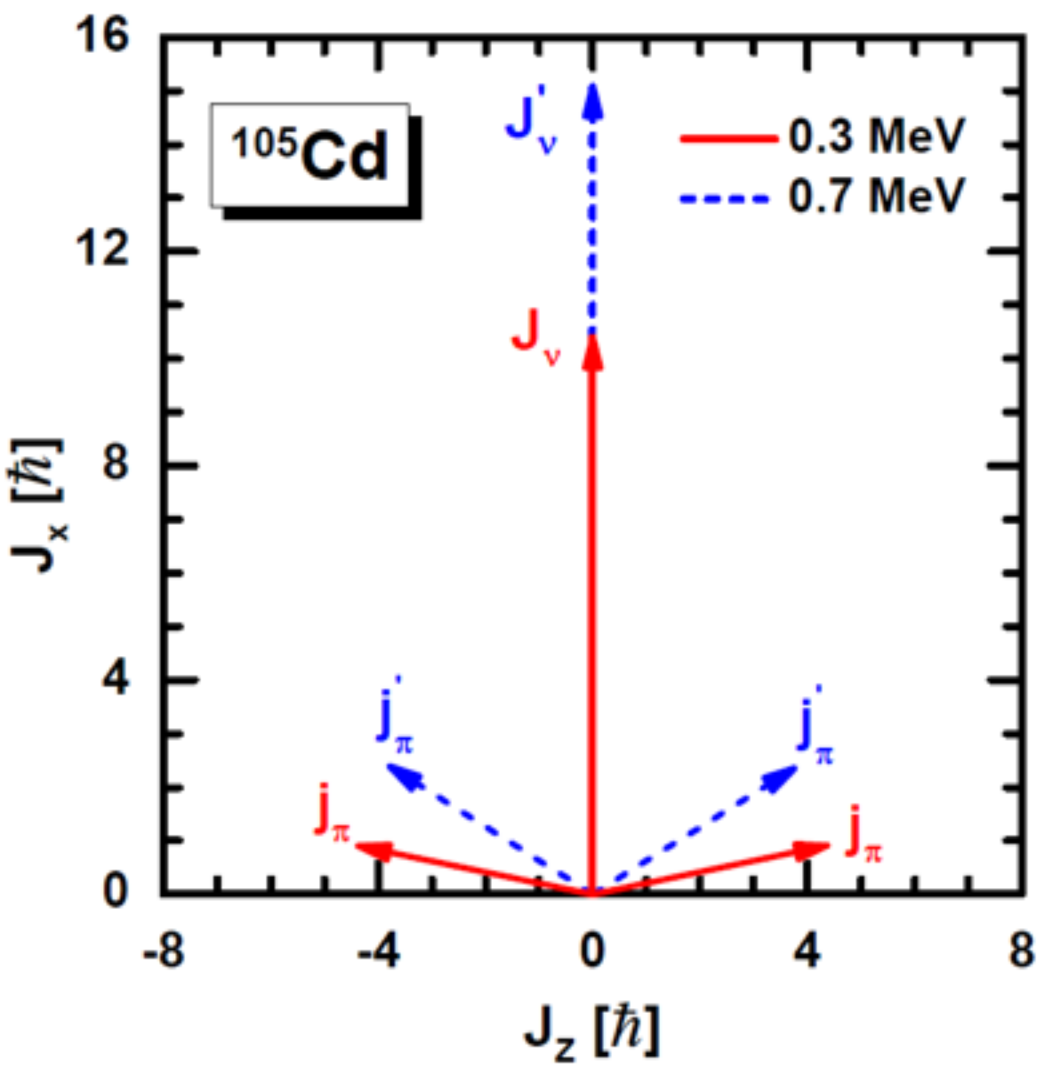


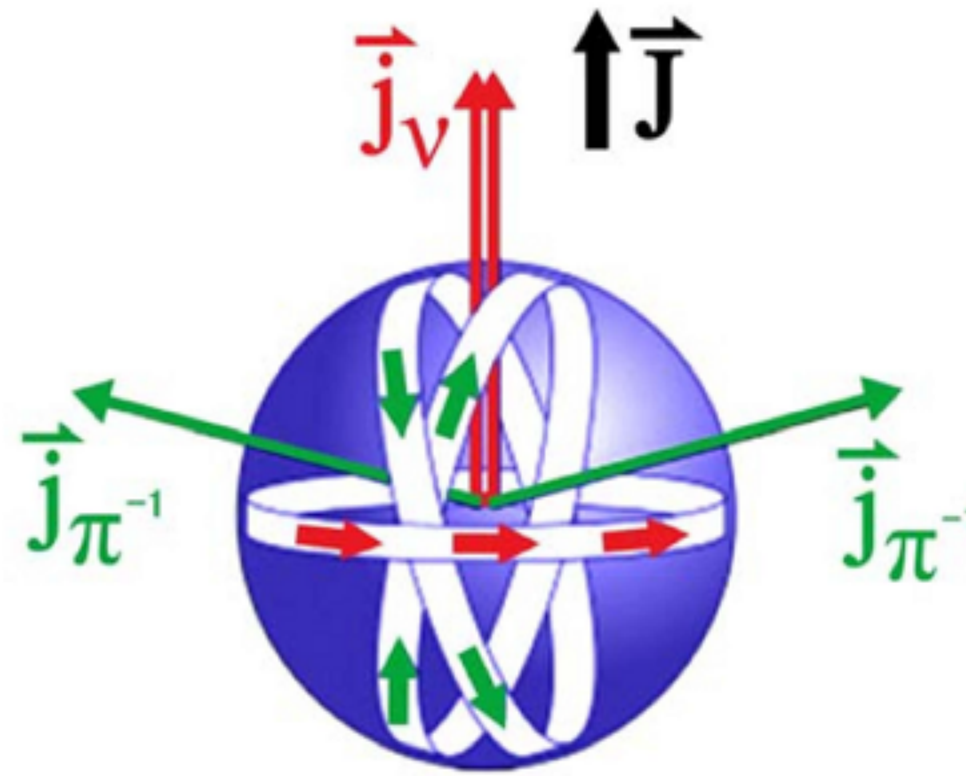
PWZ, Zhang, Meng, Phys. Rev. C 92, 034319 (2015)

