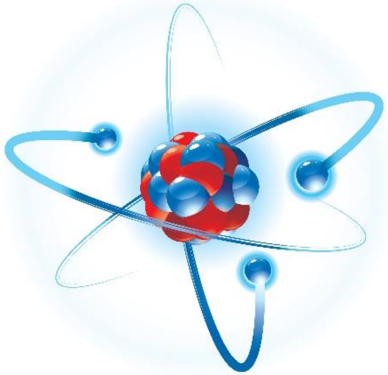
Chirality and Wobbling in Atomic Nuclei, July 10 - July 14, 2023, Huizhou, China

The evolution of the chiral symmetry in cesium isotopes

Jian Li

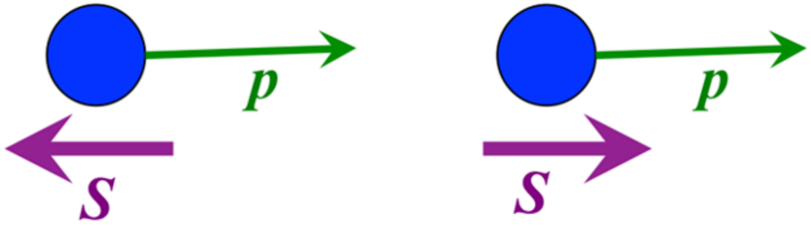
College of Physics, Jilin University



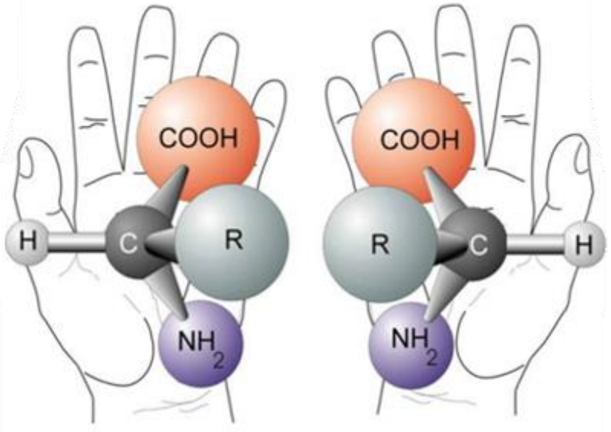
Duo Chen, Jian Li, et. al., The evolution of the chiral symmetry in cesium isotopes, Eur. Phys. J. A (2023) 59:142

Chirality in Nature

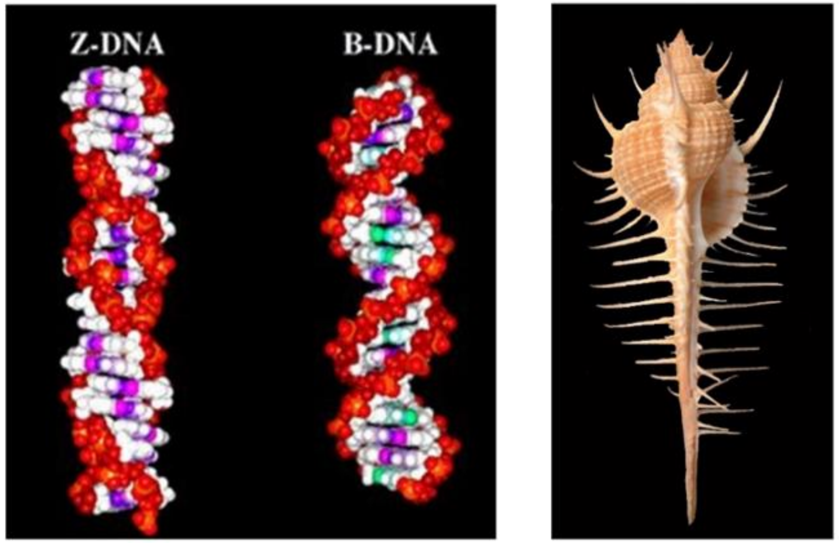
Chirality exists commonly in nature.



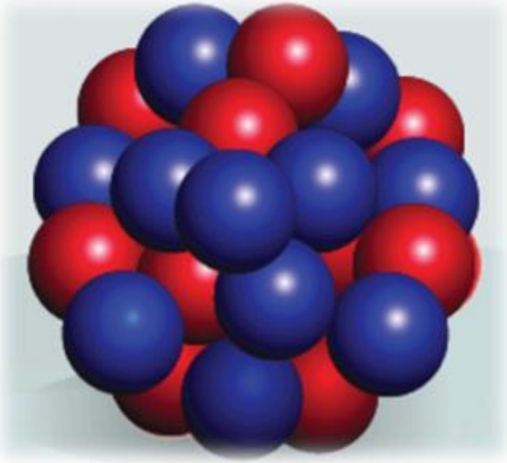
Elementary Particles



Molecules & Human Body



DNA & Spiral Shells



Chirality in Nuclear World

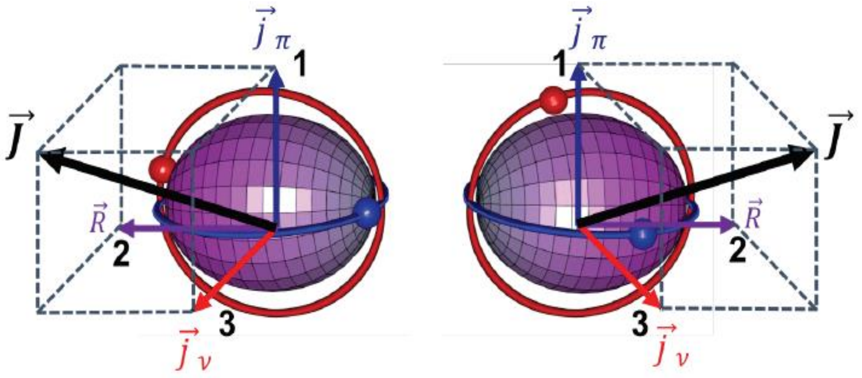
Chirality in atomic nucleus

- **In 1997, Frauendorf and Meng suggested for the first time the occurrence of chirality in nuclear physics.**

S. Frauendorf and J. Meng, Nucl. Phys. A 617, 131 (1997)

Triaxially deformed doubly odd nuclei can rotate in a left-handed and right-handed geometrical configuration, and manifest the chiral symmetry breaking in the intrinsic frame.

Angular Momentum Chiral Geometry



$|\mathcal{L}\rangle$ $|\mathcal{R}\rangle$

Courtesy of X. H. Wu

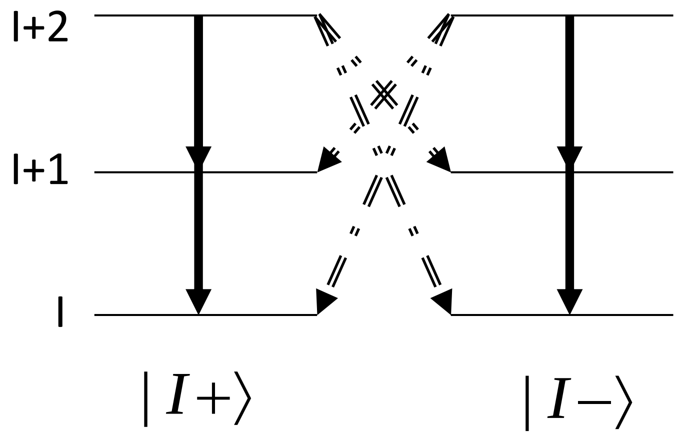
Chiral operator: $\chi = TR_y(\pi)$;

$$\chi|\mathcal{L}\rangle = |\mathcal{R}\rangle;$$
$$\chi|\mathcal{R}\rangle = |\mathcal{L}\rangle.$$

Chiral doublet bands

- **Experimental signal of nuclear chirality----Chiral doublet bands: Two near degenerate ΔI =1 bands**

Chiral doublet band



S. Frauendorf and J. Meng, Nucl. Phys. A 617, 131 (1997)

Restoration of breaking symmetry in laboratory frame

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

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

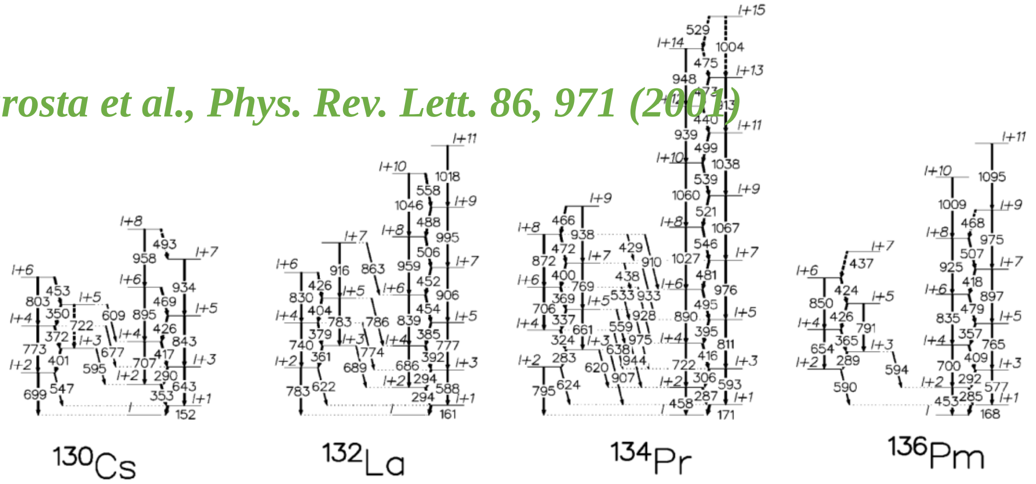
- In 2001, the chiral nuclei were firstly reported. *K. Starosta et al., Phys. Rev. Lett. 86, 971 (2001)*

VOLUME 86, NUMBER 6 PHYSICAL REVIEW LETTERS 5 FEBRUARY 2001

Chiral Doublet Structures in Odd-Odd $N = 75$ Isotones: Chiral Vibrations

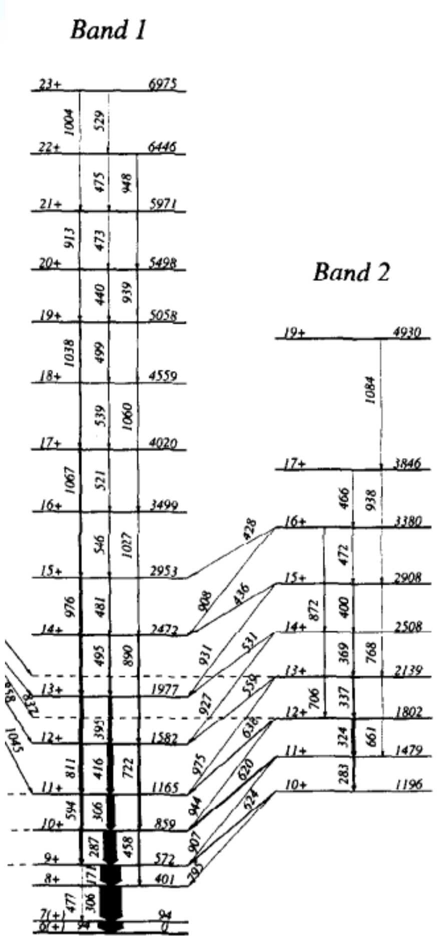
K. Starosta,[1,*] T. Koike,[1] C. J. Chiara,[1] D. B. Fossan,[1] D. R. LaFosse,[1] A. A. Hecht,[2] C. W. Beausang,[2] M. A. Caprio,[2] J. R. Cooper,[2] R. Krücken,[2] J. R. Novak,[2] N. V. Zamfir,[2,†] K. E. Zyromski,[2] D. J. Hartley,[3] D. L. Balabanski,[3,‡] Jing-ye Zhang,[3] S. Frauendorf,[4] and V. I. Dimitrov[4,‡]

[1]*Department of Physics and Astronomy, SUNY at Stony Brook, Stony Brook, New York 11794*
[2]*Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520*
[3]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996*
[4]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556*
and Institute for Nuclear and Hadronic Physics, Research Center Rossendorf, 01314 Dresden, Germany

