Triaxiality-related nuclear phenomena in the A≈100 mass region

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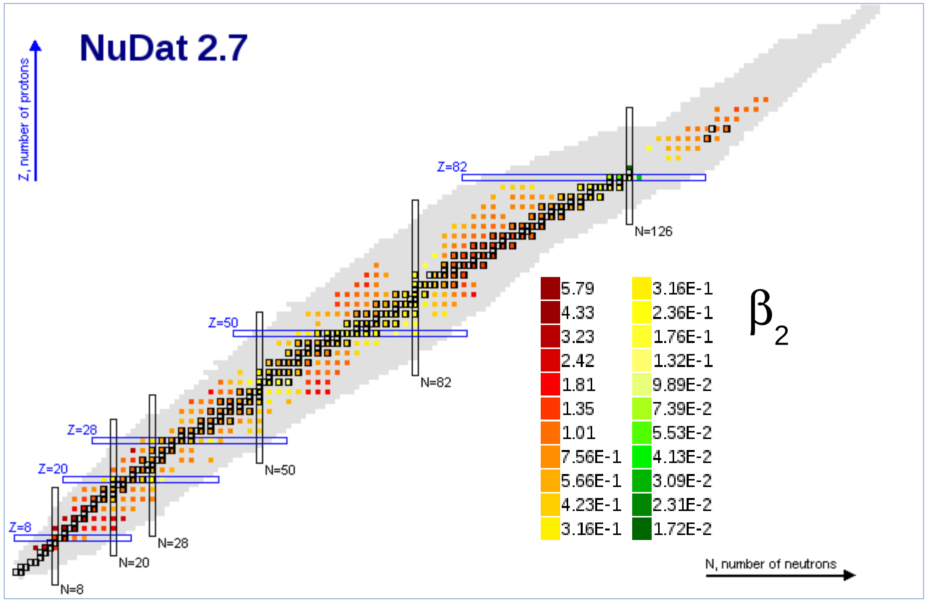
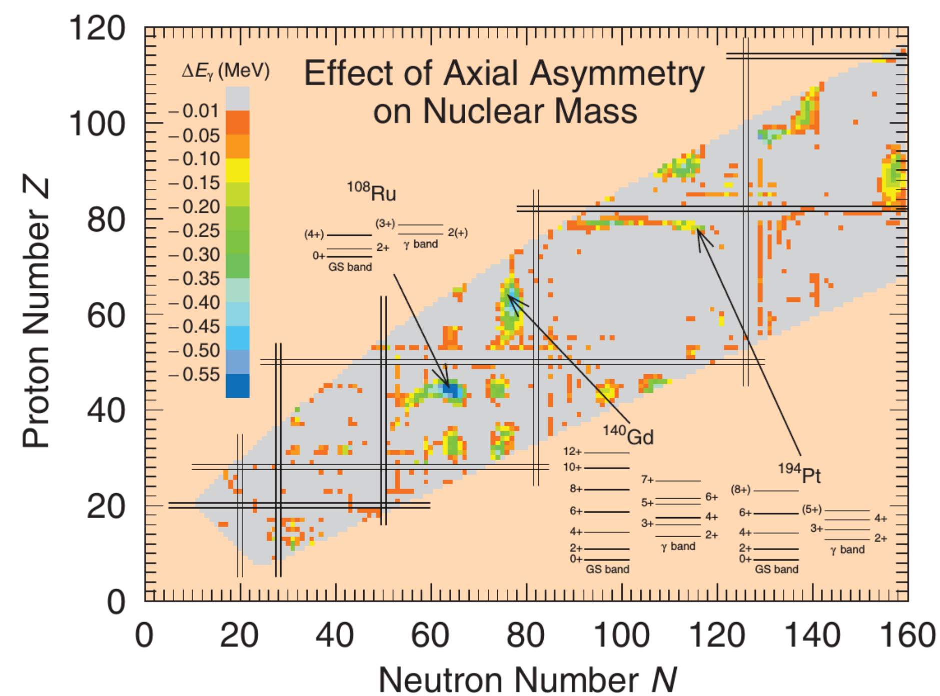
XXIII International School on Nuclear Physics, Neutron Physics and Applications, Varna, 2019

Triaxial nuclear shape

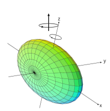
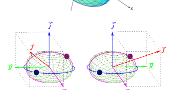




P. Möller et al., PRL 97, 162502 (2006)

Triaxial shape: no single characteristic quantity, like Q_0 for quadrupole deformation

Phenomena related with triaxial shape:

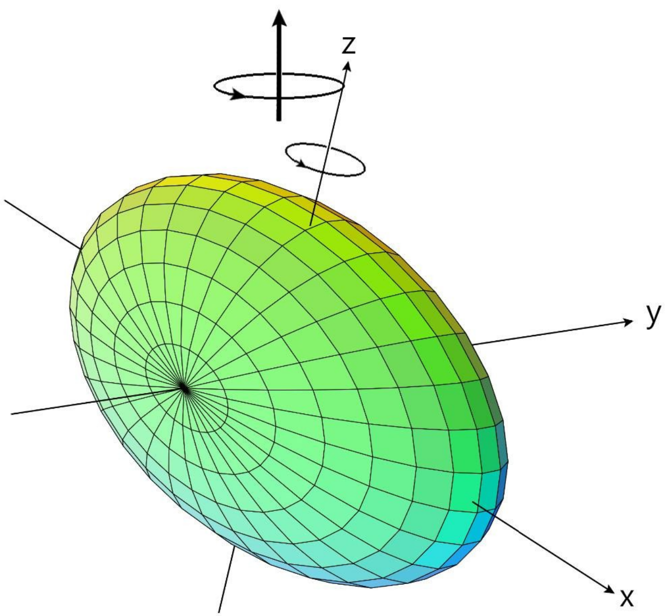
- gamma bands (*low-spin region*)
- wobbling motion  (*medium-spin region*)
- chiral rotation  (*medium-spin region*)

Subject of the present talk: our recent results on nuclear wobbling motion and chirality in the A~100 mass region

Radu Budaca: nice talk on the theoretical aspects (Tuesday afternoon)

Wobbling motion of the triaxial nucleus

A. Bohr, B.R. Mottelson, Nuclear Structure, vol. II (Benjamin, New York, 1975)



In **even-even triaxially deformed nuclei**:

$$H_{\text{rot}} = A_3\hat{\mathbf{J}}_3^2 + A_1\hat{\mathbf{J}}_1^2 + A_2\hat{\mathbf{J}}_2^2 \qquad A_i = \frac{\hbar^2}{2\mathcal{J}_i}$$

If

$$A_1 > A_2 > A_3 \ (\mathcal{J}_1 < \mathcal{J}_2 < \mathcal{J}_3),$$

then slightly above the yrast line, the energy spectrum is:

$$H = A_3 I(I+1) + (n + \frac{1}{2})\hbar\omega_w$$

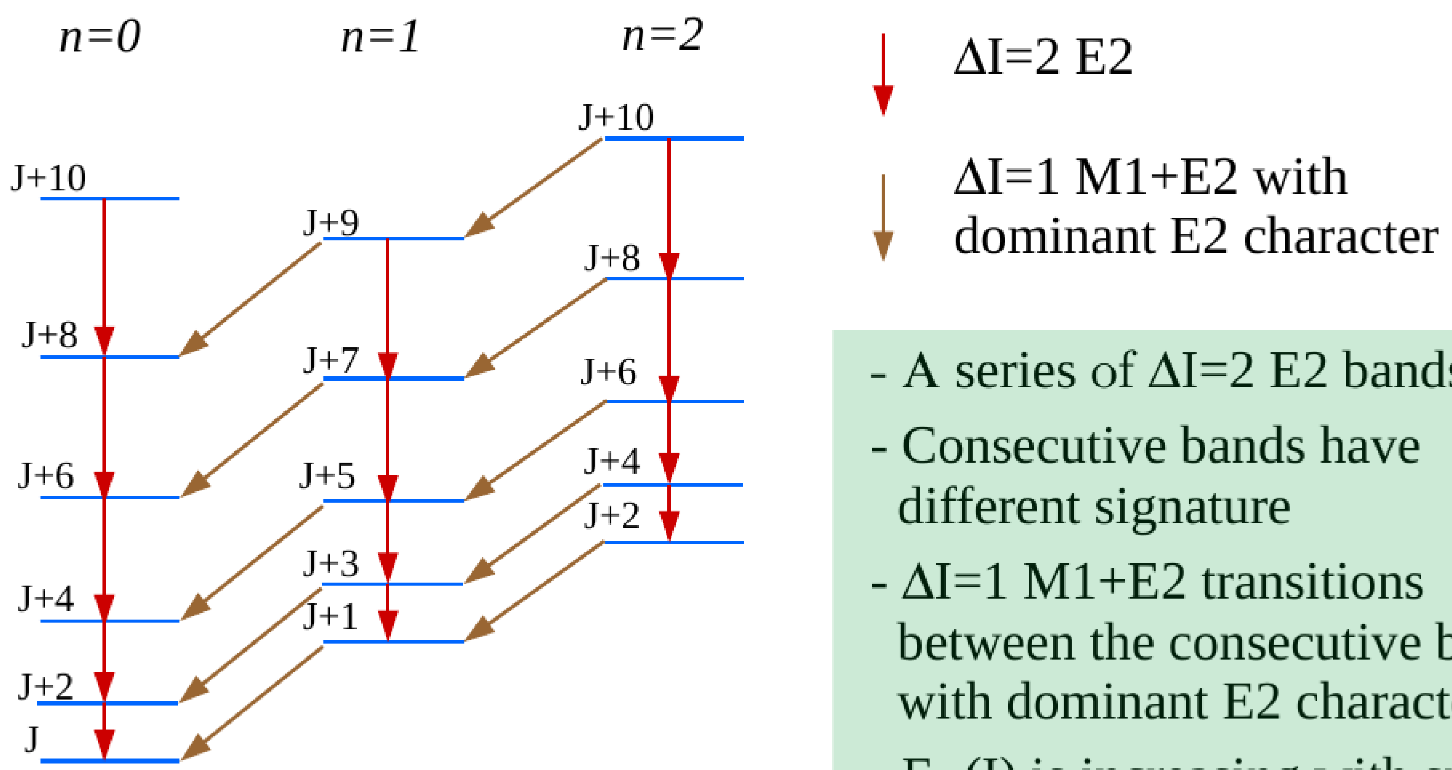
"The quantum number *n* describes the precession motion of the axes with respect to the direction of J;
for small amplitudes, this motion has the character of a harmonic vibration with frequency w_W."

The "wobbling frequency" is:

$$\hbar\omega_w = 2I\sqrt{(A_1 - A_3)(A_2 - A_3)}$$

thus, it is increasing with increasing angular momentum.

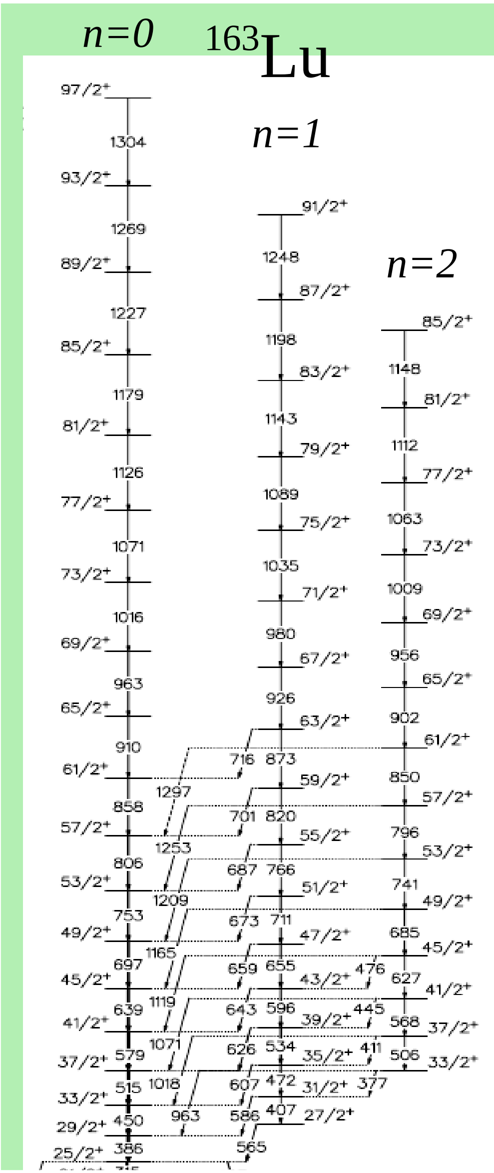
Expected experimental characteristics



- A series of ΔI=2 E2 bands
- Consecutive bands have different signature
- ΔI=1 M1+E2 transitions between the consecutive bands with dominant E2 character
- $E_w(I)$ is increasing with spin

$$\hbar\omega_w \approx E_w(I) = E(I,n=1)-[E(I-1,n=0)+E(I+1,n=0)]/2$$

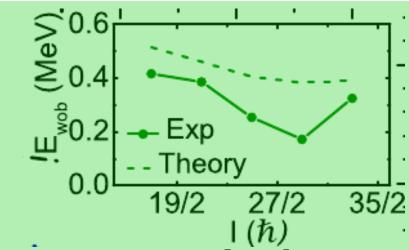
Experimentally observed wobbling in nuclei



