Relativistic description of novel nuclear structure towards extremes of spin and isospin

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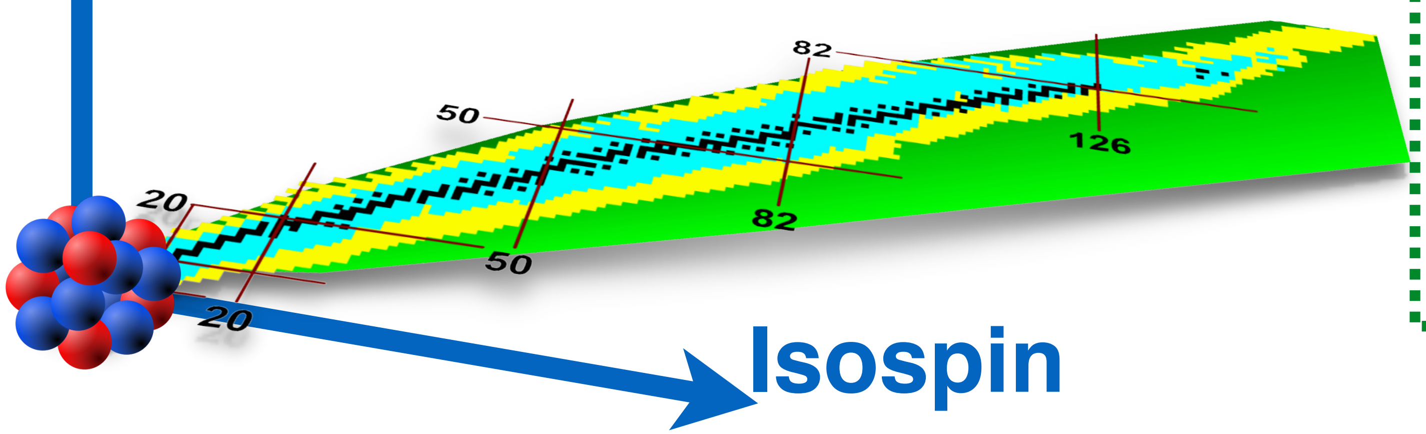
Nuclear spectroscopy

Spin

Long Range Plan 2015

Towards extreme spin and isospin

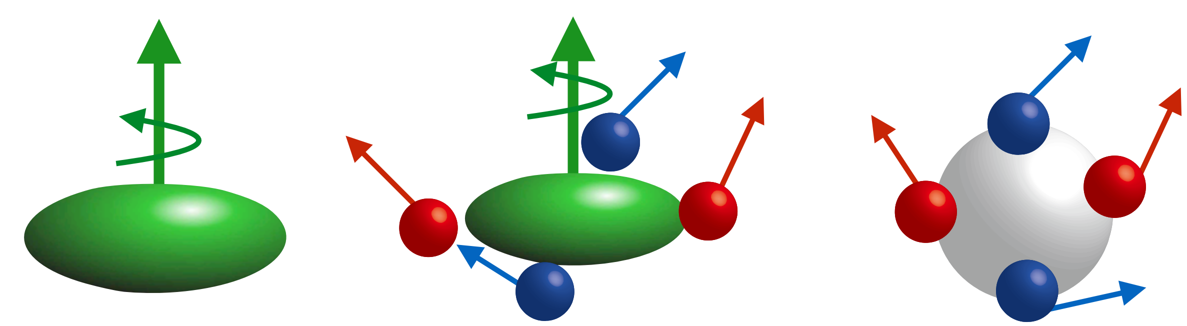
- ✓ collectivity
- ✓ shape coexistence/transition
- ✓ evolution of shell structure
- ✓ super- (hyper-) deformation
- ✓ novel modes of excitation
- ✓ superfluidity
- ✓ superheavy nuclei
- ✓ fission
- ✓ …



Isospin

Nuclear Rotation

interplay



collectivity

valence nucleon

Strong deformation

Weak deformation

Novel structure at the limits

Outline

- Covariant density functional theory
- Rod-shaped nuclei at high spin and isospin
- Chiral conundrum in ^{106}Ag
- Extending CDFT: a new spectroscopic method
- Summary

Density functional theory

The many-body problem is mapped onto an one-body problem

Hohenberg-Kohn Theorem

The exact ground-state energy of a quantum mechanical many-body system is a universal functional of the local density.

Kohn-Sham DFT

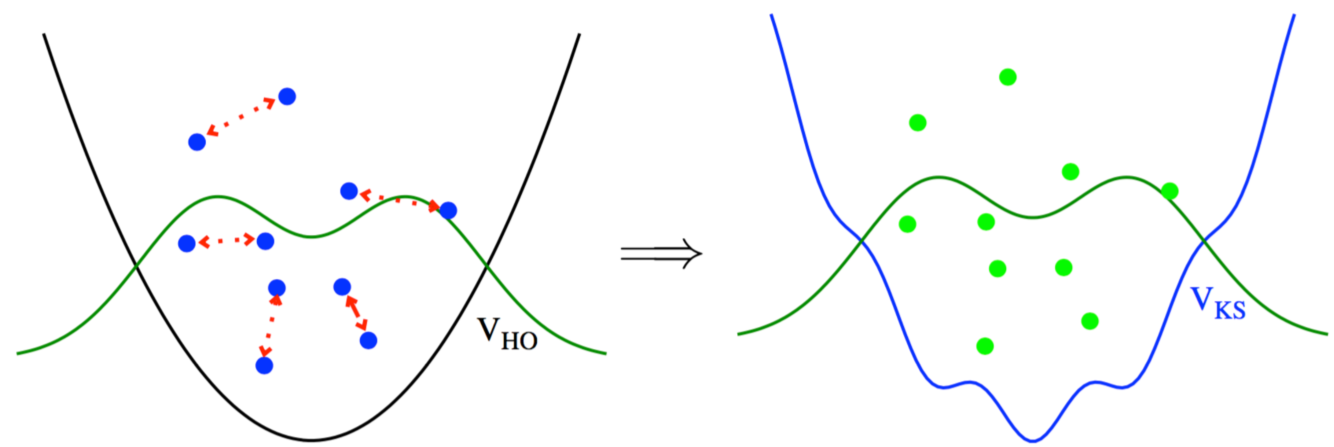
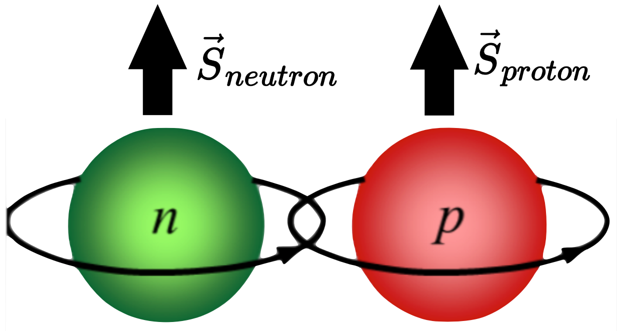


Figure from Drut PPNP 2010

$$E[\rho] \Rightarrow \boxed{\hat{h} = \frac{\delta E}{\delta \rho}} \Rightarrow \boxed{\hat{h}\varphi_i = \varepsilon_i \varphi_i} \Rightarrow \boxed{\rho = \sum_{i=1}^{A} |\varphi_i|^2}$$

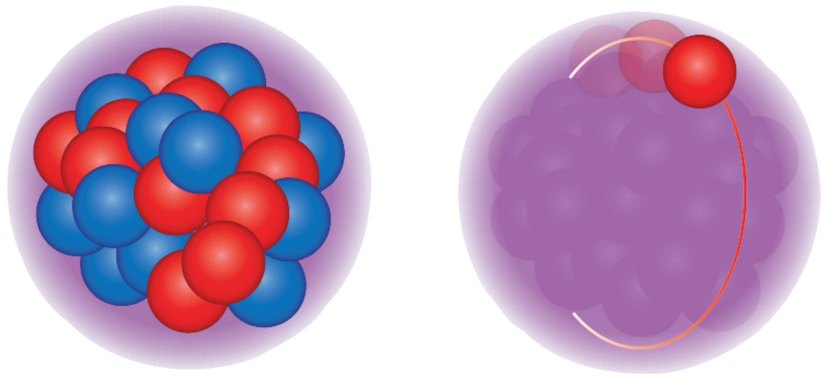
The practical usefulness of the Kohn-Sham theory depends entirely on whether an **Accurate Energy Density Functional** can be found!

Density functional theory for nuclei



✓ The nuclear force is complicated

✓ More degrees of freedom: spin, isospin, pairing, …



✓ Nuclei are self-bound systems

DFT for the intrinsic density

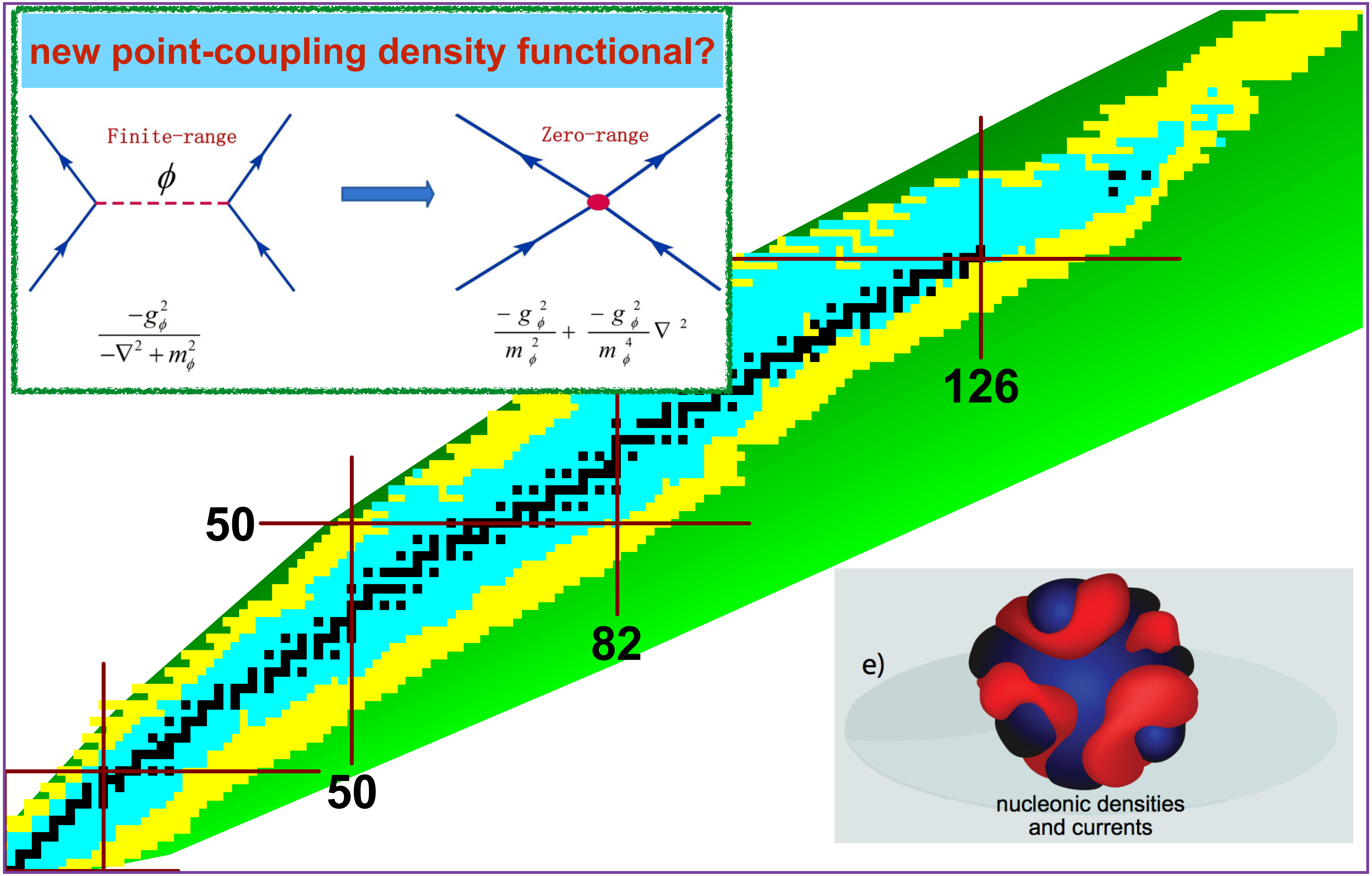
✓ At present, all successful functionals are phenomenological

not connected to any NN- or NNN-interaction

✓ Adjust to properties of nuclear matter and/or finite nuclei, and

(in future) to ab-initio results

Covariant density functionals



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

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$$j_0 = \rho_V \qquad j_i = 0$$

$$\vec{j}_0 = \rho_{TV} \qquad \vec{j}_i = 0$$

Energy Density Functional

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

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

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

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

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

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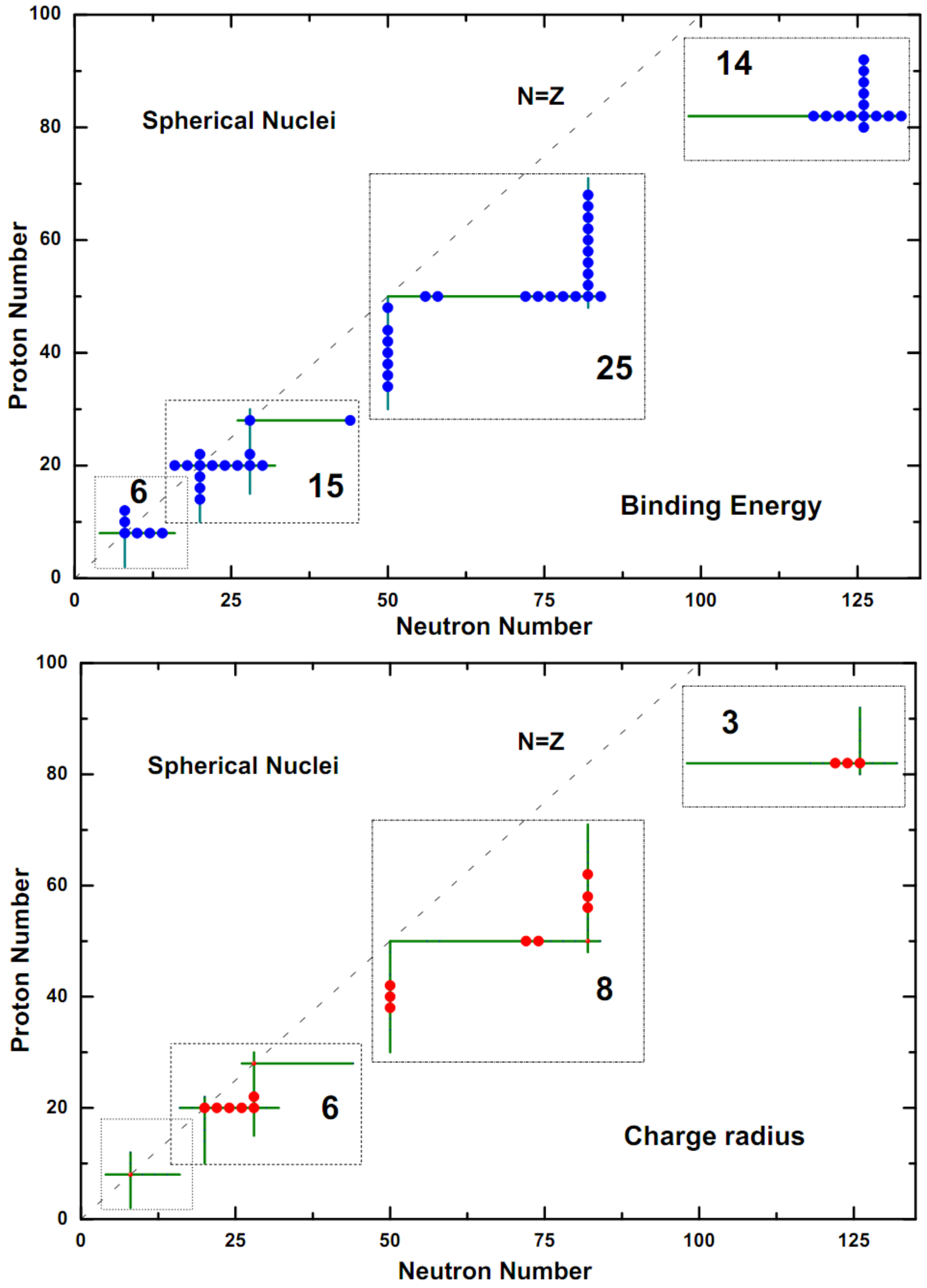
Covariant Functional: PC-PK1



