Candidate multiple chiral doublet bands in $A \sim 100$ mass region

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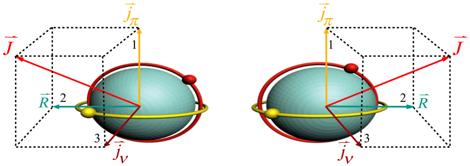
Beijing 2013-10-28

Outline

Chirality in Atomic Nuclei

- theoretical prediction of chirality in nuclear structure
  S. Frauendorf and J. Meng, Nucl. Phys.**A617**, 131 (1997).



- Chiral symmetry breaking in the body-fixed frame， $|L\rangle \& |R\rangle$
- Restore the symmetry in lab frame: chiral doublet bands
- Chiral vibration and static Chirality

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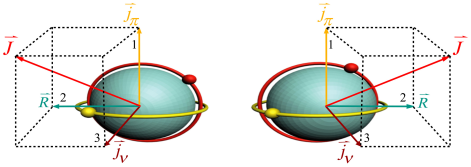

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- more than 30 candidate chiral nuclei have been reported

odd-odd nuclei

- $A \sim 100$ $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}$; ^{102,104,106}Rh, ^{104,106}Ag, ^{98,100}Tc
- $A \sim 130$ $\pi h_{11/2} \otimes \nu h_{11/2}^{-1}$; $^{124-132}$Cs, $^{130-134}$La, ^{132,134}Pr, ^{136}Pm, ^{138}Eu
- $A \sim 190$ $\pi h_{9/2} \otimes \nu i_{13/2}^{-1}$; ^{194,198}Tl
- $A \sim 80$ $\pi g_{9/2} \otimes \nu g_{9/2}^{-1}$; ^{78,80}Br

Chirality in Atomic Nuclei

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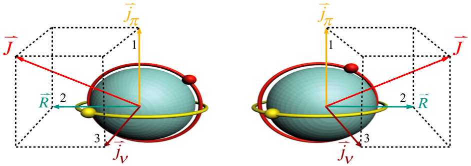

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odd-mass nuclei, ^{103,105}Rh ^{107}Ag ^{135}Nd, ^{133}Ce;
even-even nuclei, ^{106}Mo, ^{108,110}Ru, ^{136}Nd

Multiple chiral doublet bands (MχD)

In 2006, based on the adiabatic and configuration-fixed constrained triaxial relativistic mean field (RMF) theory calculation, triaxial shape coexistence with high-j proton-hole and neutron-particle configurations was found in odd-odd nuclei ^{106}Rh, which demonstrates the possibility of having multiple chiral doublet bands (acronym MχD).

J. Meng, J. Peng, S. Q. Zhang, and S. G. Zhou, Phys. Rev. C 73, 037303 (2006).

Experimental evidence for MχD

1. In experiment, a pair of candidate chiral bands in ^{105}Rh with $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{2}$ configuration, and another pair with tentatively suggested $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}(d_{5/2}/g_{7/2})$ configuration were respectively reported in 2004.

   J. A. Alcántara-Núñez *et al.*, Phys. Rev. C **69**, 024317 (2004).

   J.Tim'ar et al.,Phys. Lett. B 598, 178 (2004).

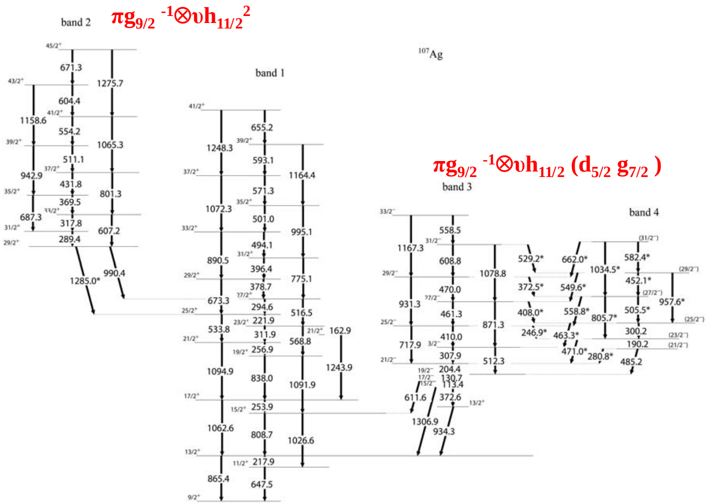
2. Very recently, two distinct sets of chiral double bands have been identified in the odd-mass nucleus^{133}Ce and are regarded as strong experimental evidence for the existence of MχD.