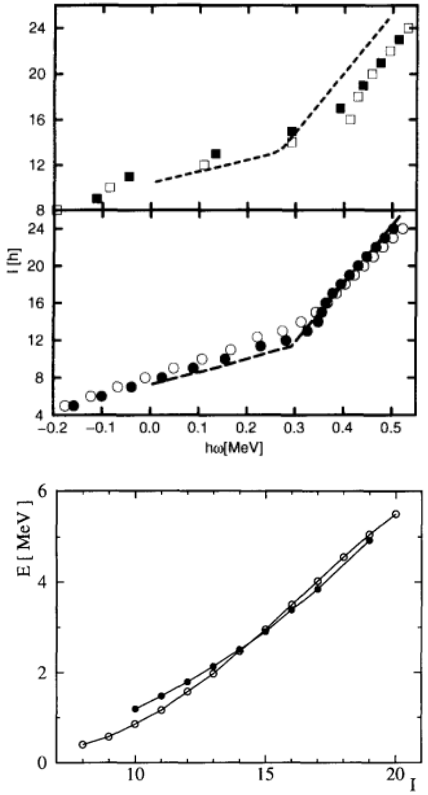


The history of chirality in ^{134}Pr

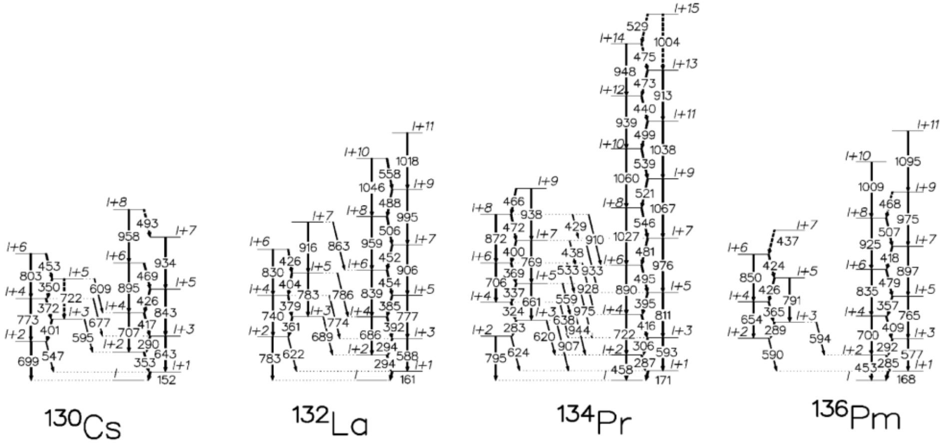
- ✓ The doublet bands in 134Pr(previously observed by Petrache et al. in 1996) were discussed by Frauendorf and Meng in 1997.



C.M. Petrache et al. Nucl. Phys. A 597, 106 (1996)



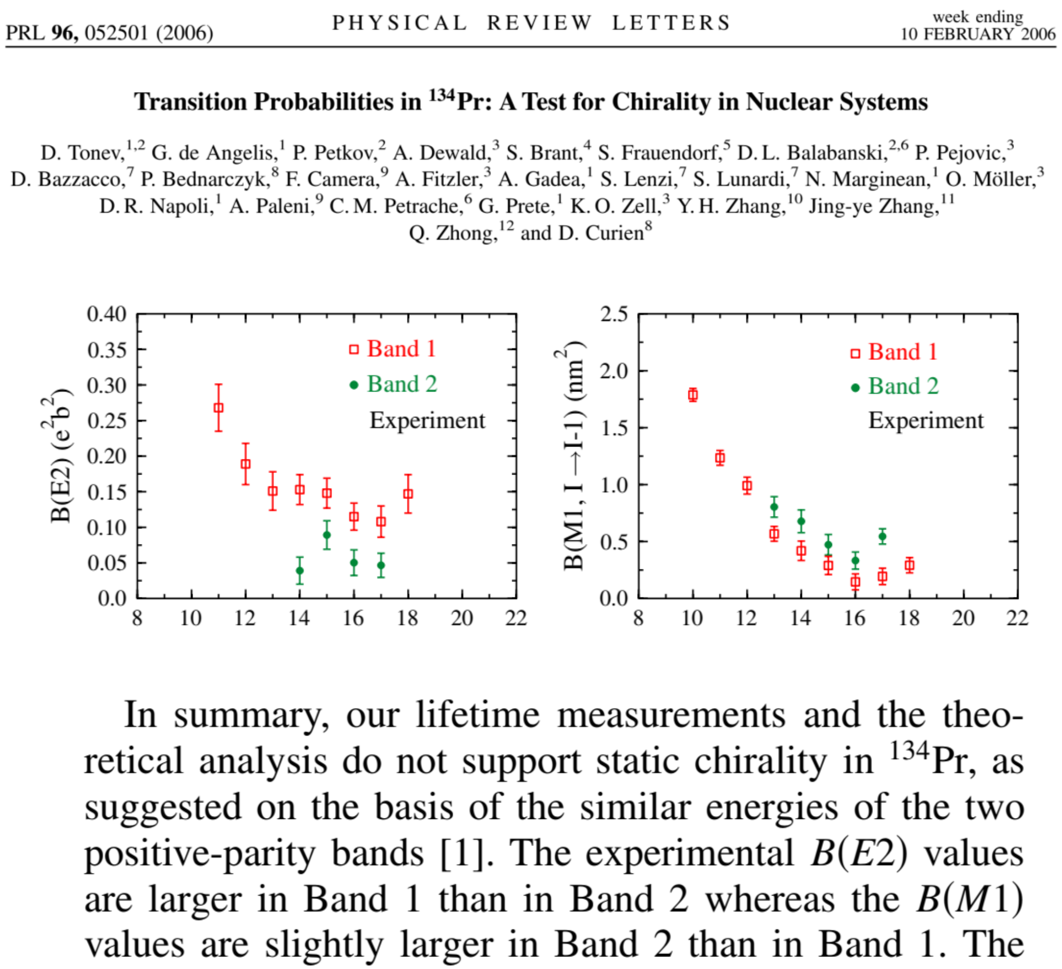
S. Frauendorf and J. Meng, Nucl. Phys. A 617, 131 (1997)



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

The history of chirality in ^{134}Pr

- ✓ However, the chirality in 134Pr was later contradicted by the papers of Tonev et al. and Petrache et al. both in 2006.



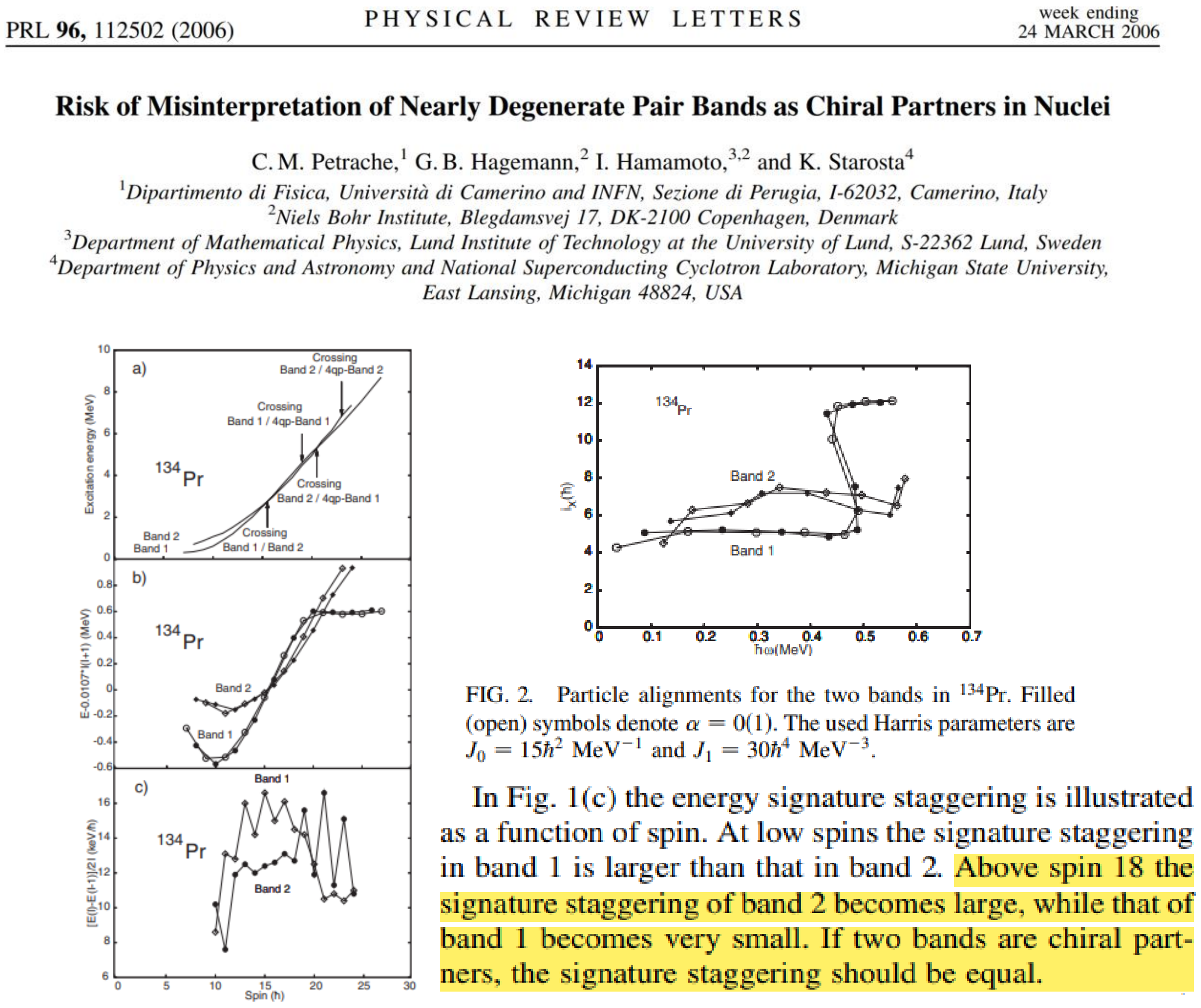
PRL **96,** 052501 (2006) PHYSICAL REVIEW LETTERS week ending 10 FEBRUARY 2006

Transition Probabilities in ^{134}Pr: A Test for Chirality in Nuclear Systems

D. Tonev,[1,2] G. de Angelis,[1] P. Petkov,[2] A. Dewald,[3] S. Brant,[4] S. Frauendorf,[5] D. L. Balabanski,[2,6] P. Pejovic,[3] D. Bazzacco,[7] P. Bednarczyk,[8] F. Camera,[9] A. Fitzler,[3] A. Gadea,[1] S. Lenzi,[7] S. Lunardi,[7] N. Marginean,[1] O. Möller,[3] D. R. Napoli,[1] A. Paleni,[9] C. M. Petrache,[6] G. Prete,[1] K. O. Zell,[3] Y. H. Zhang,[10] Jing-ye Zhang,[11] Q. Zhong,[12] and D. Curien[8]

In summary, our lifetime measurements and the theoretical analysis do not support static chirality in ^{134}Pr, as suggested on the basis of the similar energies of the two positive-parity bands [1]. The experimental $B(E2)$ values are larger in Band 1 than in Band 2 whereas the $B(M1)$ values are slightly larger in Band 2 than in Band 1. The

D. Tonev et al. Phys. Rev. Lett. 96, 052501 (2006)



PRL **96,** 112502 (2006) PHYSICAL REVIEW LETTERS week ending 24 MARCH 2006

Risk of Misinterpretation of Nearly Degenerate Pair Bands as Chiral Partners in Nuclei

C. M. Petrache,[1] G. B. Hagemann,[2] I. Hamamoto,[3,2] and K. Starosta[4]

[1]*Dipartimento di Fisica, Università di Camerino and INFN, Sezione di Perugia, I-62032, Camerino, Italy*
[2]*Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen, Denmark*
[3]*Department of Mathematical Physics, Lund Institute of Technology at the University of Lund, S-22362 Lund, Sweden*
[4]*Department of Physics and Astronomy and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*

FIG. 2. Particle alignments for the two bands in ^{134}Pr. Filled (open) symbols denote $\alpha = 0(1)$. The used Harris parameters are $J_0 = 15\hbar^2$ MeV^{-1} and $J_1 = 30\hbar^4$ MeV^{-3}.

In Fig. 1(c) the energy signature staggering is illustrated as a function of spin. At low spins the signature staggering in band 1 is larger than that in band 2. Above spin 18 the signature staggering of band 2 becomes large, while that of band 1 becomes very small. If two bands are chiral partners, the signature staggering should be equal.