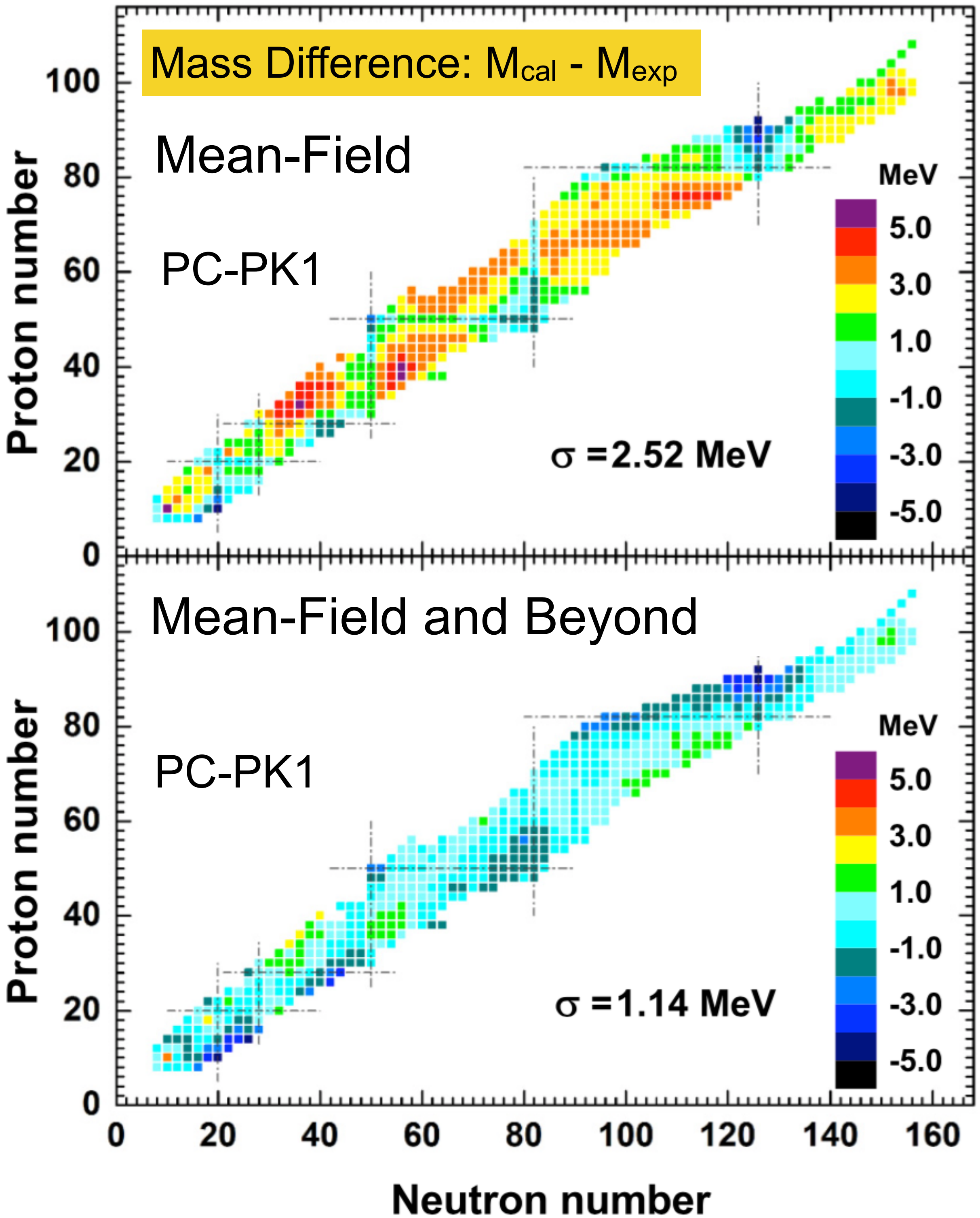
Binding energies of 60 nuclei

Charge radii of 17 nuclei

Coupl.	Cons.	PC-PK1	Dimension
α_S	$[10^{-4}]$	-3.96291	MeV^{-2}
β_S	$[10^{-11}]$	8.66530	MeV^{-5}
γ_S	$[10^{-17}]$	-3.80724	MeV^{-8}
δ_S	$[10^{-10}]$	-1.09108	MeV^{-4}
α_V	$[10^{-4}]$	2.69040	MeV^{-2}
γ_V	$[10^{-18}]$	-3.64219	MeV^{-8}
δ_V	$[10^{-10}]$	-4.32619	MeV^{-4}
α_{TV}	$[10^{-5}]$	2.95018	MeV^{-2}
δ_{TV}	$[10^{-10}]$	-4.11112	MeV^{-4}
V_n	$[10^{0}]$	-349.5	$\mathrm{MeV\ fm}^{3}$
V_p	$[10^{0}]$	-330	$\mathrm{MeV\ fm}^{3}$

PWZ, Li, Yao, Meng, PRC 82, 054319 (2010)

Nuclear Masses

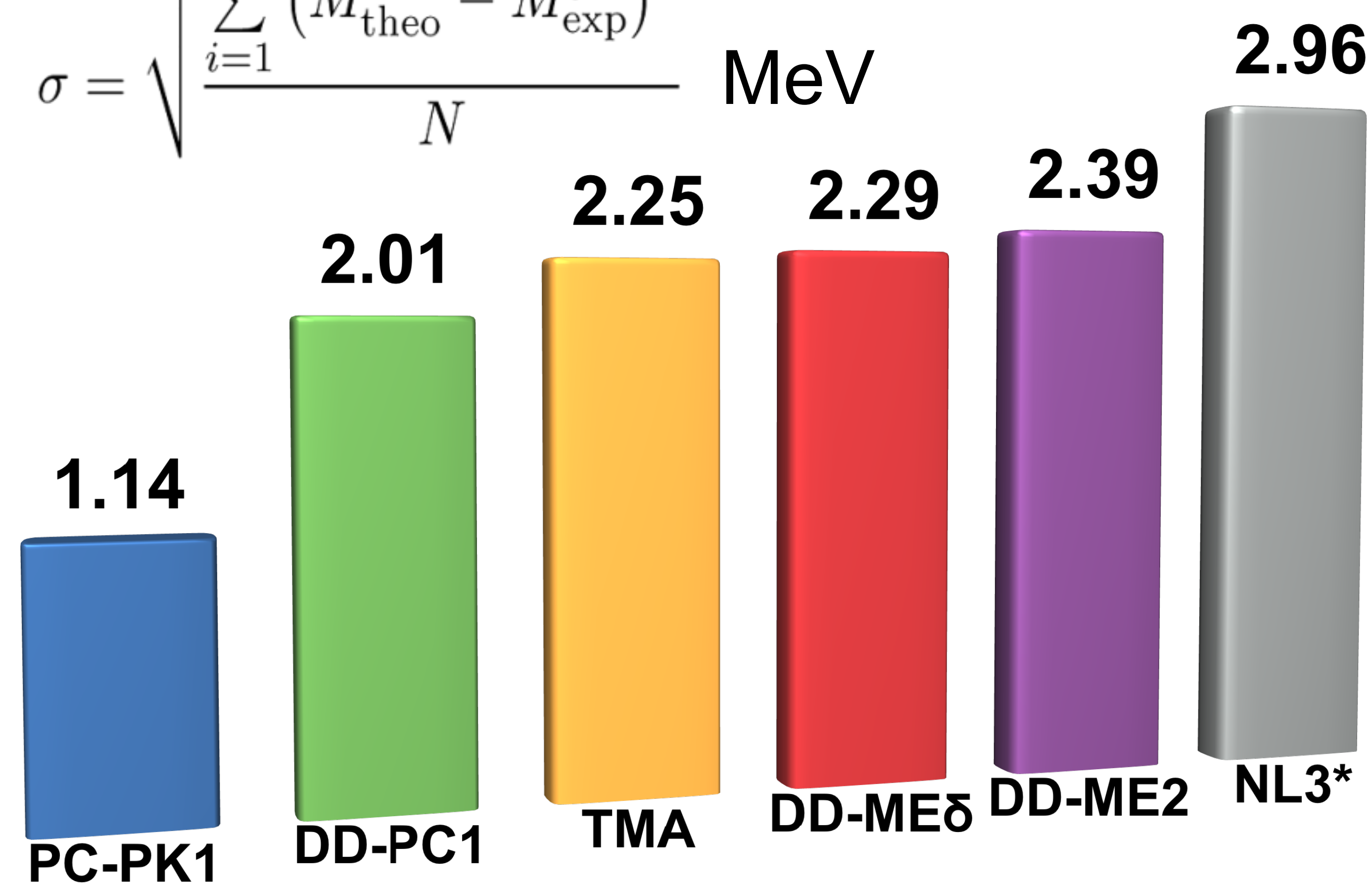


Data from AME2012

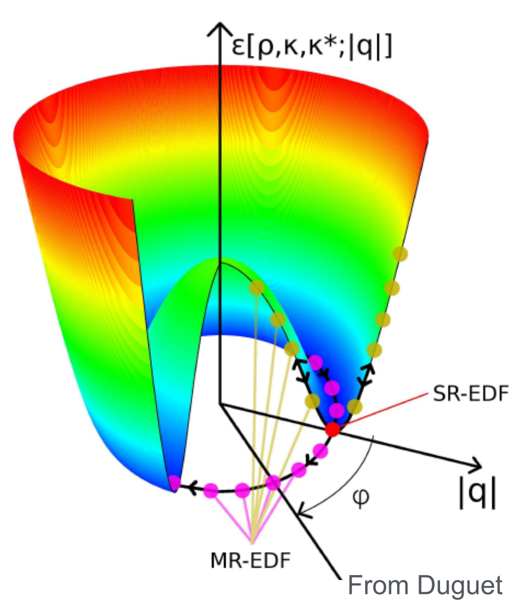
PWZ, Li, Yao, Meng, PRC 82, 054319 (2010)

Lu, Li, Li, Yao, Meng PRC 91, 027304 (2015)

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}\left(M^i_{\text{theo}} - M^i_{\text{exp}}\right)^2}{N}} \text{ MeV}$$

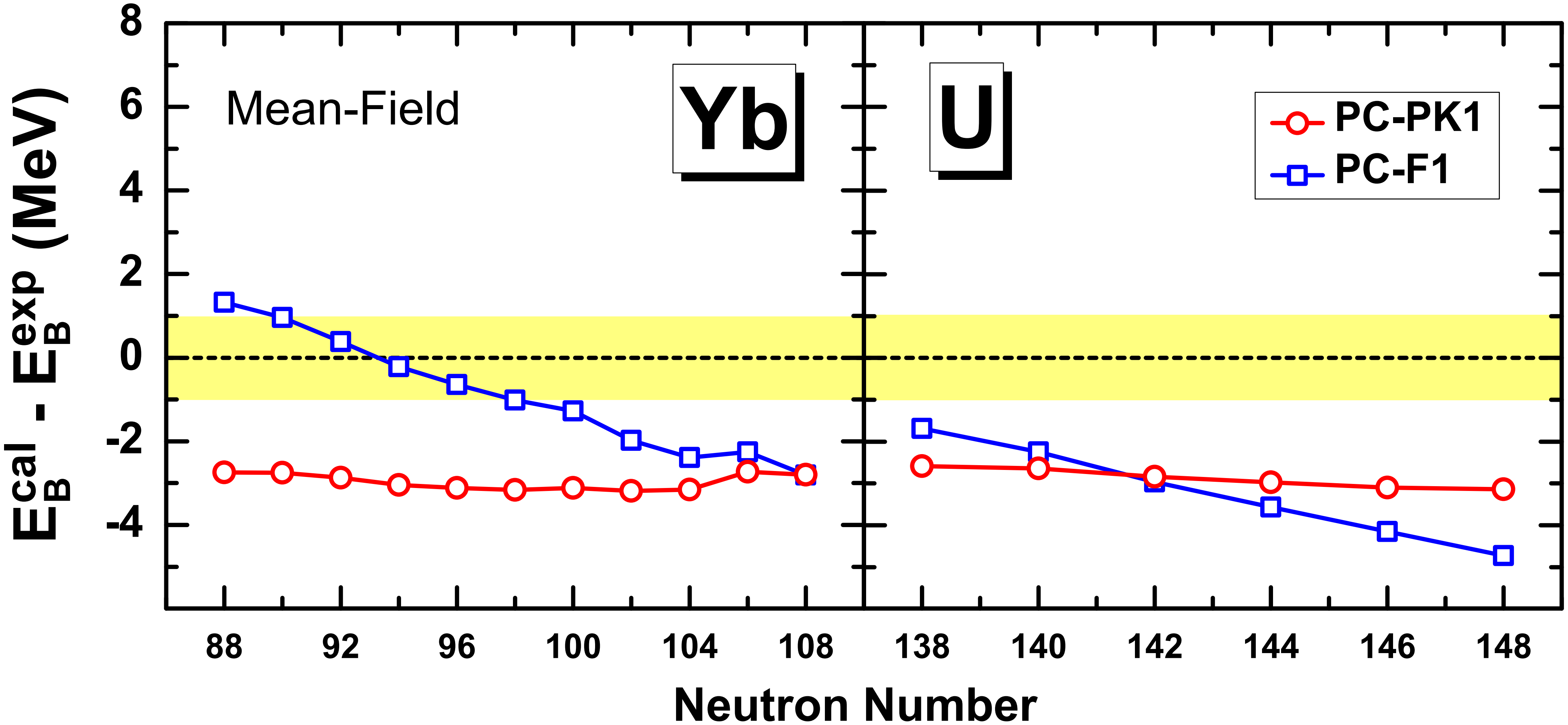


Agbemava PRC 2014
Geng PTP 2005



Best density-functional description for nuclear masses so far!

Deformed nuclei

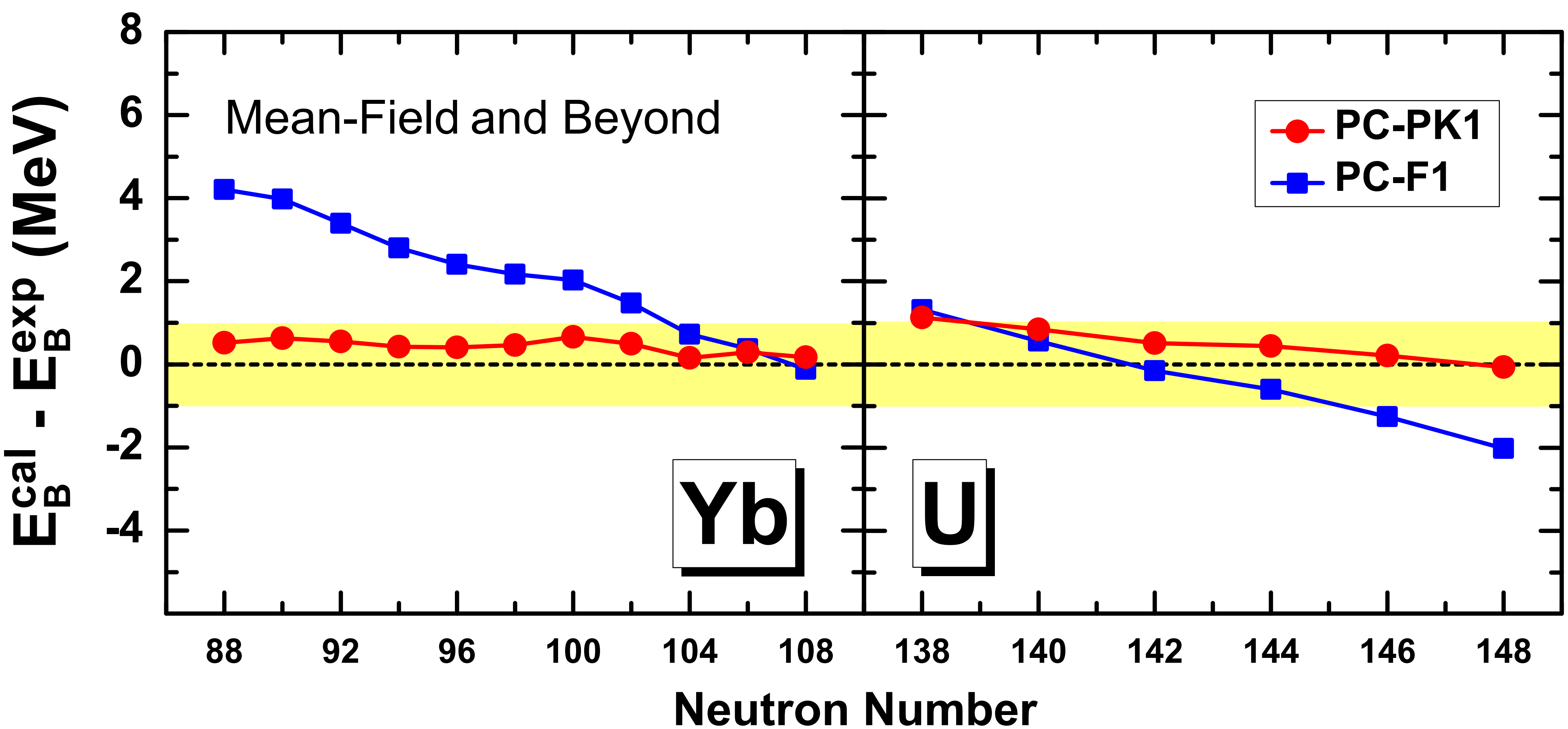


PWZ, Li, Yao, Meng, PRC 82, 054319 (2010)