More calculations in the future…

AMR in ^{105}Cd

Two shears-like mechanism



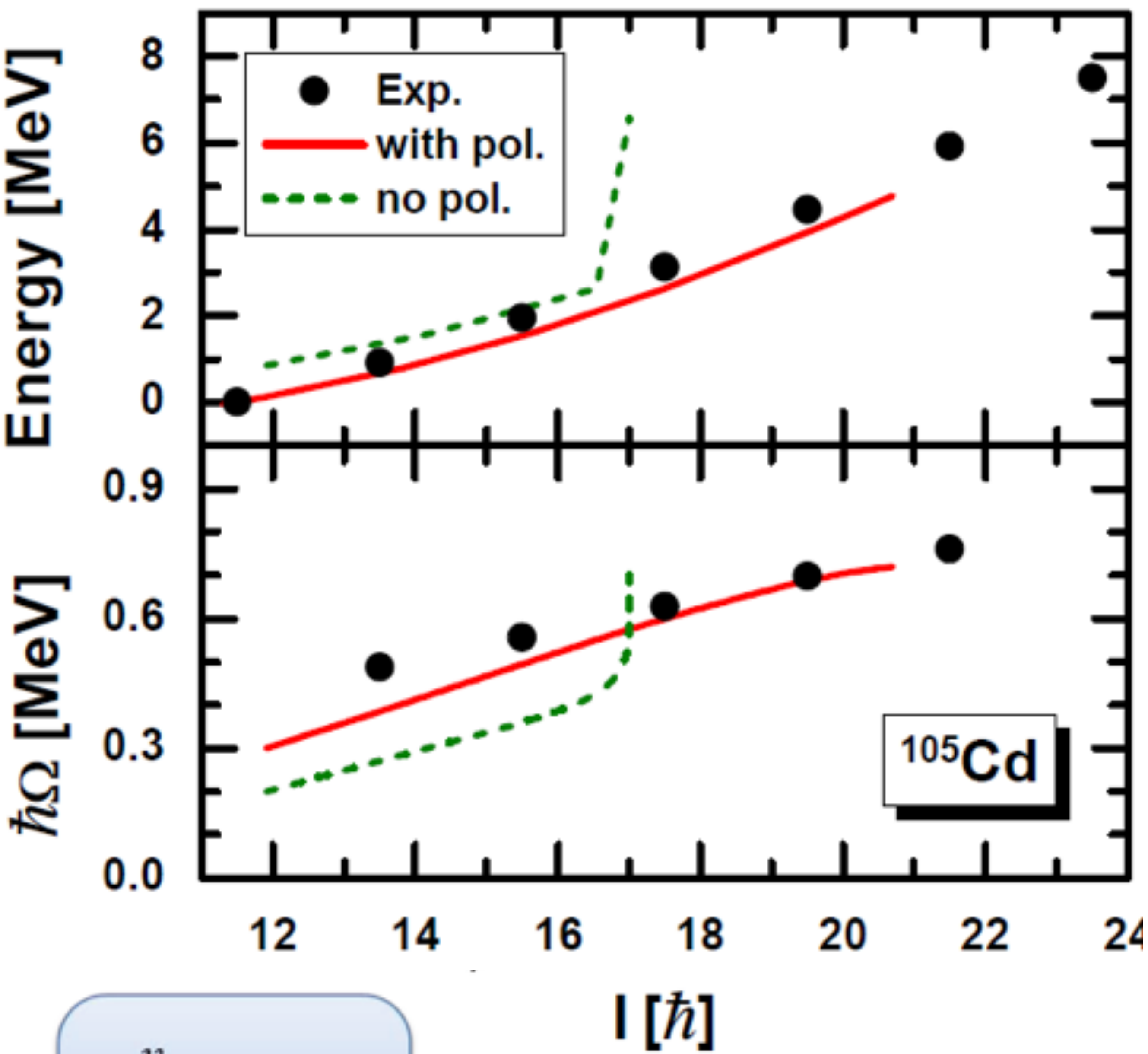


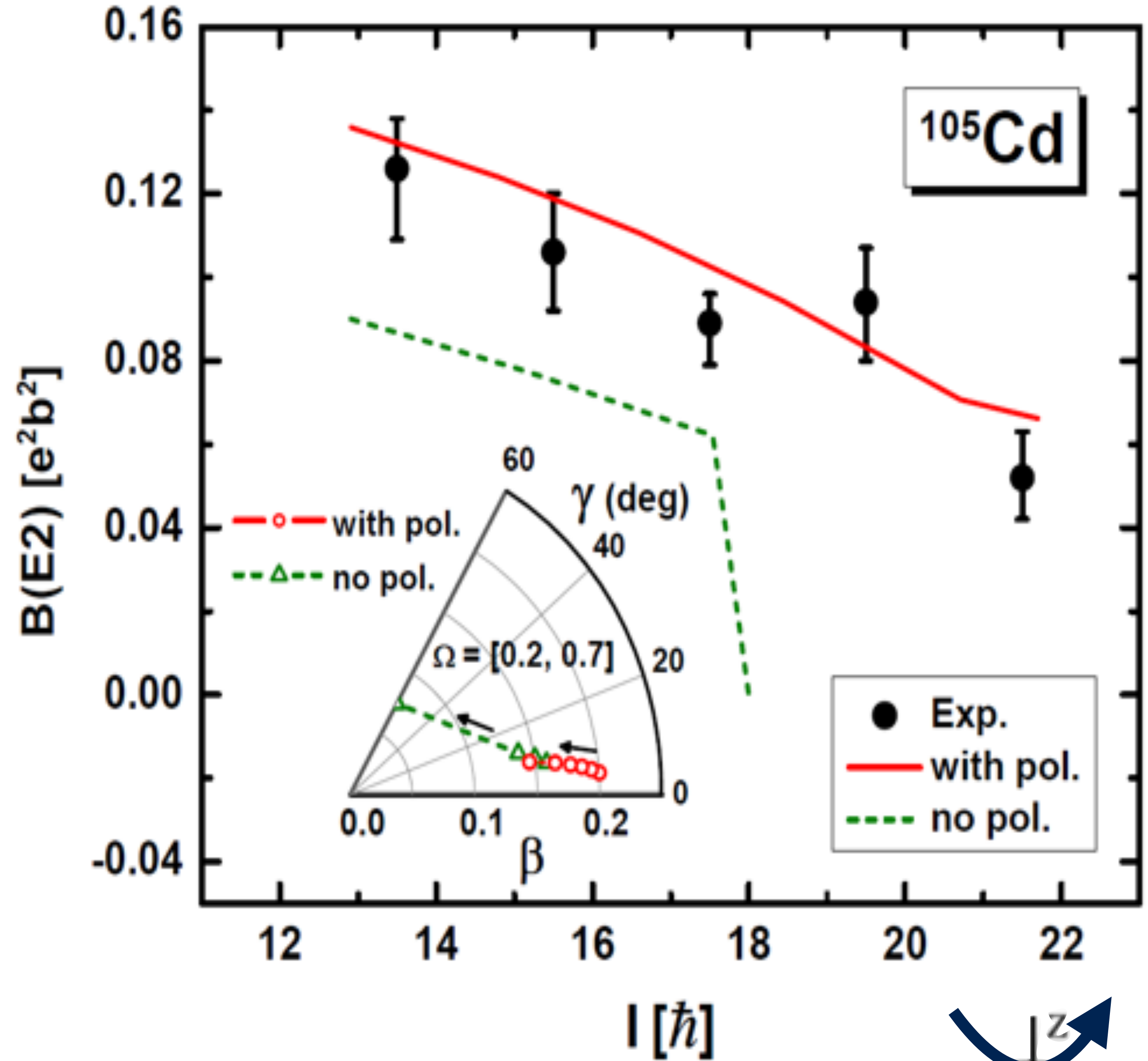
PWZ, Peng, Liang, Ring, Meng PRL 107, 122501(2011)

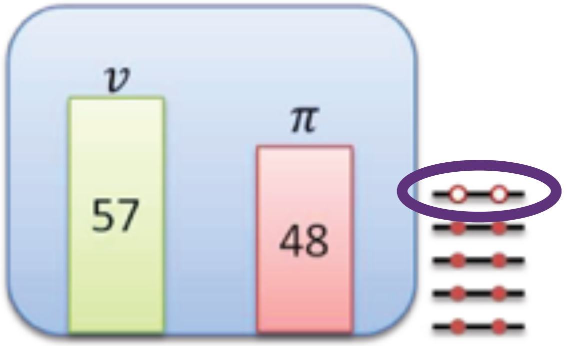
- ✓ The two proton angular momentum are pointing opposite to each other and are nearly perpendicular to the neutron angular momentum. They form the blades of the two shears.
- ✓ Increasing Ω, the two proton blades towards to each other and generates the total angular momentum.

AMR in ^{105}Cd

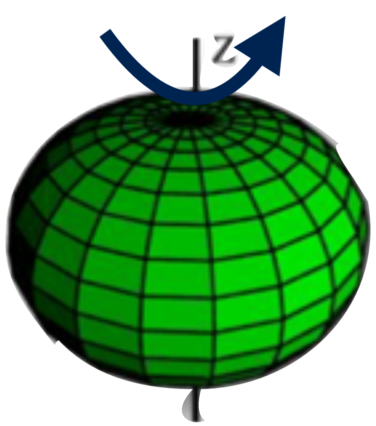
Energy and B(E2)



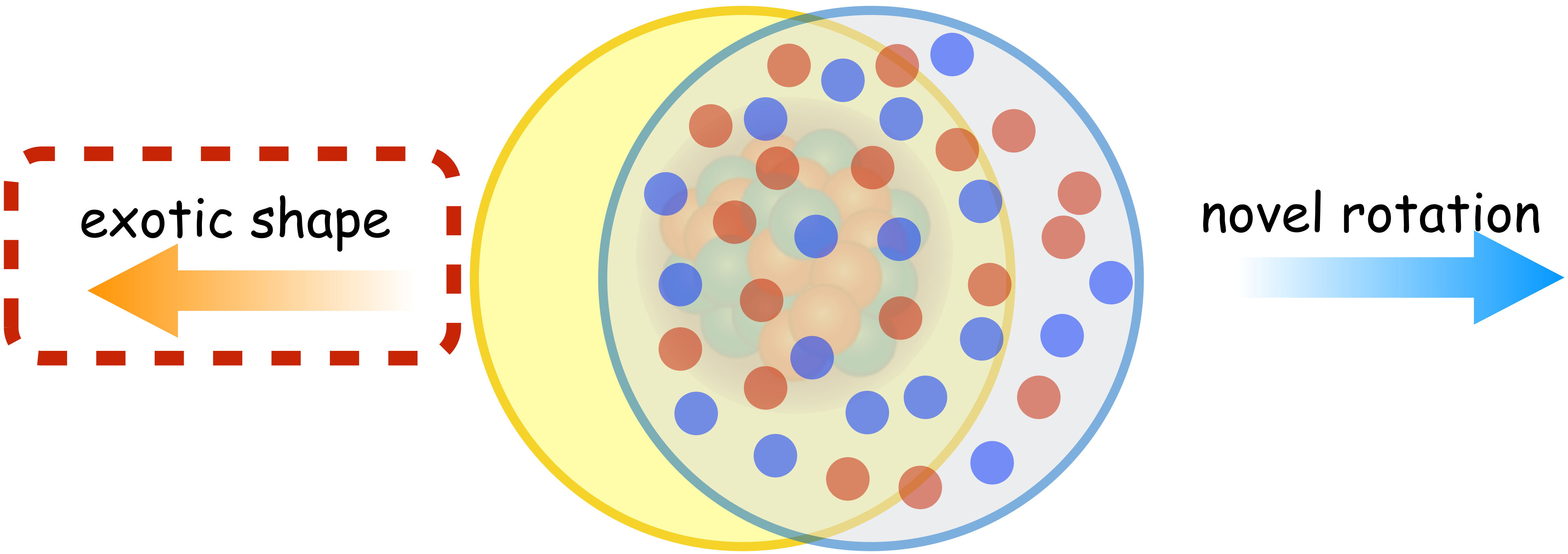




PWZ, Peng, Liang, Ring, Meng PRL 107, 122501(2011)



nuclear structure under extreme conditions



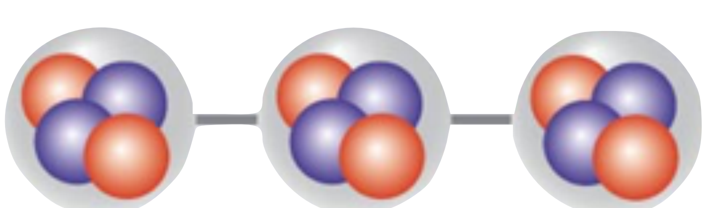
Rod shape in C isotopes

Exotic deformation

Strongly deformed states towards a hyper-deformation might exist in light N = Z nuclei due to a cluster structure.