   A.D.Ayangeakaa et al., Phys. Rev. Lett. 110, 172504 (2013).

3. The observation of MχD represents important confirmation of triaxial shape coexistence and its geometrical interpretation.

4. Is there any other experimental evidence of MχD except these two nuclei?

Possible MχD in ^{107}Ag



Band 1&2: D. Jerrestam, Nucl. Phys. A (1994). Band 3&4: B. Zhang, Chin. Phys. C (2011)

Motivation of this work

1. The mechanism of these reported near-degenerate doublet bands in ^{107}Ag were not given in the References

   D. Jerrestam, Nucl. Phys. A (1994). B. Zhang, Chin. Phys. C (2011).

2. It is interesting to study whether two such pairs of doublet bands in ^{107}Ag are associated with the nuclear chirality and further to verify whether or not the observations in ^{107}Ag are $M\chi D$.

3. For this purpose, we study two pairs of doublet bands in ^{107}Ag via the triaxial RMF theory and multiparticle plus rotor model (PRM).

Configuration and deformation of ^{107}Ag in RMF

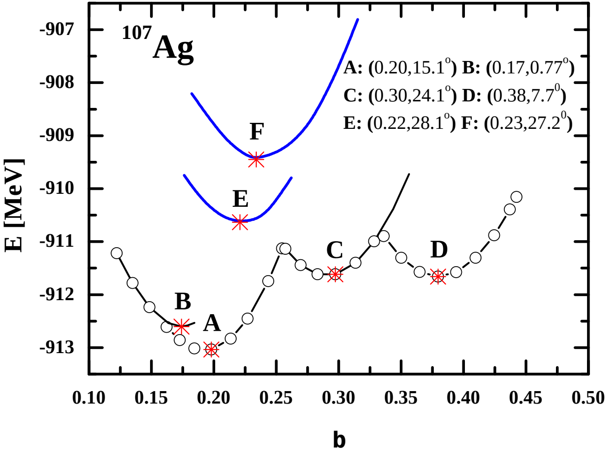
- The detailed formulism of RMF theory can be found in Refs.

  J. Meng, Peng, Zhang, and Zhou, Phys. Rev. C 73, 037303 (2006).
  J. Peng, Sagawa, Zhang, Yao, Zhang, and Meng, PRC (2008).
  J. M. Yao, Qi, Zhang, Peng, Wang, and Meng, Phys. Rev. C 79, 067302 (2009).

- In the present calculations, each Dirac spinor is expanded in terms of a set of three-dimensional harmonic oscillator bases in Cartesian coordinates with 12 major shells and meson fields with 10 major shells.
- The pairing correlations are neglected here. The effective interaction parameter set PK1 is applied.

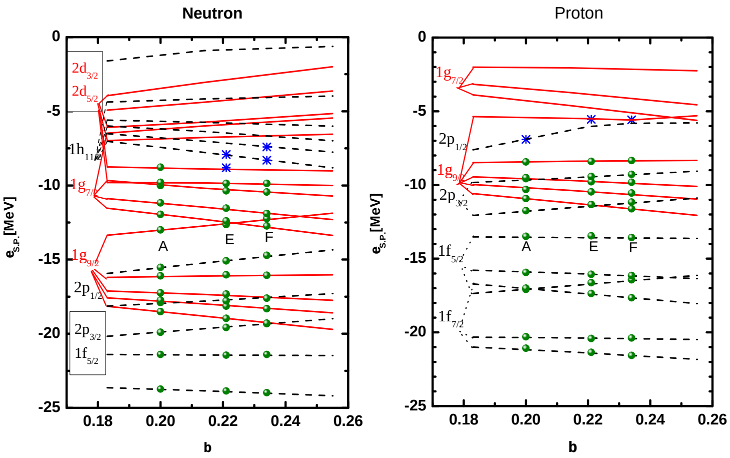
  W. Long, J. Meng, N. Van Giai, and S. G. Zhou, Phys. Rev. C 69, 034319 (2004).