D. R. Jensen et al., Phys. Rev. Lett. 89, 142503 (2002)

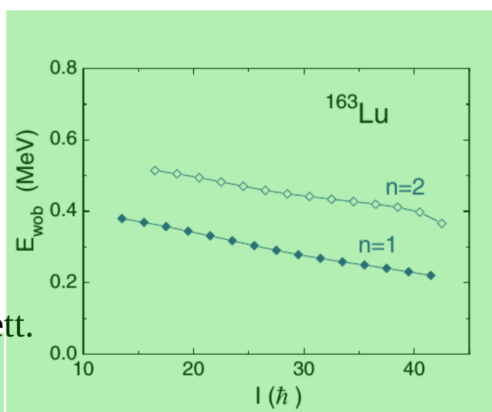
Wobbling bands published before our work are all in odd-A, odd-proton nuclei, based on particle-type high-J proton configuration

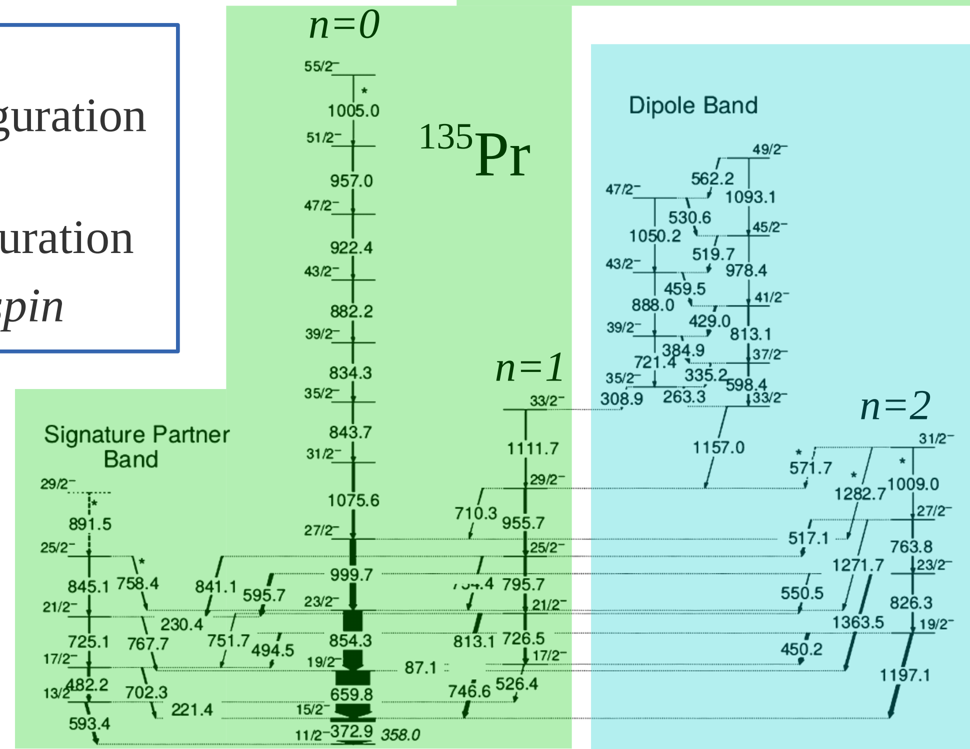
- TSD bands in ^{161}Lu, ^{163}Lu, ^{165}Lu, ^{167}Lu, ^{167}Ta
  All are based on the $\pi i_{13/2}$ configuration
- ND band in ^{135}Pr
  Based on the $\pi h_{11/2}$ configuration
  $E_W(I)$ is decreasing with spin



J. T. Matta et al., Phys. Rev. Lett. 114, 082501 (2015)

- ND band in ^{133}La
  Based on the $\pi h_{11/2}$ configuration
- ND band in ^{187}Au
  Based on the $\pi h_{9/2}$ configuration
  $E_W(I)$ is increasing with spin





N. Sensharma et al. , Physics Letters B 792 (2019) 170–174

Theoretical understanding of the observed features of wobbling in odd-A nuclei

In spite of the limited number of the experimental observations of nuclear wobbling, many theoretical papers have been published to describe the observed features in odd-A nuclei.

They use different formalisms and different assumptions for the moments of inertia.

- S. Frauendorf and F. Dönau, Phys. Rev. C 89, 014322 (2014)
- Q. B. Chen *et* al., Phys. Rev. C 90, 044306 (2014)
- S. Frauendorf and F. Dönau, Phys. Rev. C 92, 064306 (2015).
- Q. B. Chen *et* al., Phys. Rev. C 94, 044301 (2016)
- Q. B. Chen *et* al., Phys. Rev. C 94, 054308 (2016)
- K. Tanabe and K. Sugawara-Tanabe, Phys. Rev. C 95, 064315 (2017).
- A. A. Raduta *et* al., Phys. Rev. C 96, 054320 (2017)
- M. Shimada *et* al., Phys. Rev. C 97, 024318 (2018)
- R. Budaca, Phys. Rev. C 97, 024302 (2018)

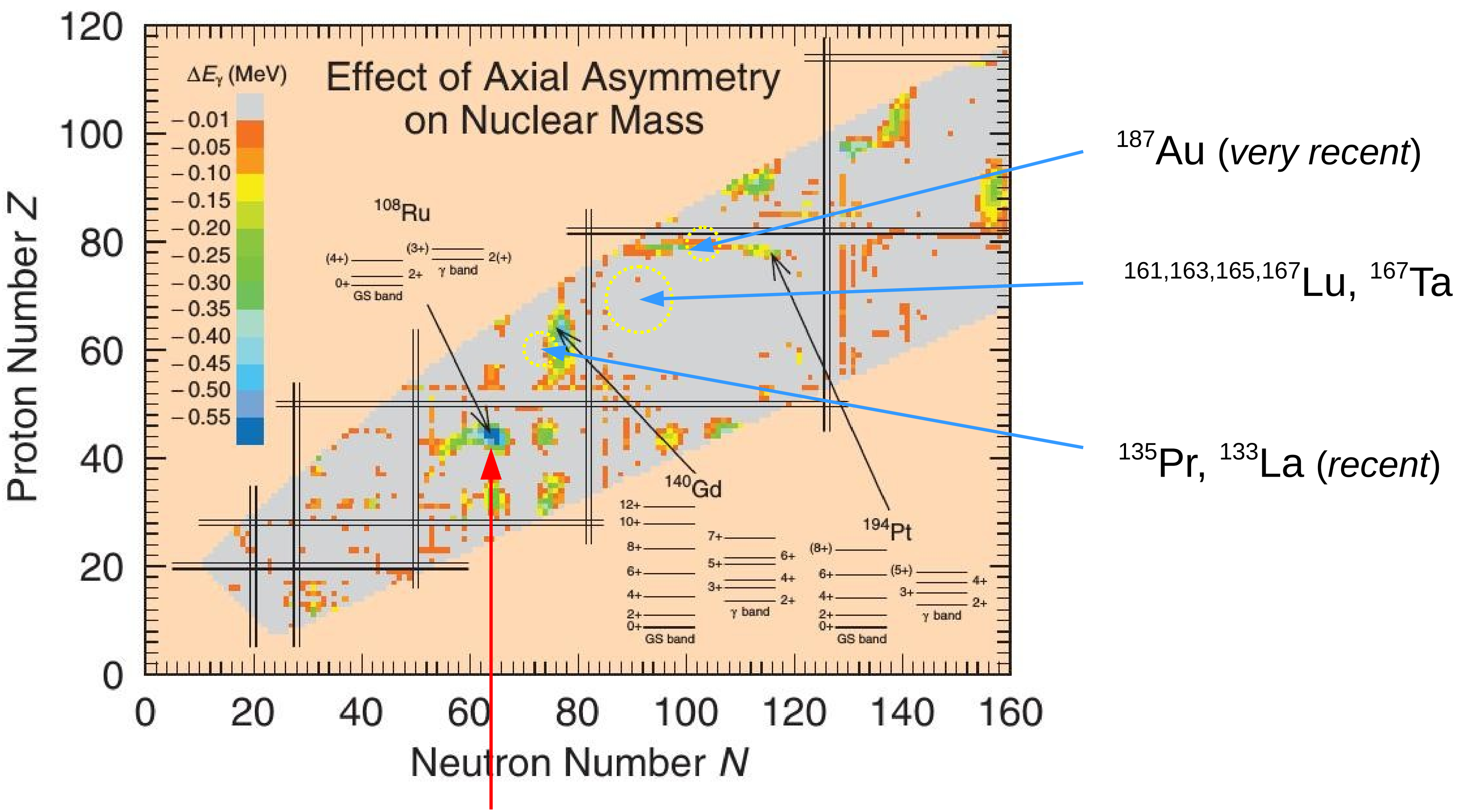
It provides an approximation, which interprets the observed behavior of $E_w(I)$.

It also leads to the classification of the wobbling cases as:
- **simple wobbling** (even-even nuclei)
- **longitudinal wobbling** (odd-A nuclei)
  The AM of the odd particle is aligned parallel with the axis of the largest MO.
- **transverse wobbling** (odd-A nuclei)
  The AM of the odd particle is aligned perpendicular to the axis of the largest MO.

- **simple wobbling**: wobbling energy is increasing with increasing spin
- **longitudinal wobbling**: wobbling energy is increasing with increasing spin
- **transverse wobbling**: wobbling energy is decreasing with increasing spin

Where to search for new wobbling bands?

P. Möller et al., PRL 97, 162502 (2006)



- The region around ^{108}Ru shows the strongest deviation from axial symmetry at low energy
- No wobbling has been observed before our studies
- Bands based on particle-type high_j **neutron** configuration exist