C. M. Petrache et al. Phys. Rev. Lett. 96, 112502 (2006)

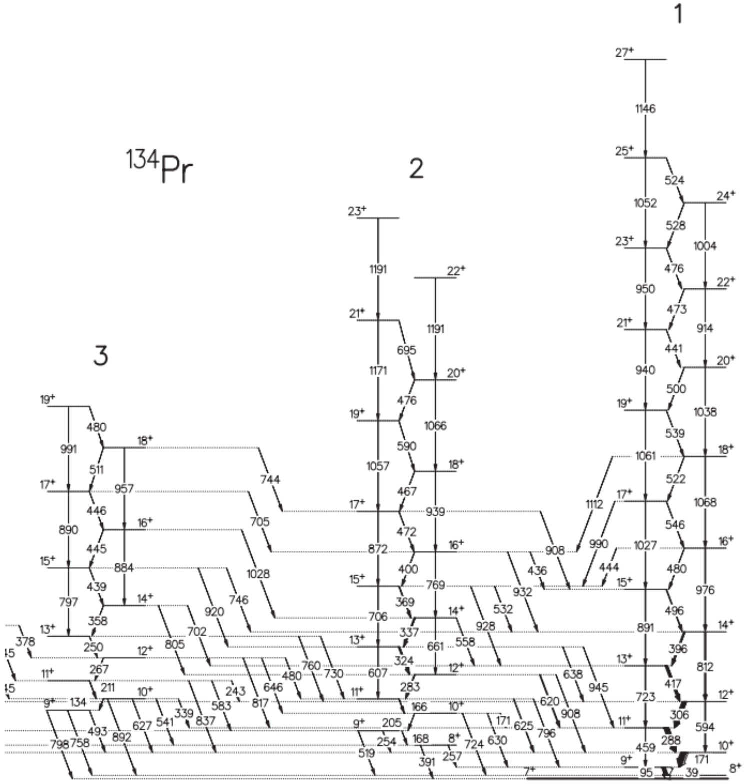
The history of chirality in ^{134}Pr

- ✓ In 2011, a paper by Timar et al. in which other chiral candidates in 134Pr are proposed

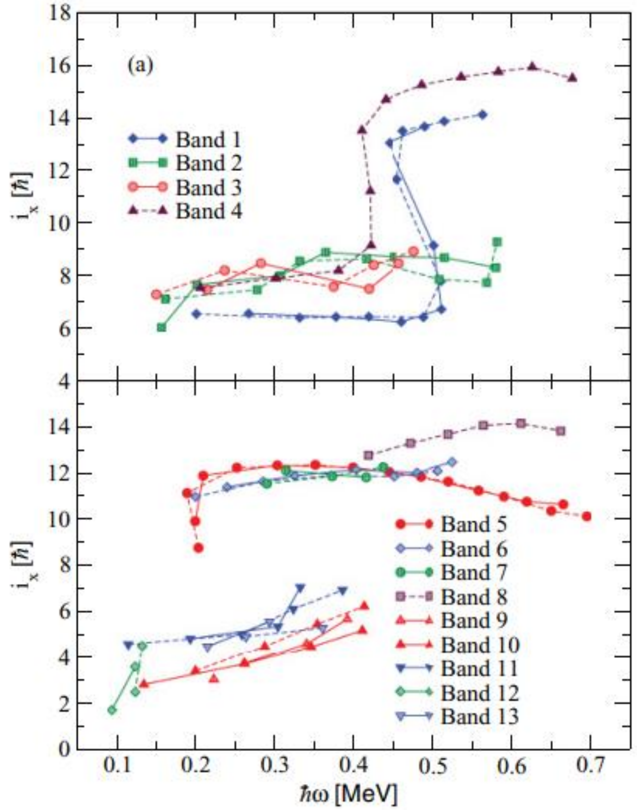
PHYSICAL REVIEW C **84**, 044302 (2011)

Medium- and high-spin band structure of the chiral-candidate nucleus ^{134}Pr

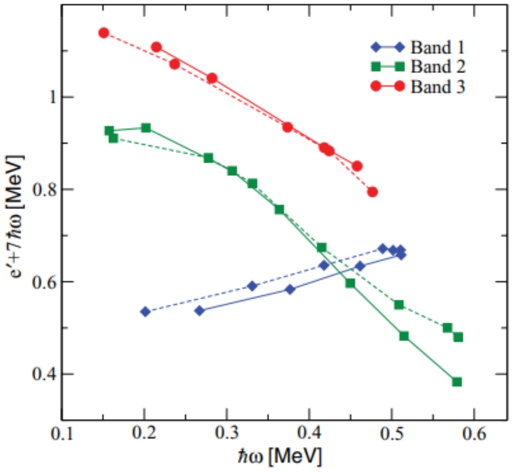
J. Timár,[1] K. Starosta,[2,3] I. Kuti,[1] D. Sohler,[1] D. B. Fossan,[2] T. Koike,[2,4] E. S. Paul,[5] A. J. Boston,[5] H. J. Chantler,[5]
M. Descovich,[5] R. M. Clark,[6] M. Cromaz,[6] P. Fallon,[6] I. Y. Lee,[6] A. O. Macchiavelli,[6] C. J. Chiara,[2,7,8] R. Wadsworth,[9]
A. A. Hecht,[10] D. Almehed,[11] and S. Frauendorf[11]



J. Timar et al. Phys. Rev. C 84, 044302 (2011)



Band 3 is newly identified in the present work. This $\Delta I = 1$ band has positive parity, and it decays through several $M1$ and $E2$ transitions to bands 1 and 2. It has an alignment value of around $8\hbar$, which corresponds to a two-quasiparticle configuration. These facts indicate that its configuration is $\pi h_{11/2} \nu h_{11/2}$, similar to the configuration of bands 1 and 2. The observed $B(M1)/B(E2)$ ratios of band 3 are two to three times larger than the corresponding ratios of band 1 and are close to the $B(M1)/B(E2)$ ratios of band 2 near the $17\hbar$ spin region. This suggests a similarity between bands 2 and 3, which might indicate that the two bands are chiral partners. In this context, it may be informative to inspect also the signature splittings of the three $\pi h_{11/2} \nu h_{11/2}$ bands. In the



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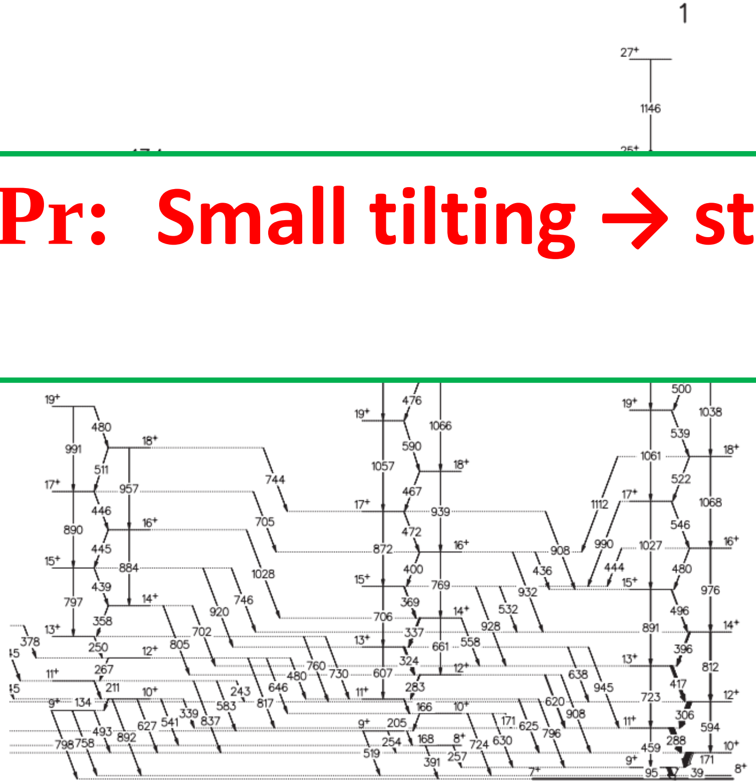

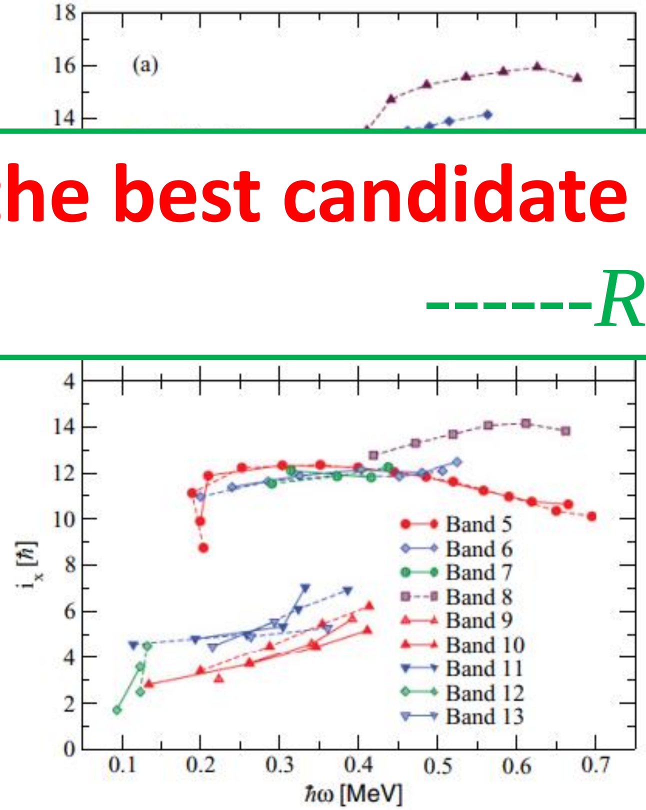

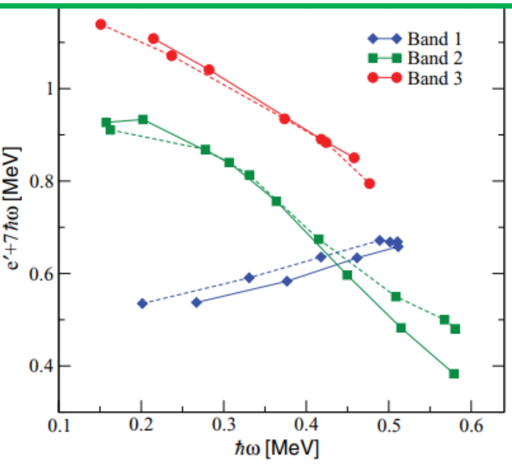

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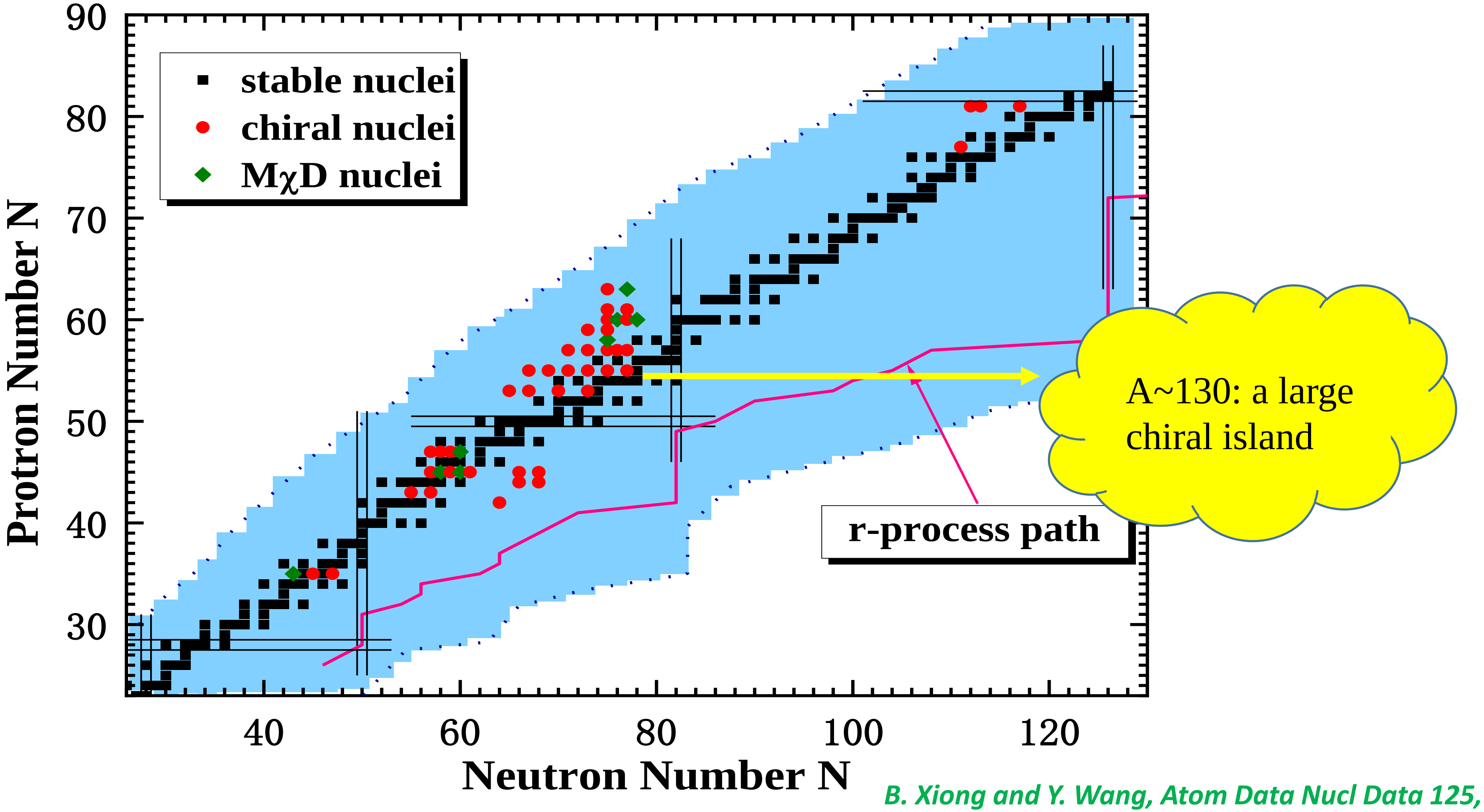
^{134}Pr: Small tilting → still the best candidate for chiral symmetry.