Configuration and deformation of ^{107}Ag in RMF



The energy surfaces in adiabatic (open circles) and configuration-fixed (solid lines) constrained triaxial RMF calculations for ^{107}Ag. The minima in the energy surfaces are labeled as A, B, C, D, E, and F. Their corresponding triaxial deformation parameters β and γ are also given.

Configuration and deformation of ^{107}Ag in RMF



Neutron and proton single-particle levels obtained in constrained triaxial RMF calculations with PK1 as functions of deformation β. Positive (negative) parity states are marked by solid (dashed) lines.

Configuration and deformation of ^{107}Ag in RMF

Table: The total energies E_{tot}, triaxial deformation parameters β and γ , and their corresponding valence nucleon configurations of minima for states A – F in the configuration-fixed constrained triaxial RMF calculations, and compared with the experimental excitation energies.

State	Configuration: Valence nucleons	Configuration: Unpaired nucleons	E_{tot} (MeV)	(β,γ)	E_x(cal.) (MeV)	E_x(exp.) (MeV)
A	$\pi(g_{9/2}^{-2}p_{1/2}^{1})\otimes\upsilon(g_{7/2}^{-2}d_{5/2}^{4})$	$\pi p_{1/2}^{1}$	-913.04	(0.20,15.1)	0	0
B	$\pi g_{9/2}^{-3}\otimes\upsilon(g_{7/2}^{-2}d_{5/2}^{4})$	$\pi g_{9/2}^{-1}$	-912.60	(0.17,0.8)	0.44	0.13
C	$\pi(g_{9/2}^{-2}g_{7/2}^{1})\otimes\upsilon(g_{7/2}^{-2}d_{5/2}^{2}h_{11/2}^{2})$	$\pi g_{7/2}^{1}$	-911.62	(0.30,24.1)		
D	$\pi(g_{7/2}^{2}g_{9/2}^{-3})\otimes\upsilon(g_{7/2}^{-4}d_{5/2}^{2}h_{11/2}^{4})$	$\pi g_{9/2}^{-1}$	-911.66	(0.38,7.7)		
E	$\pi g_{9/2}^{-1}\otimes\upsilon(h_{11/2}^{1}d_{5/2}^{3}g_{7/2}^{-2})$	$\pi g_{9/2}^{-1}\otimes\upsilon(h_{11/2}^{1}d_{5/2}^{1})$	-910.63	(0.22,28.1)	2.41	2.54$*$
F	$\pi g_{9/2}^{-1}\otimes\upsilon(h_{11/2}^{1}h_{11/2}^{1}d_{5/2}^{2}g_{7/2}^{-2})$	$\pi g_{9/2}^{-1}\otimes\upsilon(h_{11/2}^{1}h_{11/2}^{1})$	-909.45	(0.23,27.2)	3.59	3.46 $\star$

$*$ the excitation energy of band head $I^{\pi}=19/2^{-}$ of band 3

$\star$ the excitation energy of $I^{\pi}=23/2^{+}$ of band 1, where backbending occurs.

Multiple chiral doublet bands (MχD)

It represents two possible types of chiral three-quasiparticle configurations in the odd-mass nuclei.

1. One is formed by a high-j hole and an aligned pair of high-j particles;

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1. One is formed by a high-j hole and an aligned pair of high-j particles;
2. the second occurs when a low-j particle (which acts as a spectator) is coupled to the neighboring odd-odd chiral configuration.

Calculate the rotational excitation via PRM

The detailed formulism of multiparticle plus rotor model can be seen in

B. Qi, S. Q. Zhang, J. Meng, and S. Frauendorf, Phys. Lett. B **675**, 175 (2009).
B. Qi, S. Q. Zhang, S. Y. Wang, J. Meng, and T. Koike, Phys. Rev. C **83**, 034303 (2011).