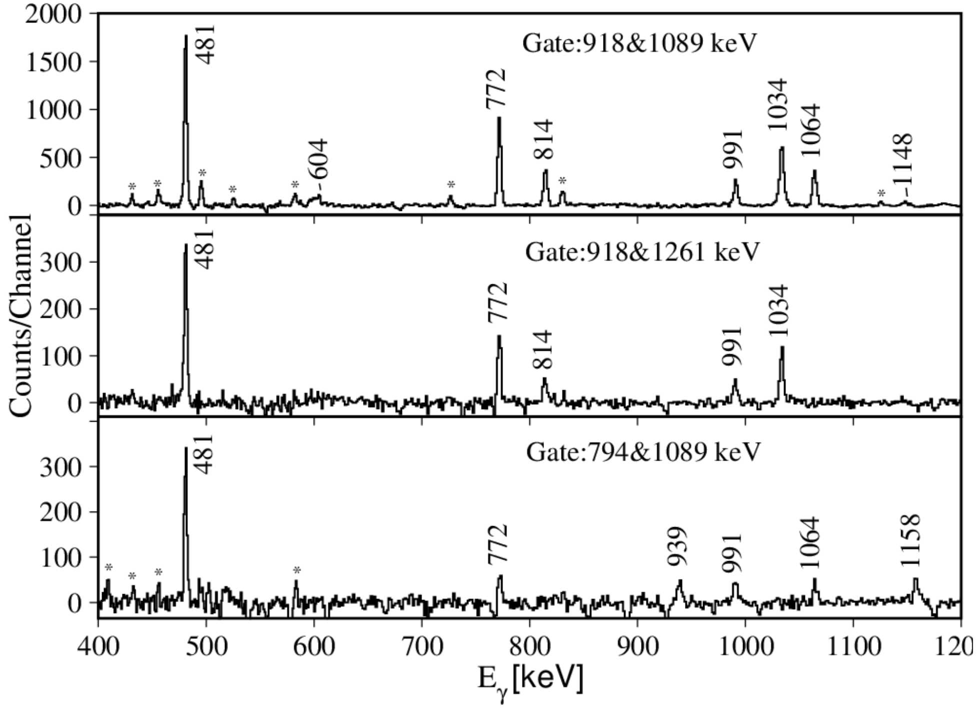
Search for wobbling bands in ^{105}Pd

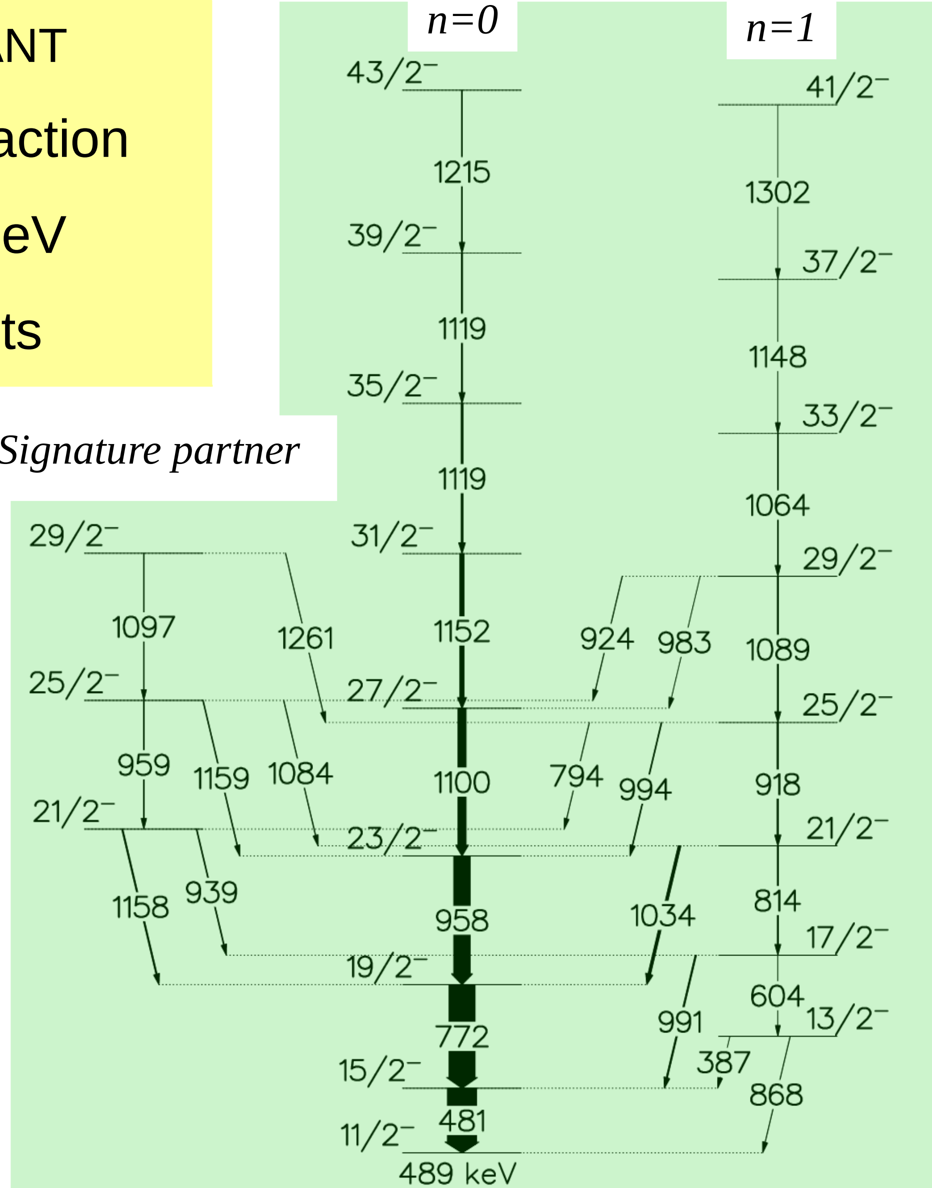
Experiment: using EUROBALL + DIAMANT

^{96}Zr(^{13}C,4n)^{105}Pd fusion-evaporation reaction

Beam energies of 51 MeV and 58 MeV

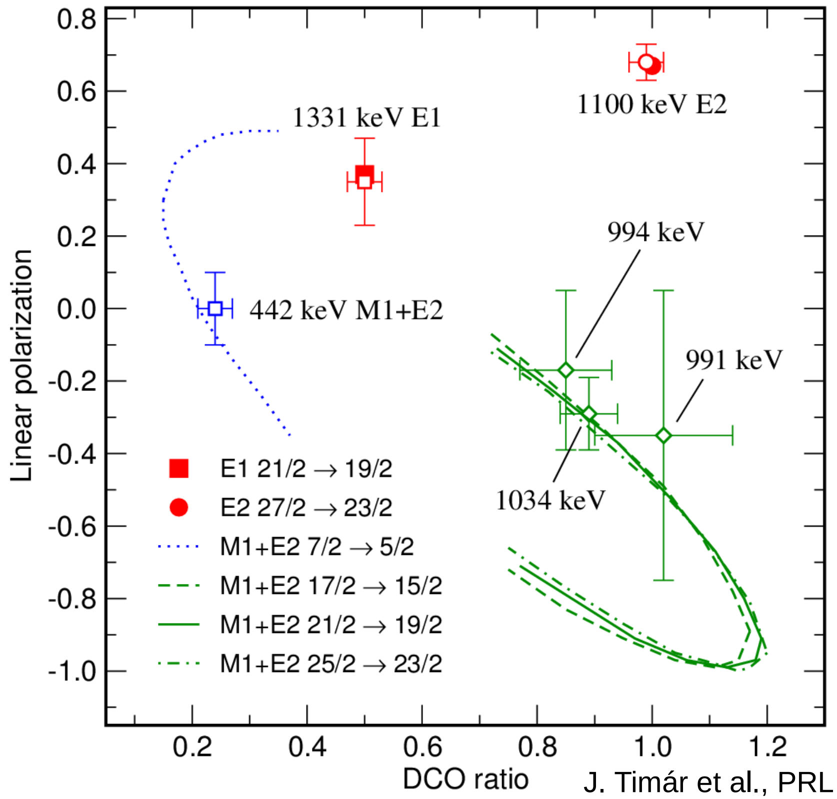
~ 2x10^{9} triple- and higher-fold events

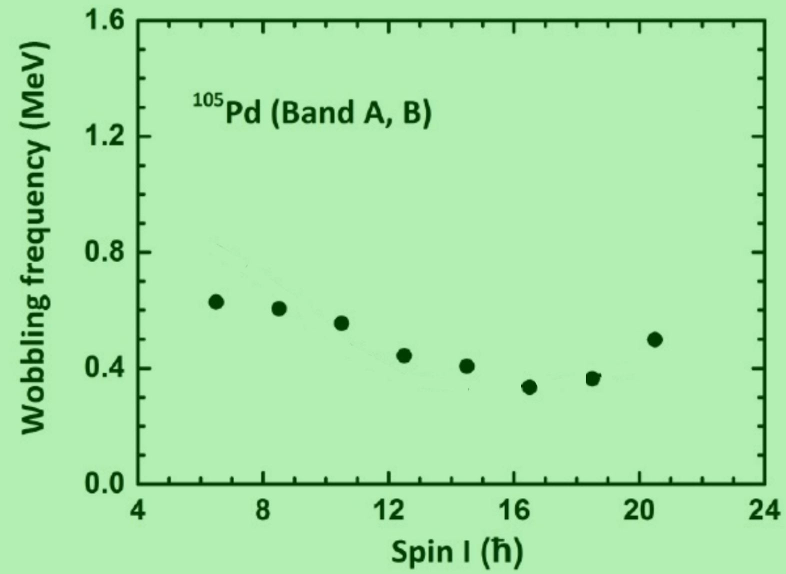




J. Timár et al., PRL 122, 062501 (2019)

Search for wobbling bands in ^{105}Pd





Wobbling frequency is decreasing with Increasing spin → transverse wobbling

J. Timár et al., PRL 122, 062501 (2019)

991 keV: δ=1.8(5) 76% E2
1034 keV: δ=2.3(3) 84% E2
994 keV: δ=2.7(6) 88% E2

- E2 contents are about the same as in the known wobbling cases → wobbling band
- the sign of δ is opposite

$$\mathrm{sign}(\delta) = -\mathrm{sign}\{(g_j - g_R)/Q_0\}$$

F. S. Stephens, Rev. Mod. Phys., 47 (1975) 43

- for high-J protons: g_j is large positive, $g_j - g_R > 0$
- for high-J neutrons: g_j is negative, $g_j - g_R < 0$

CDFT calculations for ^{105}Pd

Constrained triaxial covariant density functional theory (CDFT) calculations were performed for the low-energy configurations.

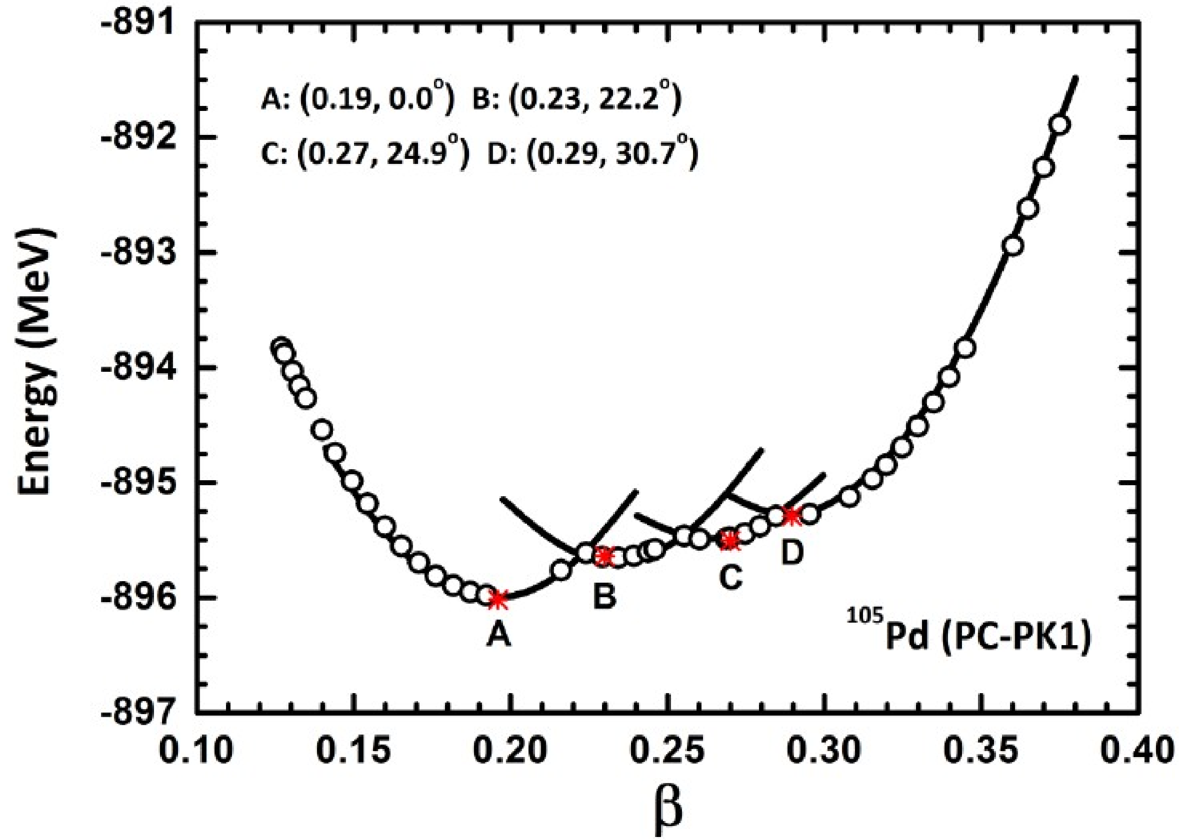
PHYSICAL REVIEW C **73**, 037303 (2006)

Possible existence of multiple chiral doublets in ^{106}Rh

J. Meng,[1,2,3,*] J. Peng,[1] S. Q. Zhang,[1] and S.-G. Zhou[2,3]
[1]*School of Physics, Peking University, Beijing 100871, China*
[2]*Institute of Theoretical Physics, Chinese Academy of Science, Beijing 100080, China*
[3]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China*
(Received 30 March 2005; published 15 March 2006)

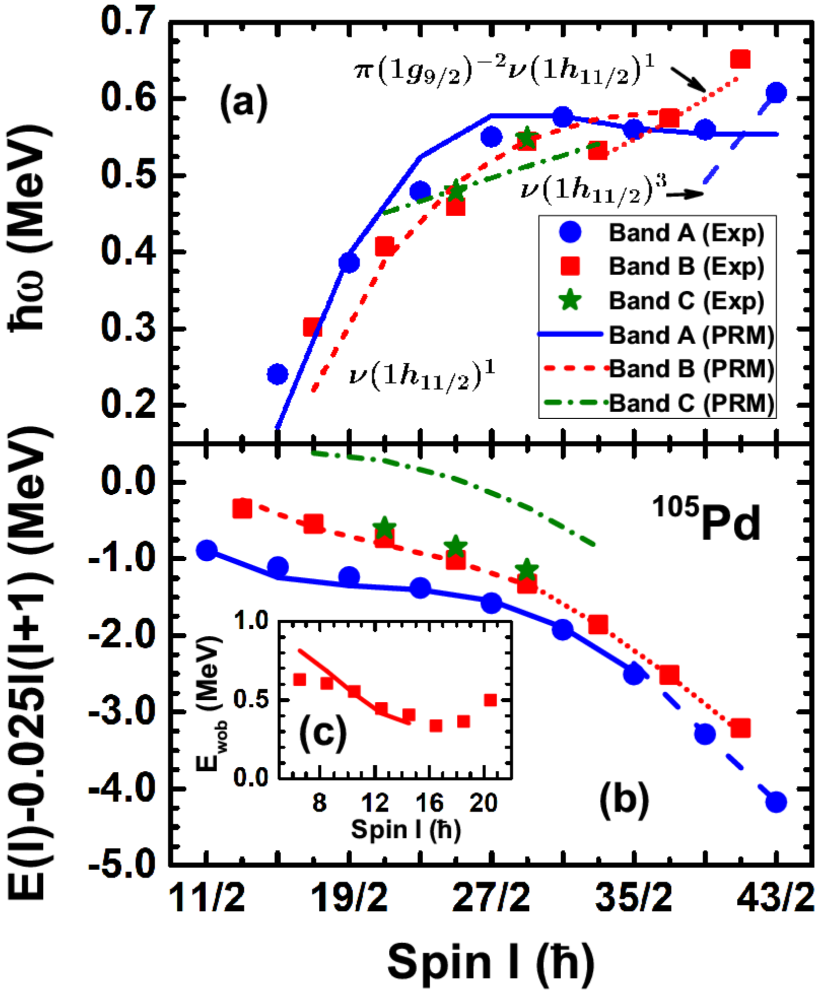
Adiabatic and configuration-fixed constrained triaxial relativistic mean field (RMF) approaches are developed for the first time. A new phenomenon, the existence of multiple chiral doublets (MχD), i.e., more than one pair of chiral doublet bands in one single nucleus, is suggested for ^{106}Rh based on the triaxial deformations and their corresponding proton and neutron configurations.