------Radu Budaca's report

J. Timar et al. Phys. Rev. C 84, 044302 (2011)

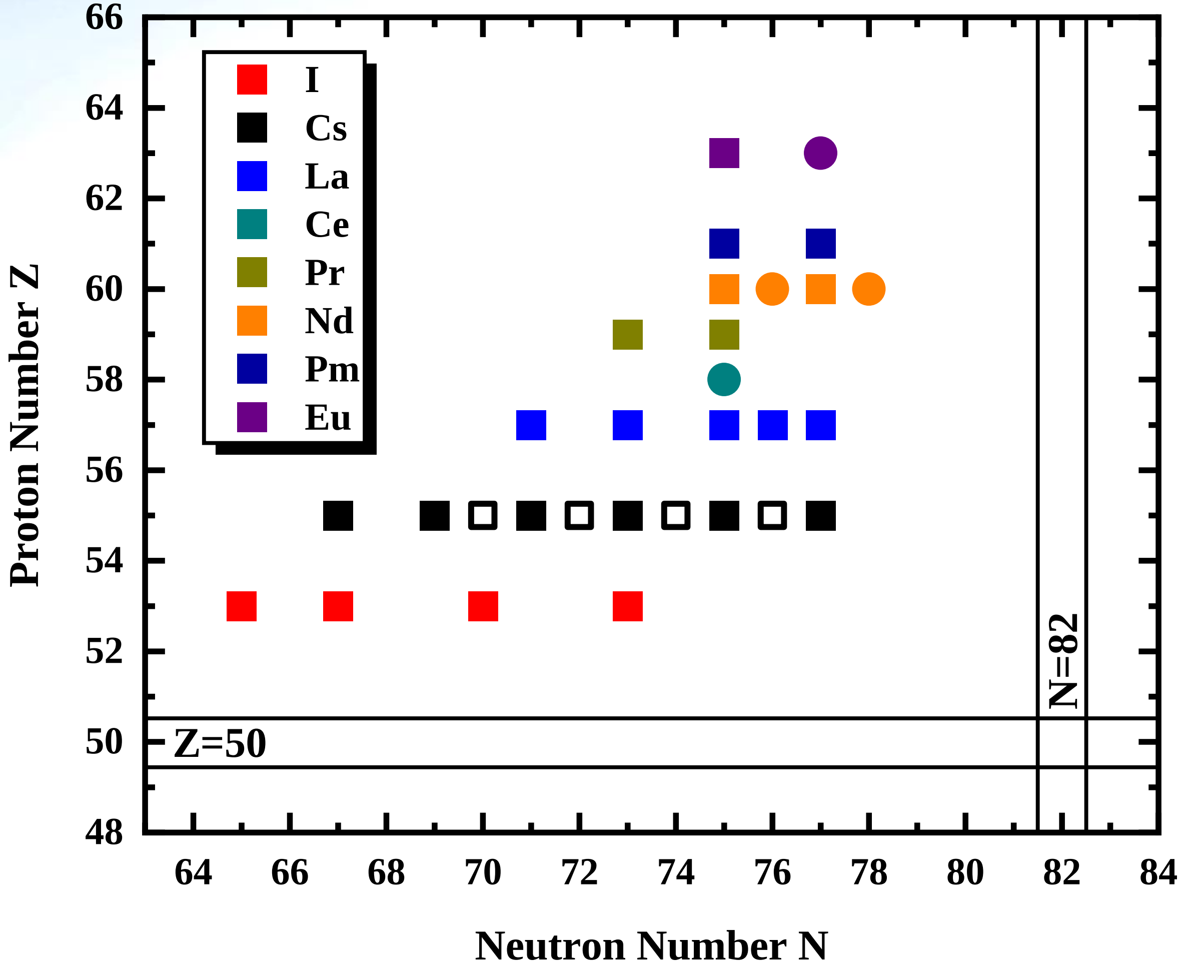
Experimental progress

In the past two decades, more than 50 chiral doublet candidate nuclei have been reported in the mass number A approximately equal to 80, 100, 130 and 190 region.



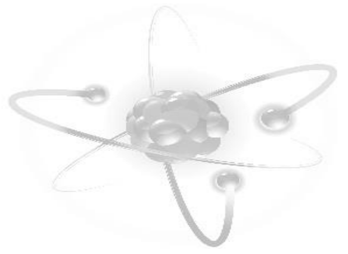
B. Xiong and Y. Wang, Atom Data Nucl Data 125, 193 (2019).

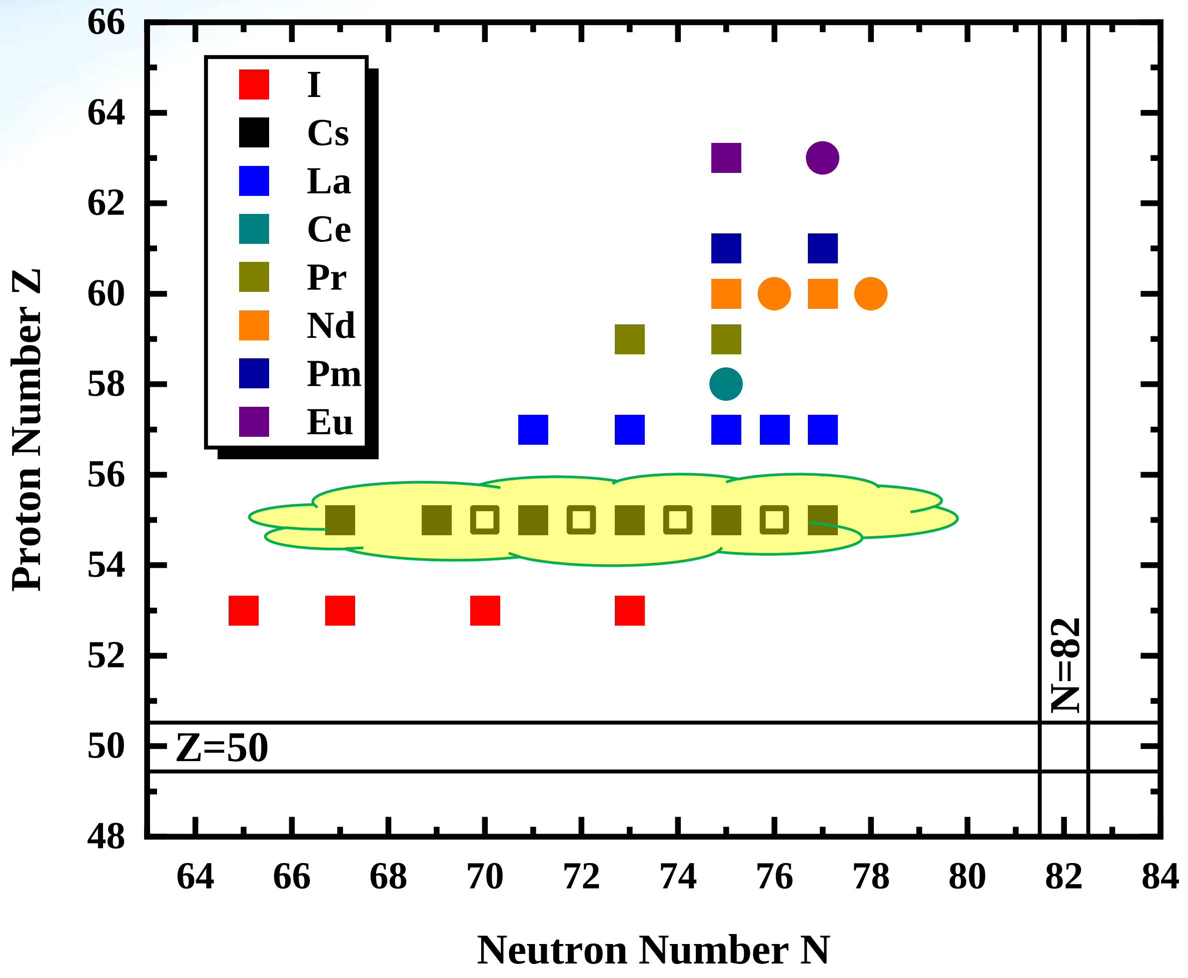
Chiral candidates in the 130 mass region



- *Some nuclei with doublet bands*
- *Neighboring nuclei of chiral candidates；*
- *The border of chiral island/isotope chain or isotone chain；*

Chiral candidates in the 130 mass region





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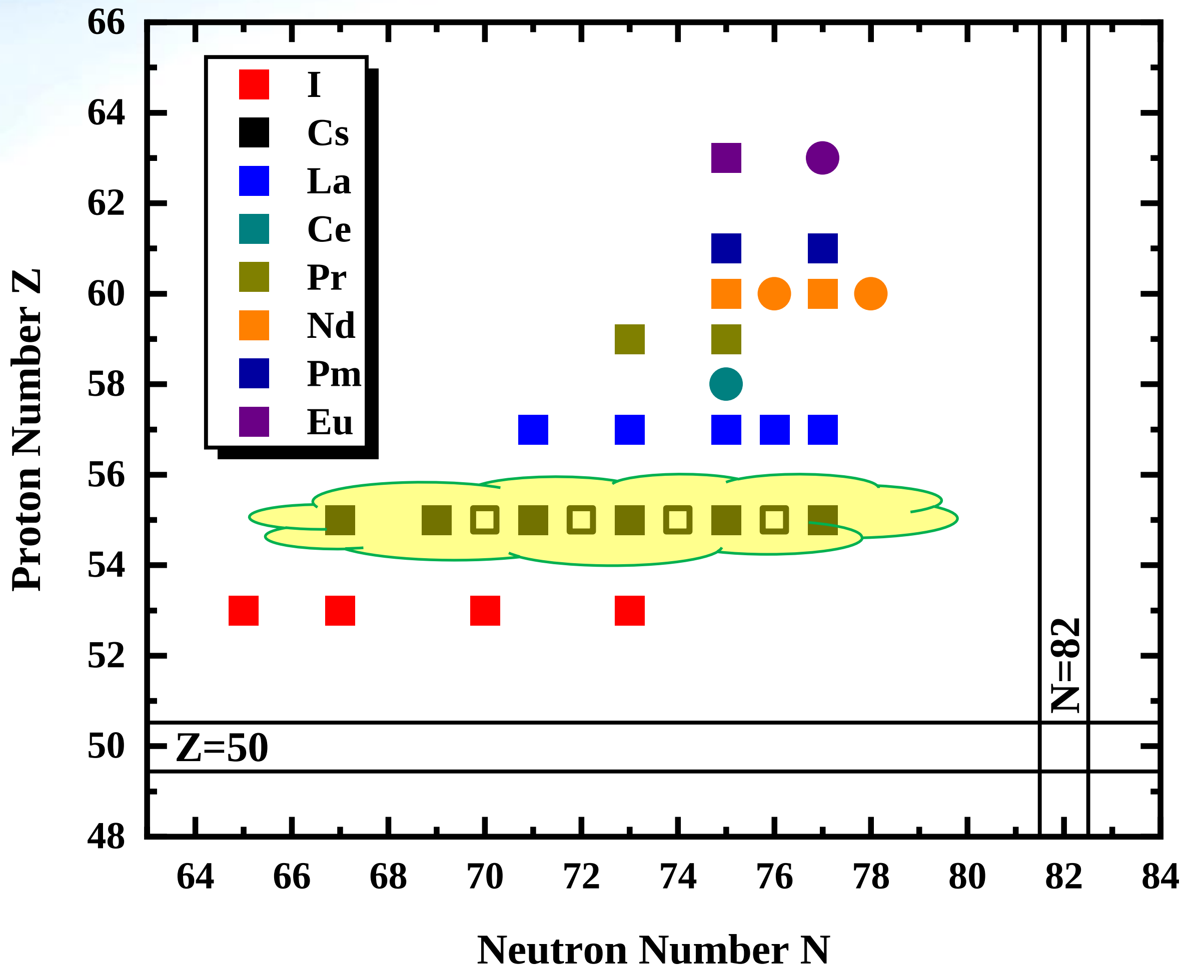
Cs isotopes: perfect candidates