Parameters for Band 1 and 2

1. $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{2}$ with deformation $\beta = 0.23$, $\gamma = 27.2^\circ$ (form RMF)
2. $\mathcal{J}_0 = 25.0 MeV/\hbar^2$ (adjusted to the experimental energy spectra)

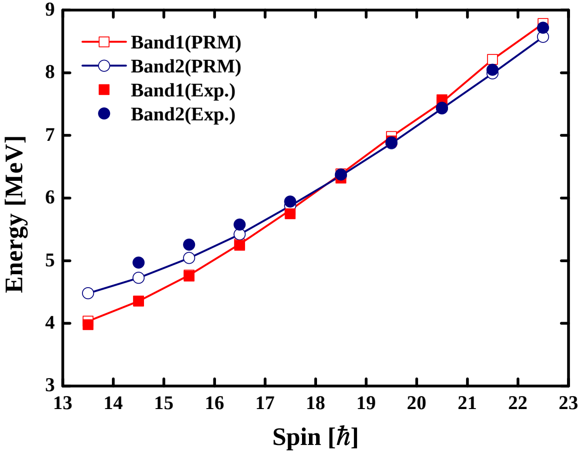
Parameters for Band 3 and 4

1. $\pi g_{9/2}^{-1} \otimes \nu (h_{11/2}^{1} d_{5/2}^{3})$ with $\beta = 0.22$,$\gamma = 28.1^\circ$(form RMF).
2. $\mathcal{J}_0 = 20 MeV/\hbar^2$ (adjusted to the experimental energy spectra)

Parameters to calculate electromagnetic transition

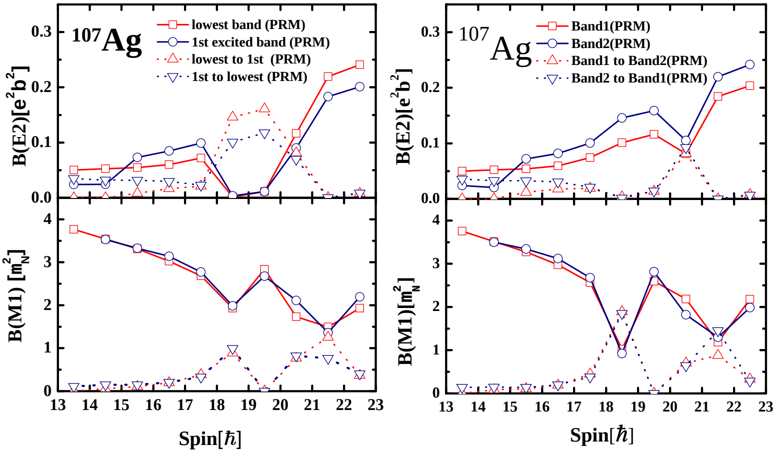
1. the intrinsic quadrupole moment $Q_0 = (3/\sqrt{5\pi}) R_0^2 Z\beta, R_0 = 1.2A^{1/3}$fm
2. gyromagnetic ratios $g_{p(n)} = g_l + (g_s - g_l)/(2l+1)$ with $g_s = 0.6 g_s(free)$, $g_R = Z/A$.

Reproduce the energy spectra of band 1 and 2 via PRM



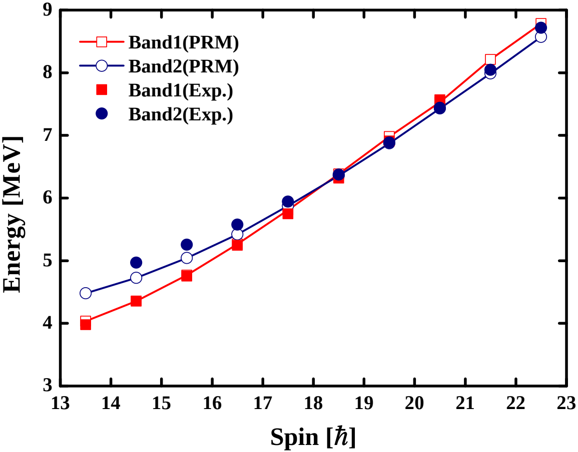
The excitation energies calculated by PRM with configuration $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{2}$ for the doublet bands, in comparison with the corresponding data of the bands 1, 2 in ^{107}Ag.