Triaxial shape has been found for the $\nu(1h_{11/2})$ configuration.



State	E_x	(β, γ)	Valence configuration	Unpaired configuration	π
A	0.00	(0.19, 0.0°)	$\pi(1g_{9/2})^6 \otimes \nu(1g_{7/2})^5(2d_{5/2})^4$	$\nu(1g_{7/2})^1$	+
B	0.38	(0.23, 22.2°)	$\pi(1g_{9/2})^8 \otimes \nu(1g_{7/2})^5(2d_{5/2})^4$	$\nu(1g_{7/2})^1$	+
C	0.51	(0.27, 24.9°)	$\pi(1g_{9/2})^8 \otimes \nu(1g_{7/2})^6(2d_{3/2})^2(1h_{11/2})^1$	$\nu(1h_{11/2})^1$	−
D	0.73	(0.29, 30.7°)	$\pi(1g_{9/2})^8 \otimes \nu(1g_{7/2})^3(2d_{5/2})^2(2d_{3/2})^2(1h_{11/2})^2$	$\nu(1g_{7/2})^1$	+

PRM calculations for ^{105}Pd



Particle rotor model (PRM) calculations were performed for the $\nu(1h_{11/2})$ configuration.

- the results describe well the experimental energies of the wobbling bands

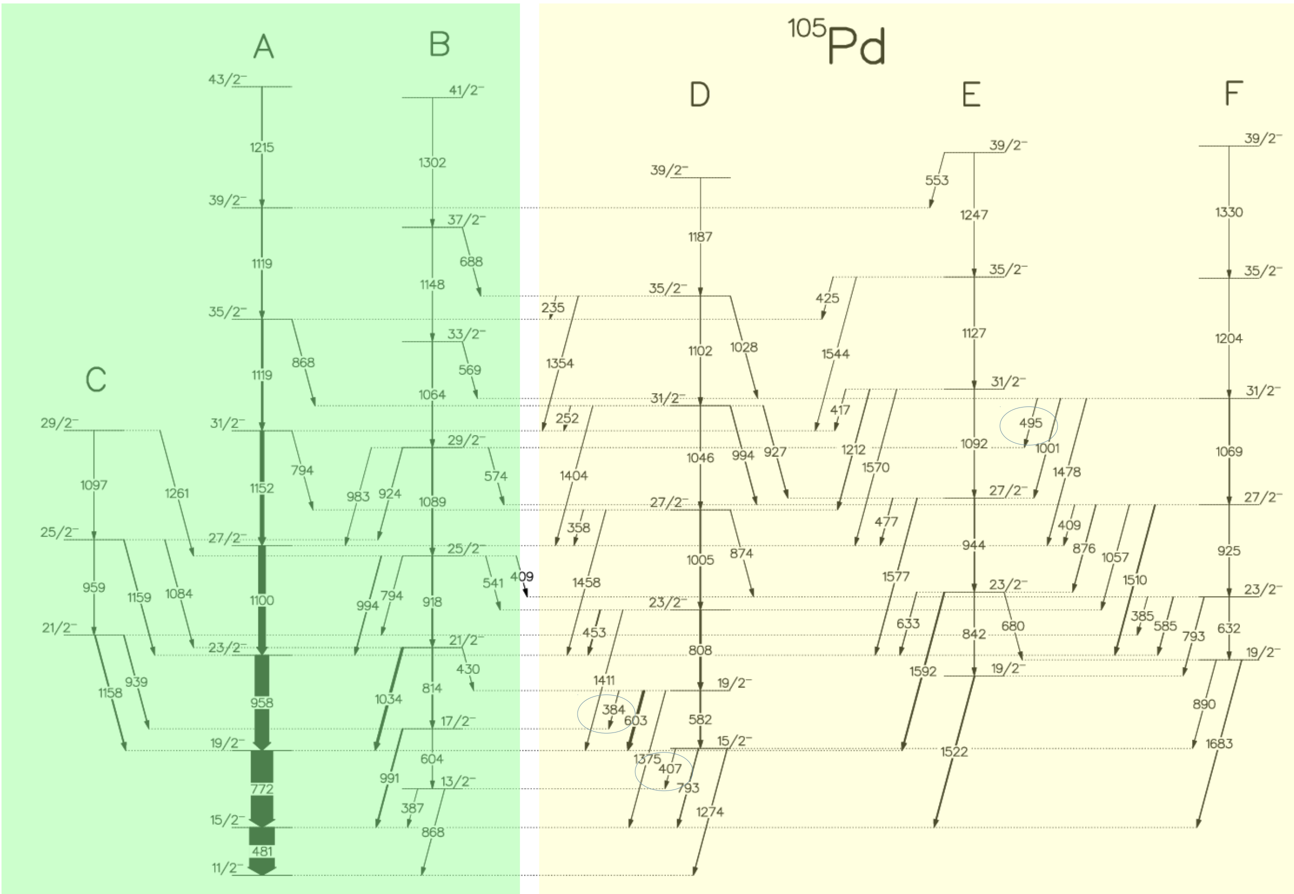
- they also describe well the experimental properties of the gamma decays

These results prove the wobbling nature of the observed Band C.

This is the first observed wobbling band in this mass region, and the first wobbling band based on neutron configuration.

		δ		$[B(M1)_{out}/B(E2)_{in}](\mu_N^2/e^2b^2)$		$[B(E2)_{out}/B(E2)_{in}]$	
$I_i^\pi \to I_f^\pi$	E_γ (keV)	Expt	PRM	Expt	PRM	Expt	PRM
$17/2^- \to 15/2^-$	991	1.8 ± 0.5	2.38	0.162 ± 0.097	0.105	0.66 ± 0.18	0.736
$21/2^- \to 19/2^-$	1034	2.3 ± 0.3	2.30	0.089 ± 0.026	0.069	0.60 ± 0.09	0.465
$25/2^- \to 23/2^-$	994	2.7 ± 0.6	1.99	0.029 ± 0.016	0.057	0.34 ± 0.07	0.329

Search for n=2 wobbling bands in ^{105}Pd



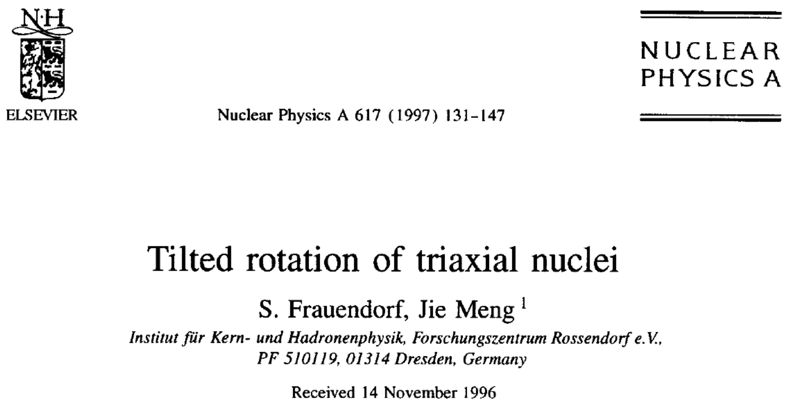
They decay mainly to the yrast band

Not n=2 wobbling bands

Plans for further search in the A~100 mass region:

- search for n=2 wobbling band
- search for longitudinal wobbling
- search for wobbling band with hole-type high-J proton configuration

Nuclear chirality



ELSEVIER

Nuclear Physics A 617 (1997) 131–147

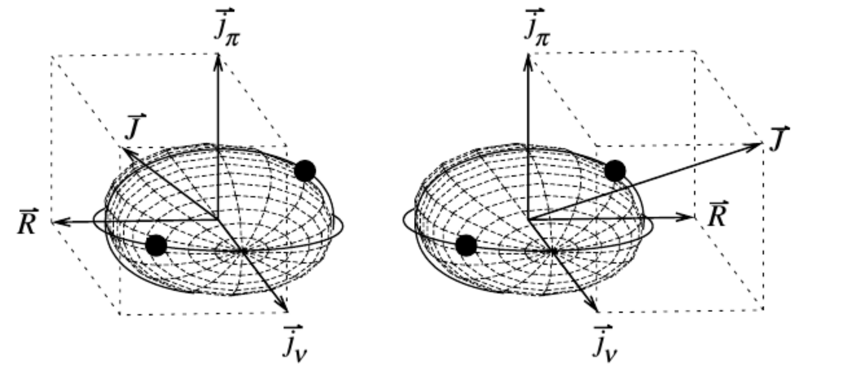
NUCLEAR PHYSICS A

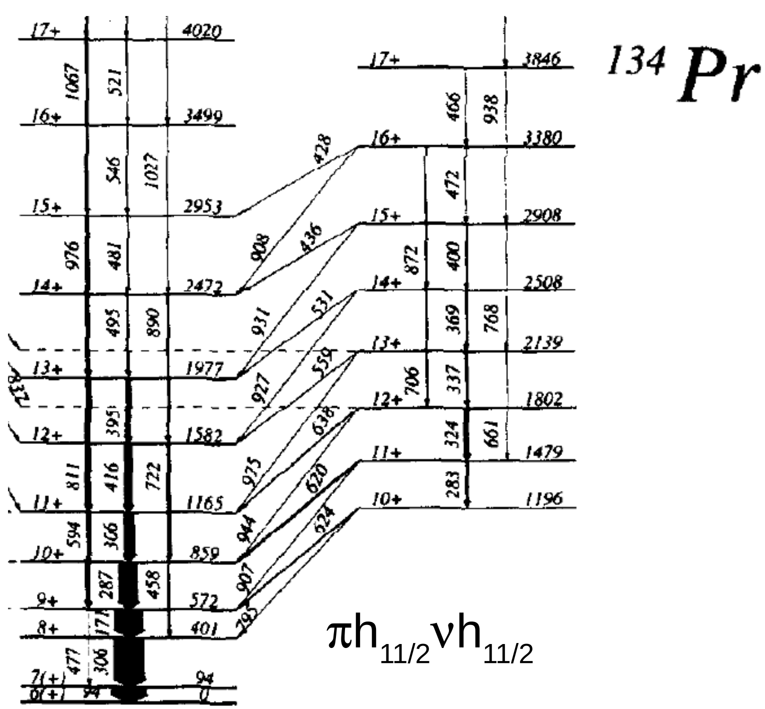
Tilted rotation of triaxial nuclei

S. Frauendorf, Jie Meng [1]

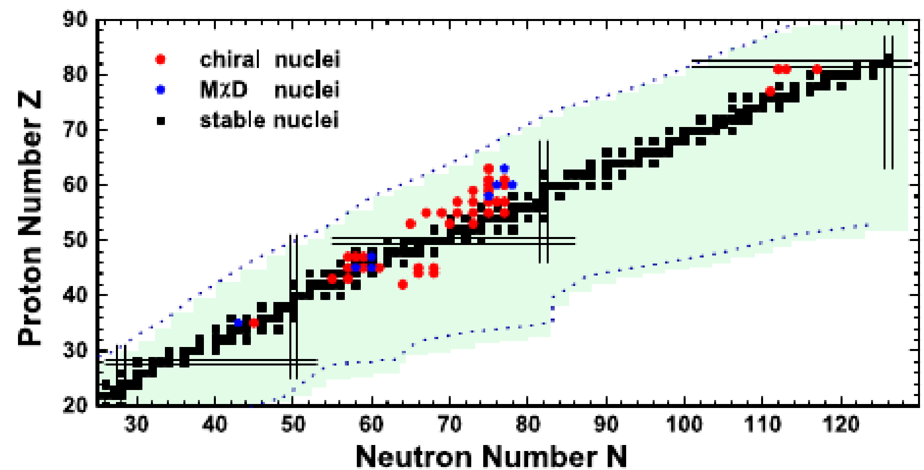
Institut für Kern- und Hadronenphysik, Forschungszentrum Rossendorf e.V., PF 510119, 01314 Dresden, Germany

Received 14 November 1996





C. M. Petrache et al., Nucl. Phys. A597, 106 (1996).



B.W. Xiong, Y.Y. Wang / Atomic Data and Nuclear Data Tables 125 (2019) 193–225

Another recent review:
K Starosta and T Koike, Phys. Scr. 92 (2017) 093002

They do not represent static chirality

- *D. Tonev et al., Phys. Rev. Lett. 96, 052501 (2006)*
- *C. M. Petrache et al., Phys. Rev. Lett. 96, 112502 (2006)*

Multiple chiral doublet bands (MχD)

PHYSICAL REVIEW C **73**, 037303 (2006)

Possible existence of multiple chiral doublets in ^{106}Rh

J. Meng,[1,2,3,*] J. Peng,[1] S. Q. Zhang,[1] and S.-G. Zhou[2,3]
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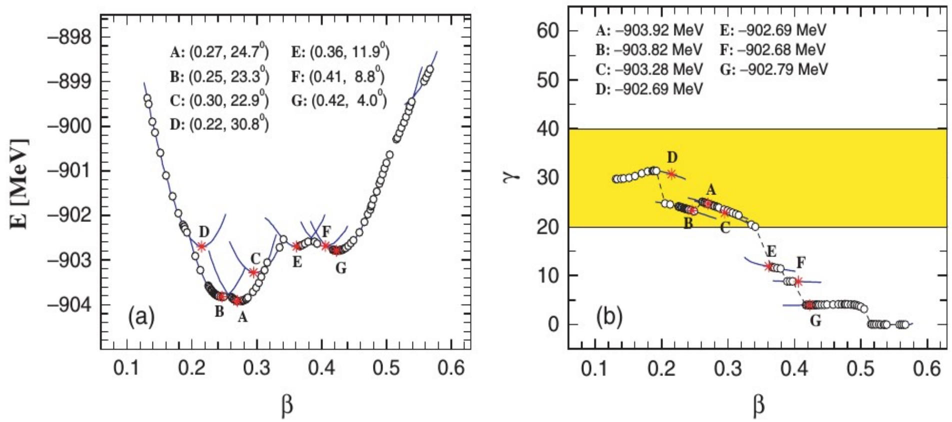
(Received 30 March 2005; published 15 March 2006)

Adiabatic and configuration-fixed constrained triaxial relativistic mean field (RMF) approaches are developed for the first time. A new phenomenon, the existence of multiple chiral doublets (MχD), i.e., more than one pair of chiral doublet bands in one single nucleus, is suggested for ^{106}Rh based on the triaxial deformations and their corresponding proton and neutron configurations.