Improved isospin dependence

Maybe more reliable for neutron-rich exotic nuclei …

Deformed nuclei



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Extending CDFT for nuclear rotations

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

- **Tilted axis cranking CDFT**

<u>Meson exchange version:</u>

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:

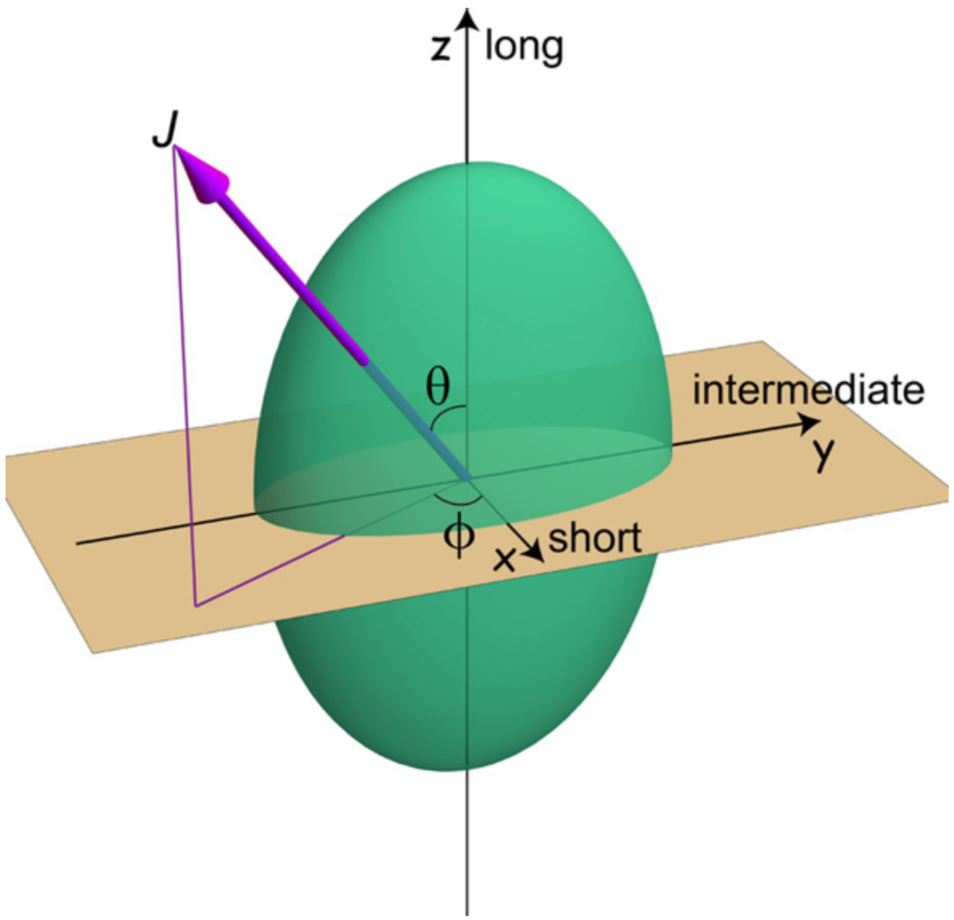
Simple and more suitable for systematic investigations

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*



- Tilted axis cranking Skyrme DFTs are also available:

2-D Cranking: *Olbratowski, et al., APPB 33, 389(2002)*; 3-D Cranking: *Olbratowski et al., PRL 93, 052501(2004)*

Self-consistent and microscopic investigations

- 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

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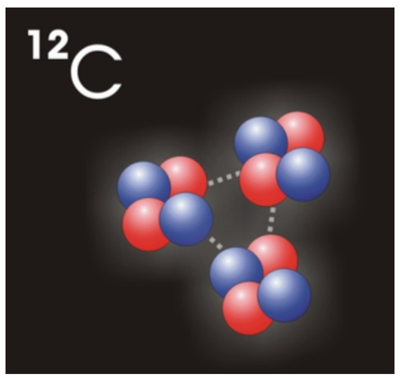
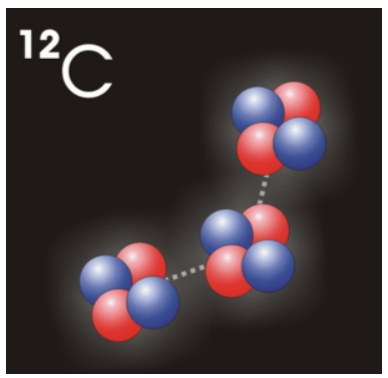
Rod-shaped nuclei

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

Ground

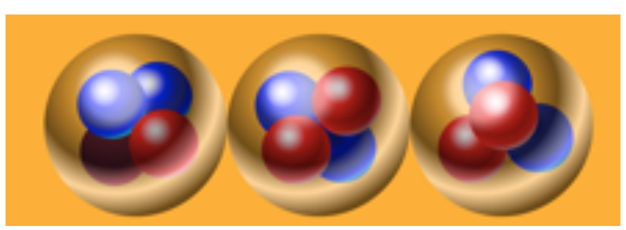


Hoyle



- ✦ the linear alpha cluster chain has been searched more than 60 years.
- ✦ new radioactive beams provide new opportunities in realizing the linear chain state.

No firm evidence



Two difficulties

- ✓ antisymmetrization effects
- ✓ weak-coupling nature

Two mechanisms

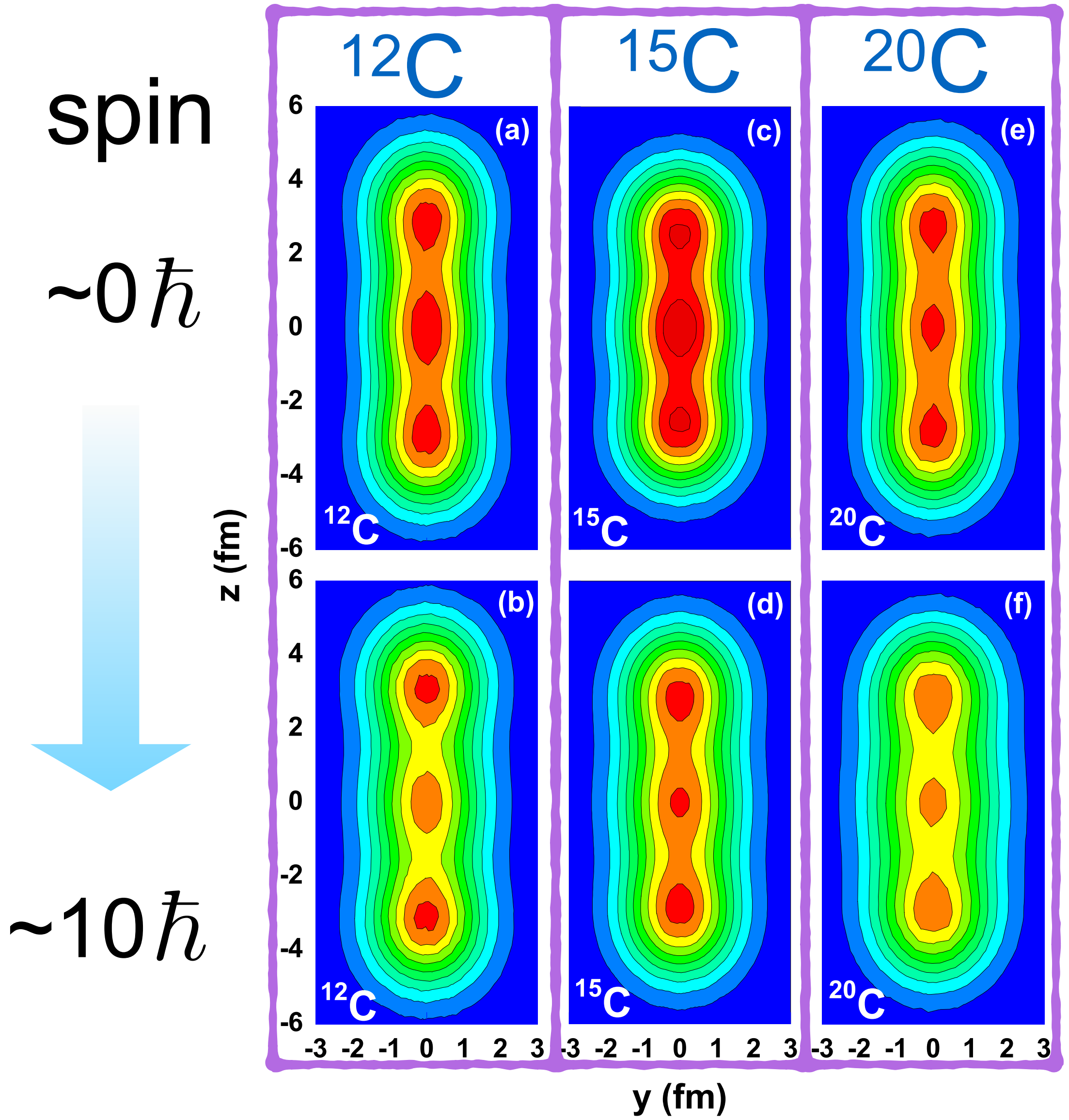
- ✓ adding neutrons (isospin)
- ✓ rotating the system (spin)

Itagaki, PRC2001; Maruhn, NPA2010; Ichikawa, PRL2011

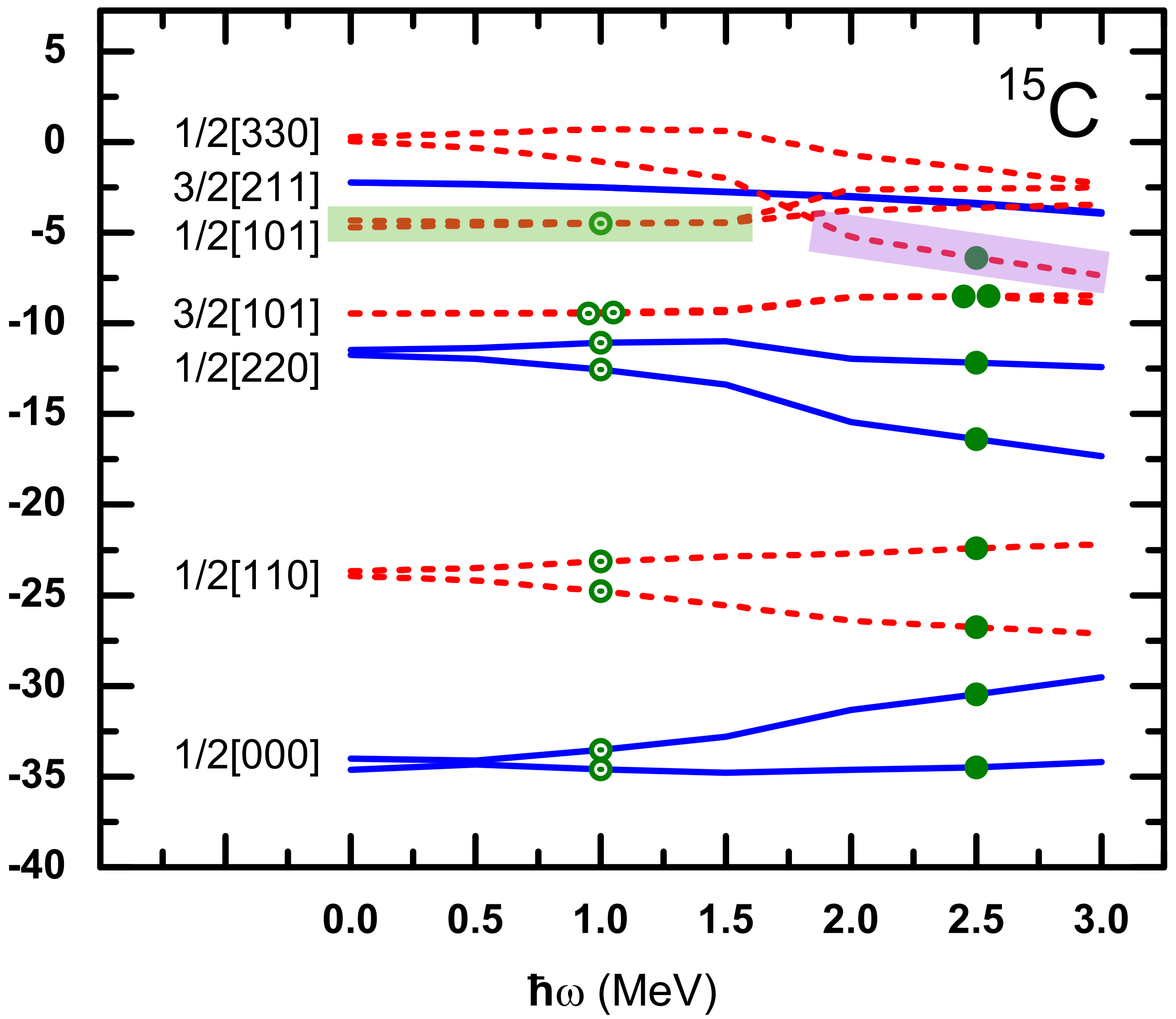
CDFT is employed without assuming clustering a priori.