Energy crossing of band 1 and 2 in PRM



- The calculated partner bands in PRM with $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{2}$ conf.
  Left panel: lowest band and 1st excited band.
  Right panels: Arrange band based on in-band $E2$ transition

Reproduce the energy spectra of band 1 and 2 via PRM



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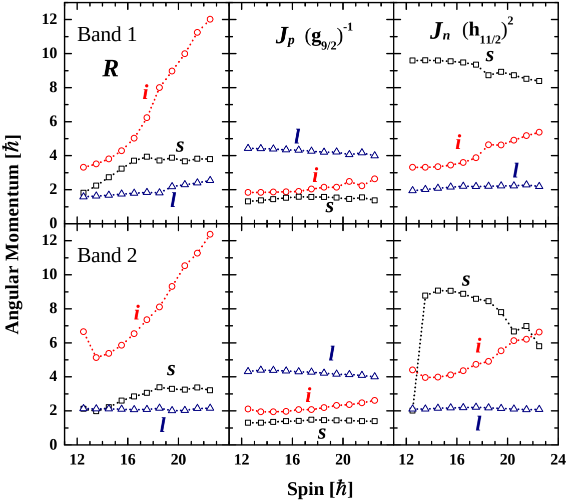
chiral geometry

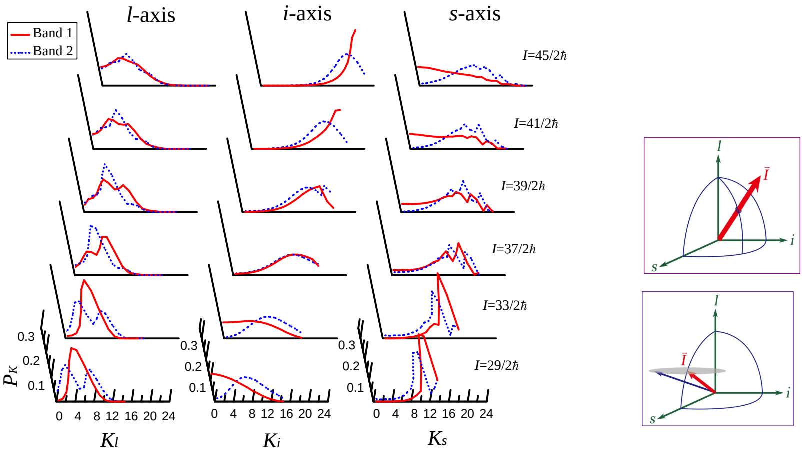


$$R_k = \sqrt{\langle \hat{R}_k^2 \rangle}$$
$$J_{pk} = \sqrt{\langle \hat{j}_{pk}^2 \rangle}$$
$$J_{nk} = \sqrt{\langle (\hat{j}_{(n1)k} + \hat{j}_{(n2)k})^2 \rangle}$$

intermediate (*i*-), short (*s*-,) and long (*l*-) axis

The rms components of the angular momenta calculated as functions of spin by PRM for the positive parity doublet bands with configuration$\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^2$ in ^{107}Ag.

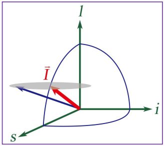
Probability distributions for projection of *I*



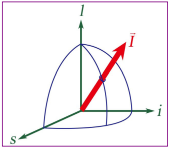
The probability distributions for projection of total angular momentum on the long (l-), intermediate (i-) and short (s-) axis in PRM for band 1 & 2 in ^{107}Ag.

How to understand the evolution of chiral mode?