Evidence for Multiple Chiral Doublet Bands in ^{133}Ce

A. D. Ayangeakaa,[1] U. Garg,[1] M. D. Anthony,[1] S. Frauendorf,[1] J. T. Matta,[1] B. K. Nayak,[1,*] D. Patel,[1] Q. B. Chen (陈启博),[2] S. Q. Zhang (张双全),[2] P. W. Zhao (赵鹏巍),[2] B. Qi (亓斌),[3] J. Meng (孟杰),[2,4,5] R. V. F. Janssens,[6] M. P. Carpenter,[6] C. J. Chiara,[6,7] F. G. Kondev,[8] T. Lauritsen,[6] D. Seweryniak,[6] S. Zhu,[6] S. S. Ghugre,[9] and R. Palit[10,11]
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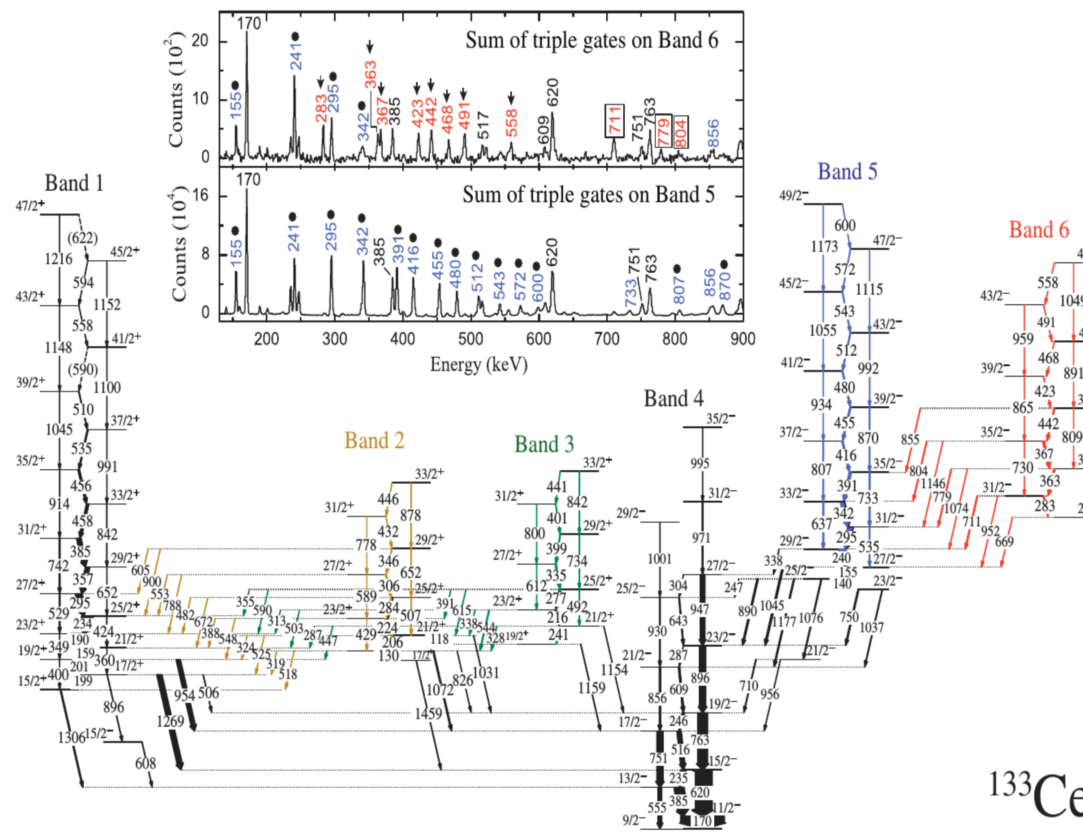
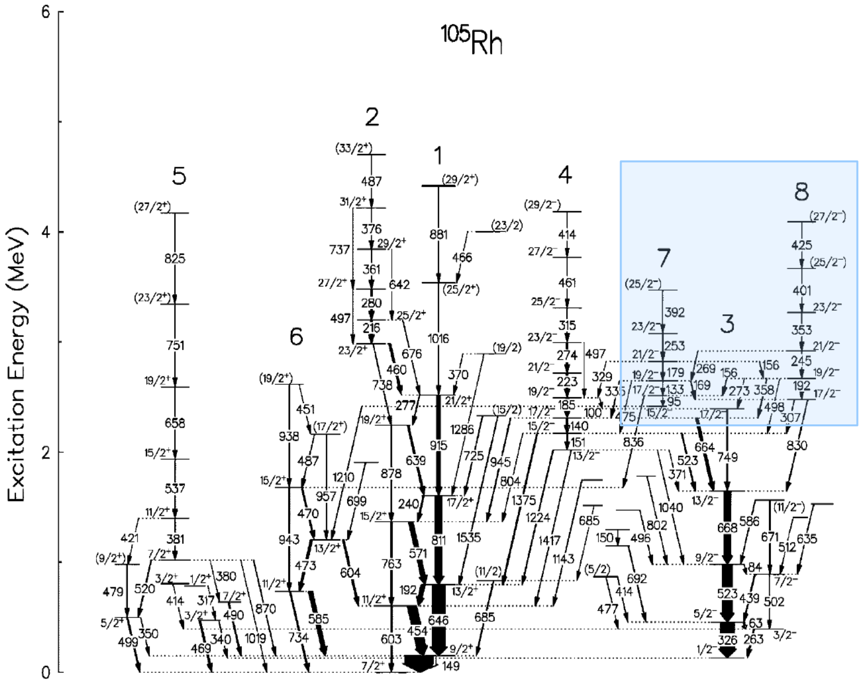
[7]*Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA*
[8]*Nuclear Engineering Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[9]*UGC-DAE Consortium for Science Research, Kolkata 700 098, India*
[10]*Tata Institute of Fundamental Research, Mumbai 400 005, India*
[11]*The Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
(Received 31 January 2013; published 24 April 2013)

Two distinct sets of chiral-partner bands have been identified in the nucleus ^{133}Ce. They constitute a multiple chiral doublet, a phenomenon predicted by relativistic mean field (RMF) calculations and observed experimentally here for the first time. The properties of these chiral bands are in good agreement with results of calculations based on a combination of the constrained triaxial RMF theory and the particle-rotor model.



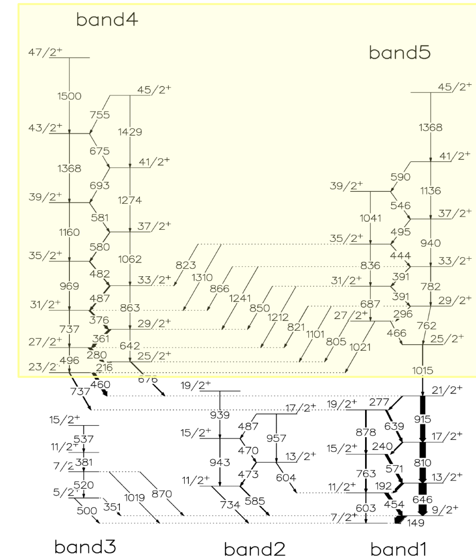
First hints for multiple chiral doublet bands



J. A. ALCÁNTARA-NÚÑEZ *et al.* PHYSICAL REVIEW C **69**, 024317 (2004)

$\pi g_{9/2} \otimes \nu h_{11/2}(g_{7/2}, d_{5/2})$ excited $\pi g_{9/2}$ $\varepsilon_2 = 0.21, \gamma = 30°$

Hybrid TAC model



J. Timár et al. / Physics Letters B 598 (2004) 178–187

$\pi g_{9/2} \nu (h_{11/2})^2$

$\epsilon_2 = 0.224, \ \gamma = 29°$

TAC calculations

PHYSICAL REVIEW C **83**, 037301 (2011)

Multiple chiral doublet candidate nucleus ^{105}Rh in a relativistic mean-field approach

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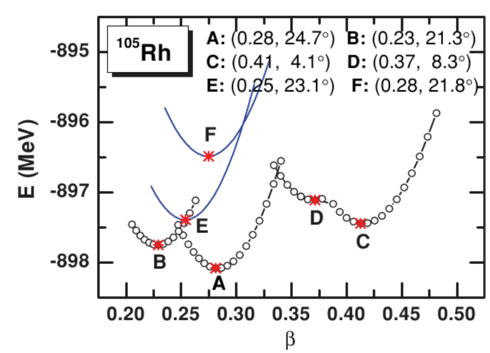
School of Physics, State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

J. Meng (孟杰)*
School of Physics and Nuclear Energy Engineering, Beihang University, Beijing 100191, China,
School of Physics, State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China and
Department of Physics, University of Stellenbosch, Stellenbosch, South Africa
(Received 7 January 2011; published 10 March 2011)

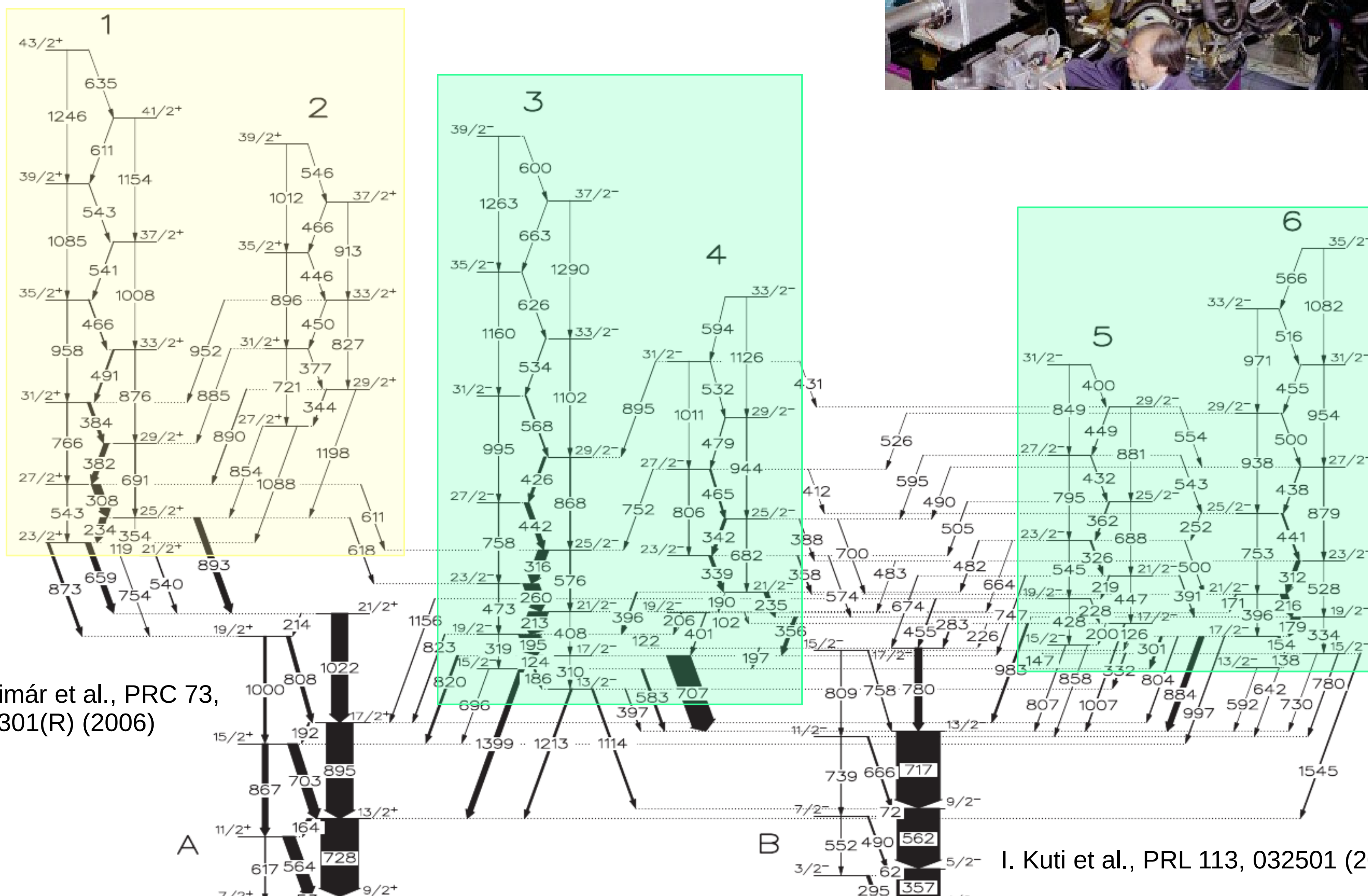
Adiabatic and configuration-fixed constrained triaxial relativistic mean-field calculations: MχD bands in ^{105}Rh are highly expected E: $\pi g_{9/2} \otimes \nu h_{11/2} (g_{7/2}, d_{5/2})$