Isotopes	Exp.	Theor.
^{122,124,126,128,130,132}Cs	√	√
^{125,127,129,131}Cs	Doublet bands	√
^{121,123}Cs	Doublet bands	
^{120,133,134}Cs	Only one band	

Chiral candidates in the 130 mass region



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^{121,123}Cs	Doublet bands	
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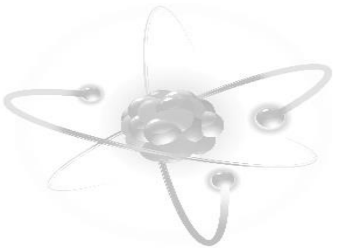
Motivation: to study the evolution of the chiral symmetry in the Cs isotopes.

Theoretical approaches for nuclear chirality



- Theoretical methods：
  - Particle plus rotor model(PRM) *S.Frauendorf and J. Meng, Nucl. Phys. A (1997)* *B. Qi et al. Phys. Lett. B (2009)* *Q. B. Chen et al. Phys. Lett. B (2018)*

    A reflection-asymmetric triaxial (RAT) + PRM *Y. Y. Wang et al. Phys. Lett. B (2019) ; Phys. Rev. C (2020)*
  - Project shell model（PSM） *F. Q. Chen et al., Phys. Rev. C (2017)* *Y. K. Wang et al. PRC (2019)*
  - Interacting boson fermion-fermion model（IBFFM） *D. Tonev et al. Phys. Rev. Lett. (2006)*
  - Tilted axis cranking model (TAC) *S.Frauendorf and J. Meng, Nucl. Phys. A (1997)* *S. Frauendorf, Nucl. Phys. A (2000)*

    TAC + the random phase approximation（RPA） *S. Mukhopadhyay et al. Phys. Rev. Lett. (2007)* *Daniel Almehed et al. Phys. Rev. C (2017)*

    3D-TAC + Covariant density functional theory（CDFT） *P. W. Zhao, Phys. Lett. B (2017)*
- The advantages of 3DTAC-CDFT
  - Self-consistent and microscopic investigations, no additional parameter beyond a well-determined functional
  - Full account of polarization effects
  - Self-consistent treatment of the nuclear currents
- This previous work of nuclear chirality by 3DTAC-CDFT：
  - ^{106}Rh *P. W. Zhao, Phys. Lett. B (2017).*
  - ^{135}Nd *J. Peng and Q. B. Chen, Phys. Lett. B (2020)* *Y.P. Wang and J. Meng Phys. Lett. B (2023)*
  - ^{106}Ag *P. W. Zhao Y. K. Wang, and Q. B. Chen. Phys. Rev. C (2019)*
  - $^{102-107}$Rh *J. Peng and Q. B. Chen Phys. Rev. C (2022)*

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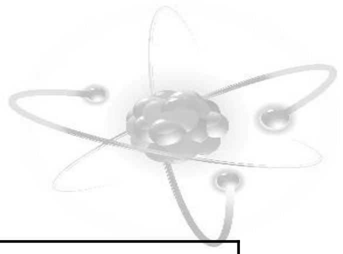
3DTAC-CDFT will be adopted to study the nuclear chirality in Cs isotopes.

- This previous work of nuclear chirality by 3DTAC-CDFT：
  - ^{106}Rh *P. W. Zhao, Phys. Lett. B (2017).*
  - ^{106}Ag *P. W. Zhao Y. K. Wang, and Q. B. Chen. Phys. Rev. C (2019)*
  - ^{135}Nd *J. Peng and Q. B. Chen, Phys. Lett. B (2020)* *Y.P. Wang and J. Meng Phys. Lett. B (2023)*
  - $^{102-107}$Rh *J. Peng and Q. B. Chen Phys. Rev. C (2022)*

Configurations in Cs isotopes

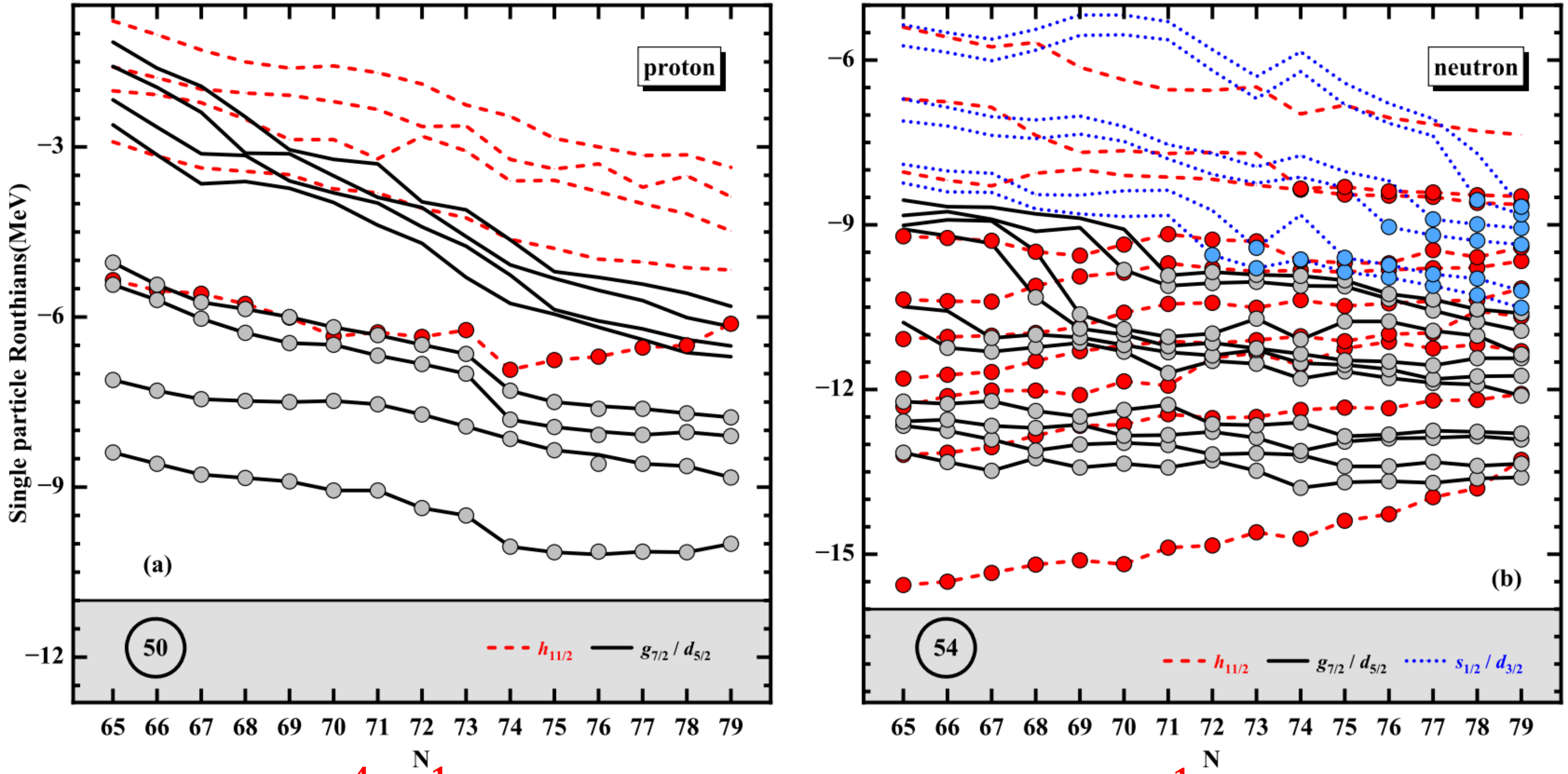
Isotope	Valence nucleons	Unpaired nucleons	References
$^{120}\mathrm{Cs}$	$\pi g^{4}_{7/2} h^{1}_{11/2} \otimes \nu h^{7}_{11/2} (g_{7/2}/d_{5/2})^{8}$	$\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2}$	*Y. Liu et al, PRC 58 (1998)* *C. B. Moon et al, NPA 696 (2001)*
$^{121}\mathrm{Cs}$	$\pi g^{4}_{7/2} h^{1}_{11/2} \otimes \nu h^{7}_{11/2} (g_{7/2}/d_{5/2})^{9}$	$\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2} g^{-1}_{7/2}$	*C. B. Moon et al, JKPS, Vol. 38, (2001)*
$^{122}\mathrm{Cs}$	$\pi g^{4}_{7/2} h^{1}_{11/2} \otimes \nu h^{7}_{11/2} (g_{7/2}/d_{5/2})^{10}$	$\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2}$	*Y. N. U, J. Meng et al, JPG. 31 (2005)*
$^{123}\mathrm{Cs}$	$\pi g^{4}_{7/2} h^{1}_{11/2} \otimes \nu h^{7}_{11/2} (g_{7/2}/d_{5/2})^{11}$	$\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2} g^{-1}_{7/2}$	*K. Singh et al, EPJA 24, 359 (2004)*
$^{124}\mathrm{Cs}$	$\pi g^{4}_{7/2} h^{1}_{11/2} \otimes \nu h^{7}_{11/2} (g_{7/2}/d_{5/2})^{12}$	$\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2}$	*J. B. Lu et al, PRC 62, 057304 (2002)* *Y. Dong et al, CPL Vol. 26, 082101 (2009)* *S. Y. Wang et al， B. Qi， PRC 82, 027303 (2010)*
$^{125}\mathrm{Cs}$	$\pi g^{4}_{7/2} h^{1}_{11/2} \otimes \nu h^{7}_{11/2} (g_{7/2}/d_{5/2})^{13}$	$\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2} g^{-1}_{7/2}$	*K. Singh et al， EPJA 27, 321324 (2006)* *J. Li , PRC 97, 034306 (2018)* *R. Guo et al, PRC 100, 034328 (2019)*
$^{126}\mathrm{Cs}$	$\pi g^{4}_{7/2} h^{1}_{11/2} \otimes \nu h^{7}_{11/2} (g_{7/2}/d_{5/2})^{14}$	$\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2}$	*L. X. Feng et al, CPL 19 1779 (2002)* *S. Y. Wang et al, PRC 74, 017302 (2006)* *S. Y. Wang et al, PRC 75, 024309 (2007)*
$^{127}\mathrm{Cs}$	$\pi g^{4}_{7/2} h^{1}_{11/2} \otimes \nu h^{7}_{11/2} (s_{1/2}/d_{3/2})^{1}$	$\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2} (s_{1/2}/d_{3/2})^{1}$	*Y. Liang et al, PRC VOL 42, (1990)* *J. Li , PRC 97, 034306 (2018)* *R. Guo et al, PRC 100, 034328 (2019)*