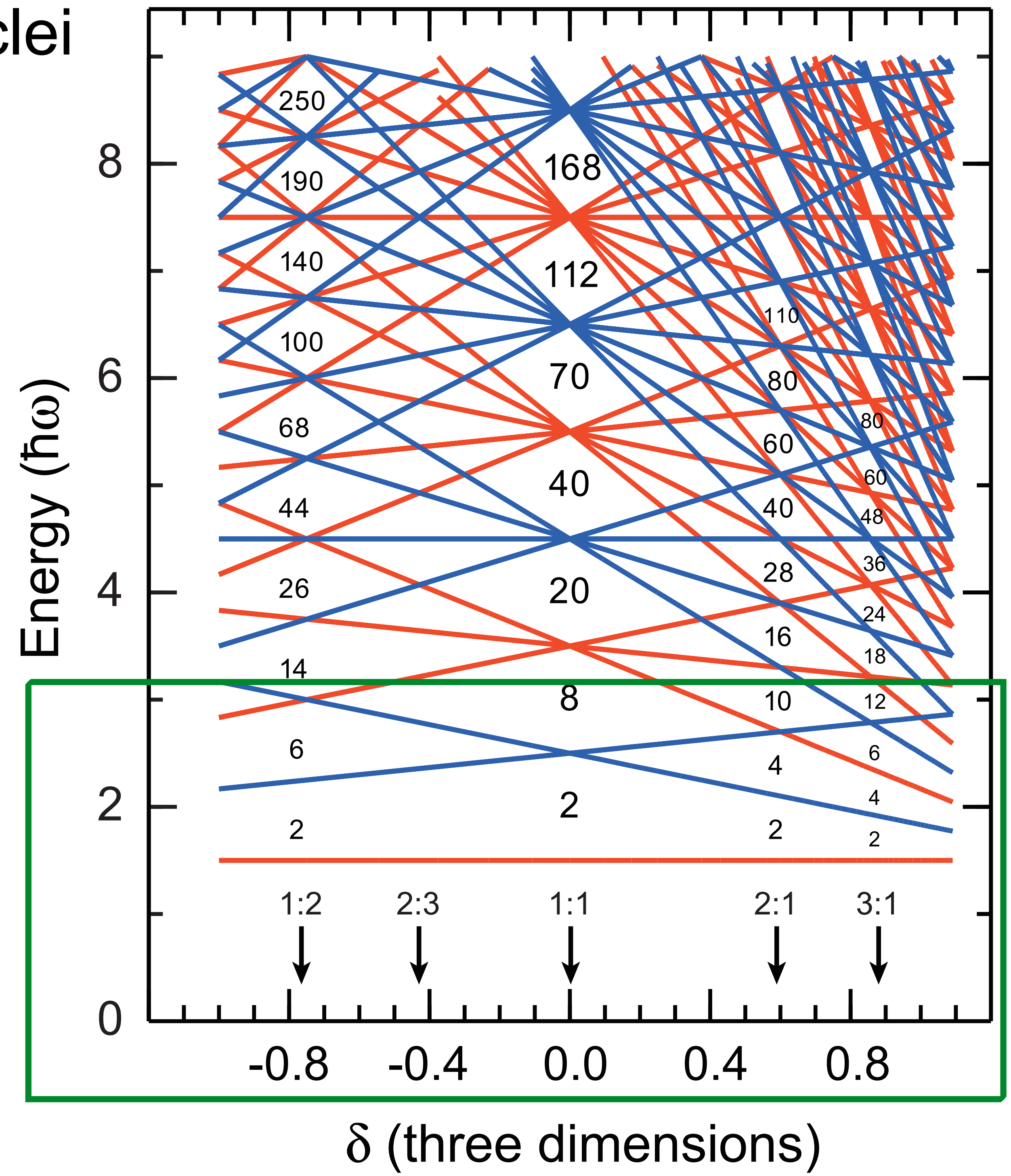
✓ Linear-chain structure of three-α clusters was suggested about 60 years ago to explain the Hoyle state. **Morinaga PR 1956**

✓ However, Hoyle state was later found to be a mixing of the linear-chain configuration and other configurations, and recently reinterpreted as an α-condensate-like state.
Fujiwara PTP1980; Tohsaki PRL 2001; Suhara PRL 2014



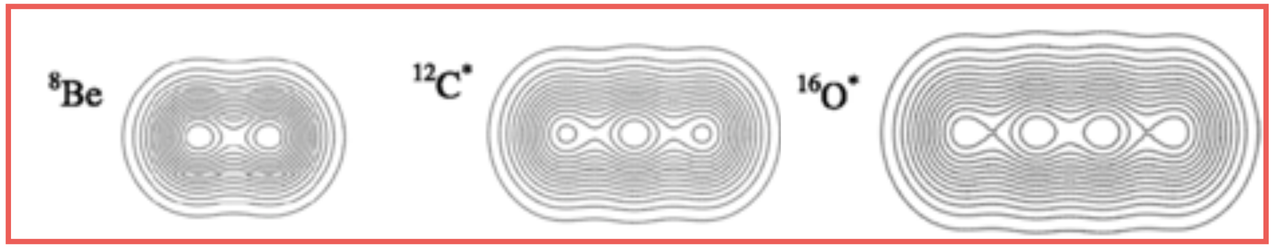
Cluster structure in light nuclei

Harmonic oscillator



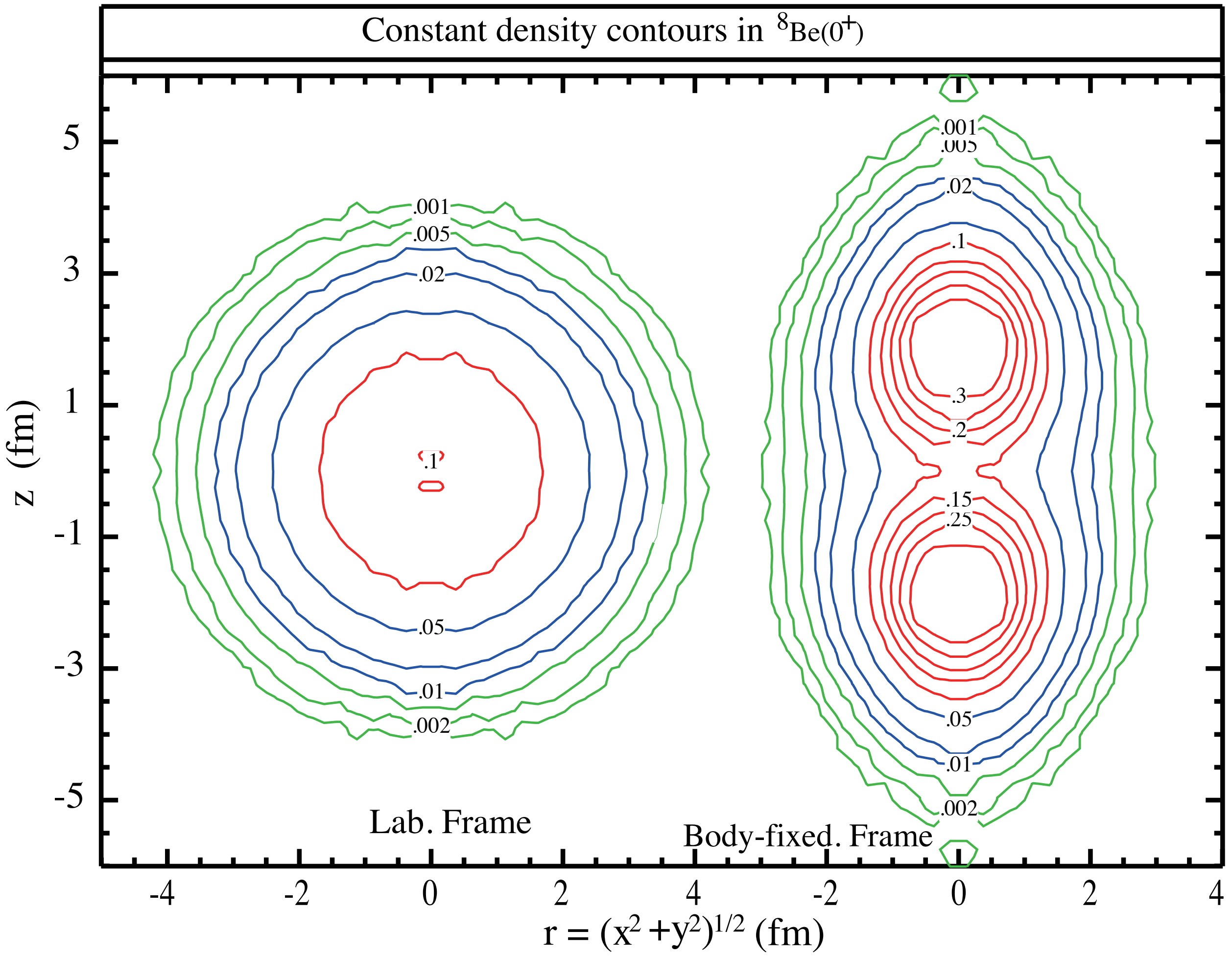
Alpha cluster chain and rod shape

Harmonic oscillator density

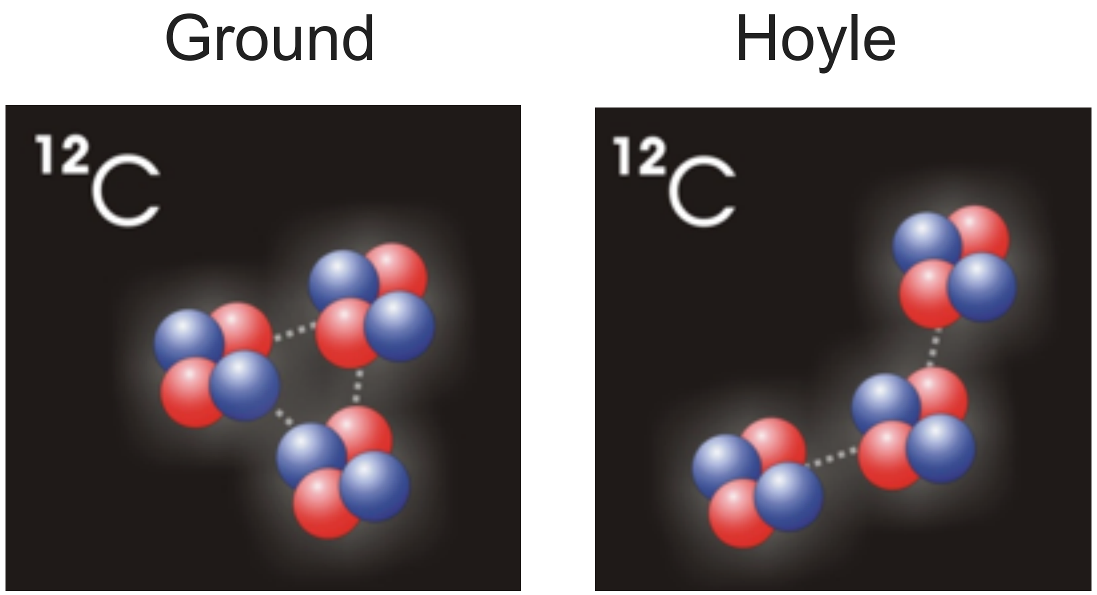


Freer RPP 2007

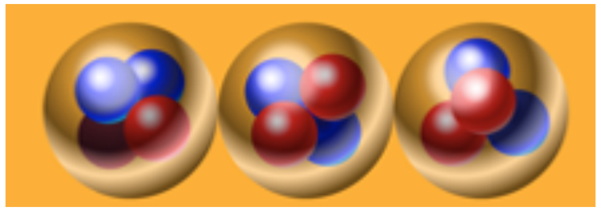
Be-8 Ground state



Green Function Monto Carlo **Wiringa PRC 2000**



No firm evidence



Because of

- ✓ antisymmetrization effects
- ✓ weak-coupling nature

It is difficult to stabilize the rod-shaped configuration in nuclear systems.

How can we stabilize linear chain configurations?

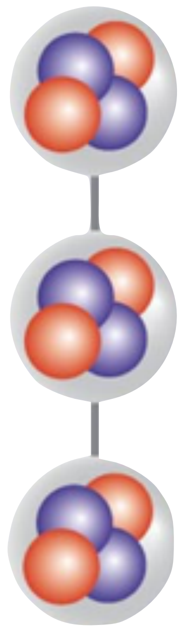
Two important mechanisms

- ✓ Adding valence neutrons

  Itagaki, PRC2001; Maruhn, NPA2010

- ✓ Rotating the system

  Ichikawa, PRL2011



How can we stabilize linear chain configurations?