F: $\pi g_{9/2} \otimes \nu (h_{11/2})^2$



Multiple chiral doublets in ^{103}Rh

Experiment: with the GAMMASPHERE array
$^{96}Zr(^{11}B,4n)^{103}Rh$ fusion-evaporation reaction
Beam energy of 40 MeV
~ 9×10^{8} quadruple- and higher-fold events
Strongest reaction channel



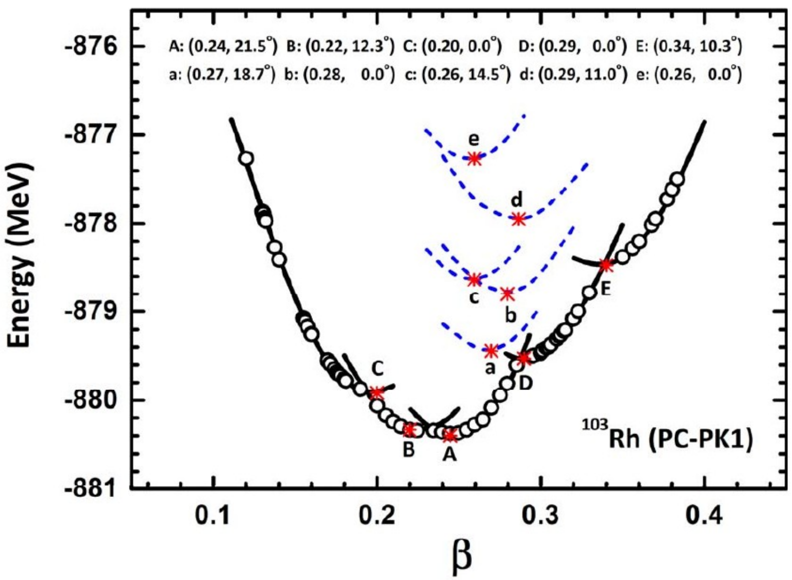
J. Timár et al., PRC 73, 011301(R) (2006)

I. Kuti et al., PRL 113, 032501 (2014)

Multiple chiral doublets in ^{103}Rh

Calculations in 3 steps (J. Meng et al., PRC 73, 037303 (2006))

- adiabatic and configuration fixed constrained CDFT: configurations, deformations



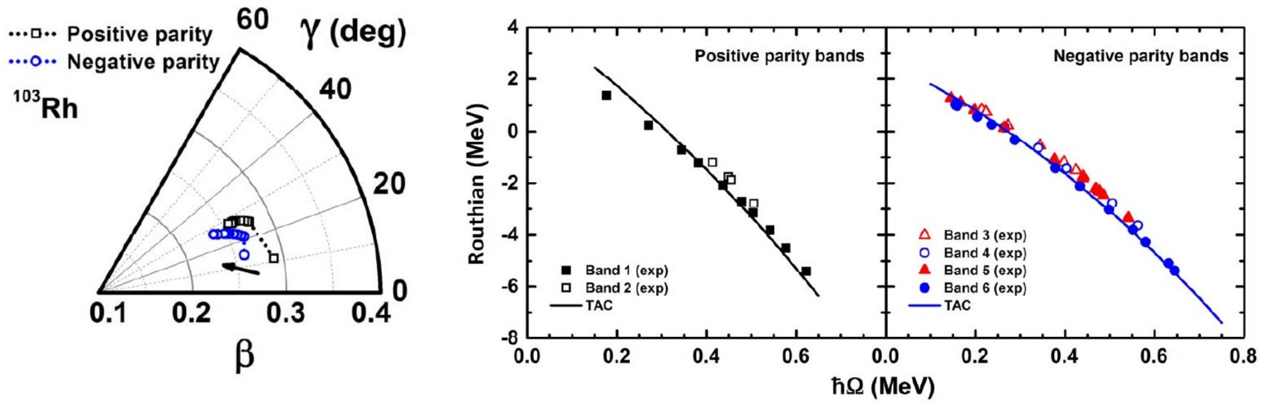
A,B,C,D,E: configurations with no unpaired neutron
a,b,c,d,e: configurations with unpaired neutrons

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

c: $\pi(1g_{9/2})^{-1}\otimes\nu(1h_{11/2})^{1}(1g_{7/2})^{-1}$

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

- TAC CDFT: rotational behavior of bands (only the high-J orbitals fixed)



Positive parity bands:
$\pi(1g_{9/2})^{-1}\otimes\nu(1h_{11/2})^{2}$

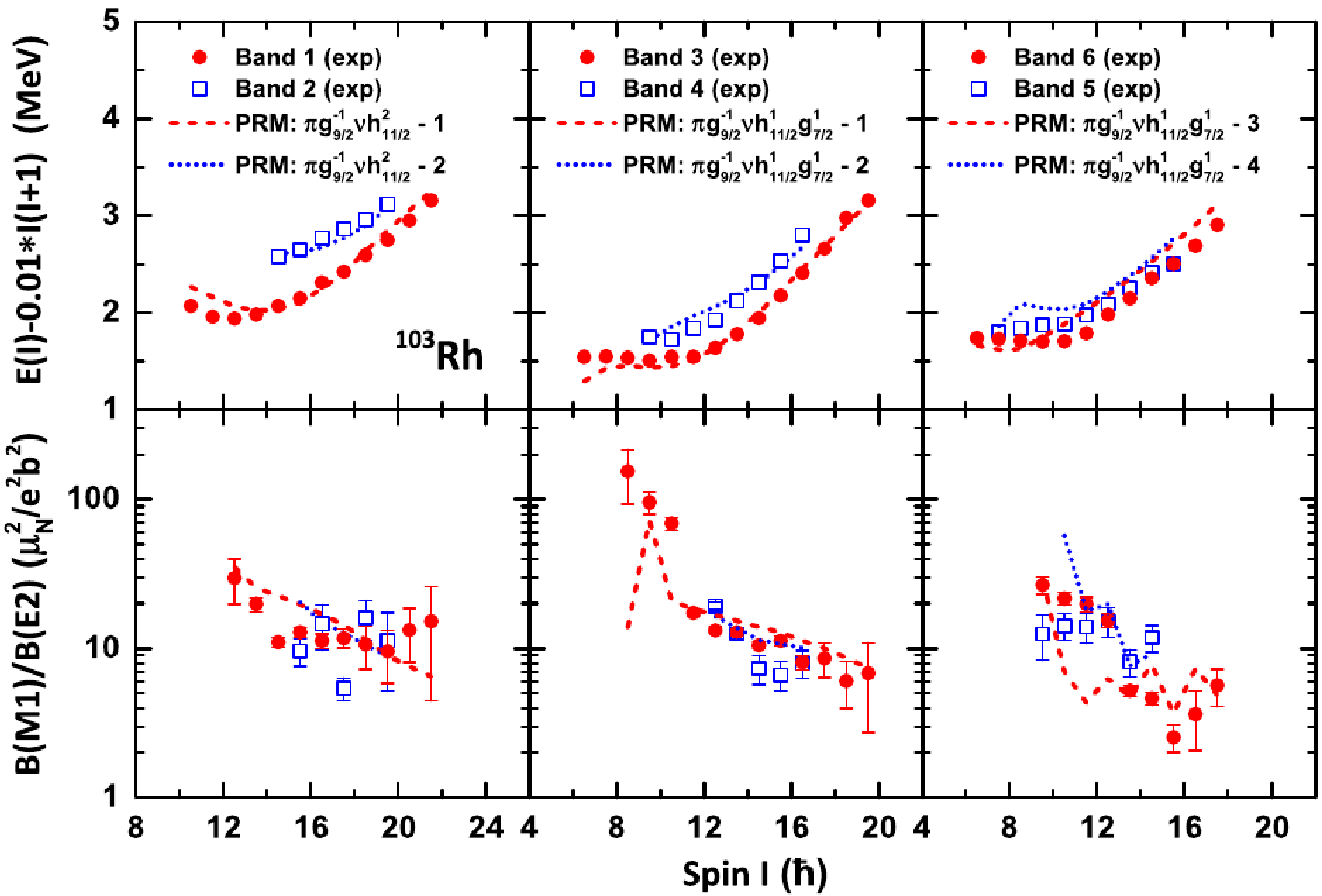
Negative parity bands:
$\pi(1g_{9/2})^{-1}\otimes\nu(1h_{11/2})^{1}$

Effective configuration for the negative parity bands:
$\pi(1g_{9/2})^{-1}\otimes\nu(1h_{11/2})^{1}(1g_{7/2})^{1}$

Multiple chiral doublets in ^{103}Rh

- PRM calculations: energy spectra and B(M1)/B(E2) ratios

β and γ were taken from the TAC CDFT results
moments of inertia were fitted to the energy spectra of the bands



3 chiral doublets

2 belong to the same $\pi(1g_{9/2})^{-1} \otimes \nu(1h_{11/2})^1(1g_{7/2})^1$ configuration

First such MχD

Chiral geometry can be robust against intrinsic excitation.

Possible multiple chiral doublets in ^{104}Rh

PHYSICAL REVIEW C **77**, 024309 (2008)

Search for multiple chiral doublets in rhodium isotopes

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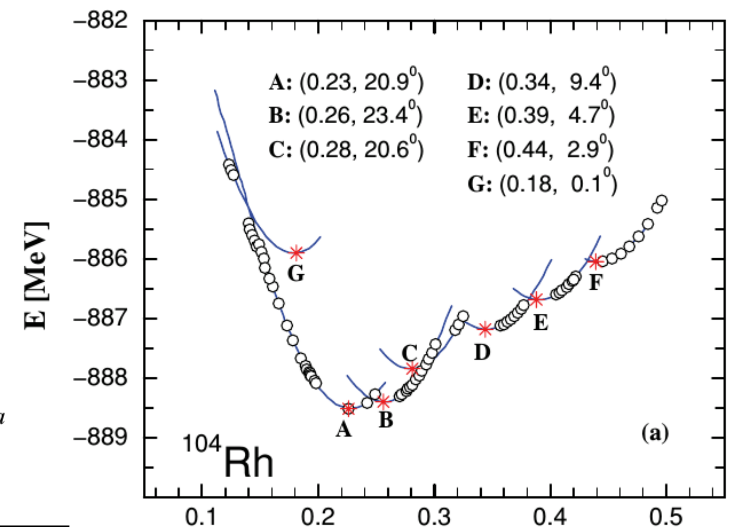
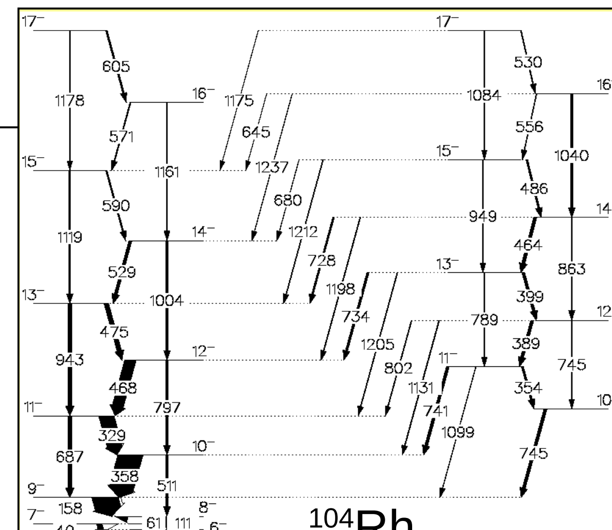


Nuclei	State	$E_{\rm cal}$	$\beta_{\rm cal}$	$\gamma_{\rm cal}$	Valence nucleon configuration
	A	−888.51	0.23	20.9°	$\pi g_{9/2}^{-3} \otimes \nu(2d_{5/2})^1$
	B	−888.40	0.26	23.4°	$\pi g_{9/2}^{-3} \otimes \nu h_{11/2}^1$
	C	−887.84	0.28	20.6°	$\pi g_{9/2}^{-3} \otimes \nu[h_{11/2}^2 g_{7/2}^{-1}]$
^{104}Rh	D	−887.18	0.34	9.4°	$\pi g_{7/2}^{1} \otimes \nu h_{11/2}^3$
	E	−886.69	0.39	4.7°	$\pi(2p_{3/2})^{-1} \otimes \nu h_{11/2}^3$
	F	−885.05	0.44	2.9°	$\pi(2p_{3/2})^{-1} \otimes \nu(h_{11/2}^4 g_{9/2}^{-1})$
	G	−885.90	0.18	0.1°	$\pi g_{9/2}^{-5} \otimes \nu(2d_{5/2})^1$



Vaman et al., Phys. Rev. Lett. 92 (2004) 032501.