Configurations in Cs isotopes



Isotope	Valence nucleons	Unpaired nucleons	References
$^{128}\mathrm{Cs}$	$\pi g^{4}_{7/2} h^{1}_{11/2} \otimes \nu h^{7}_{11/2} (s_{1/2}/d_{3/2})^{2}$	$\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2}$	*T. Koike et al, PRC 67, 044319 (2003)* *E. Grodner et al, PRL 97, 172501 (2006)* *Qi Bin et al, CPC, 33 (2009)* *F. Q. Chen ,Q. B. Chen et al, PRC 96, 051303 (2017)*
$^{129}\mathrm{Cs}$	$\pi g^{4}_{7/2} h^{1}_{11/2} \otimes \nu h^{9}_{11/2} (s_{1/2}/d_{3/2})^{1}$	$\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2} (s_{1/2}/d_{3/2})^{1}$	*Z. Y. Xin et al, CPL 26, 092301 (2009)* *J. Li , PRC 97, 034306 (2018)* *R. Guoet al, PRC 100, 034328 (2019)*
$^{130}\mathrm{Cs}$	$\pi g^{4}_{7/2} h^{1}_{11/2} \otimes \nu h^{9}_{11/2} (s_{1/2}/d_{3/2})^{2}$	$\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2}$	*K. Starosta et al, PRL 86, 6 (2001)* *J. Peng, J. Meng et al, PRC 68, 044324 (2003)* *F. Q. Chen et al, PLB 785 (2018)*
$^{131}\mathrm{Cs}$	$\pi g^{4}_{7/2} h^{1}_{11/2} \otimes \nu h^{9}_{11/2} (s_{1/2}/d_{3/2})^{3}$	$\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2} (s_{1/2}/d_{3/2})^{1}$	*S. Sihotra et al, PRC 78, 034313 (2008)* *J. Li , PRC 97, 034306 (2018)* *R. Guo et al, PRC 100, 034328 (2019)*
$^{132}\mathrm{Cs}$	$\pi g^{4}_{7/2} h^{1}_{11/2} \otimes \nu h^{9}_{11/2} (s_{1/2}/d_{3/2})^{4}$	$\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2}$	*T. Koike et al, PRC 67, 044319 (2003)* *G. Rainovski et al, PRC 68, 024318 (2003)*
$^{133}\mathrm{Cs}$	$\pi g^{4}_{7/2} h^{1}_{11/2} \otimes \nu h^{9}_{11/2} (s_{1/2}/d_{3/2})^{5}$	$\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2} (s_{1/2}/d_{3/2})^{1}$	*S. Biswas et al, PRC 95, 064320 (2017)* *Q. Xu et al, EPJA 54, 83 (2018)*
$^{134}\mathrm{Cs}$	$\pi g^{4}_{7/2} h^{1}_{11/2} \otimes \nu h^{9}_{11/2} (s_{1/2}/d_{3/2})^{6}$	$\pi h^{1}_{11/2} \otimes \nu h^{-1}_{11/2}$	*T. Koike et al, PRC 67, 044319 (2003)* *H. Pai et al, PRC 84, 041301(R) (2011)*

Single proton and neutron Routhians in $^{120-134}$Cs

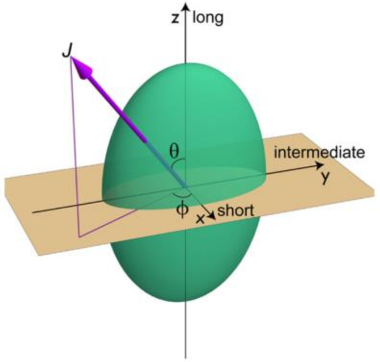


$\pi g^{4}_{7/2} h^{1}_{11/2}$

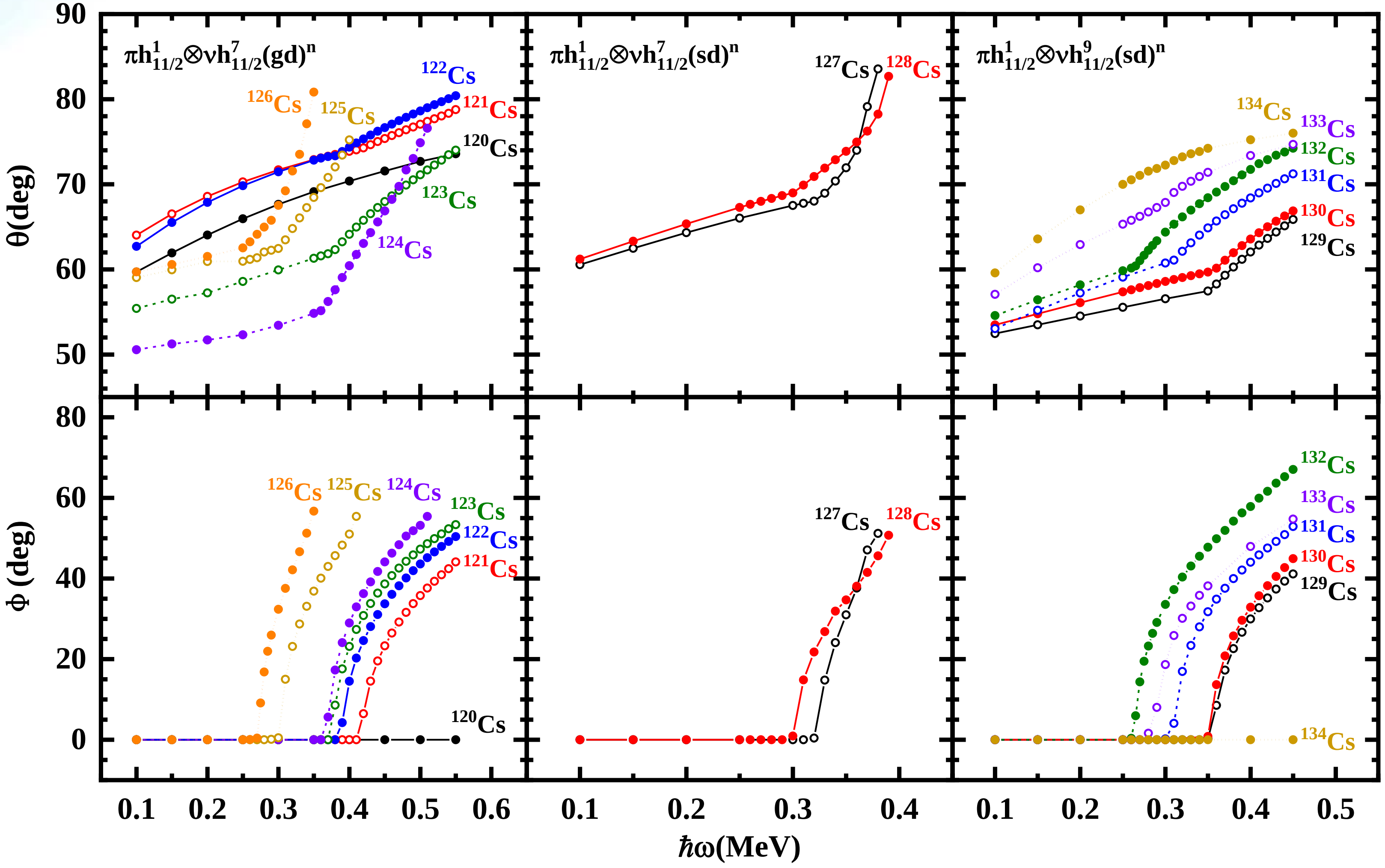
$\nu h^{-1}_{11/2}(gd/sd)^{n}$

Single proton and neutron Routhians near the Fermi surface in $^{120-134}$Cs as a function of the neutron number based on the fixed configuration with rotational frequency 0.3 MeV.

Evolution of polar angle θ and azimuth angle ϕ



The evolution of the polar angle θ and azimuth angle ϕ for the total angular momentum J as driven by the increasing rotational frequency $\hbar\omega$ in $^{120\text{-}134}$Cs.



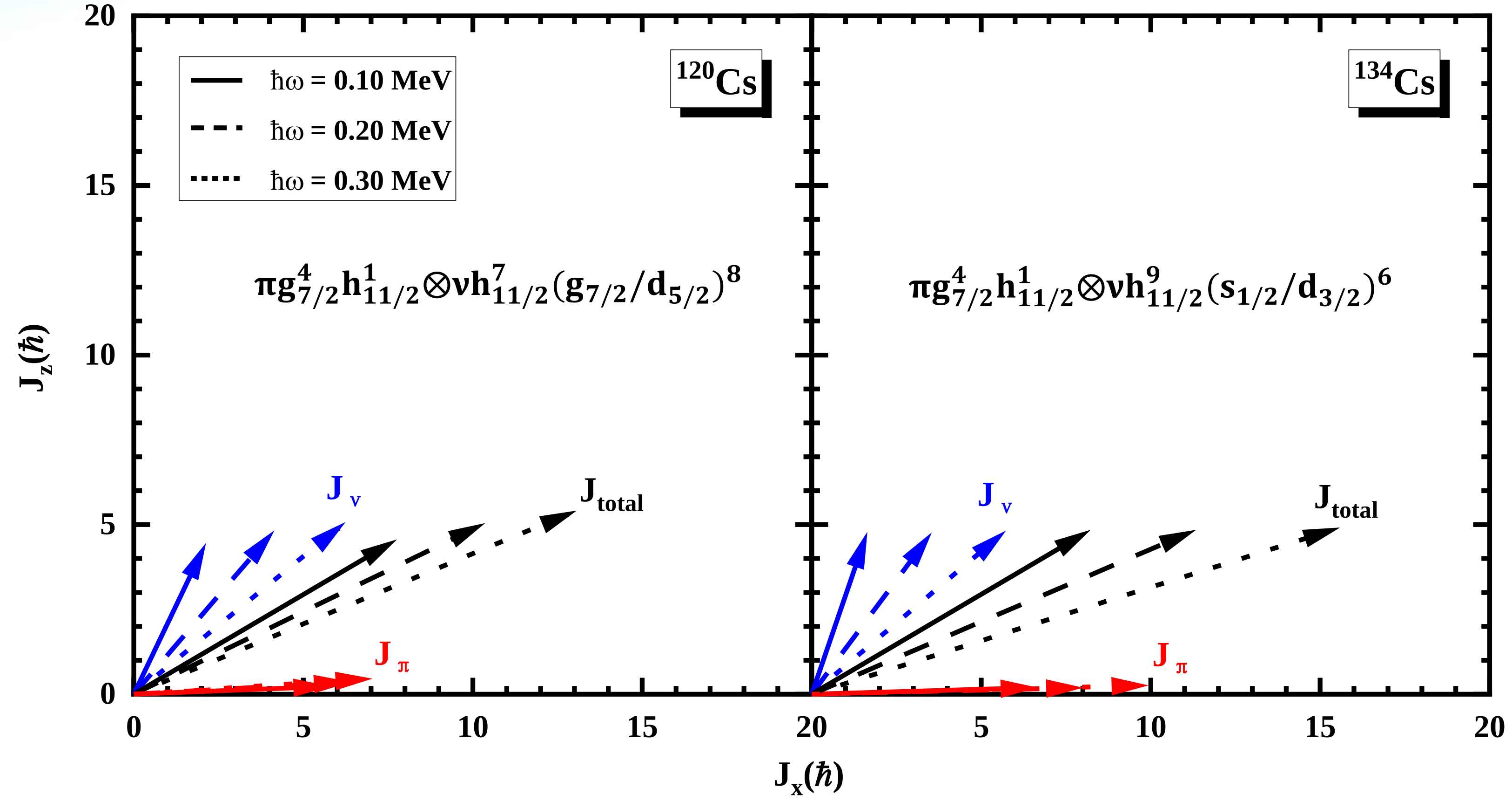
✓ Polar angle θ: similar behavior in $^{120-134}$Cs, i.e., increase with the rotational frequency and always larger than 50°.

✓ Azimuth angle ϕ:

- $^{121\text{-}133}$Cs: zero at low rotational frequencies; become nonzero above the so-called critical frequency $\omega_{\rm crit}$ $\phi \Longrightarrow$ the transition from planar to aplanar rotation.
- ^{120,134}Cs: always zero.