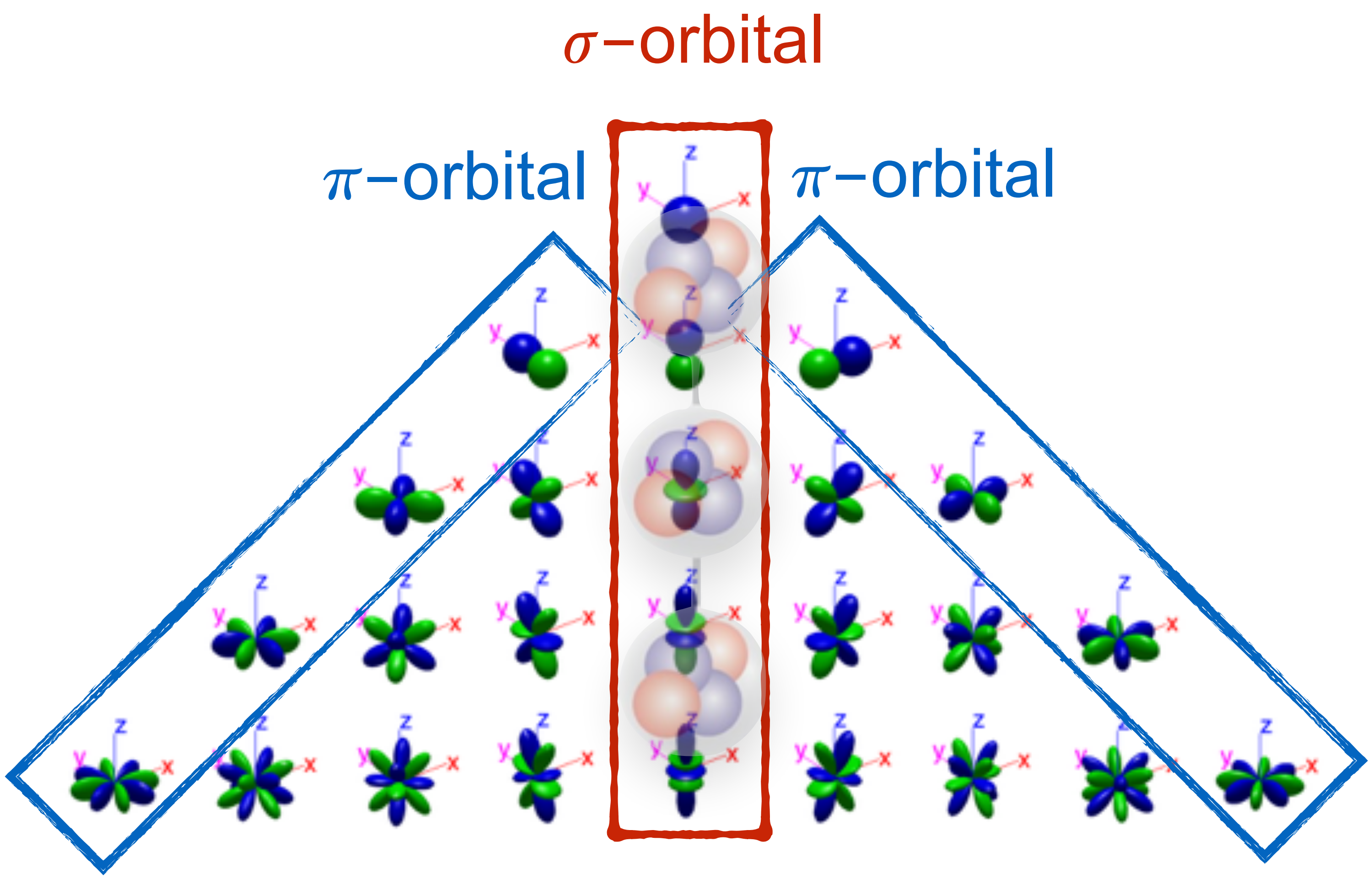
Two important mechanisms

- ✓ Adding valence neutrons

  Itagaki, PRC2001; Maruhn, NPA2010

- ✓ Rotating the system

  Ichikawa, PRL2011



How can we stabilize linear chain configurations?

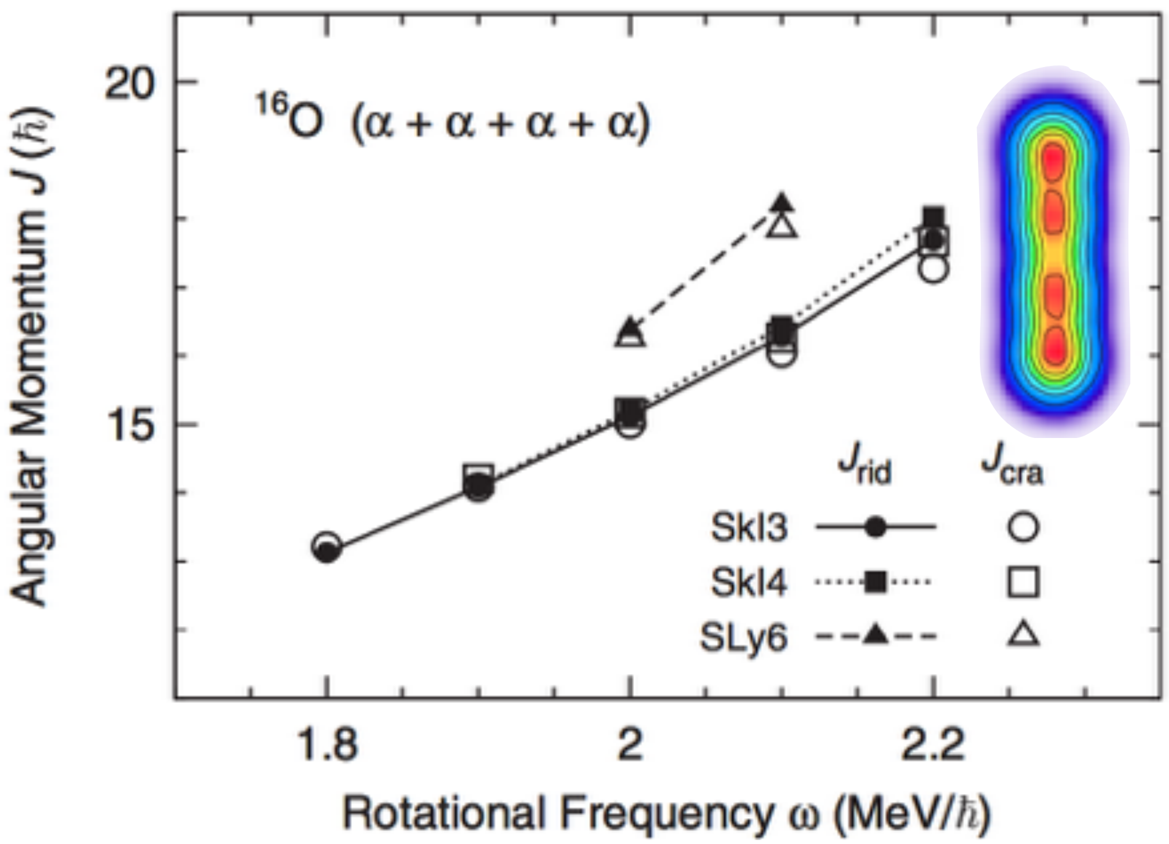
Two important mechanisms

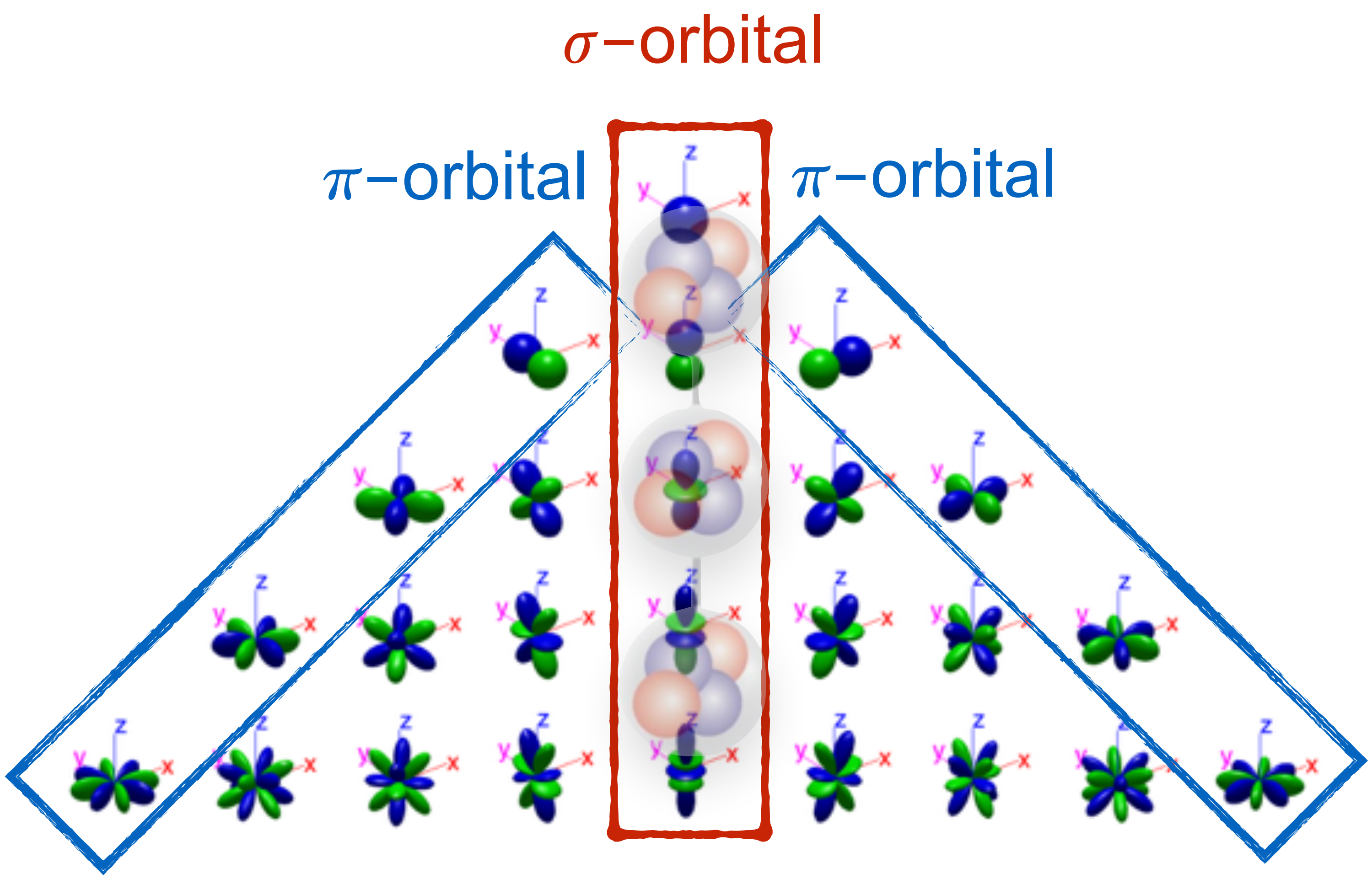
- ✓ Adding valence neutrons

  Itagaki, PRC2001; Maruhn, NPA2010

- ✓ Rotating the system

  Ichikawa, PRL2011





How can we stabilize linear chain configurations?