Spin and Isospin Coherent Effects

Proton density distribution



neutron orbitals



PWZ, Itagaki, Meng, PRL 115, 022501 (2015)

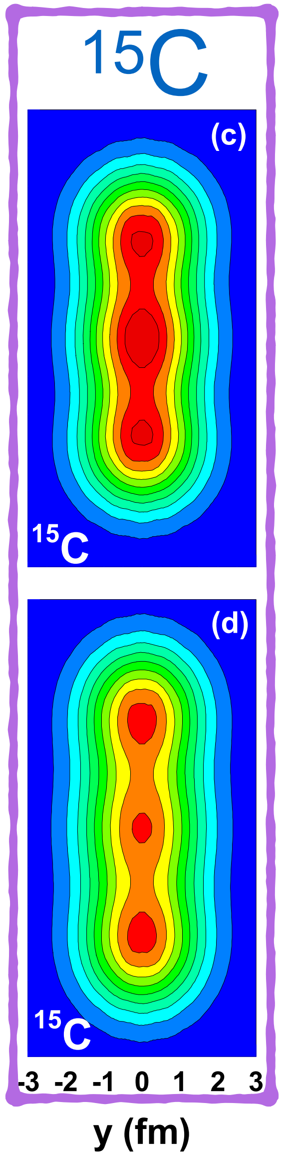
Spin and Isospin Coherent Effects

Proton density distribution

spin

~0$\hbar$

~10$\hbar$



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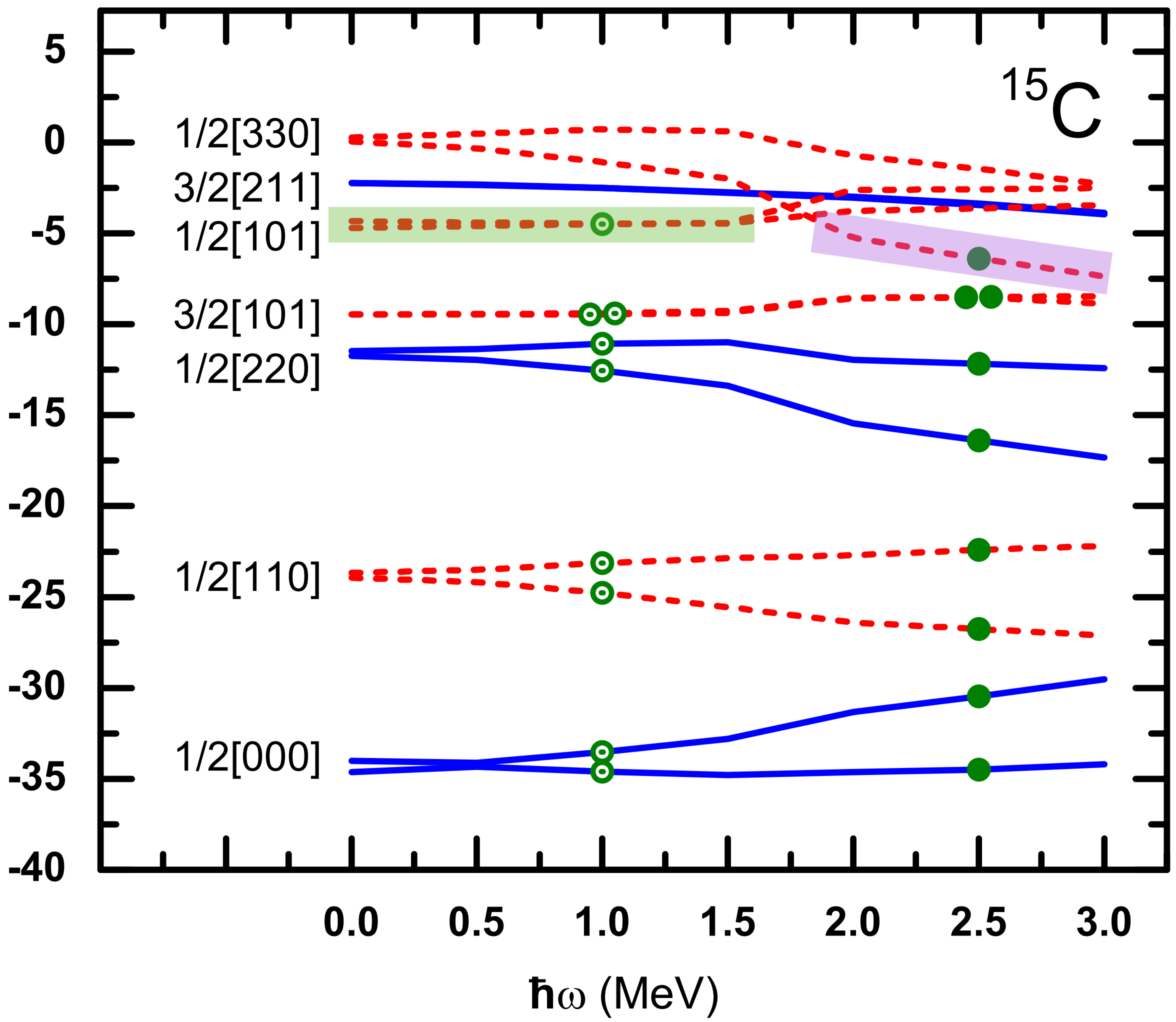


PWZ, Itagaki, Meng, PRL 115, 022501 (2015)

Spin and Isospin Coherent Effects

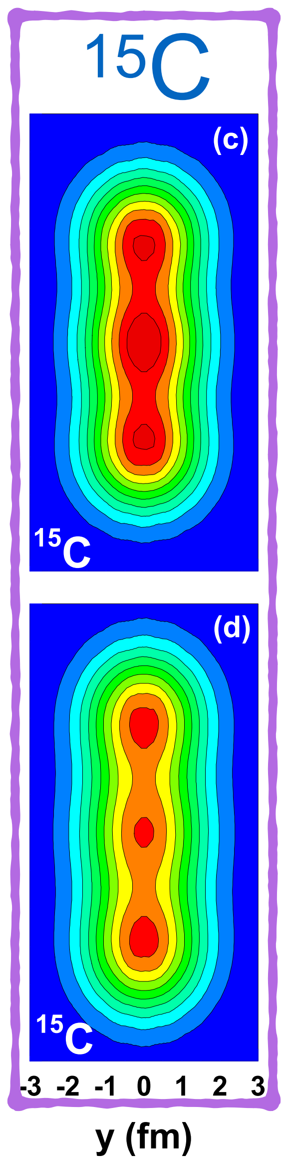
Proton density distribution

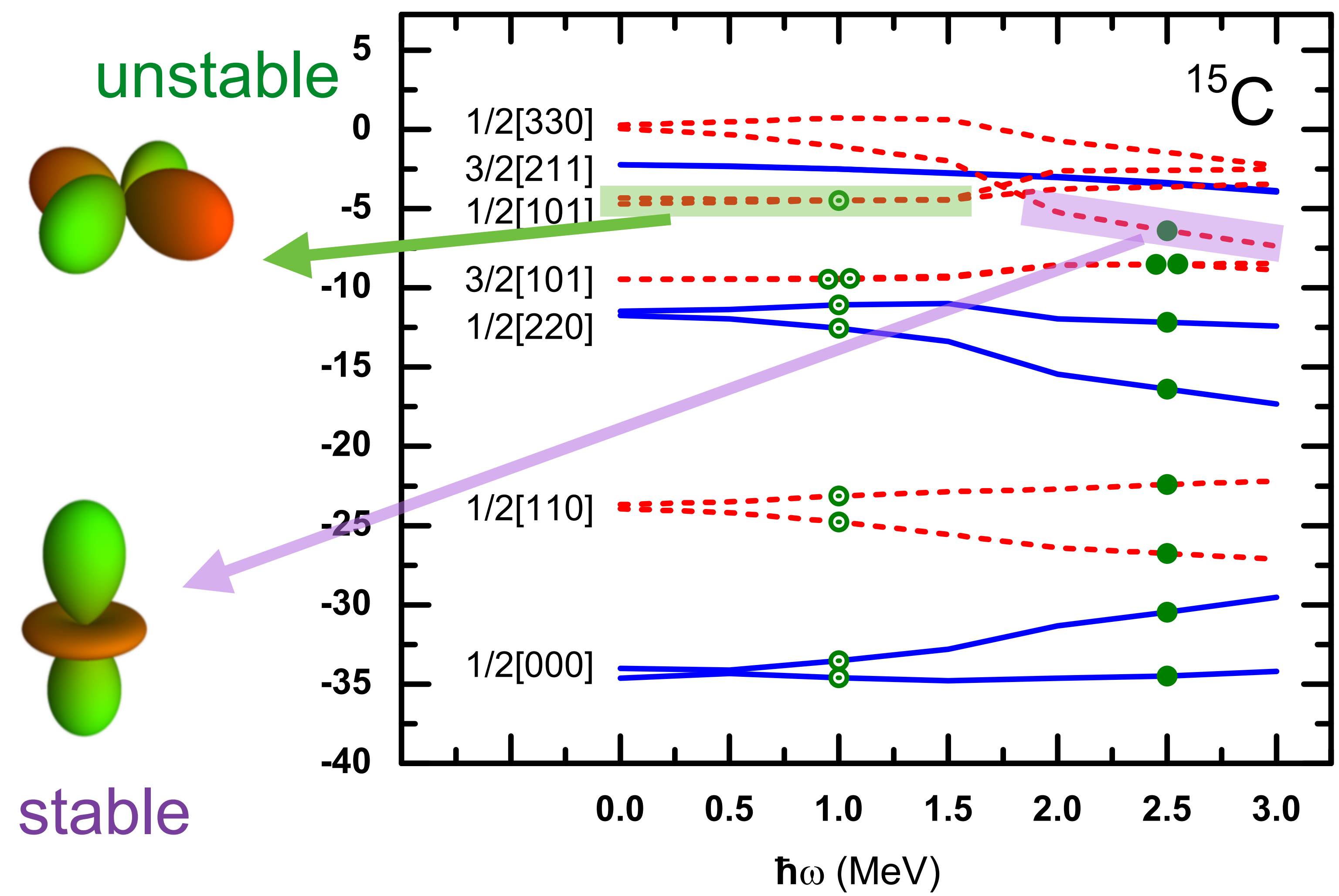
neutron orbitals

spin

$\sim 0\hbar$

$\sim 10\hbar$





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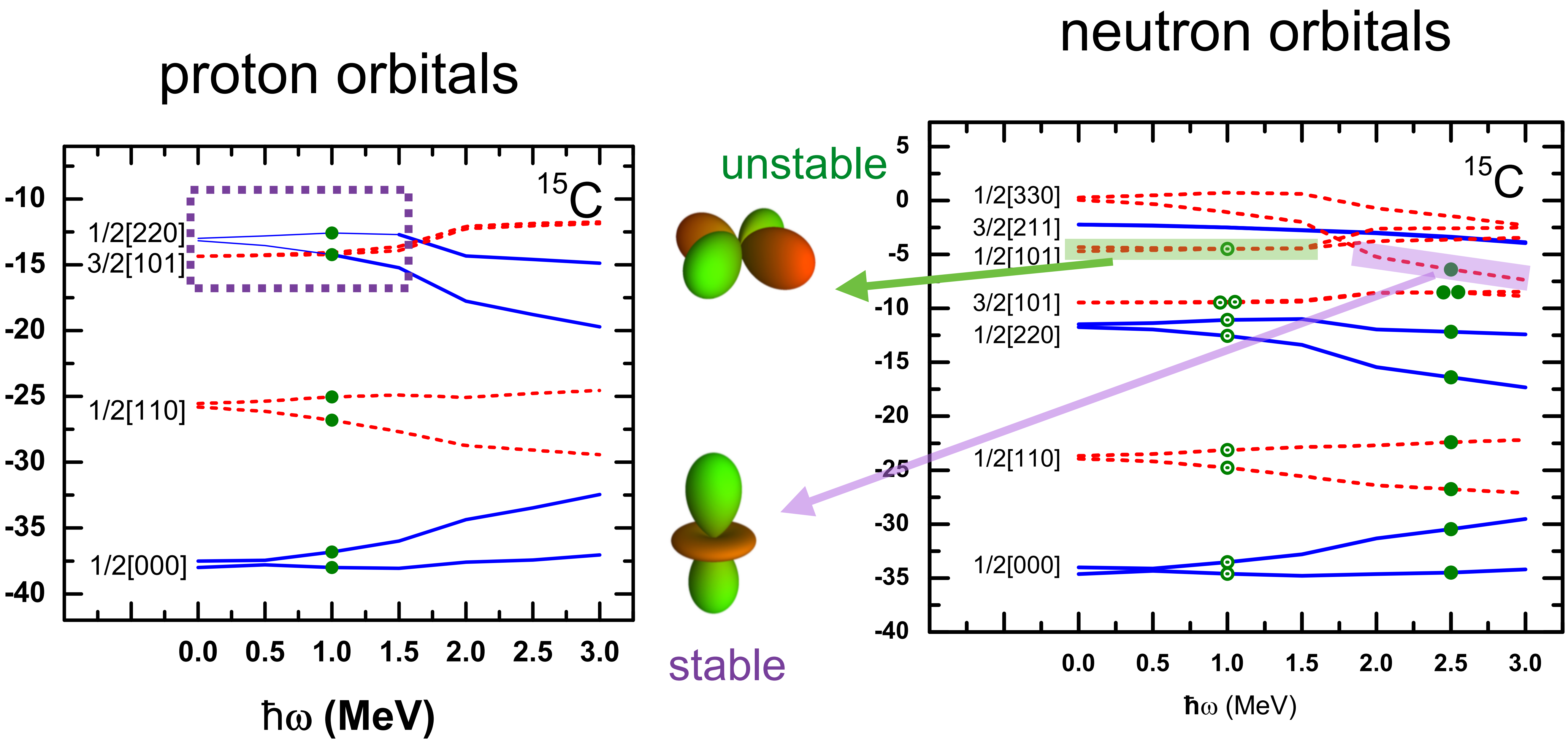
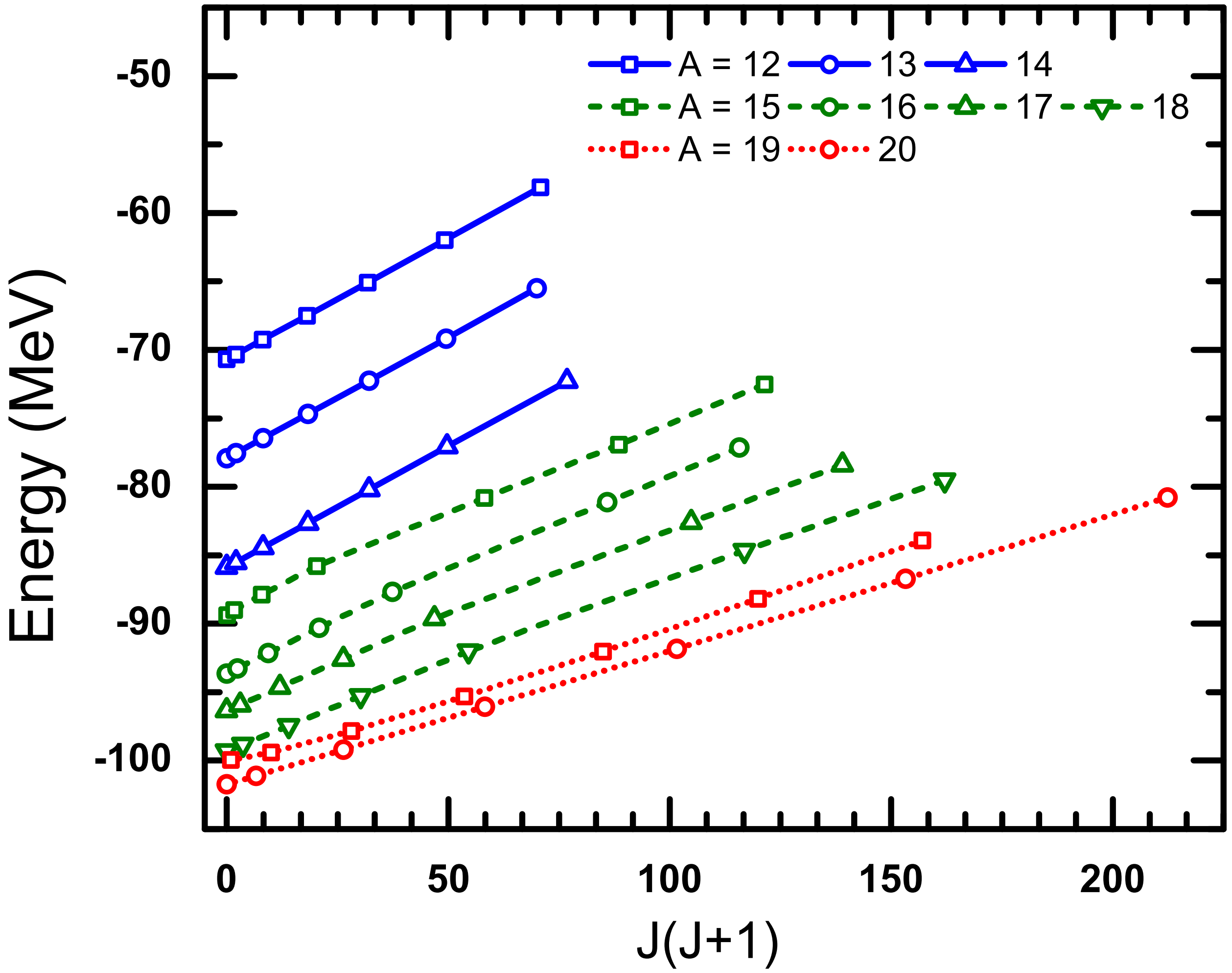


PWZ, Itagaki, Meng, PRL 115, 022501 (2015)

Recent experiments…

Our predictions

PWZ, et al, PRL 115, 022501 (2015)