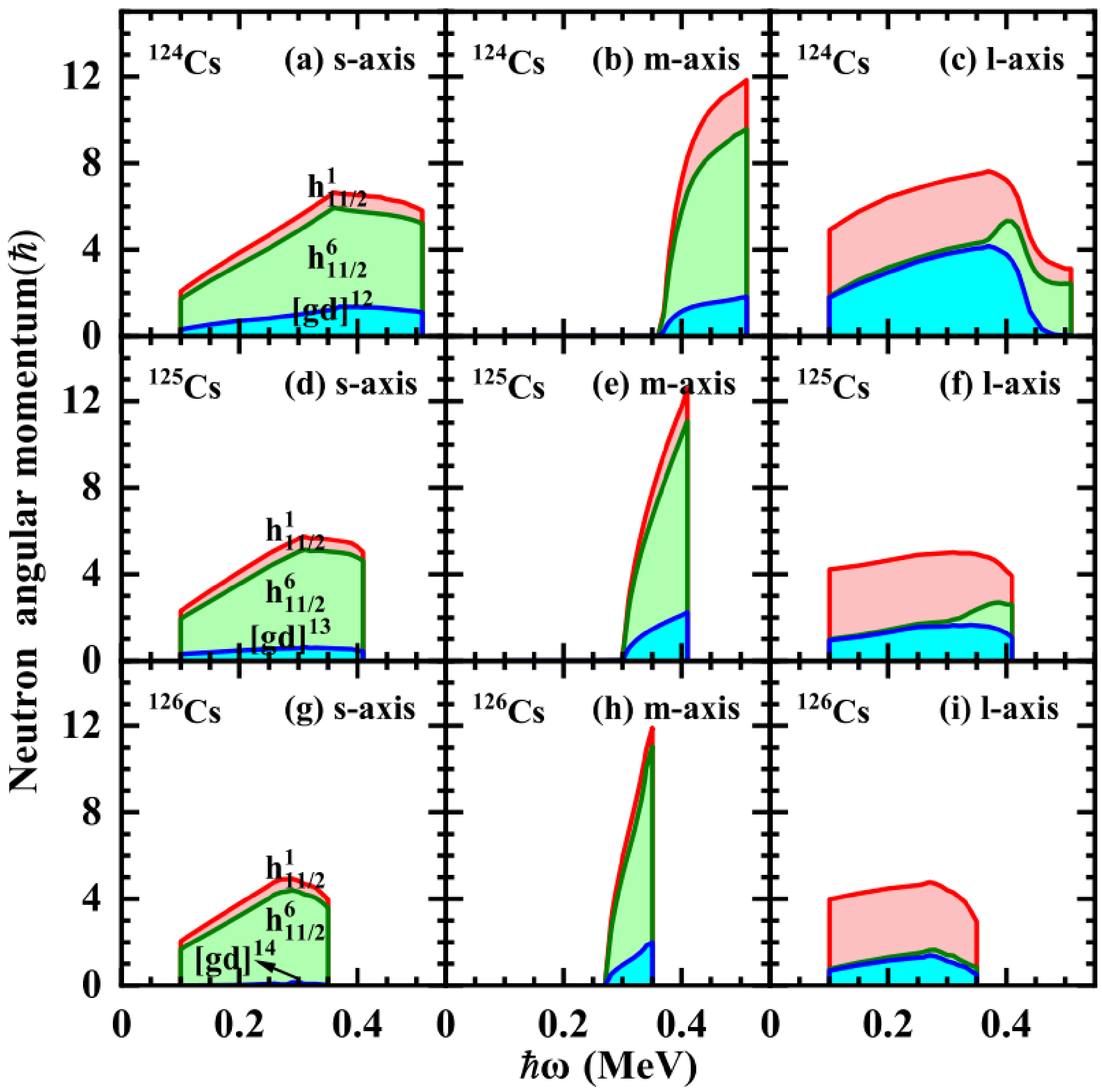
Composition of total angular momentum in ^{120,134}Cs

Planar rotation



- ✓ The proton angular momentum comes mainly from the particles in the $h_{11/2}$ orbit, which aligns along the s axis;
- ✓ The neutron hole in the h11/2 orbit and neutrons in low-j orbits (gd)/(sd) give substantial contributions to the neutron angular momentum, which leads to large components both in l axis and s axis.
- ✓ Higher spin states in the band are created by aligning the neutron angular momentum toward the *s* axis, while the proton angular momentum keeps unchanged in the *s* axis

Angular momenta along s, m and l axis in ^{124,125,126}Cs



For $^{121\text{-}133}$Cs

It should be emphasized that the angular momentum contribution from proton part is approximately along the s axis at low rotational frequency. Therefore, the angular momentum components along l axis and m axis are mainly from neutron part.

Contributions of the valence neutrons in the $h_{11/2}$, (gd) and (sd) orbits to the total angular momenta along the s, m and l axis in ^{124,125,126}Cs

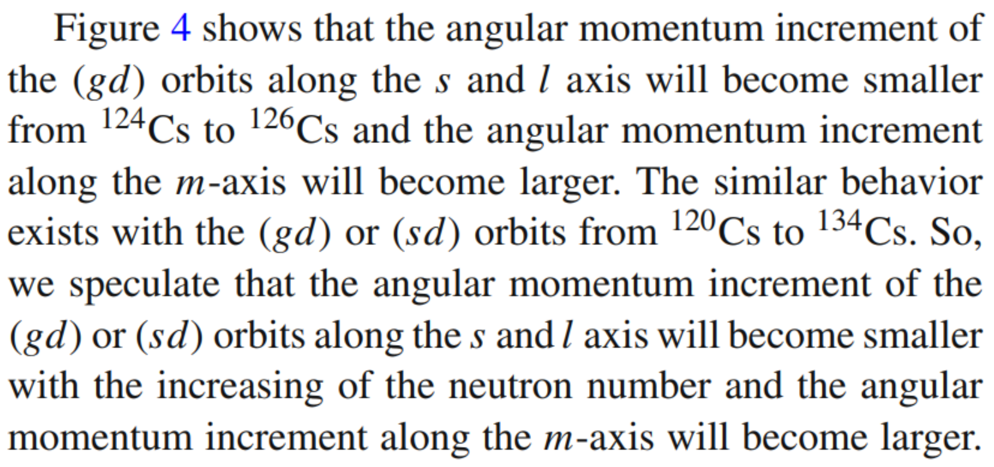
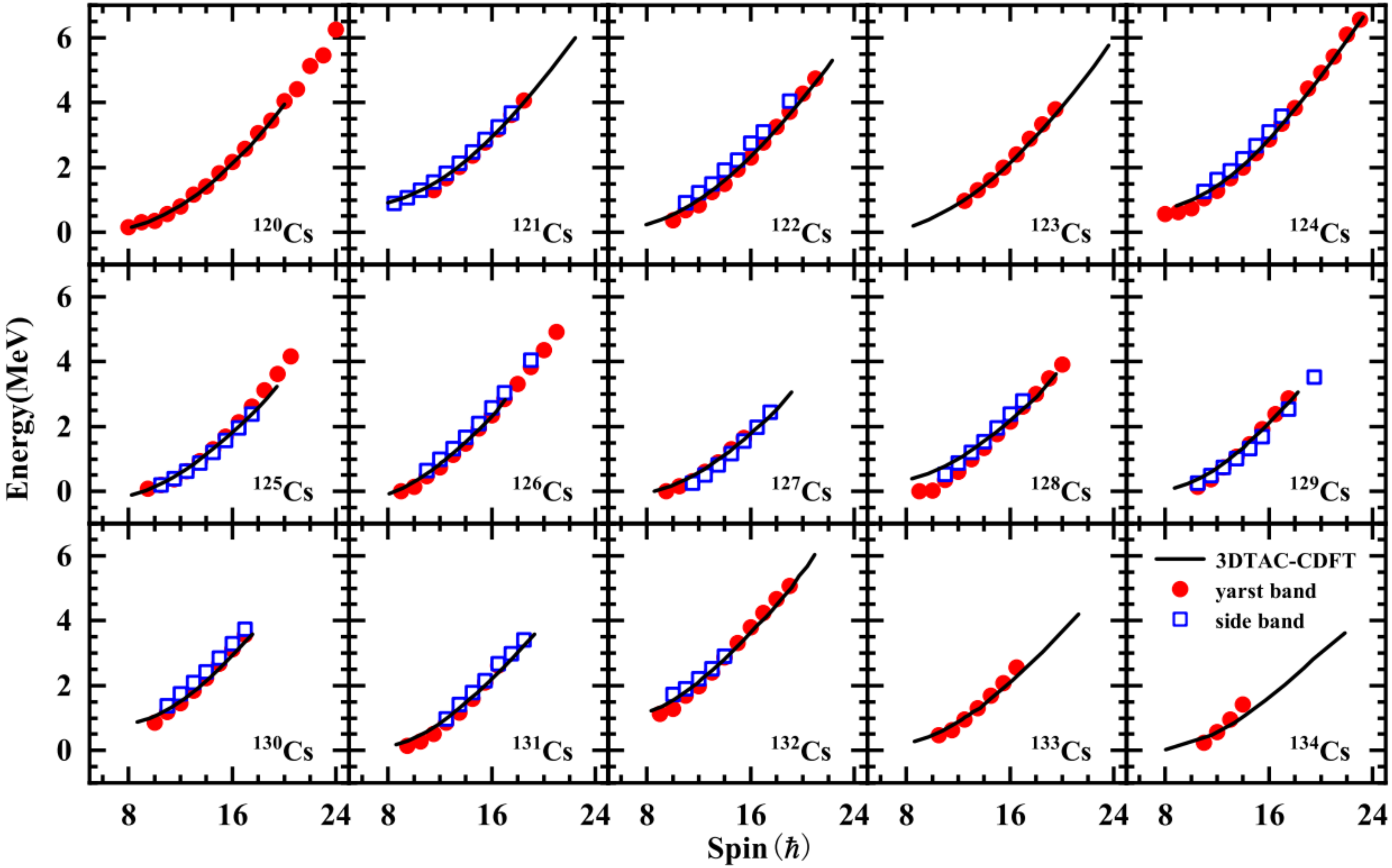


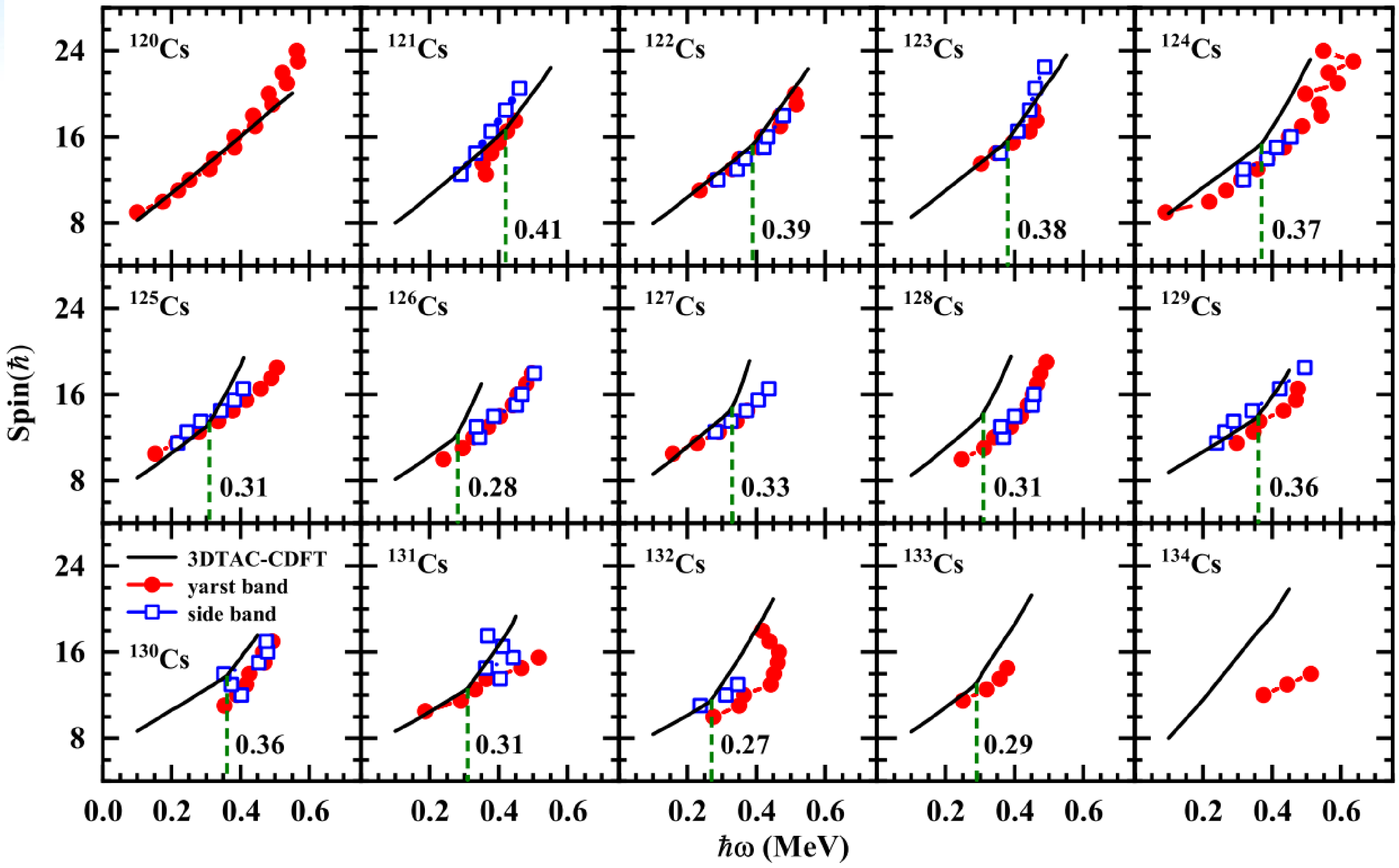
Figure 4 shows that the angular momentum increment of the (gd) orbits along the s and l axis will become smaller from ^{124}Cs to ^{126}Cs and the angular momentum increment along the m-axis will become larger. The similar behavior exists with the (gd) or (sd) orbits from ^{120}Cs to ^{134}Cs. So, we speculate that the angular momentum increment of the (gd) or (sd) orbits along the s and l axis will become smaller with the increasing of the neutron number and the angular momentum increment along the m-axis will become larger.