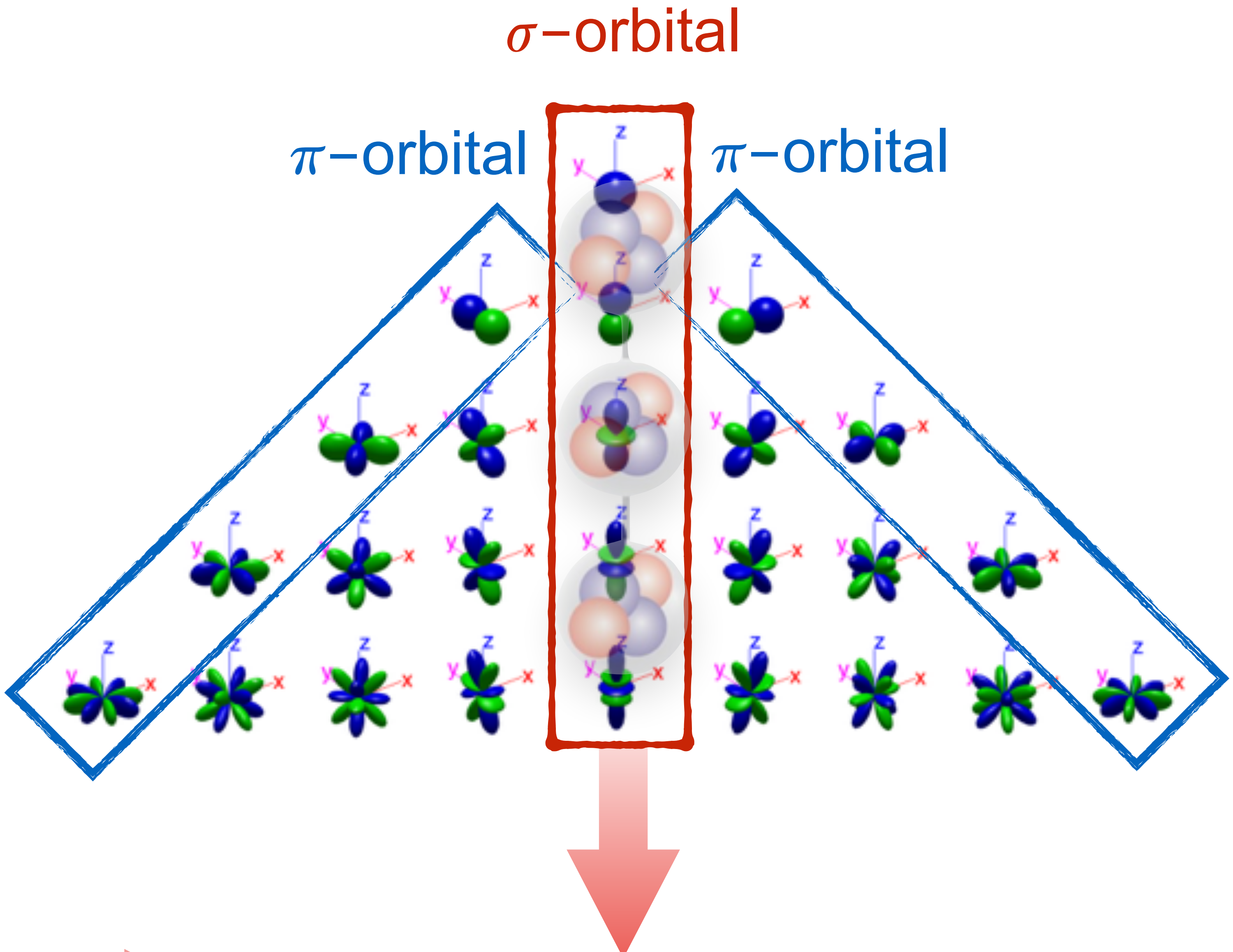
Two important mechanisms

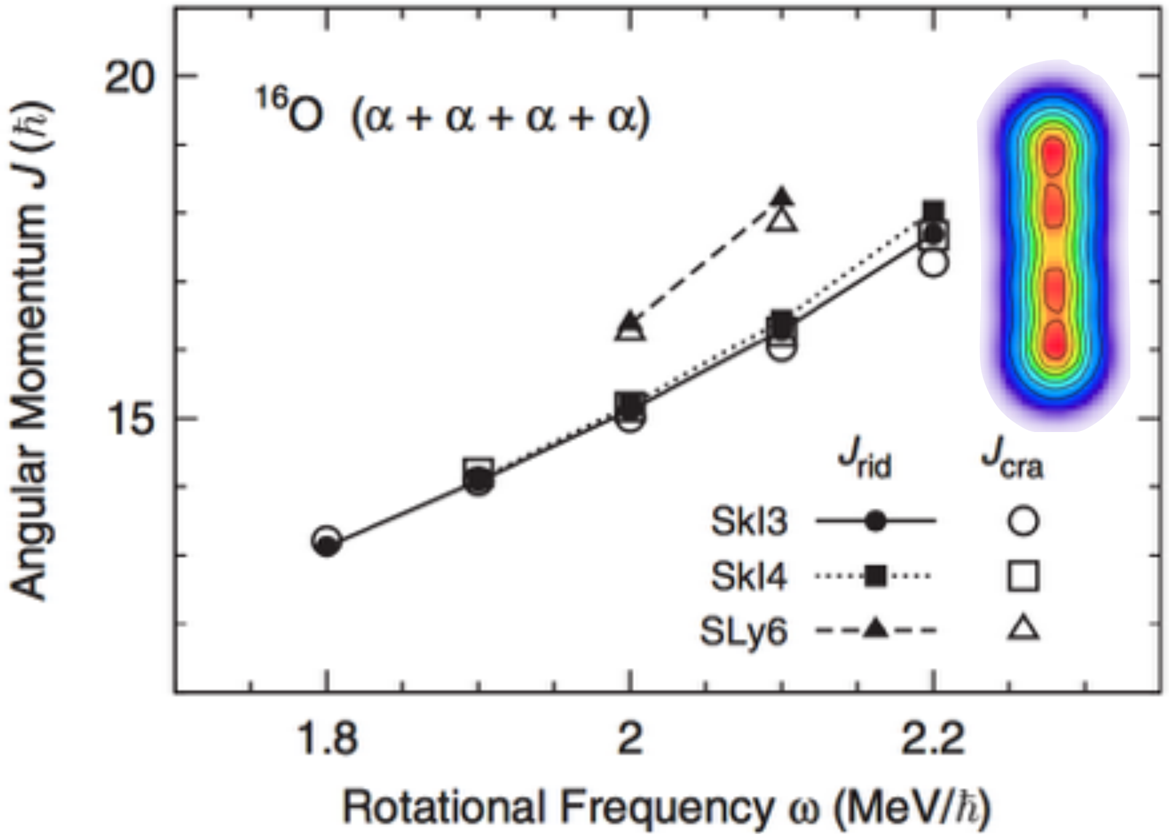
- ✓ Adding valence neutrons

  Itagaki, PRC2001; Maruhn, NPA2010

- ✓ Rotating the system

  Ichikawa, PRL2011



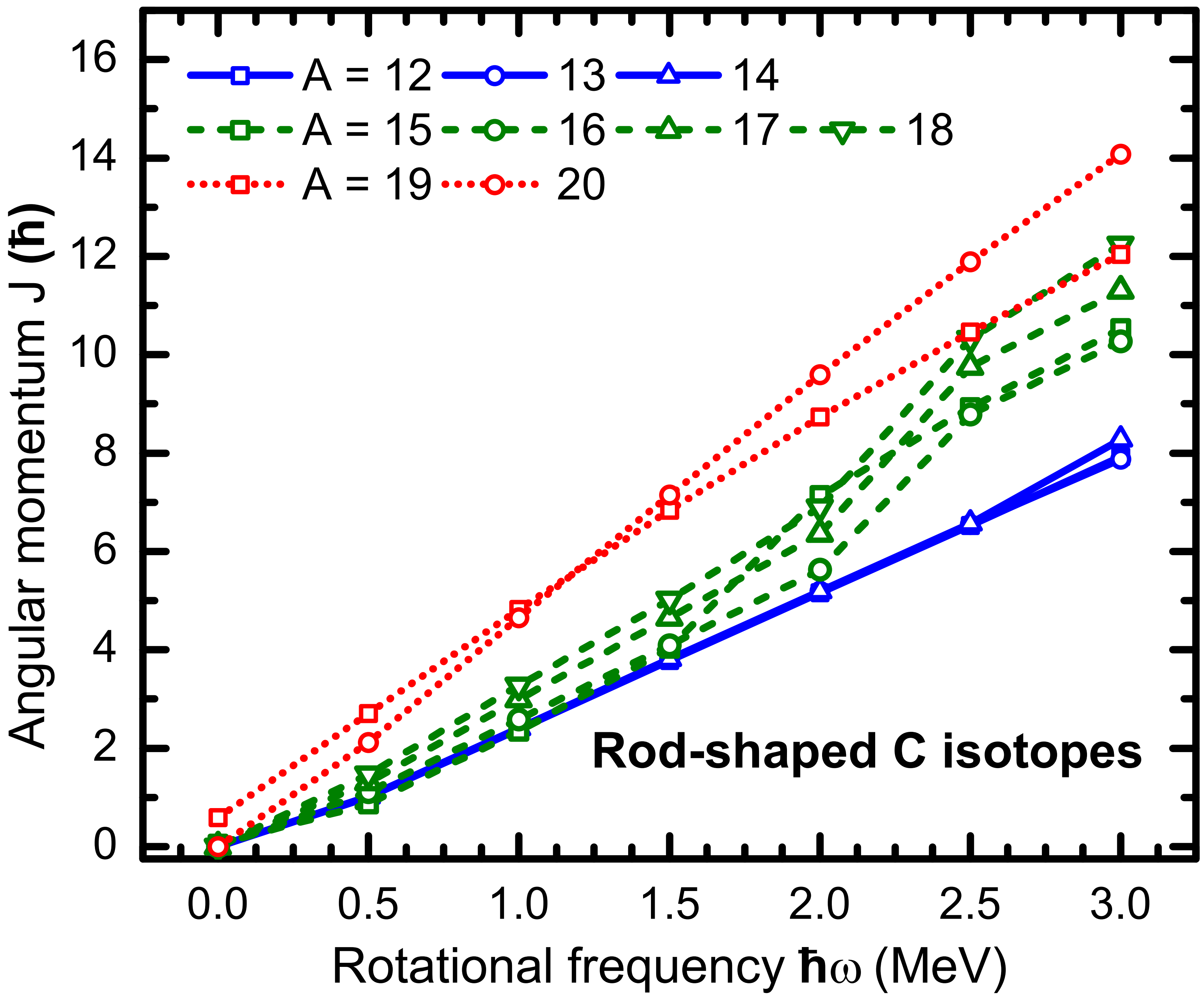


Coherent effects exist?