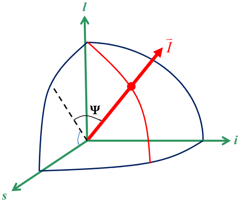
chiral vibration

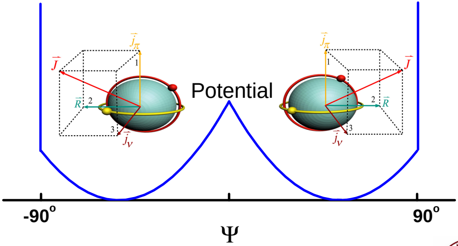


$\Longrightarrow$



static chirality





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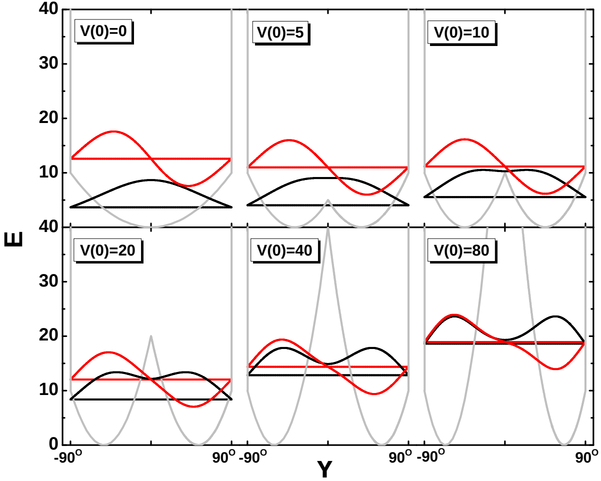
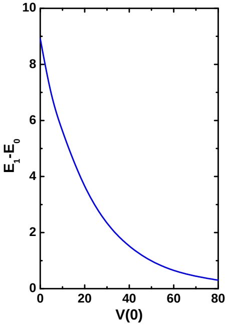
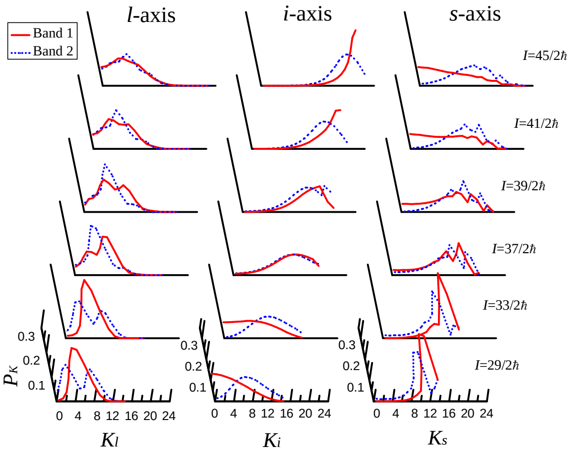
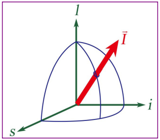


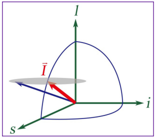


Extract the potential barrier between chiral doublets in particle rotor model, Bin Qi et al. in progress.

Probability distributions for projection of *I*







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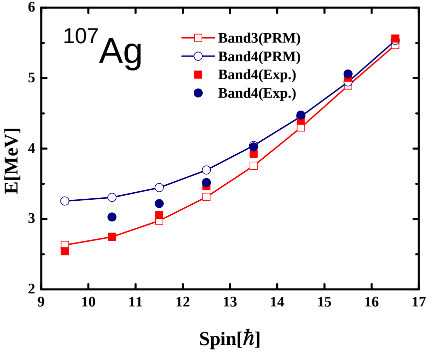
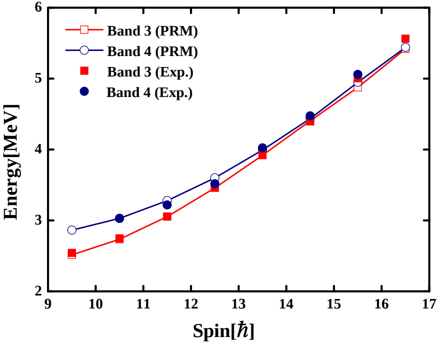
Reproduce the energy spectra of band 3 and 4 via PRM

left: $\pi g_{9/2}^{-1} \otimes \nu(h_{11/2}^{1} d_{5/2}^{1})$

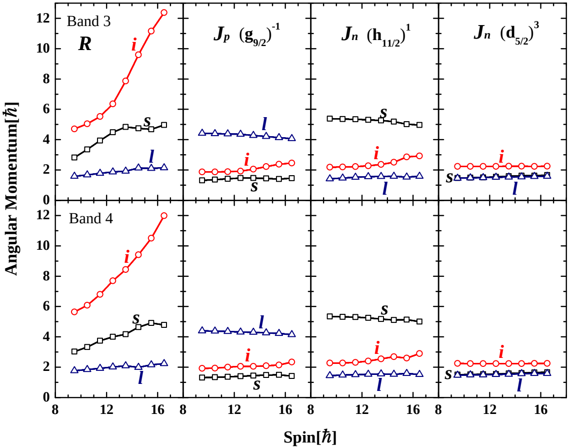


right: $\pi g_{9/2}^{-1} \otimes \nu(h_{11/2}^{1} d_{5/2}^{3})$



The excitation energies calculated by PRM for the doublet bands, in comparison with the data of the bands 3, 4 in ^{107}Ag.