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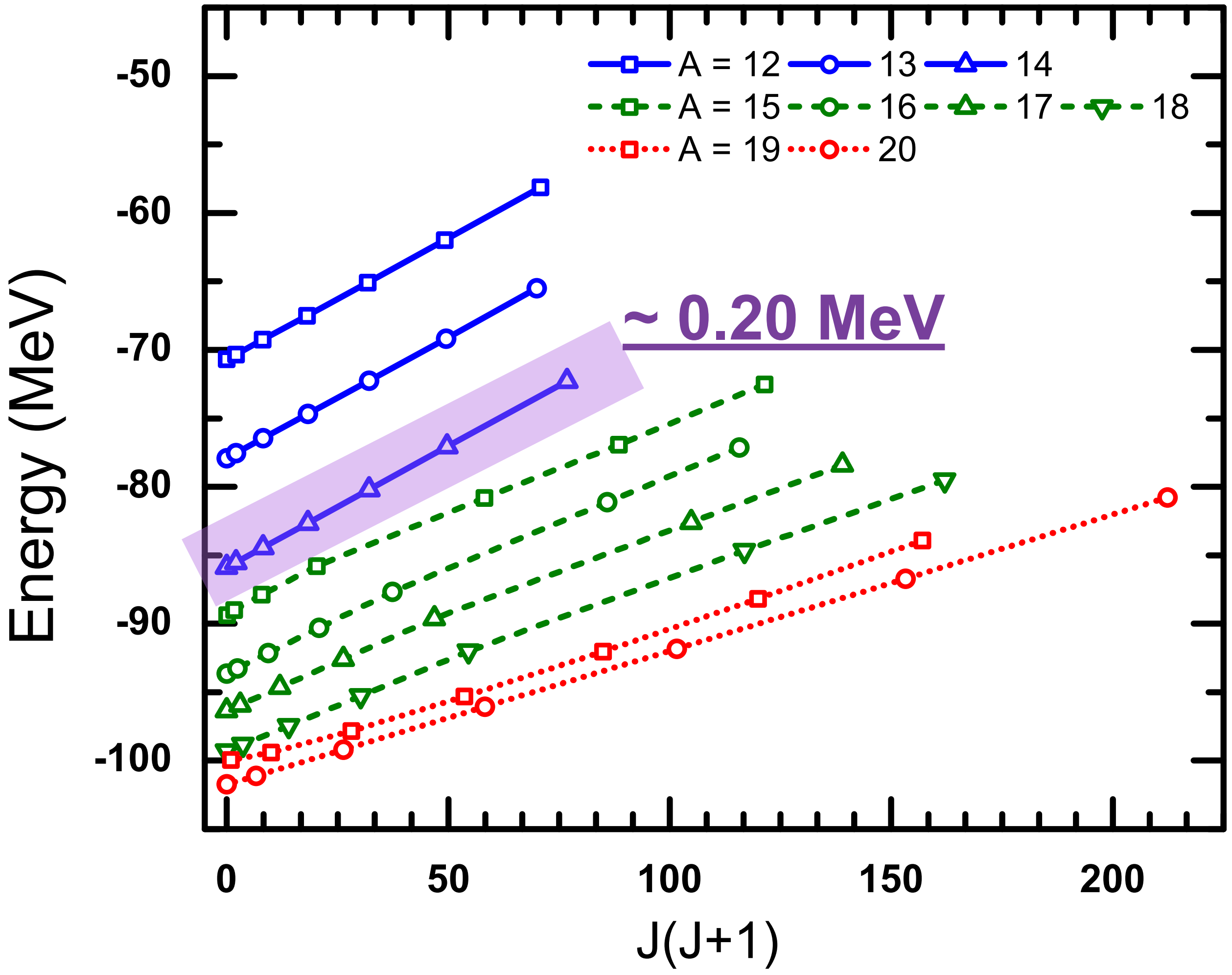
PWZ, et al, PRL 115, 022501 (2015)



Exp @RIKEN

> where $\Im$ is the moment of inertia of the nucleus. The linearity allows us to interpret the levels as a rotational band, and the low $\hbar^2/2\Im = 0.19$ MeV implies the nucleus could be strongly deformed, consistent with the interpretation of an LCCS. Although we ob-

Yamaguchi et al., PLB 766 (2017) 11–16

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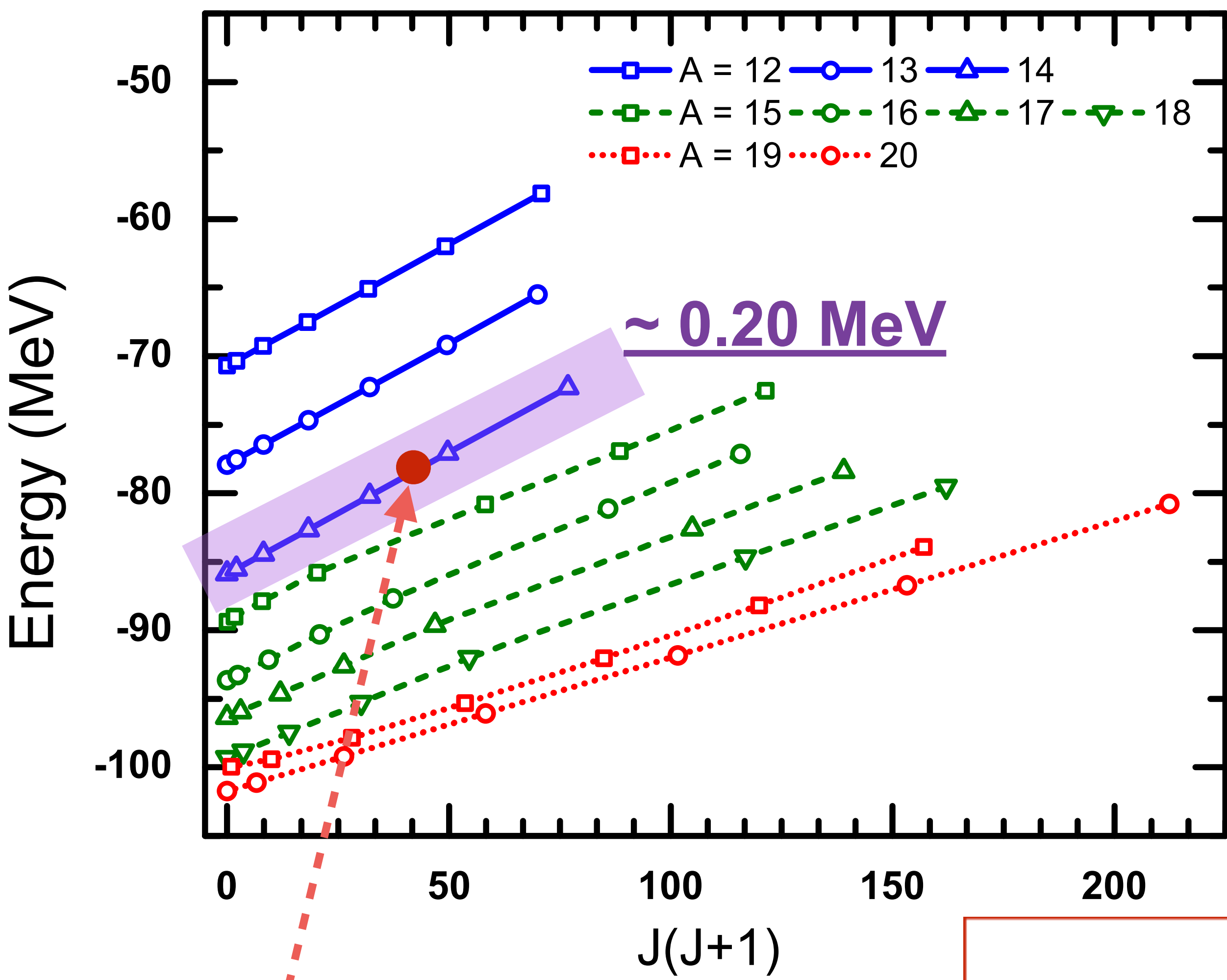

A state at 22.5(1) MeV in ^{14}C

Exp @RIKEN

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Yamaguchi et al., PLB 766 (2017) 11–16

Exp @PKU

Li et al., PRC 95 (2017) 021303(R)

PHYSICAL REVIEW C **95**, 021303(R) (2017)

Selective decay from a candidate of the σ-bond linear-chain state in ^{14}C

J. Li,[1] Y. L. Ye,[1,*] Z. H. Li,[1] C. J. Lin,[2] Q. T. Li,[1] Y. C. Ge,[1] J. L. Lou,[1] Z. Y. Tian,[1] W. Jiang,[1] Z. H. Yang,[3] J. Feng,[1] P. J. Li,[1] J. Chen,[1] Q. Liu,[1] H. L. Zang,[1] B. Yang,[1] Y. Zhang,[1] Z. Q. Chen,[1] Y. Liu,[1] X. H. Sun,[1] J. Ma,[1] H. M. Jia,[2] X. X. Xu,[2] L. Yang,[2] N. R. Ma,[2] and L. J. Sun[2]

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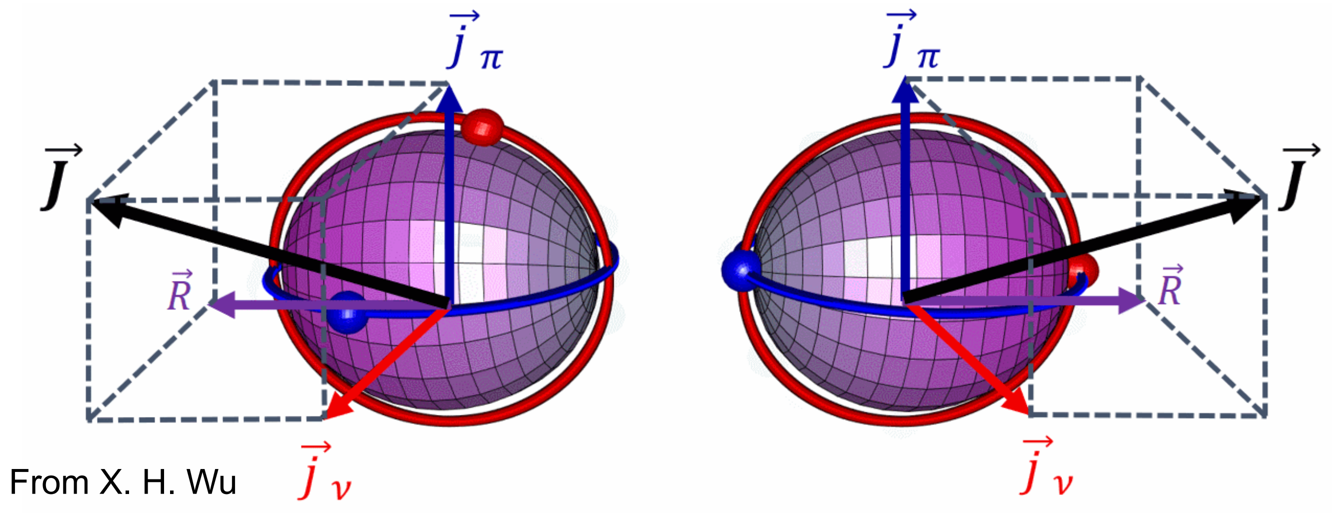
- Summary

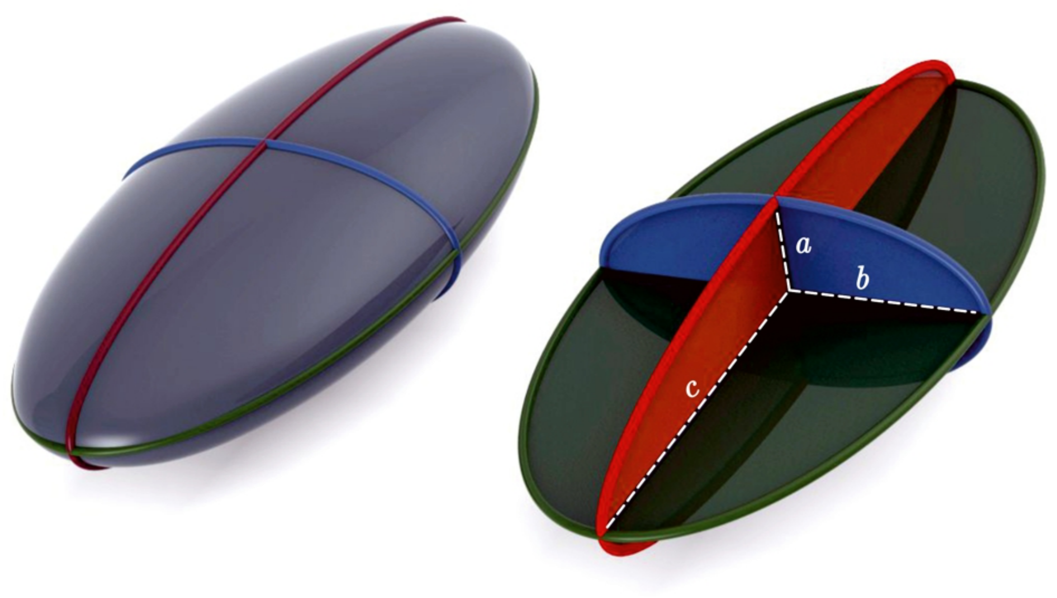
Nuclear spin-chirality

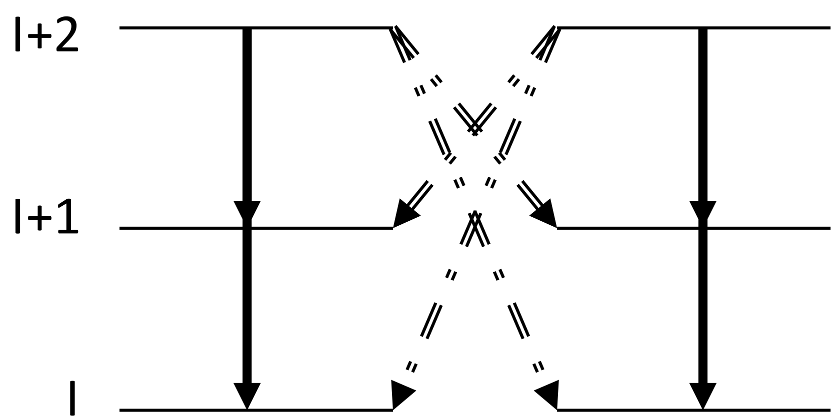
The aplanar (3D-) rotation of a triaxial nucleus could present chiral geometry.

Frauendorf and Meng NPA 1997



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





$|I+\rangle$ $|I-\rangle$

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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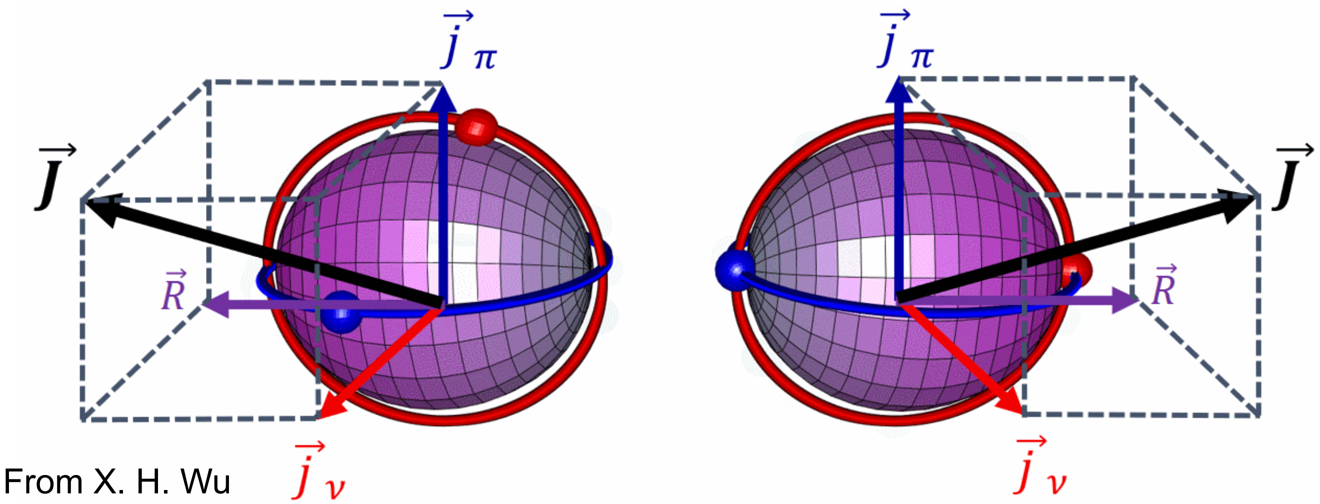


From X. H. Wu

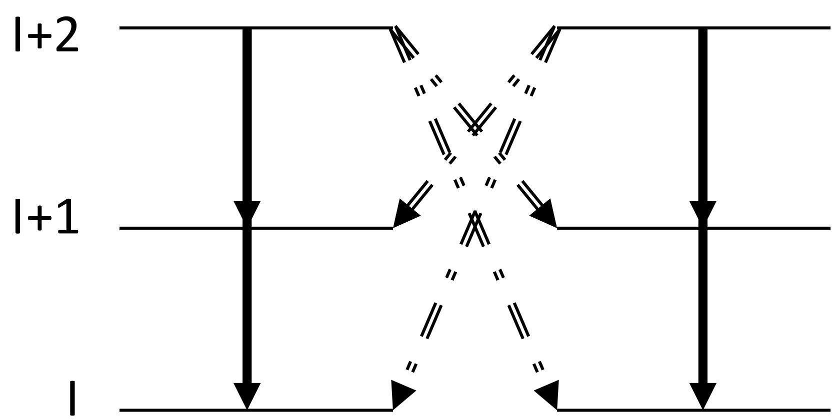
Left-handed $|\mathcal{L}\rangle$ Right-handed $|\mathcal{R}\rangle$