They facilitate the stabilization?

Angular momentum

DD-ME2, 3D HO basis with N = 12 major shells



- C-12, C-13, C-14

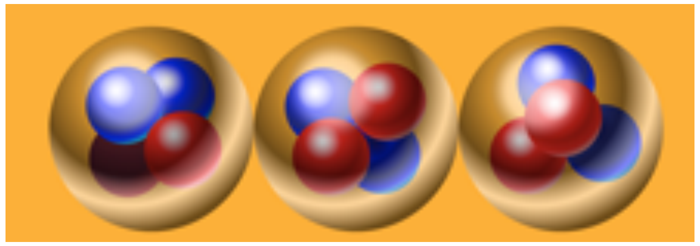
  constant moments of inertia (MOI); like a rotor

- C-15, C-16, C-17, C-18

  abrupt increase of MOI; some changes in structure

- C-19; C-20

  constant moments of inertia; much larger

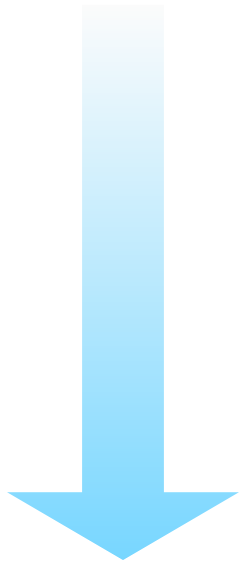


PWZ, Itagaki, Meng, Phys. Rev. Lett. 115, 022501 (2015)

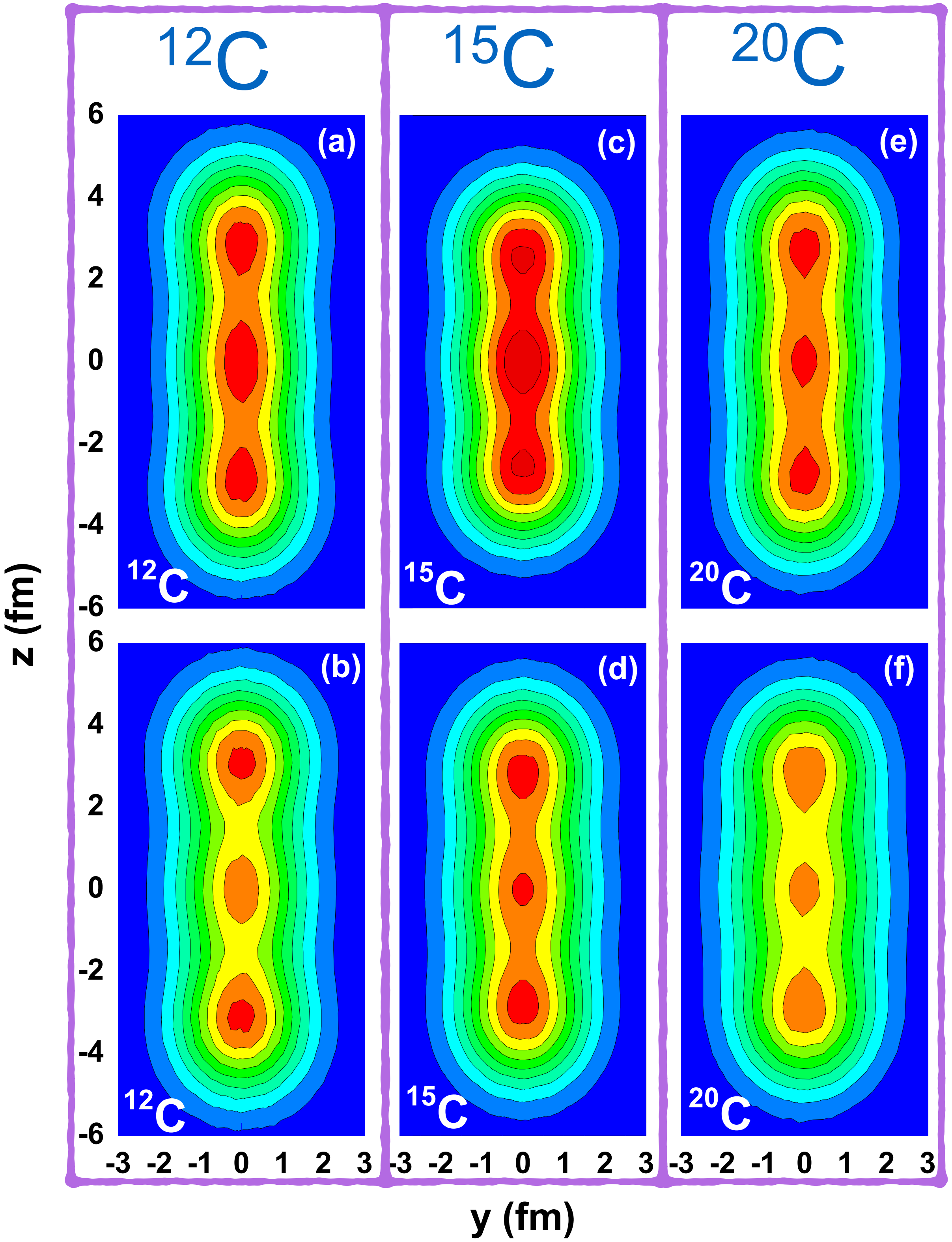
Proton density distribution

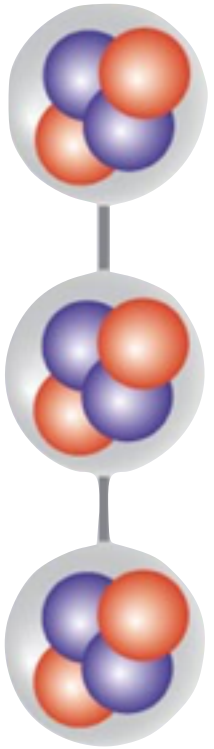
$\hbar\omega$

0.0 MeV



3.0 MeV





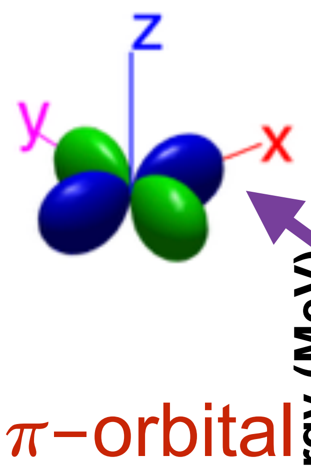
Very large deformation

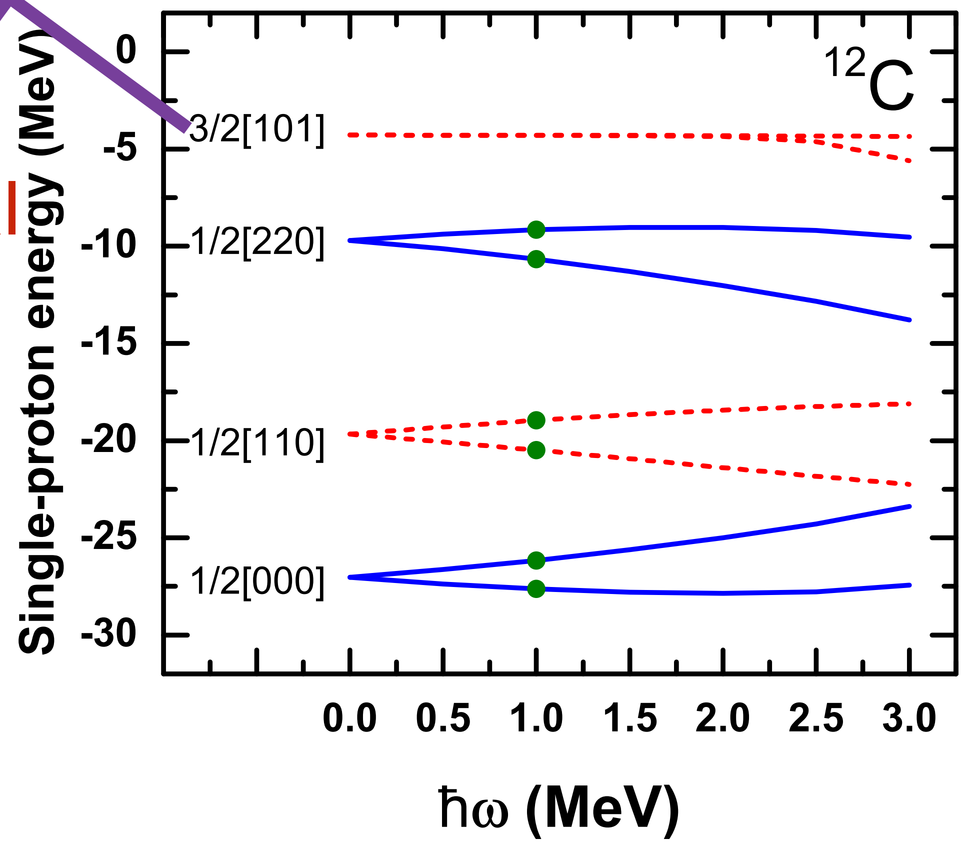
Very clear clustering

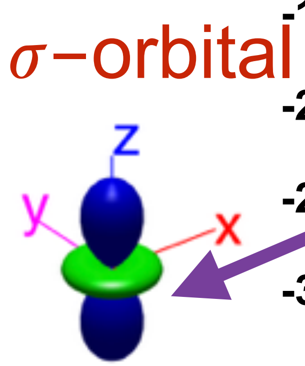
Rod shape are obtained in all isotopes by tracing the corresponding rod-shaped configuration.