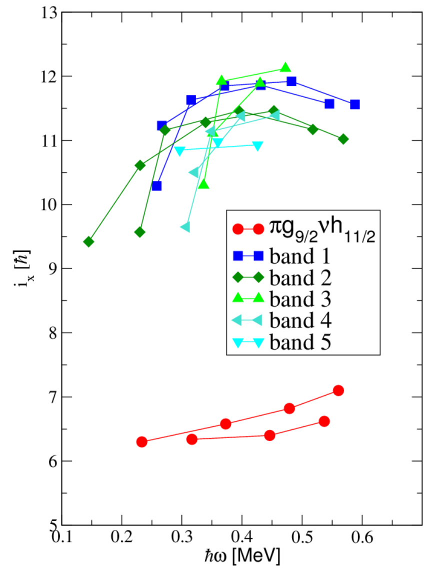
The positive-parity band structure is not well known.

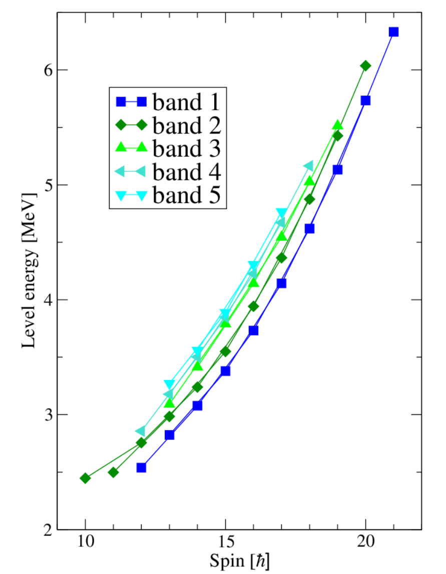
Possible multiple chiral doublets in ^{104}Rh (PRELIMINARY)

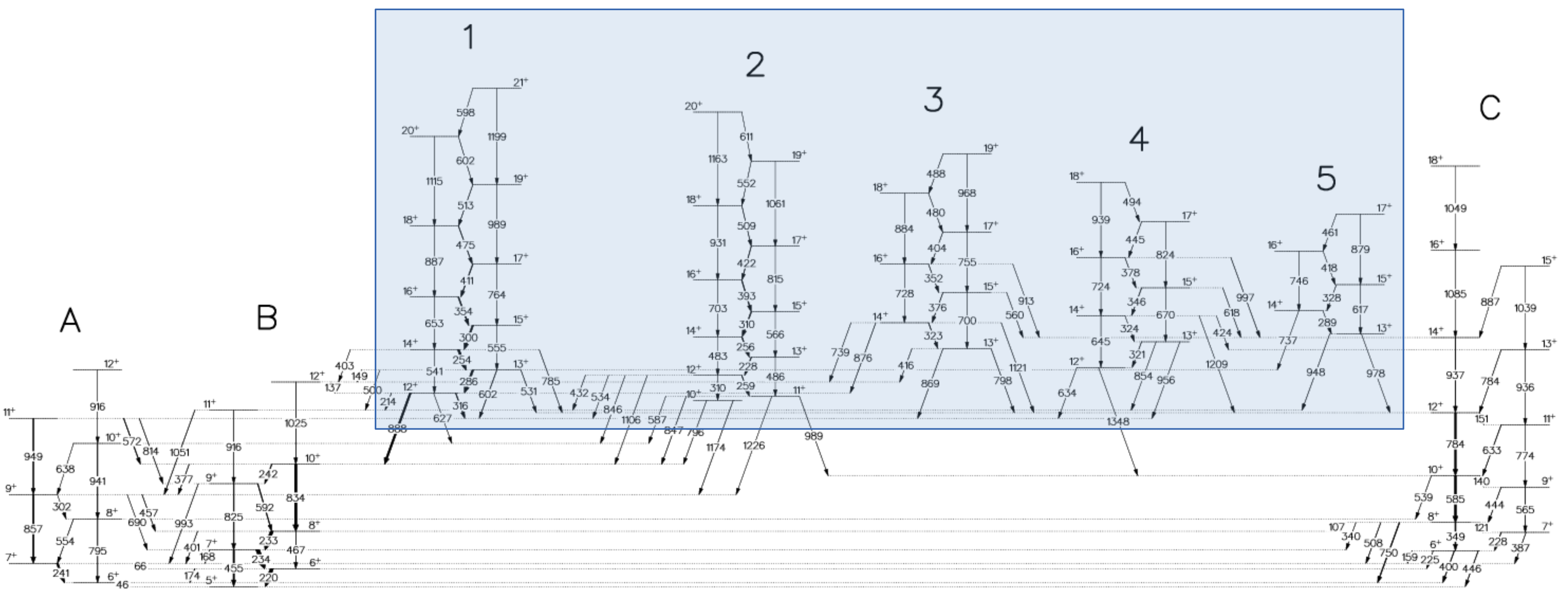
Experiment: with GAMMASPHERE array
^{11}B beam on ^{96}Zr target at 40 MeV
fusion-evaporation reaction
~ 9×10^8 quadruple- and higher-fold events
second strongest reaction channel

- Based on their parity and alignment, bands 1,2,3,4,5 have the same $\pi(1g_{9/2})^{-1} \otimes \nu(1h_{11/2})^2$ high-J config.
- They are near degenerate (separations: ~100-200 keV)

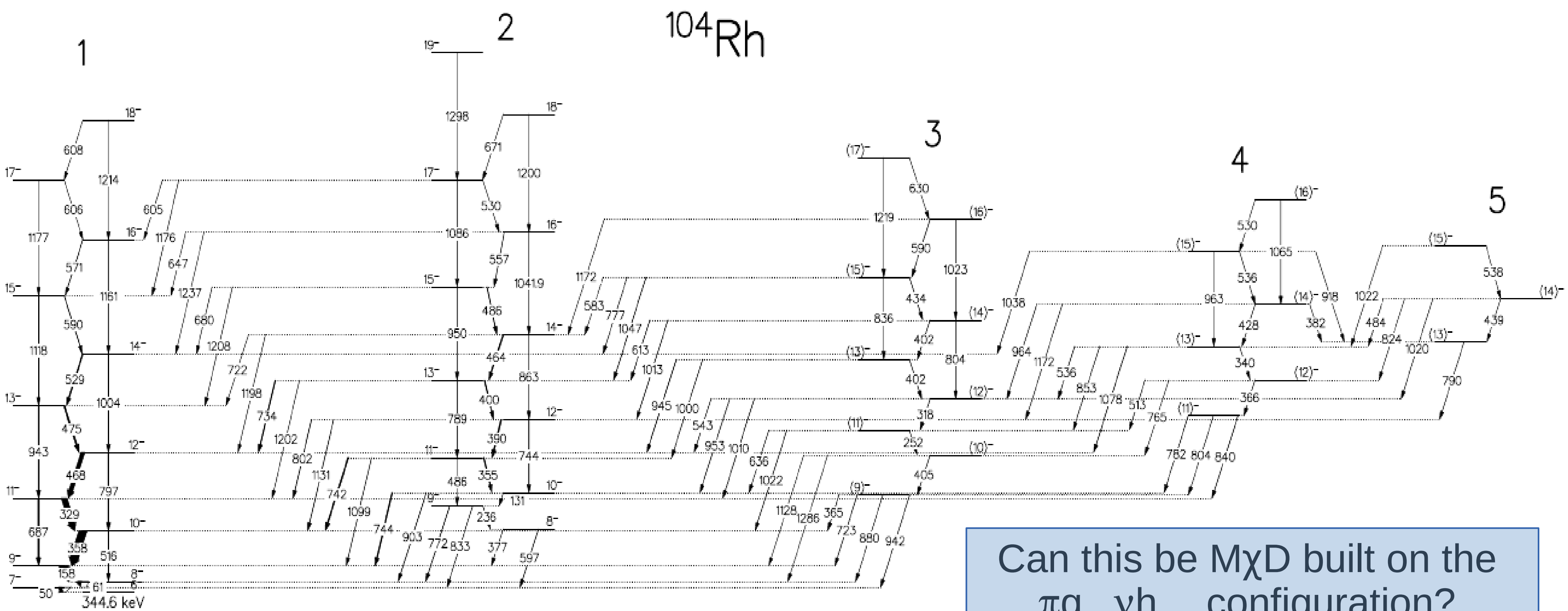
There may be chiral band-pair among them



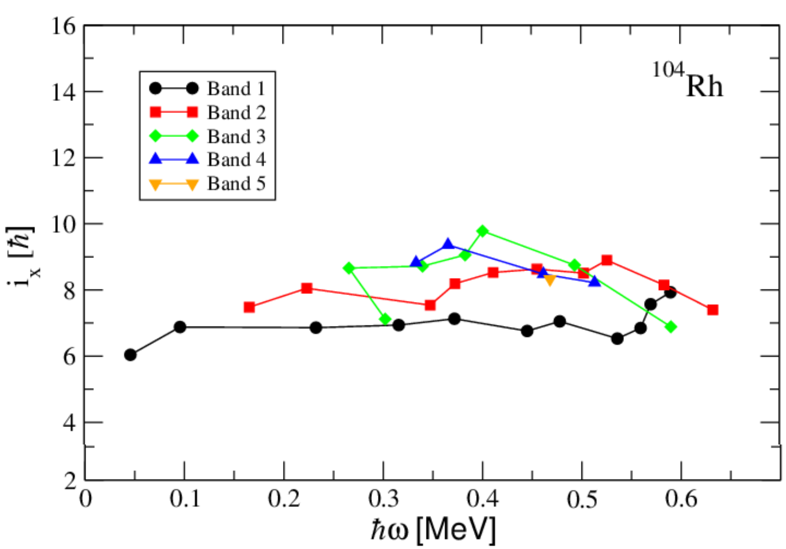


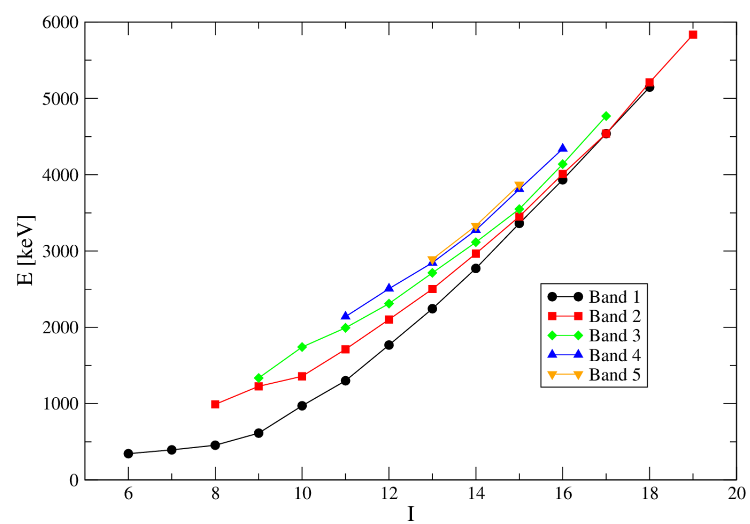


Possible multiple chiral doublets in ^{104}Rh (RELIMINARY)



Can this be MχD built on the $\pi g_{9/2} \nu h_{11/2}$ configuration?





Possible multiple chiral doublets in ^{104}Rh

PHYSICAL REVIEW C **88**, 024327 (2013)

Possible presence and properties of multi-chiral-pair bands in odd-odd nuclei with the same intrinsic configuration

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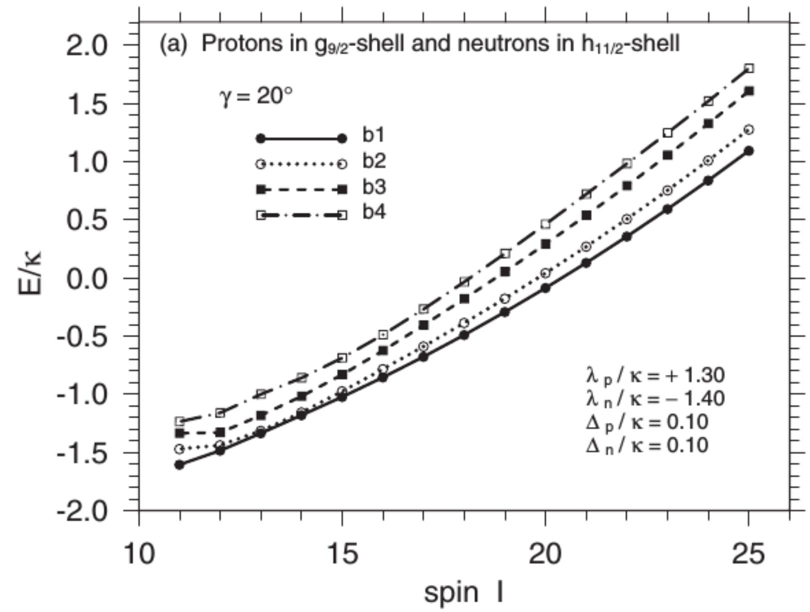
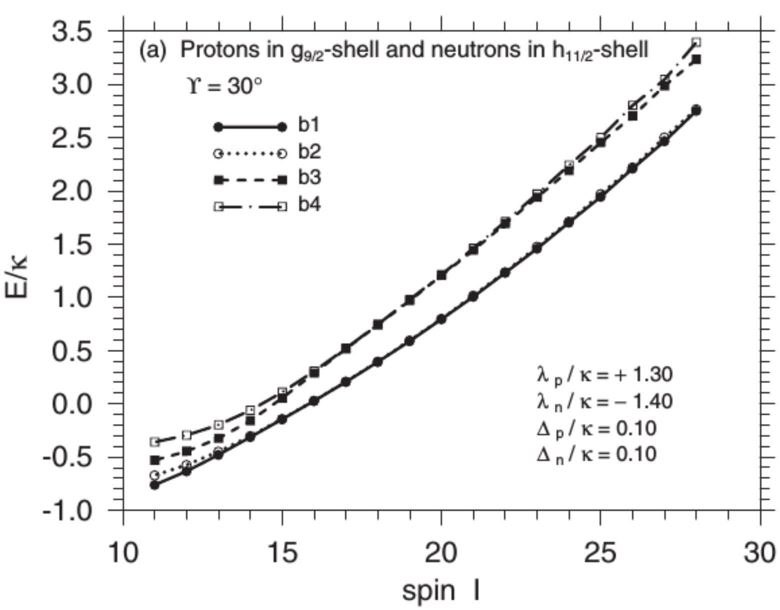
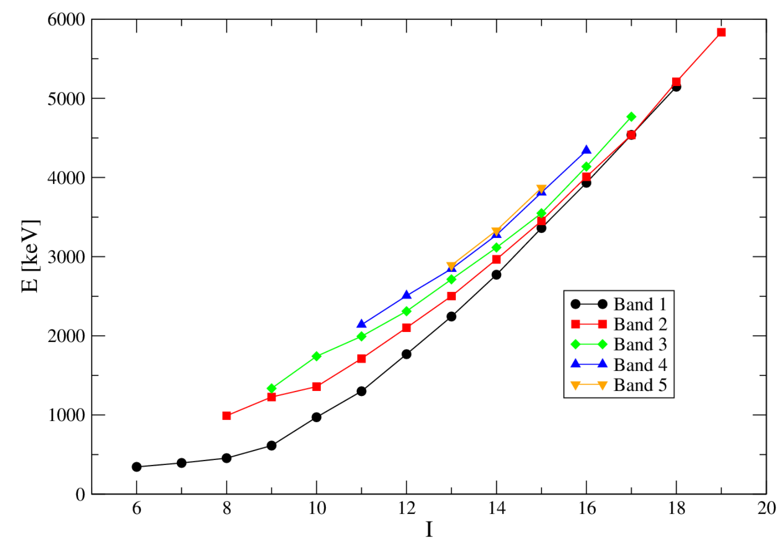