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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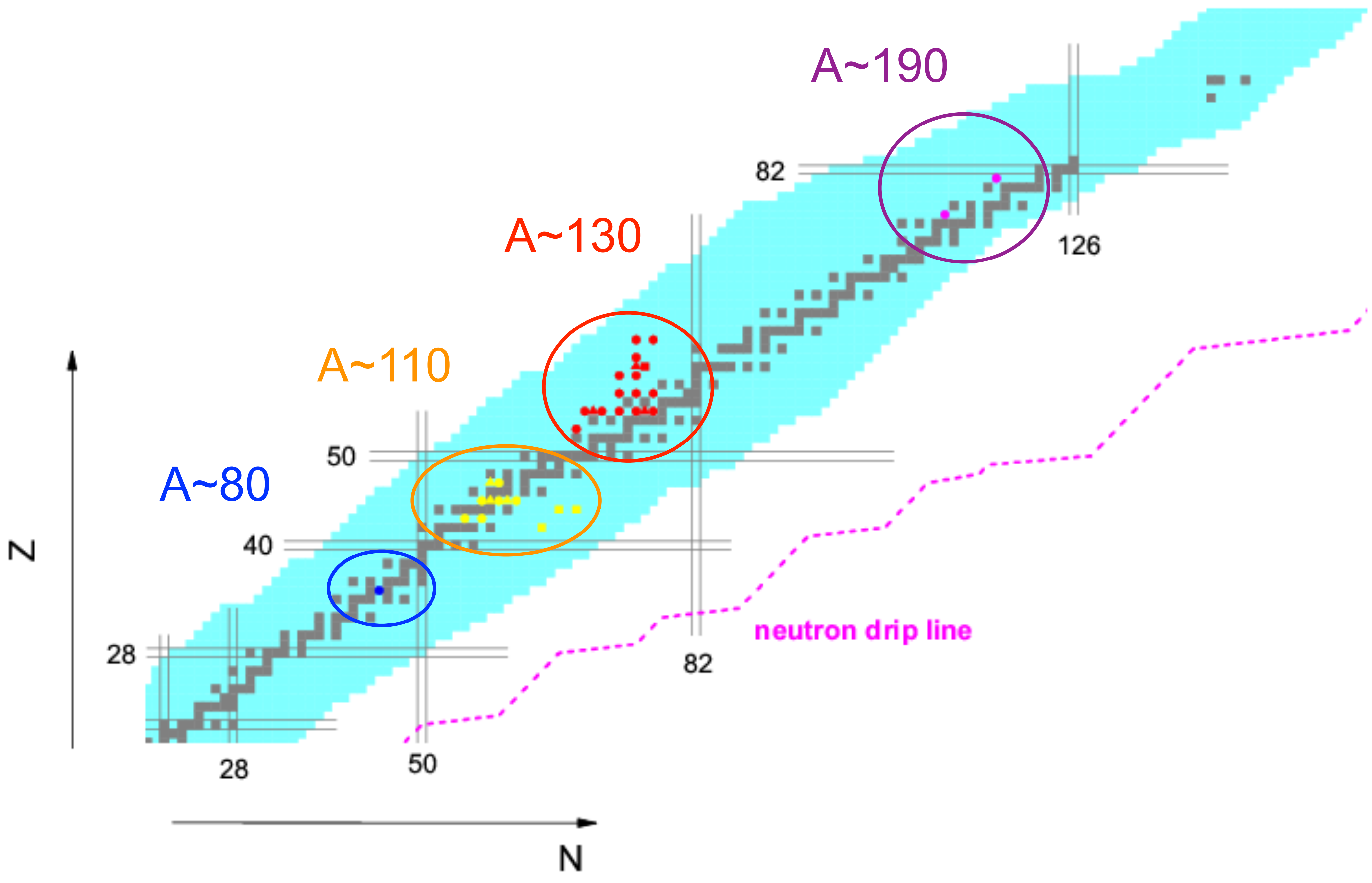
Observed chiral nuclei

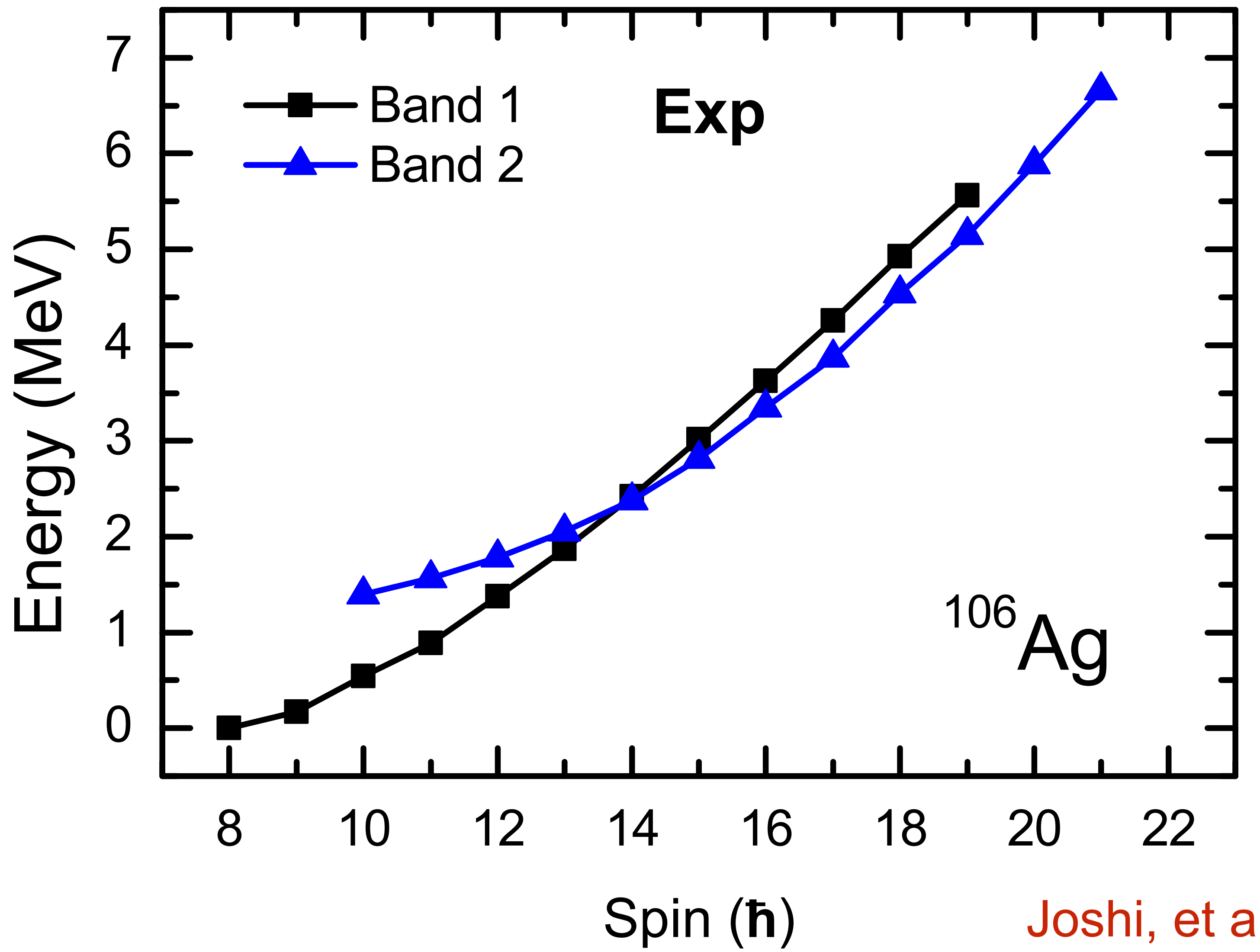
More than 45 candidate chiral nuclei have been reported in the A~80, 100, 130, and 190 mass regions, so far.

Xiong, Wang arXiv:1804.04437



Chiral conundrum in ^{106}Ag

Experimental observations in 2007: Energy Spectrum



Joshi, et al., PRL 98, 102501 (2007)

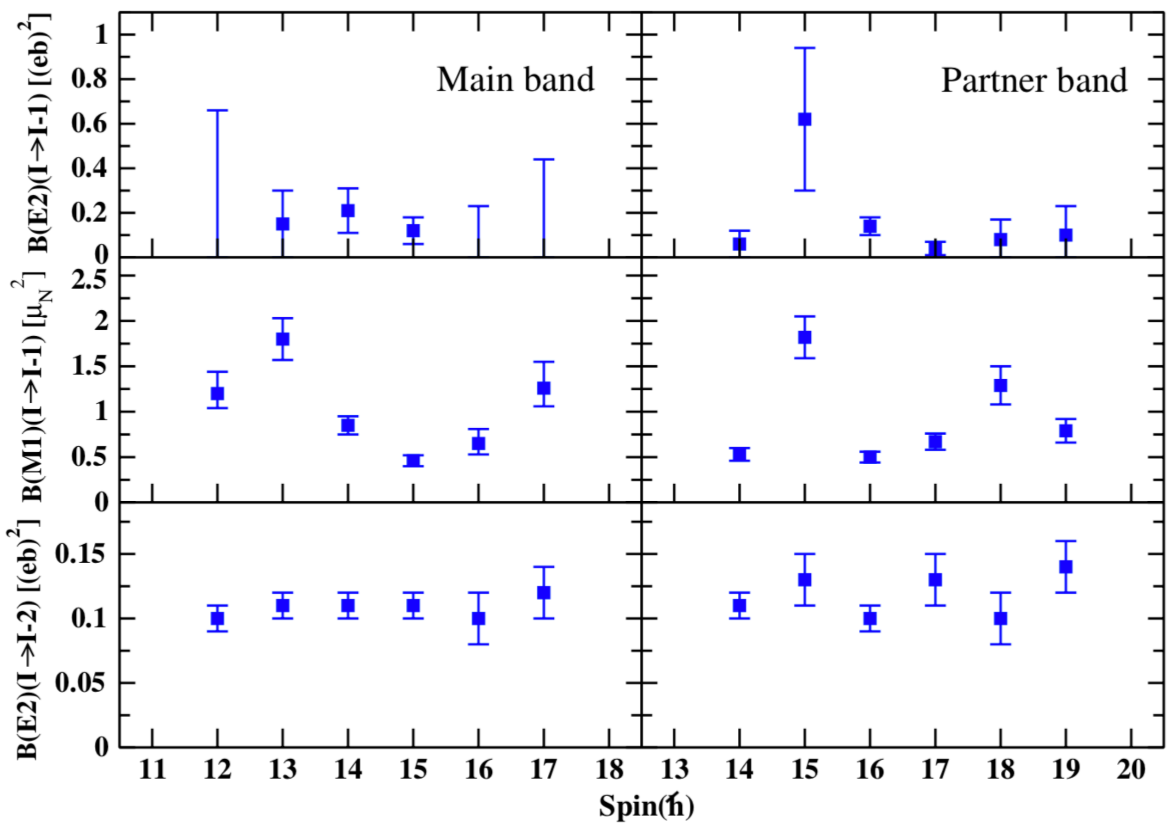
A pair of strongly coupled bands observed

Chiral bands? But why crossing?

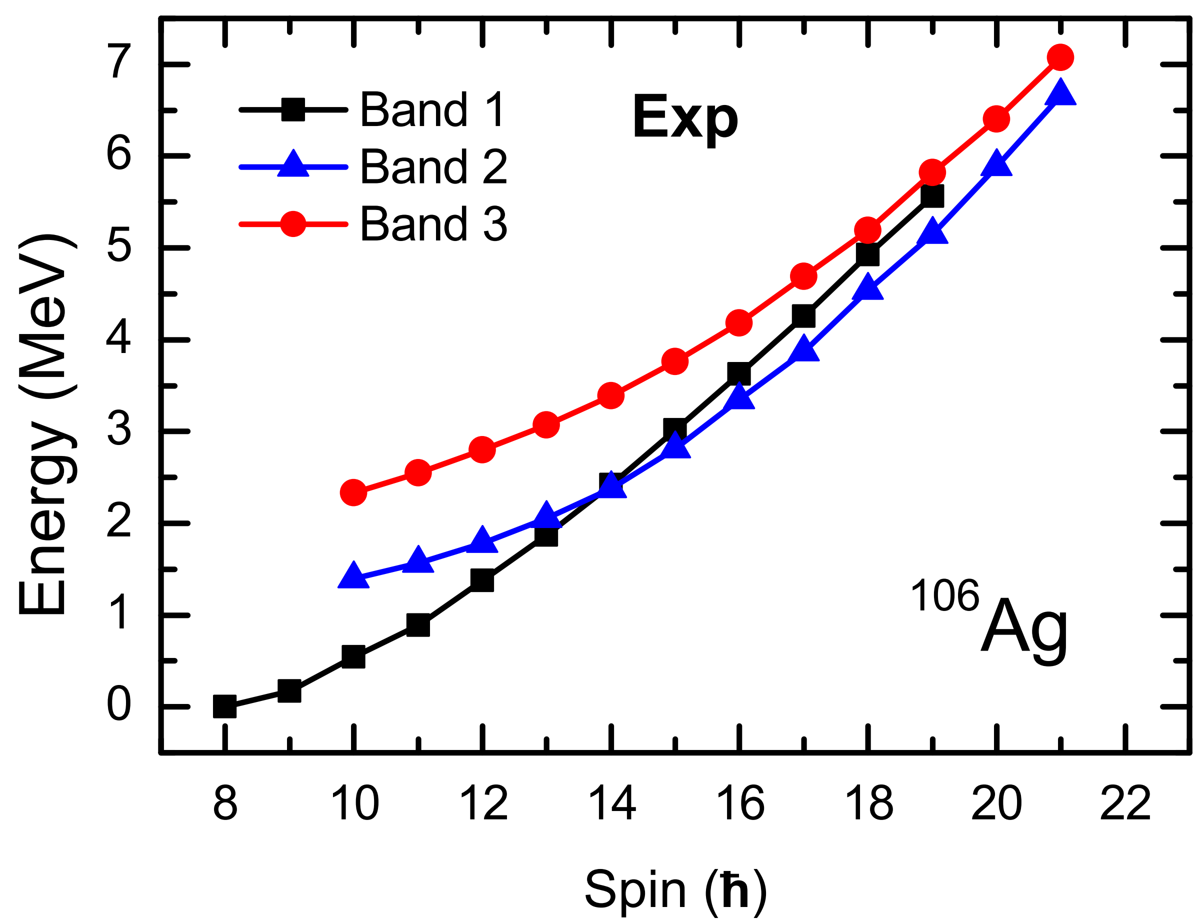
Chiral conundrum in ^{106}Ag

Experimental observations in 2014: Transition strength

Rather, et al., PRL 112, 202503 (2014)



Lieder, et al., PRL 112, 202502 (2014)