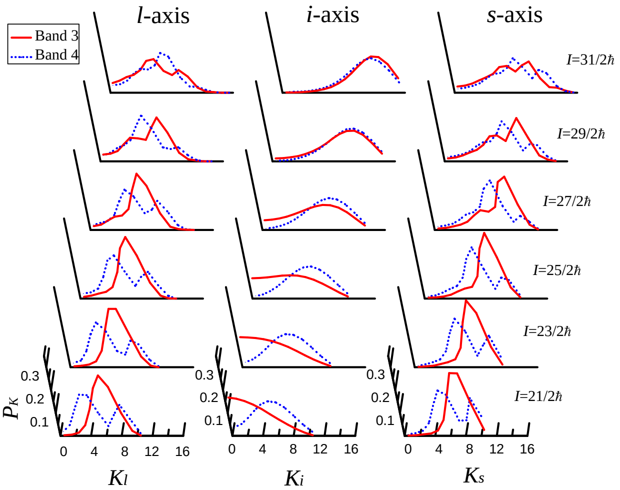
Chiral geometry

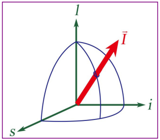


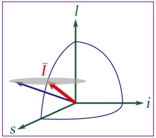
Same as Band1,2, but for the negative parity doublet bands with configuration $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{1} d_{5/2}^{3}$ in ^{107}Ag.

neutron in $d_{5/2}$ sub-shell act as spectators

Probability distributions for projection of I







The probability distributions for projection of total angular momentum on the long (l-), intermediate (i-) and short (s-) axis in PRM for band 3 & 4 in ^{107}Ag.

Conclusion

1. Two pairs of nearly degenerate doublet bands in ^{107}Ag are studied by RMF theory and PRM.

2. The triaxial deformations favorable for the construction of the chiral doublet bands with the suggested configurations $\pi g_{9/2}^{-1} \otimes \nu h_{11/2}^{2}$ and $\pi g_{9/2}^{-1} \otimes \nu h_{11/2} d_{5/2}$ are obtained from the configuration-fixed constrained triaxial RMF calculations.

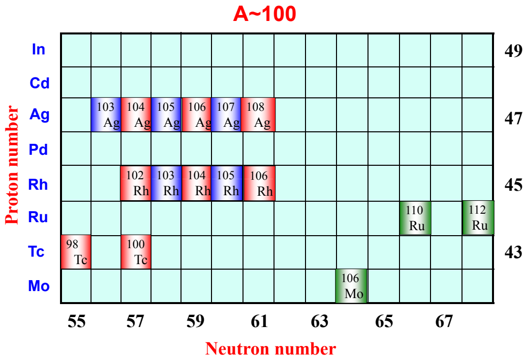
3. Adopting the PRM, the data are reproduced excellently for the two pairs of doublet bands, even the energy crossing of bands 1 and 2 is obtained self-consistently. The chiral geometry of the aplanar rotation is further conformed by analyzing the angular momentum components.

4. Thus we suggest two pairs of doublet bands in ^{107}Ag as two distinct sets of chiral doublet bands, which might be more evidence of MχD after the observed candidate MχD in ^{105}Rh and ^{133}Ce