PRM calculations: "When the chiral condition is almost fulfilled, the energy distance between the first pair and the second pair for the same angular momentum is typically (an order of 1 MeV) several times larger compared with the splitting of the two (almost degenerate) levels belonging to a given chiral pair band."

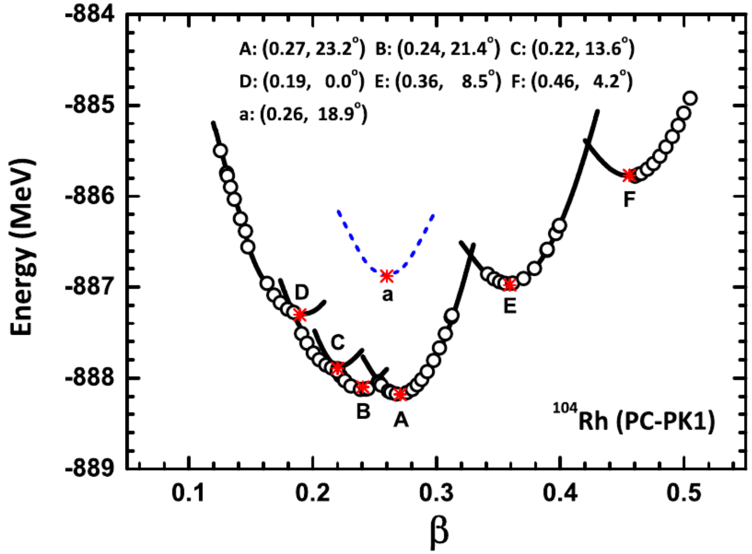




Bands 1,2,3,4 do not correspond to MχD based on the same configuration

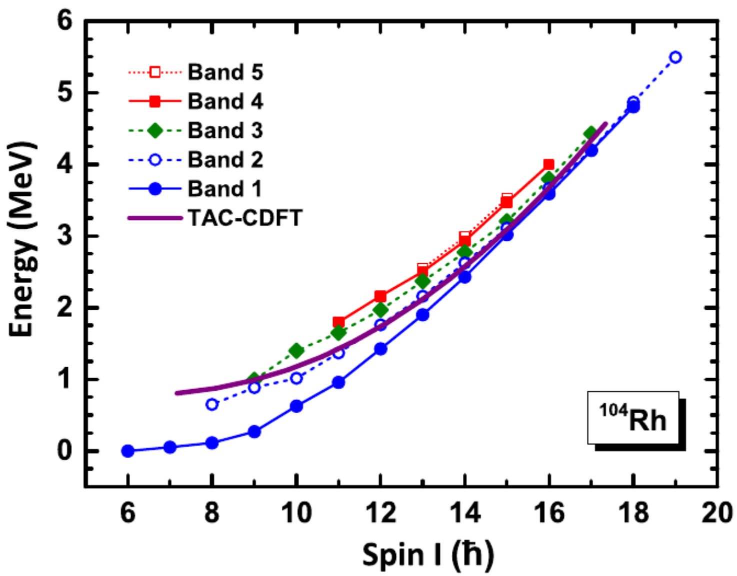
CDFT and TAC-CDFT calculations (PRELIMINARY)

CDFT



State	E_x	(β, γ)	Unpaired configuration	π
A	0.00	$(0.27, 23.2°)$	$\pi(1g_{9/2})^{-1} \otimes \nu(1h_{11/2})^1$	$-$
B	0.08	$(0.24, 21.4°)$	$\pi(1g_{9/2})^{-1} \otimes \nu(1g_{7/2})^{-1}$	$+$
C	0.29	$(0.22, 13.6°)$	$\pi(2p_{1/2})^1 \otimes \nu(1g_{7/2})^{-1}$	$-$
D	0.87	$(0.19, 0.0°)$	$\pi(1g_{9/2})^1 \otimes \nu(1g_{7/2})^{-1}$	$+$
E	1.21	$(0.36, 8.5°)$	$\pi(1g_{7/2})^1 \otimes \nu(1h_{11/2})^1$	$-$
F	2.41	$(0.46, 4.2°)$	$\pi(2p_{3/2})^{-1} \otimes \nu(1g_{9/2})^{-1}$	$-$
a	1.30	$(0.26, 18.9°)$	$\pi(1g_{9/2})^{-1} \otimes \nu(1g_{7/2}, 2d_{5/2})^2(1h_{11/2})^1$	$-$

TAC-CDFT



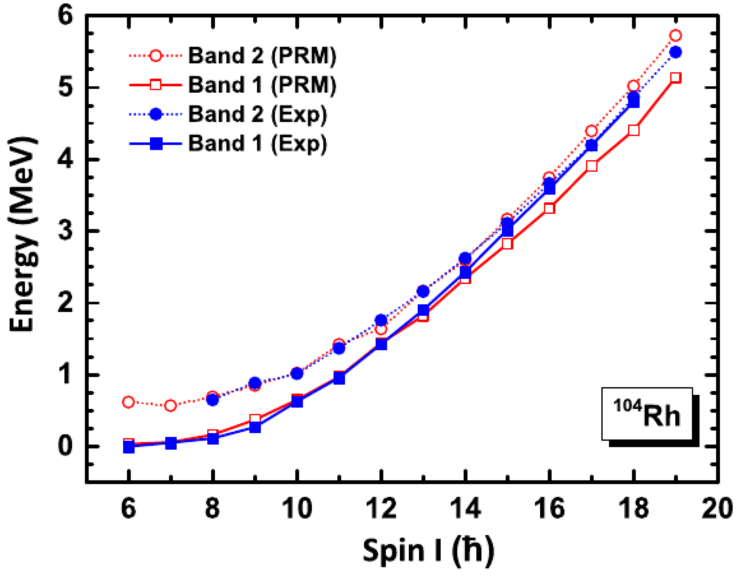
High-J orbitals were fixed during the calculation

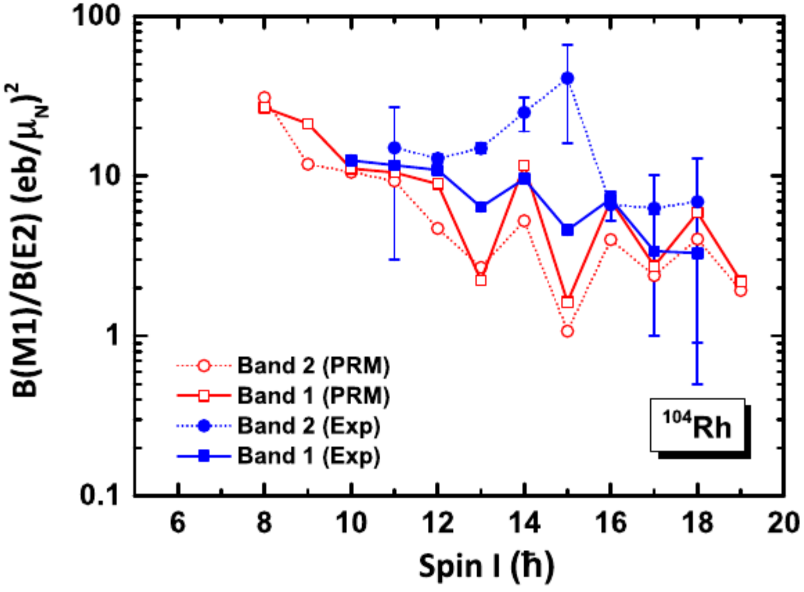
The “effective” configuration of the remaining 8 neutrons can be described as $\nu(1g_{7/2},2d_{5/2})^2$

Good agreement with bands 2,3 and with band 1 at higher spins

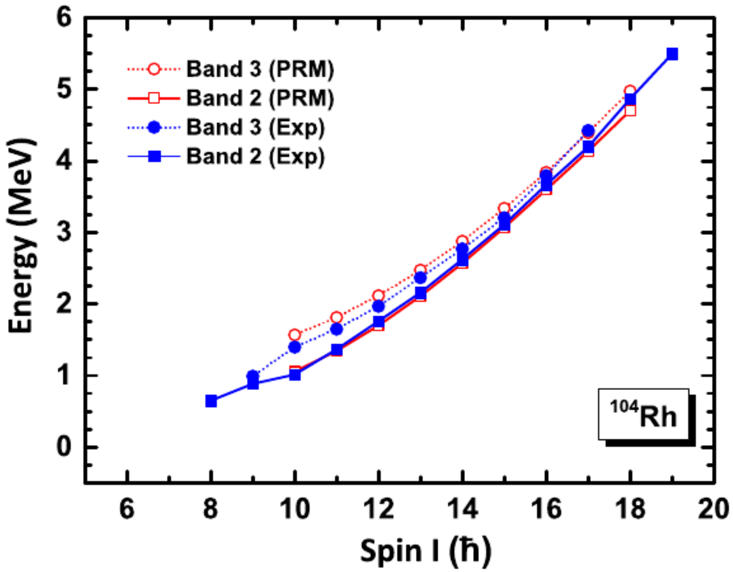
PRM calculations (PRELIMINARY)

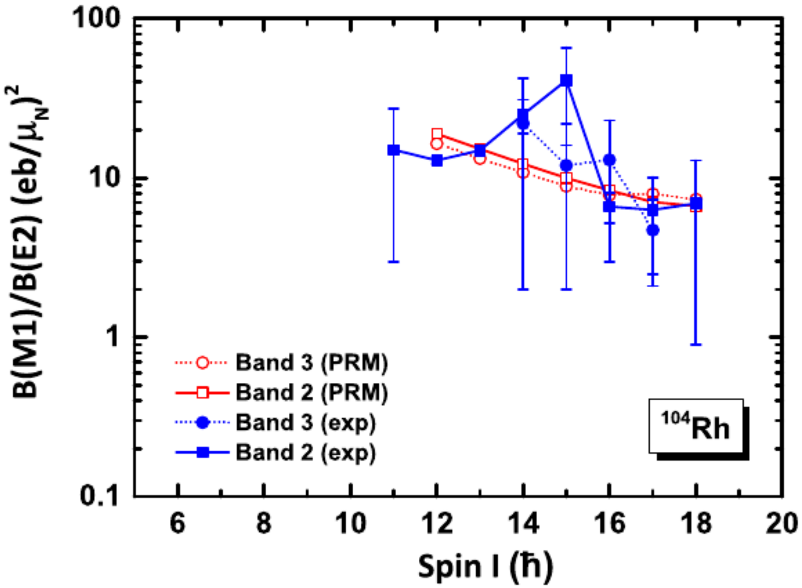
$\pi(1g_{9/2})^{-1} \otimes \nu(1h_{11/2})^{1}$





$\pi(1g_{9/2})^{-1} \otimes \nu(1h_{11/2})^{1}(2d_{5/2},1g_{7/2})^{2}$





Possible MχD with the two above configurations

Summary

Evidence for transverse wobbling in ^{105}Pd has been found

- first observation of wobbling in the A~100 region
- first observation of wobbling band based on one-neutron configuraton

Existence of MχD is proved or possible in several nuclides of the A~100 region

- hints of MχD in ^{105}Rh
- proved MχD based on the same configuration in ^{103}Rh
- possible MχD in ^{104}Rh

Conclusion

Wobbling and multiple chiral bands exist in the A~100 mass region in agreement with the predicted triaxiality

An important thing that we have learnt:

Do not throw away the old experimental data, they can be useful in the future!