B(M1) and B(E2) values were measured in both experiments

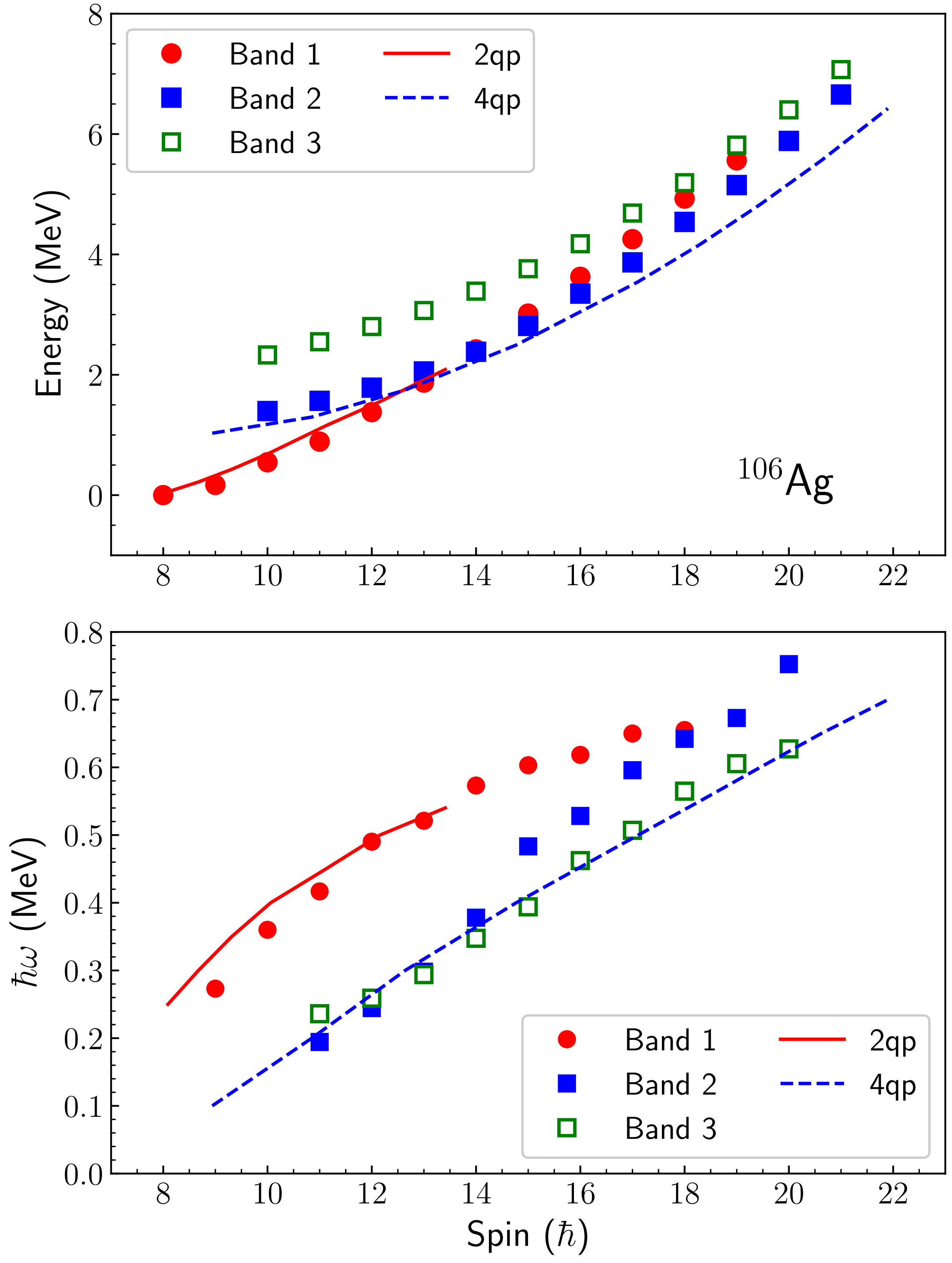
A third band is reported in Lieder's experiment

Chiral bands ? But why crossing ? Why three bands ?

Chiral conundrum in ^{106}Ag

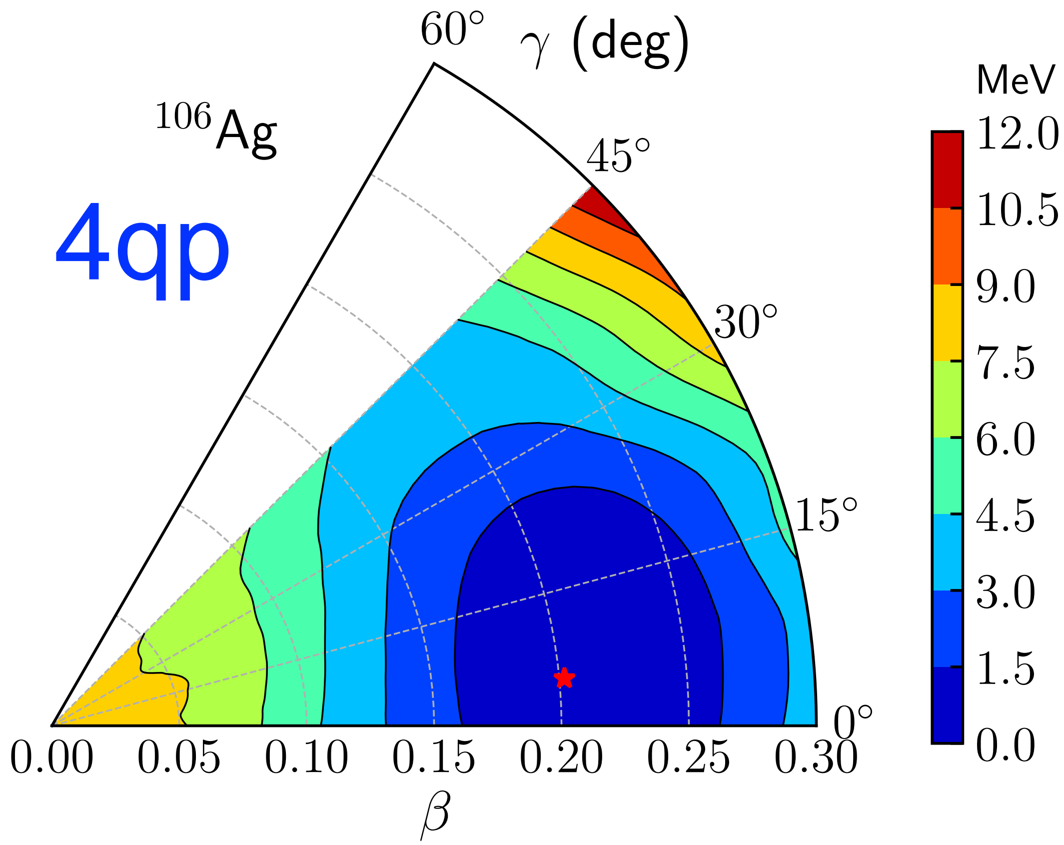
TAC-CDFT calculations

PWZ, Wang, Chen PRC 99, 054319 (2019)



2qp $\pi g_{9/2} \otimes \nu h_{11/2}$

4qp $\pi g_{9/2} \otimes \nu h_{11/2}(gd)^2$



Outline

- Covariant density functional theory
- Rod-shaped nuclei at high spin and isospin
- Chiral conundrum in ^{106}Ag
- Extending CDFT: a new spectroscopic method
- Summary

(C)DFT and Shell Model

(C)DFT

- ✓ Universal density functionals

  Symmetry broken
  Single config. fruitful physics
  No Configuration mixing

- ✓ Applicable for almost all nuclei
- ✗ No spectroscopic properties

Shell Model

- ✗ Non-universal effective interactions

  No symmetry broken
  Single config. little physics
  Configuration mixing

- ✗ intractable for deformed heavy nuclei
- ✓ spectroscopy from multi config.

a theory combining the advantages from both approaches?

Configuration Interaction Projected DFT (CI-PDFT)

Successful projected shell model based on the Nilsson potential

Hara and Sun IJMPE1995
Sun Phys. Scr. 2016

1. **Covariant Density Functional Theory**
   a minimum of the energy surface
2. **Configuration space**
   multi-quasiparticle states
3. **Angular momentum projection**
   rotational symmetry restoration
4. **Shell model calculation**
   configuration mixing / interaction from CDFT

Energy Density Functional

good angular momentum;
from low- to high- spin;

Nuclear Spectroscopy

CI-PDFT: to provide a global study of many nuclear properties with no parameters beyond a well-established density functional.

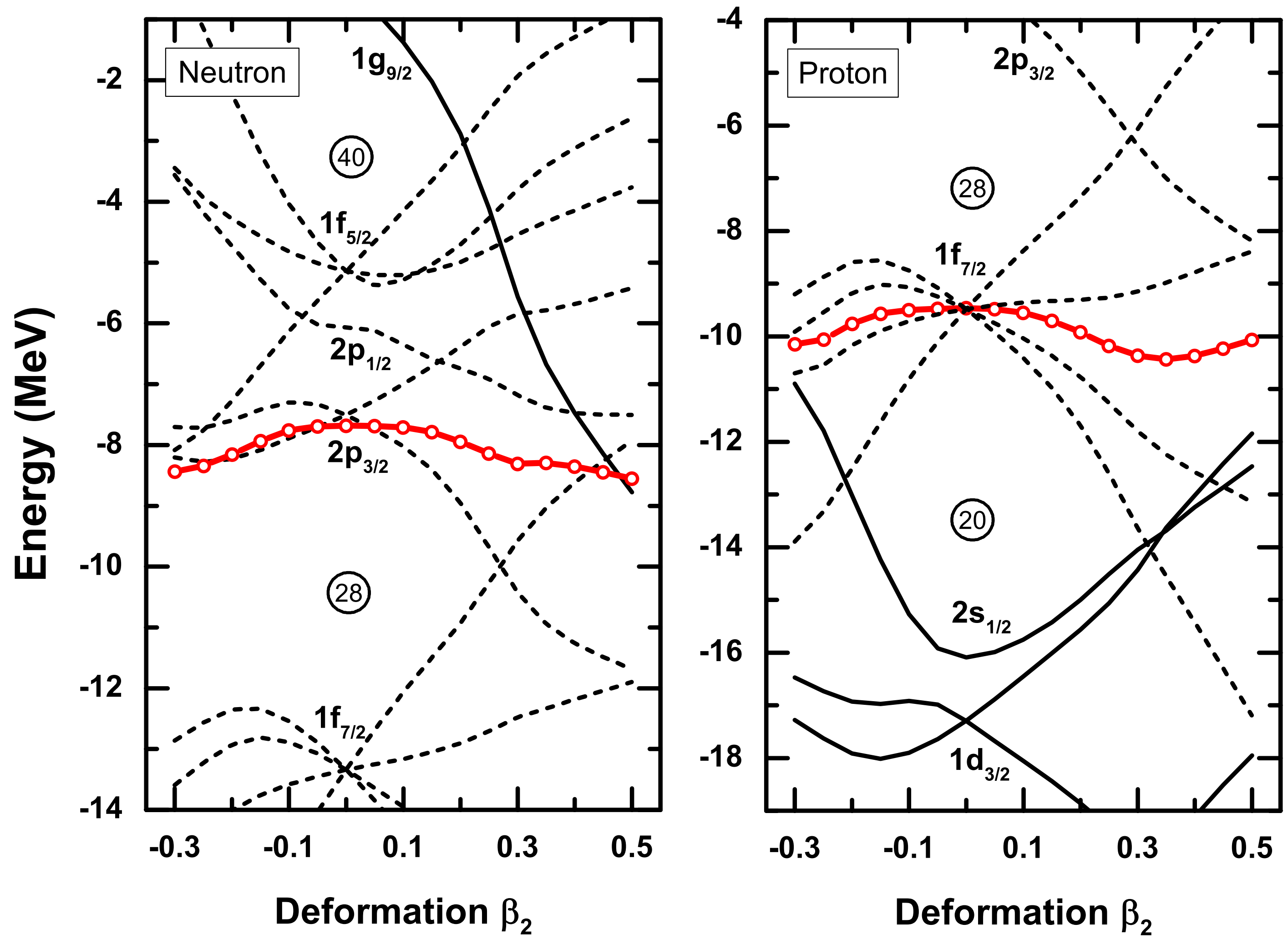
PWZ, Ring, Meng, PRC 94 (2016) 041301(R)

First application for ^{54}Cr

PWZ, Ring, Meng, PRC 94 (2016) 041301(R)

- Axial symmetry assumed
- Density functional:
  PC-PK1+ δ-force BCS
- Configuration space
  0-qp and 2-qp excitations &
  E < 6.5 MeV

$$|0\rangle, \quad \alpha^\dagger_\nu \alpha^\dagger_{\nu'}|0\rangle, \quad \alpha^\dagger_\pi \alpha^\dagger_{\pi'}|0\rangle$$



The configuration space consists of 37 states including 18 two-quasi-neutron, 18 two-quasi-proton excited states, and the quasi-particle vacuum $|0\rangle$.

Configuration mixing for ^{54}Cr

PWZ, Ring, Meng, PRC 94 (2016) 041301(R)

<u>Important configurations and their probability amplitudes in the yrast state</u>

	E	K	Configurations	0	2	4	6	8	10
gs	0.00	0	–	0.959	0.856	0.623	0.280	0.150	0.113
2n1	2.68	1	$(2p_{3/2})_{k=1/2} \otimes (1f_{5/2})_{k=1/2}$		0.314	0.448	0.241	0.098	0.100
	3.36	1	$(2p_{3/2})_{k=1/2} \otimes (2p_{3/2})_{k=-3/2}$		0.225	0.308	0.164	0.055	0.000
	4.64	2	$(2p_{3/2})_{k=1/2} \otimes (1f_{5/2})_{k=3/2}$		-0.044	-0.146	-0.076	-0.037	-0.064
	4.64	1	$(2p_{3/2})_{k=1/2} \otimes (1f_{5/2})_{k=-3/2}$		0.068	0.126	0.085	0.037	0.028
	2.39	0	$(1f_{7/2})_{k=5/2} \otimes (1f_{7/2})_{k=-5/2}$	0.265	0.146	-0.084	-0.232	-0.228	-0.166
2p1	2.55	1	$(1f_{7/2})_{k=3/2} \otimes (1f_{7/2})_{k=-5/2}$		0.224	0.430	0.521	0.400	0.341
	2.55	4	$(1f_{7/2})_{k=3/2} \otimes (1f_{7/2})_{k=5/2}$			0.013	0.205	0.183	0.146
	2.71	0	$(1f_{7/2})_{k=3/2} \otimes (1f_{7/2})_{k=-3/2}$	-0.055	-0.028	0.020	0.283	0.297	0.280
2p2	3.56	2	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=-5/2}$		-0.047	-0.127	-0.386	-0.416	-0.409
	3.56	3	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=5/2}$			-0.018	-0.270	-0.320	-0.332
	3.71	1	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=-3/2}$		0.076	0.159	-0.088	-0.277	-0.256
	3.71	2	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=3/2}$		-0.043	-0.075	0.070	0.178	0.152
	4.42	1	$(1f_{7/2})_{k=5/2} \otimes (1f_{7/2})_{k=-7/2}$		-0.152	-0.142	-0.019	0.020	0.061
	4.42	6	$(1f_{7/2})_{k=5/2} \otimes (1f_{7/2})_{k=7/2}$				-0.130	-0.069	-0.054
	4.57	2	$(1f_{7/2})_{k=3/2} \otimes (1f_{7/2})_{k=-7/2}$		0.009	-0.073	-0.180	-0.204	-0.227
	4.57	5	$(1f_{7/2})_{k=3/2} \otimes (1f_{7/2})_{k=7/2}$				0.194	0.216	0.192
	5.58	3	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=-7/2}$			0.032	0.148	0.286	0.367
	5.58	4	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=7/2}$			-0.002	-0.152	-0.251	-0.355