B. Qi, H. Jia, N. B. Zhang, C. Liu, S. Y. Wang, Phys. Rev. C, 88, 027302 (2013).

Other candidate MχD in $A \sim 100$ mass region

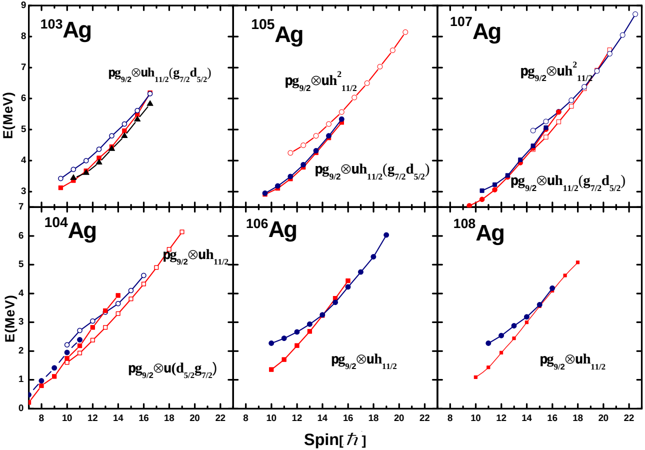
reported chiral nuclei in $A \sim 100$ mass region:



- Ag: S.Ray,PRC(2008)
  Z.G.Wang,PRC(2013)
  J.Timár,PRC(2007)
  Joshi,PRL(2007)
  B.Zhang,Chin. Phys.C(2011)
  C.Liu,PRC (2013).
- Rh:J.Gizon,NPA(1999)
  J.Timár,PLB(2004)
  C.Vaman,PRL,(2004)
  J.Timár,PRC(2006)
  Joshi,PLB(2004)
- Ru:Y.X.Luo,PLB(2009).
- Tc:Joshi,Eur.Phys.J(2005).
- Mo:S.J.Zhu,Eur.Phys.J.A(2005)

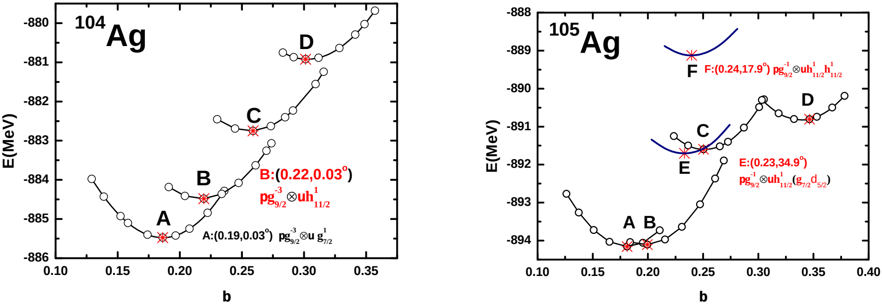
open question: MχD in odd-A isotopes of Rh and Ag; in odd-odd nuclei?

Other candidate MχD in $A \sim 100$ mass region



expect the partner band of ^{105}Ag; possible $M\chi D$ in ^{104}Ag, triplet states in ^{103}Ag, in progress

Other candidate MχD in $A \sim 100$ mass region



The energy surfaces in triaxial RMF calculations for ^{104}Ag and ^{105}Ag.

Acknowledgement

1. Peking Univ.: J. Meng, S.Q. Zhang, P.W. Zhao, Q.B. Chen, H.Hua, X.Q. Li, C. Xu
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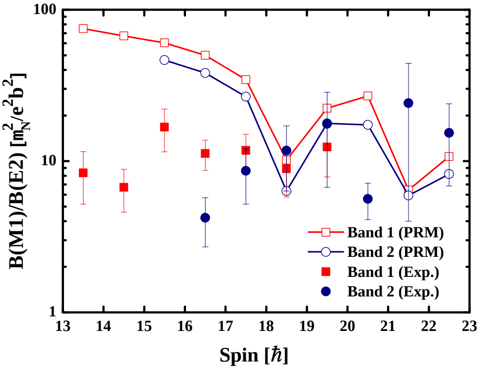
3. Jilin Univ.: J. Li
4. CIAE: X. G. Wu, C. Y. He
5. Stellenbosch Univ.: S. M. Wyngaardt, R. Newman, P. Papka,
6. iThemba Labs: R. Bark, E. Lawrie, J.J. Lawrie, S. Mullins, J. F. Sharpey-Schafer, S. Majola, L.P. Masitery, P. Datta

Thank you for your attention!

原子核的手征性


100
10
1
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16
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21
22
23
B(M1)/B(E2) [m_N^2/e^2b^2]
Spin [ħ]
Band 1 (PRM)
Band 2 (PRM)
Band 1 (Exp.)
Band 2 (Exp.)