Rotational excitation energies in $^{120-134}$Cs



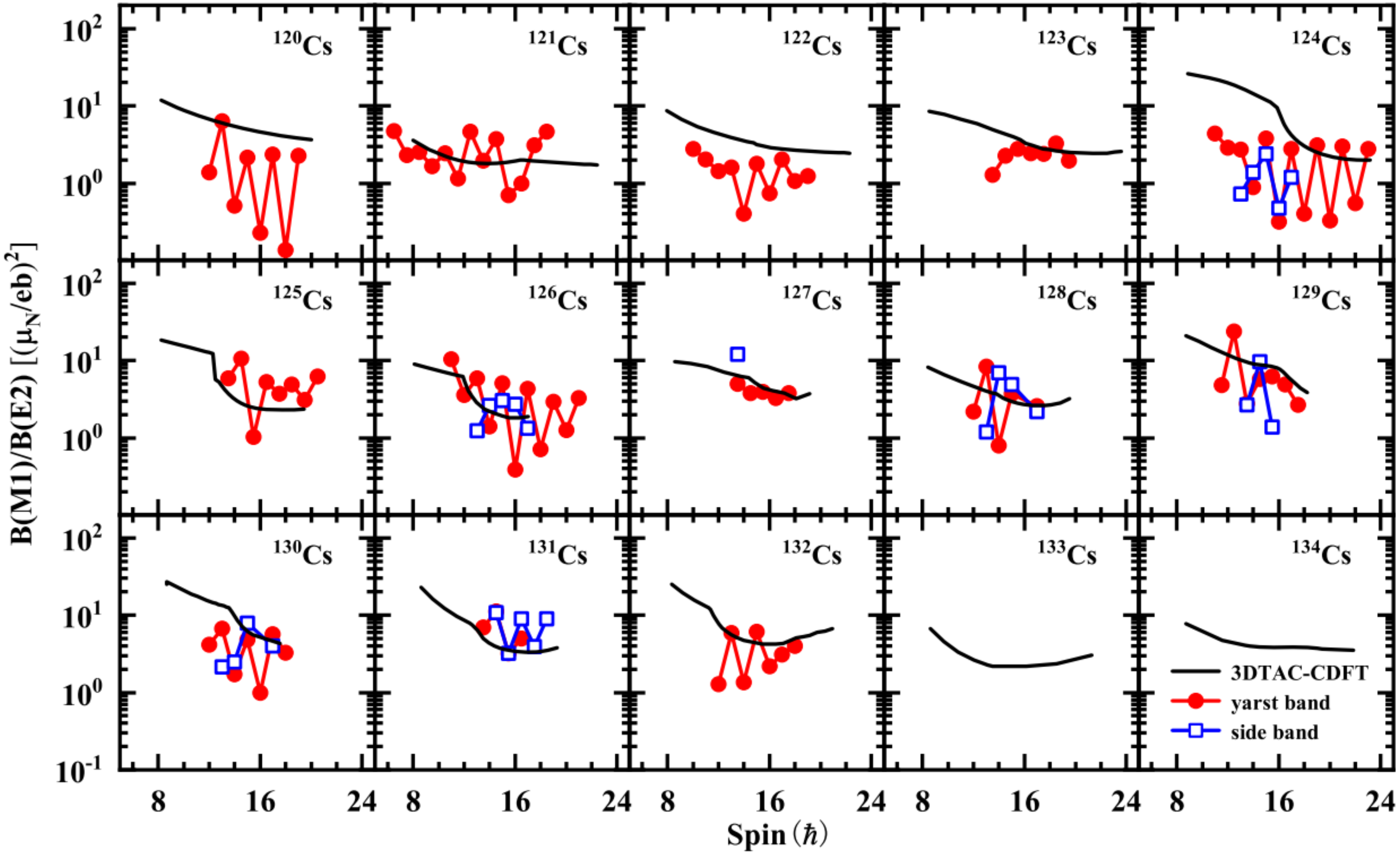
- ✓ The experimental excitation energies of the lower band can be reproduced well.
- ✓ To describe the partner band, one needs to go beyond the mean-field calculations.

The spin as functions of the rotational frequencies



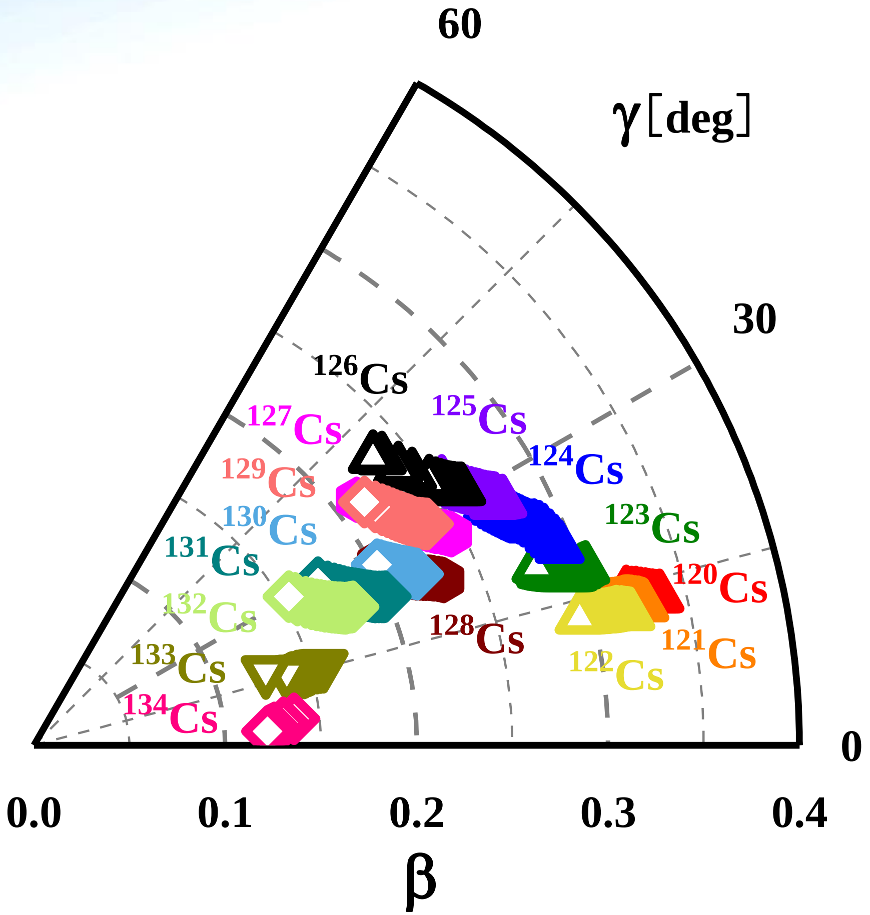
- ✓ The calculated values of spin I (ω) agree well with the experimental data for $^{120-123}$Cs, and overestimate the data for $^{124-127,129-131,133}$Cs, much higher than the experimental data for ^{128,132,134}Cs

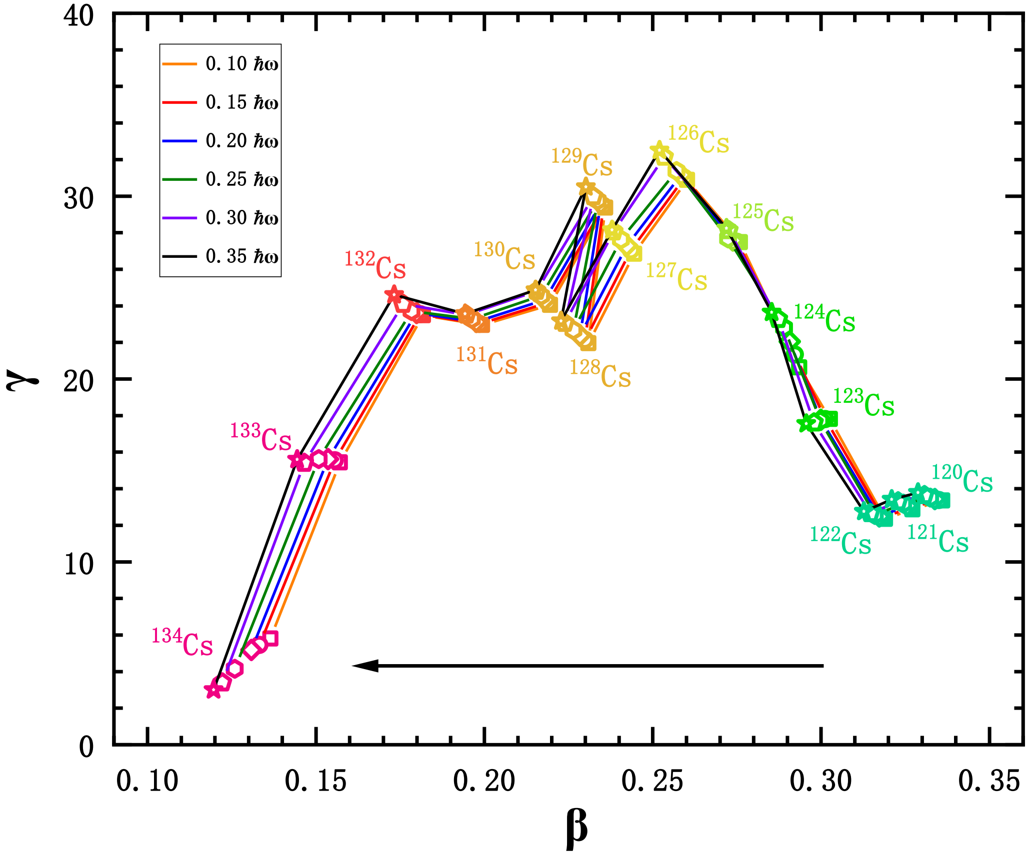
B(M1)/B(E2) ratios in $^{120-134}$Cs



The 3DTAC-CDFT results for $^{121,123,125-134}$Cs show good agreements with the data, while the calculation overestimates the data for ^{120,122,124}Cs. For $^{121-133}$Cs, a smooth falling behavior in the planar rotation, and the falling tendency slows down above the critical frequency $\omega_{\text{crit.}}$

Evolutions of deformation parameters β and γ





- ✓ It could be found that β and γ are stable and there is only slight change with the increasing rotational frequency in $^{120-134}$Cs
- ✓ Triaxial deformation in ^{134}Cs is approximately zero, and it further indicates no chirality in ^{134}Cs
- ✓ ^{120}Cs: the existence of chirality can not be completely obtained only based on the high-j particle-hole configurations plus stable triaxial deformation

Summary

A fully self-consistent and microscopic investigation for the evolution of chirality in the cesium isotopes $^{120-134}$Cs has been performed with the 3DTAC-CDFT.

- ✓ $^{121-133}$Cs: transition from the planar rotation to the chiral rotation has been obtained
- ✓ ^{120,124}Cs: only planar rotation, borders
- ✓ ^{119}Cs: do not support the chirality built on a configuration with three protons $\pi g_{9/2}^{-1} h_{11/2}^{2}$