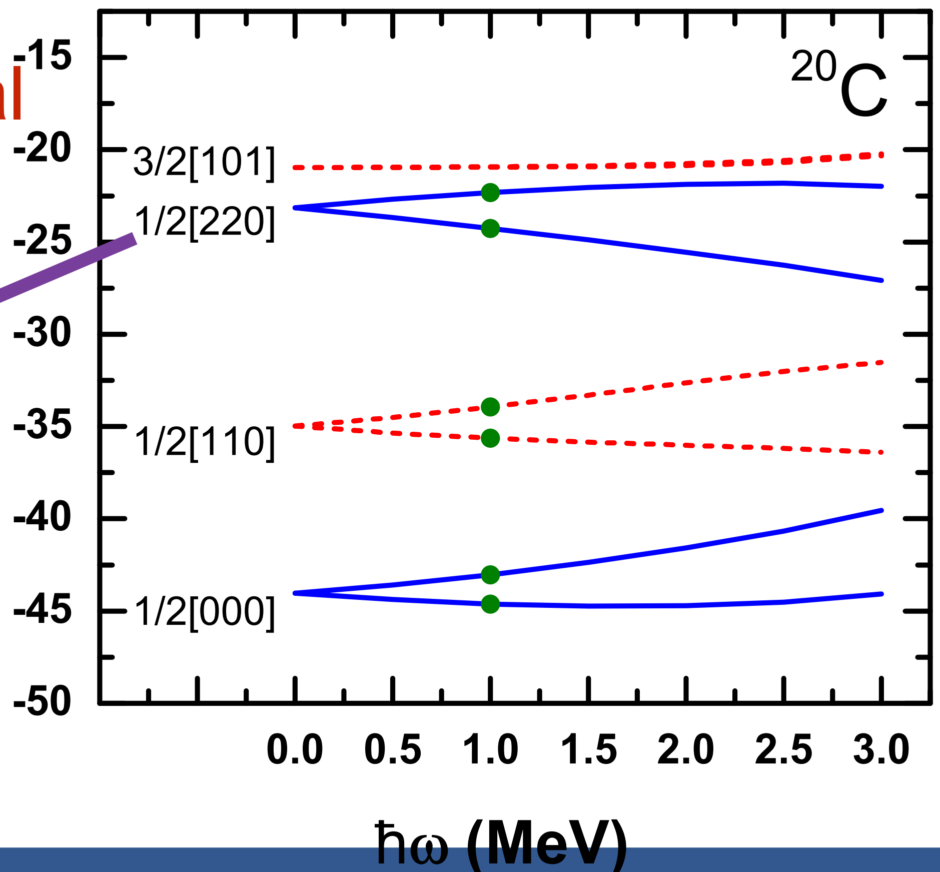
PWZ, Itagaki, Meng, Phys. Rev. Lett. 115, 022501 (2015)

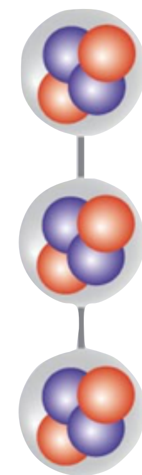
Single-proton energy



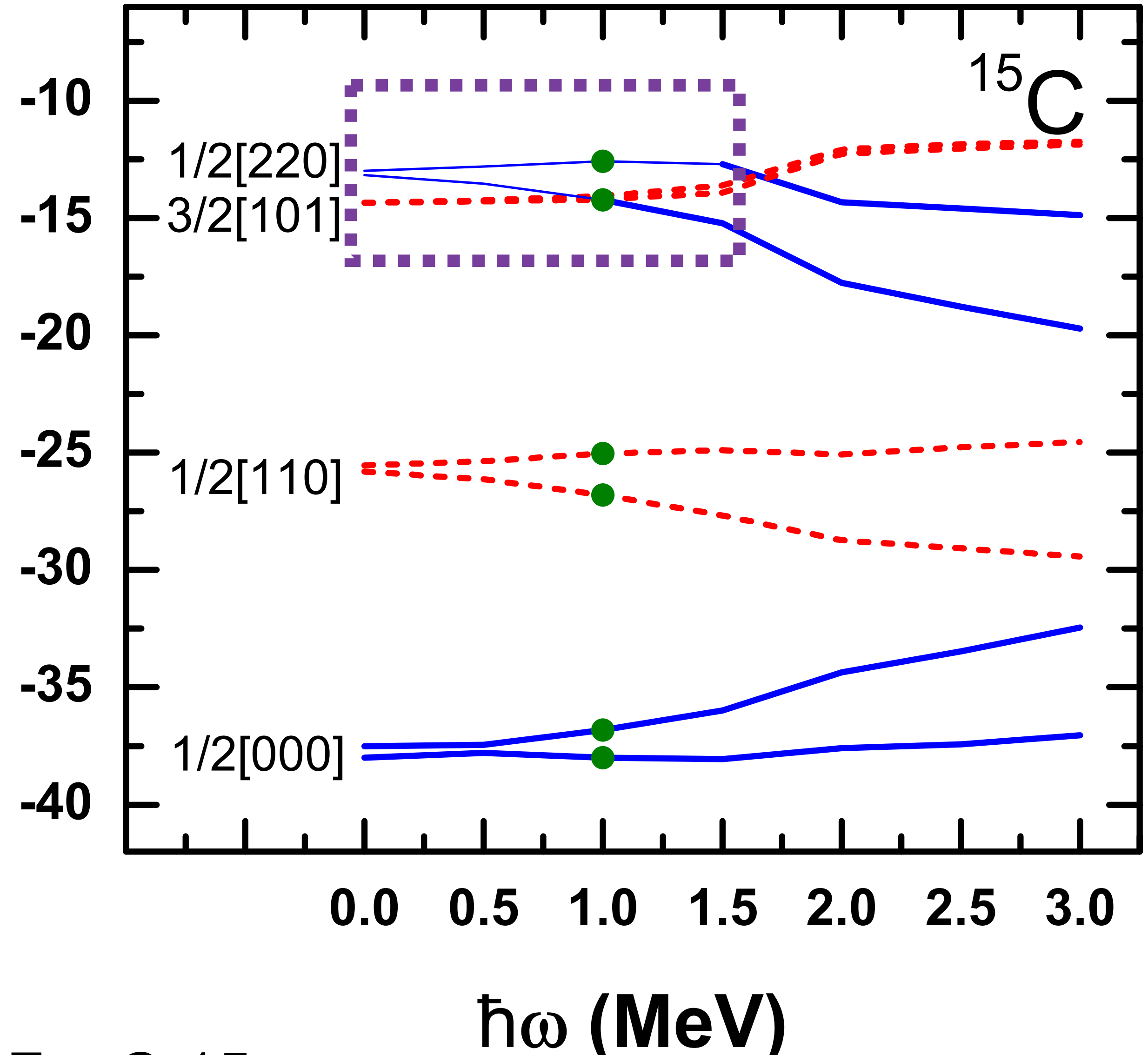








Rotating effects

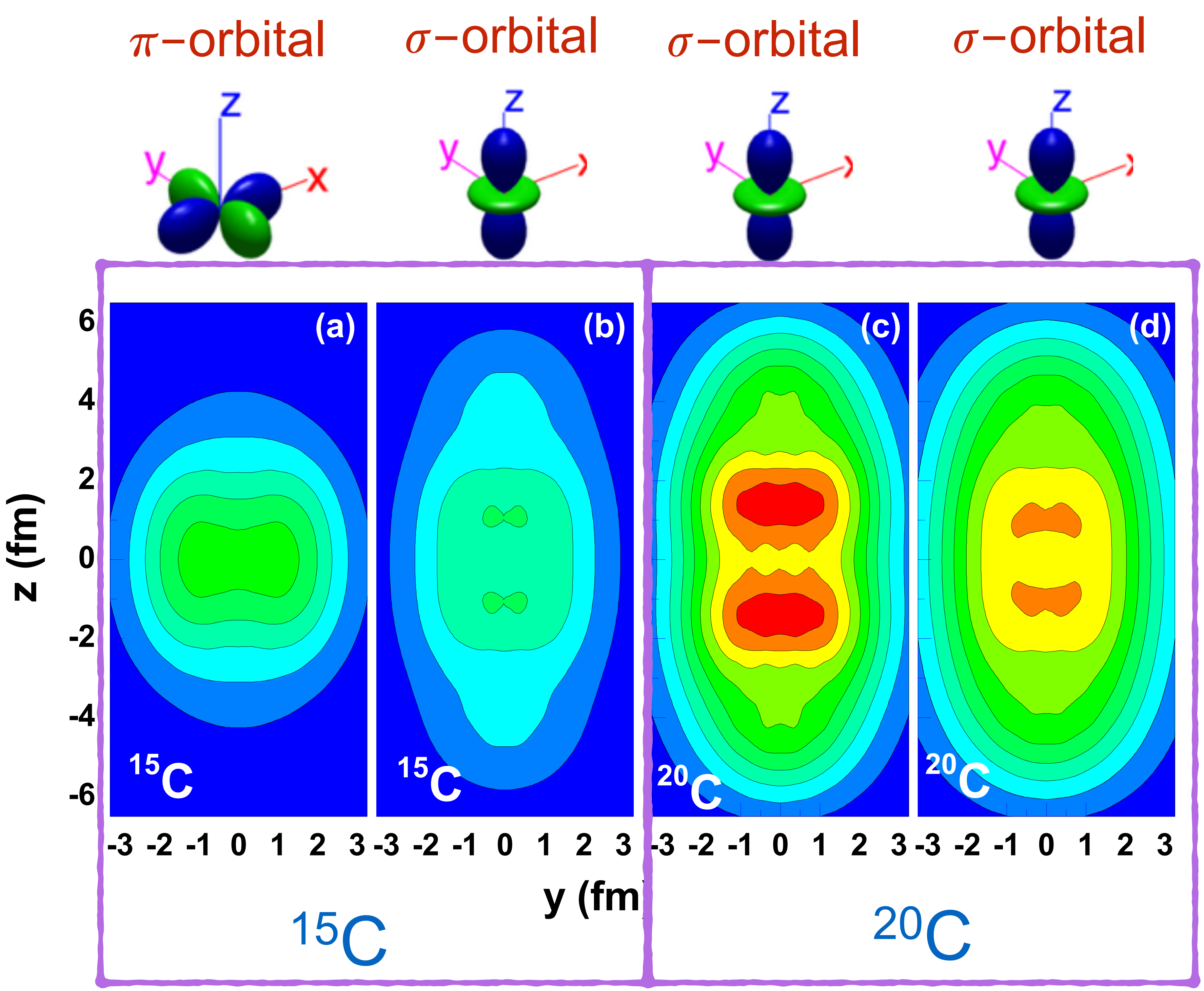


For C-15:

Low spin: deexcitations easily happen

High spin: More stable against deexcitations

Valence neutron density distribution



$^{A}C - ^{12}C$

Isospin effects

C-15: valence neutrons

Low spin: π−orbital; proton unstable

High spin: σ−orbital; proton stable

C-20: valence neutrons

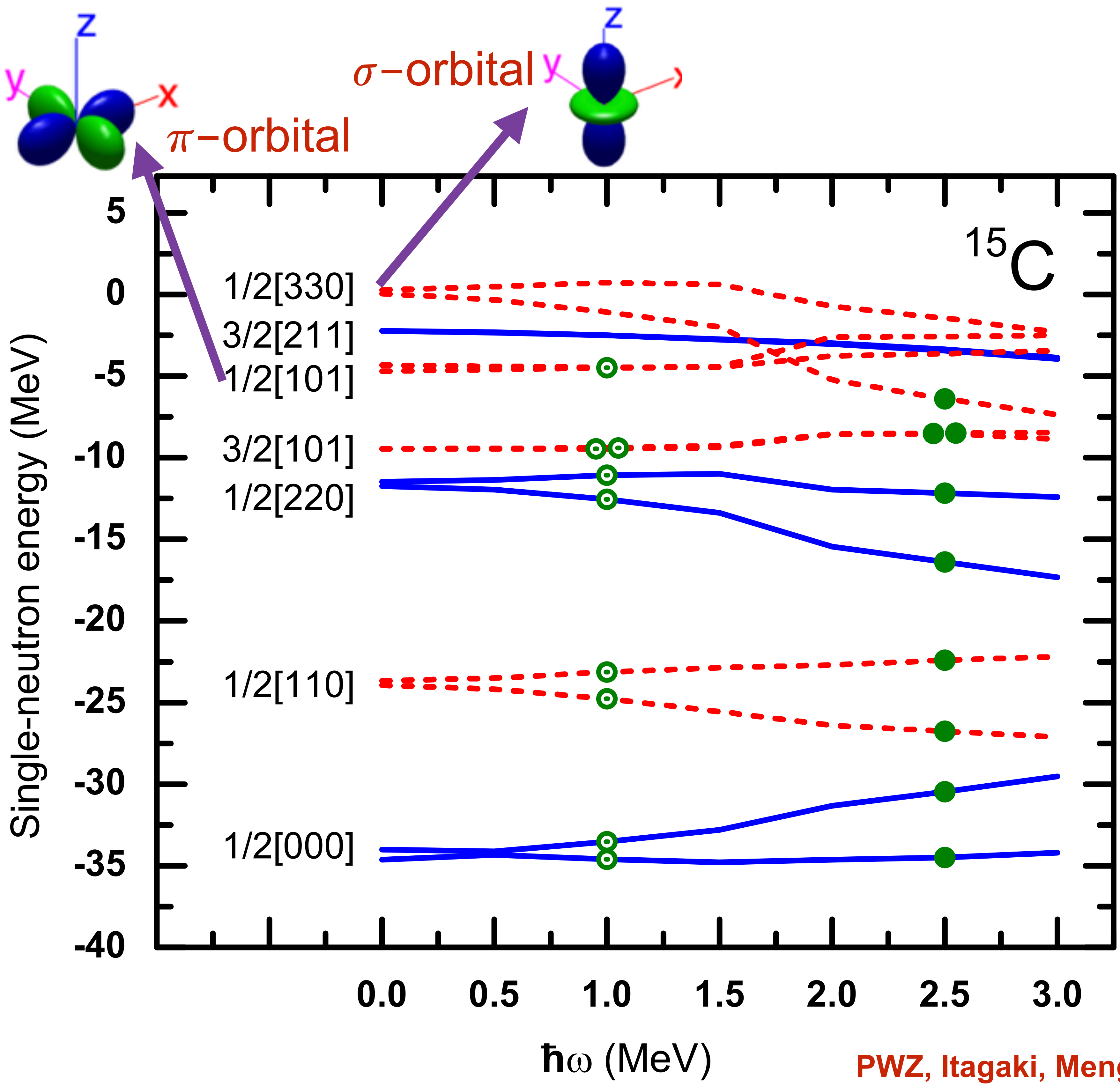
Low spin: σ−orbital; proton stable

High spin: σ−orbital; proton stable

$\hbar\omega$ 0.0 MeV → 3.0 MeV

PWZ, Itagaki, Meng, Phys. Rev. Lett. 115, 022501 (2015)

Single-neutron energy

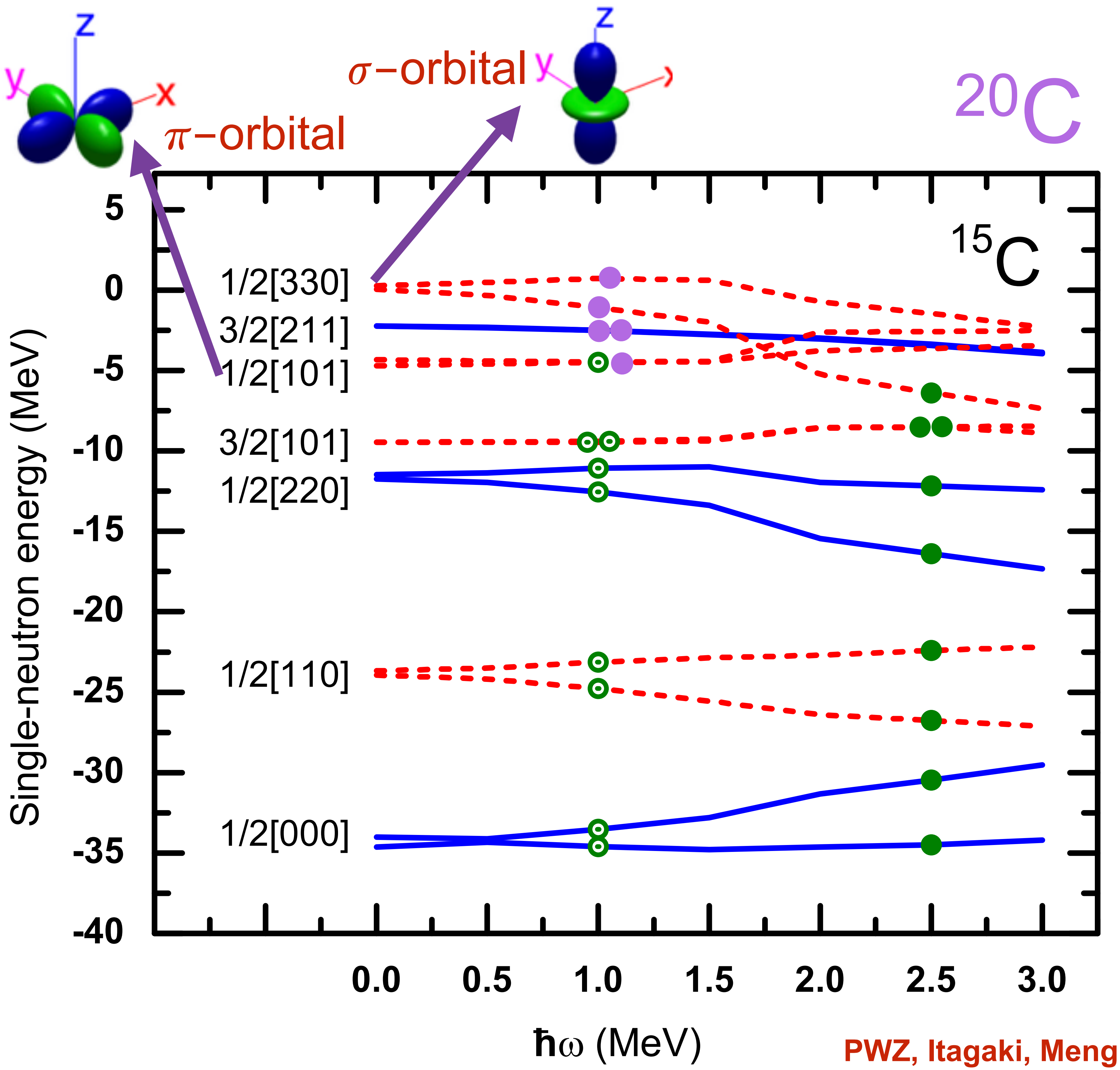


Spin and Isospin Coherent Effects

Rotation makes the sigma valence neutron orbital lower and easier to be occupied, and thus pull down the sigma proton orbitals.

PWZ, Itagaki, Meng, Phys. Rev. Lett. 115, 022501 (2015)

Single-neutron energy



Spin and Isospin Coherent Effects

Rotation makes the sigma valence neutron orbital lower and easier to be occupied, and thus pull down the sigma proton orbitals.

PWZ, Itagaki, Meng, Phys. Rev. Lett. 115, 022501 (2015)

Summary

Covariant density functional theory has been extended to describe rotational excitations.

- Both MR and AMR and their mechanism could be described well.
- Pairing correlation could improve descriptions (more examples)
- Two mechanisms to stabilize the rod shape,
  rotation (high spin) and adding neutrons (high Isospin),
  coherently work in C isotopes
- Coherent Effects:
  Rotation makes the sigma valence neutron orbital lower, and thus
  1. pull down the sigma proton orbitals
  2. enhances the prolate deformation of protons

In collaboration with

Technical Univ. Munich

Peter Ring

Peking Univ.

Qibo Chen

Lingfei Yu

Jie Meng

Shuangquan Zhang

Zhenhua Zhang

YITP, Kyoto Univ.

Naoyuki Itagaki

Beijing Normal Univ.

Jing Peng

RIKEN

Haozhao Liang

many experimental colleagues @Argonne, GSI, iThemba Lab, …

Thank you for your attention!