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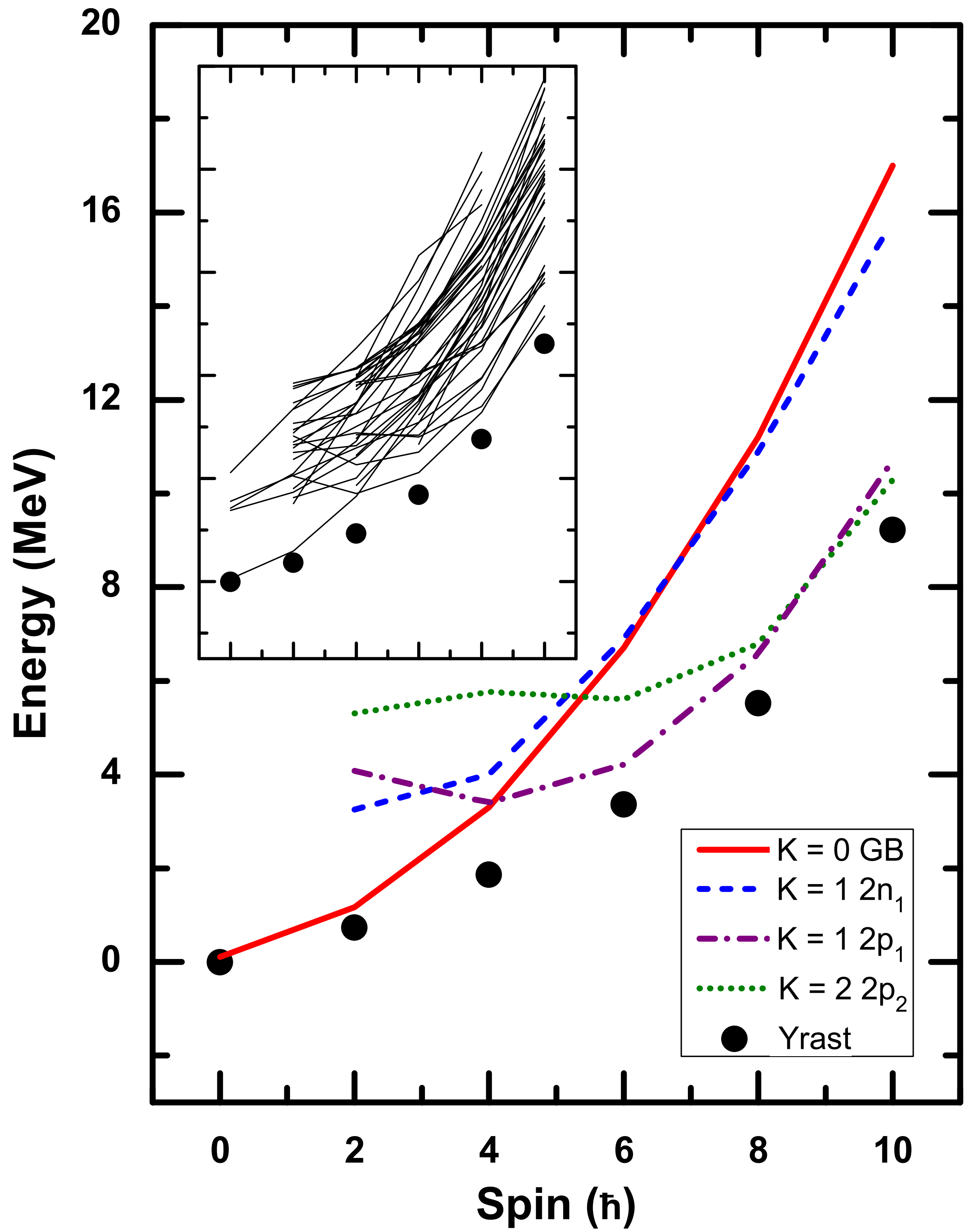
2p2	3.56	2	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=-5/2}$		-0.047	-0.127	-0.386	-0.416	-0.409
	3.56	3	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=5/2}$			-0.018	-0.270	-0.320	-0.332
	3.71	1	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=-3/2}$		0.076	0.159	-0.088	-0.277	-0.256
	3.71	2	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=3/2}$		-0.043	-0.075	0.070	0.178	0.152
	4.42	1	$(1f_{7/2})_{k=5/2} \otimes (1f_{7/2})_{k=-7/2}$		-0.152	-0.142	-0.019	0.020	0.061
	4.42	6	$(1f_{7/2})_{k=5/2} \otimes (1f_{7/2})_{k=7/2}$				-0.130	-0.069	-0.054
	4.57	2	$(1f_{7/2})_{k=3/2} \otimes (1f_{7/2})_{k=-7/2}$		0.009	-0.073	-0.180	-0.204	-0.227
	4.57	5	$(1f_{7/2})_{k=3/2} \otimes (1f_{7/2})_{k=7/2}$				0.194	0.216	0.192
	5.58	3	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=-7/2}$			0.032	0.148	0.286	0.367
	5.58	4	$(1f_{7/2})_{k=1/2} \otimes (1f_{7/2})_{k=7/2}$			-0.002	-0.152	-0.251	-0.355

contributions to the yrast state are larger than 1%

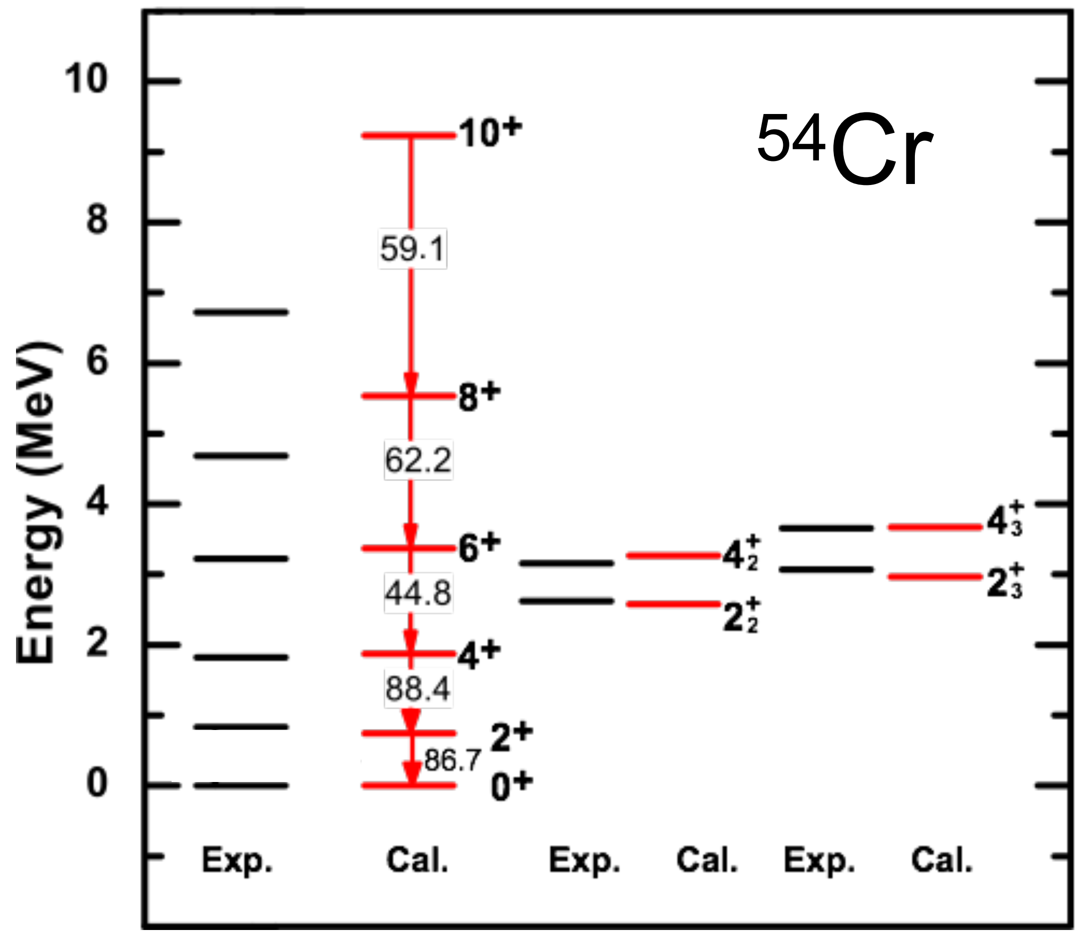
Level scheme for ^{54}Cr

PWZ, Ring, Meng, PRC 94 (2016) 041301(R)



time-odd interaction;

beyond 2-qp configurations;



Towards neutron-rich nuclei

Outline

- Covariant density functional theory
- Rod-shaped nuclei at high spin and isospin
- Chiral conundrum in ^{106}Ag
- Extending CDFT: a new spectroscopic method
- Summary

Summary

Covariant density functional theory has been improved and extended for nuclear spectroscopic properties.

- A point-coupling covariant energy density functional PC-PK1
  improves isospin dependence
  good performance for nuclear global properties towards neutron-rich…
- Titled axis cranking CDFT
  coherent effects between spin and isospin to stabilize the exotic rod shape.
  chiral conundrum in Ag-106
- Configuration interaction projected DFT: CI-PDFT
  merits of (C)DFT and Shell Model preserved
  no parameters beyond a well-established density functional

Collaborations

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Jiangming Yao

Munich
Peter Ring
Qibo Chen

Kyoto
Naoyuki Itagaki

...

Thank you for your attention!

13	BSk19	BSk20	BSk21	BSk18
t_0 [MeV fm^3]	-4115.21	-4056.04	-3961.39	-1837.96
t_1 [MeV fm^5]	403.072	438.219	396.131	428.880
t_2 [MeV fm^5]	0	0	0	-3.23704
t_3 [MeV fm$^{3+3\alpha}$]	23670.4	23256.6	22588.2	11528.9
t_4 [MeV fm$^{5+3\beta}$]	-60.0	-100.000	-100.000	-400.000
t_5 [MeV fm$^{5+3\gamma}$]	-90.0	-120.000	-150.000	-400.000
x_0	0.398848	0.569613	0.885231	0.421290
x_1	-0.137960	-0.392047	0.0648452	-0.907175
t_2x_2 [MeV fm^5]	-1055.55	-1147.64	-1390.38	-186.837
x_3	0.375201	0.614276	1.03928	0.683926
x_4	-6.0	-3.00000	2.00000	-2.00000
x_5	-13.0	-11.0000	-11.0000	-2.00000
W_0 [MeV fm^5]	110.802	110.228	109.622	138.904

α	1/12	1/12	1/12	0.3
β	1/3	1/6	1/2	1.0
γ	1/12	1/12	1/12	1.0
f_n^+	1.00	1.00	1.00	1.00
f_n^-	1.05	1.06	1.05	1.06
f_p^+	1.10	1.09	1.07	1.04
f_p^-	1.17	1.16	1.13	1.09
ε_Λ [MeV]	16.0	16.0	16.0	16.0
V_W [MeV]	-2.00	-2.10	-1.80	-2.10
λ	250	280	280	340
V'_W [MeV]	1.16	0.96	0.96	0.74
A_0	24	24	24	28

3 density dependence

5 pairing properties

4 Wigner term

5 rotational correction

b (MeV)	0.80
c	10
d (MeV)	3.4
l	17
β_2^0	0.1

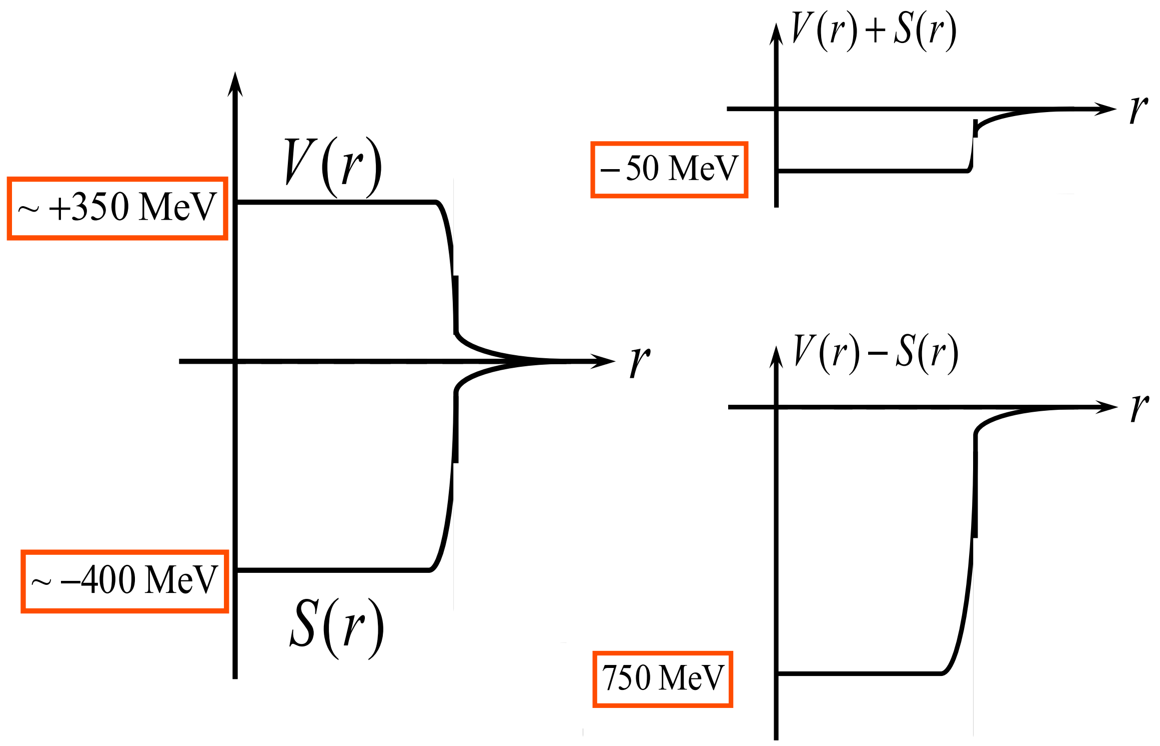
Gorieli et al, (2010)

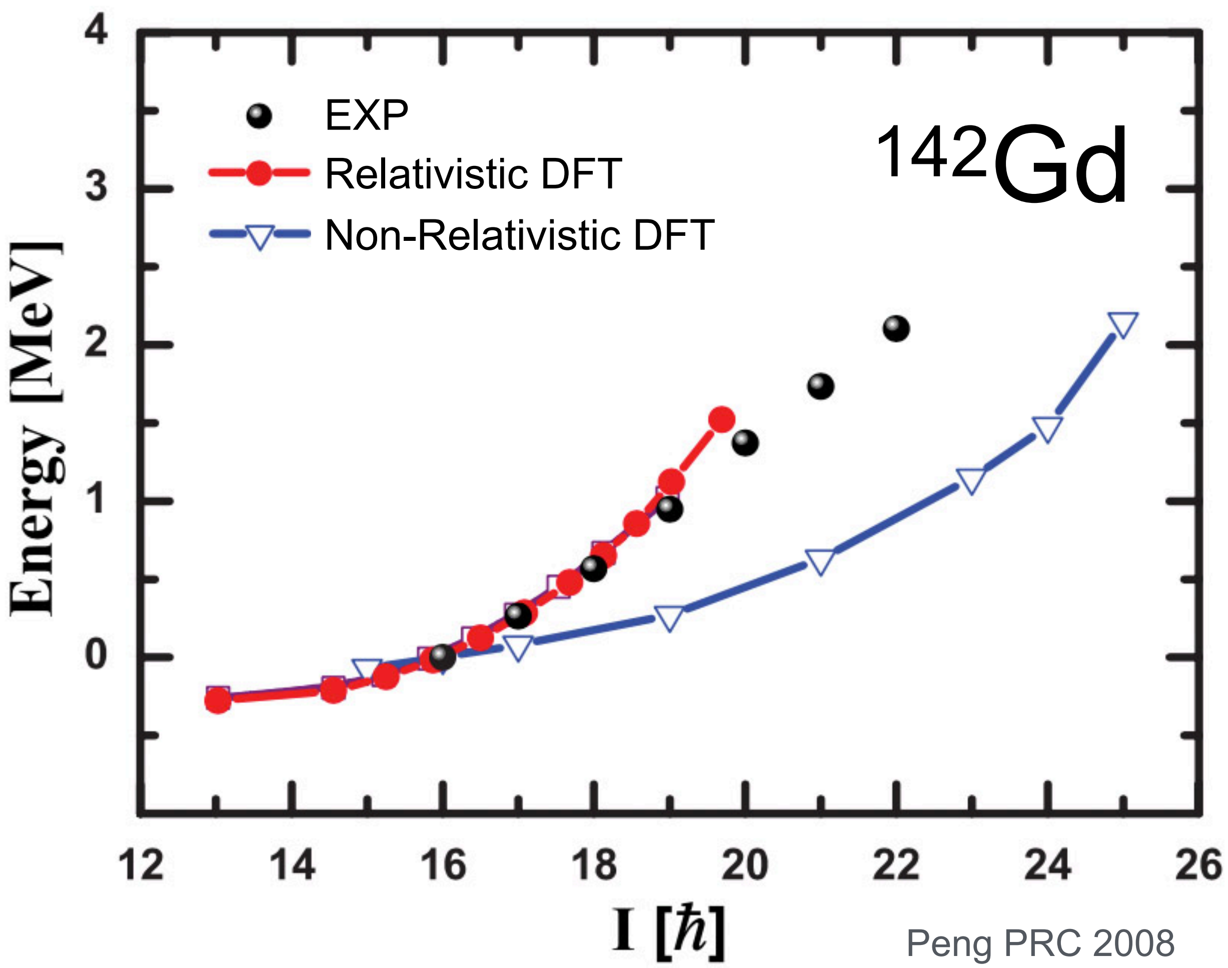
13+3+5+4+5 = 30 parameters

Why Covariant?

- ✓ No relativistic kinematics necessary
- ✓ Large mean fields S≈-400 MeV, V≈350 MeV
- ✓ Large spin-orbit splitting
- ✓ Pseudo-spin Symmetry
- ✓ Success of Relativistic Brueckner
- ✓ Consistent treatment of time-odd fields

$$\sqrt{p_F^2 + m_N^2} = m_N\sqrt{1 + 0.075}$$





Peng PRC 2008

P. Ring Physica Scripta, T150, 014035 (2012)
Cohen, Furnstahl, Griegel PRL 67, 961(1991)
Brockmann, Machleidt, PRC42, 1965 (1990)
…

Chiral conundrum in ^{106}Ag