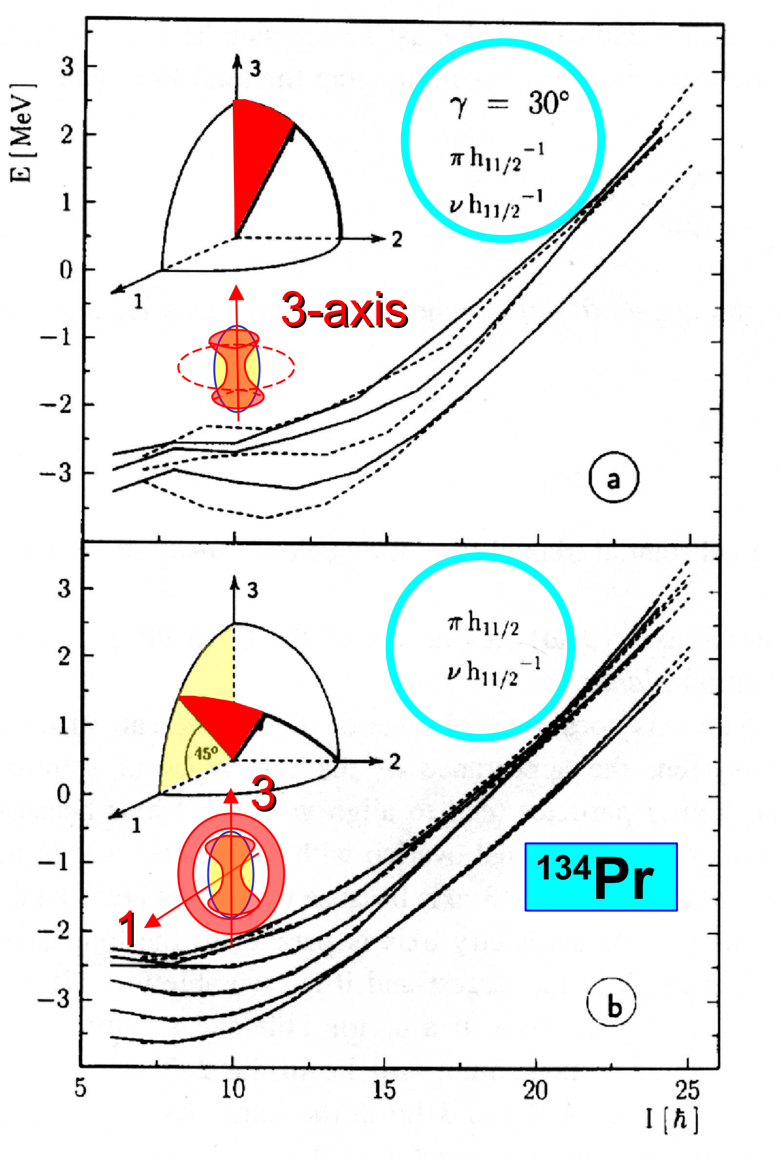
# Chiral bands in nuclei
# Experimental status

C. Petrache
University Paris Sud and CSNSM

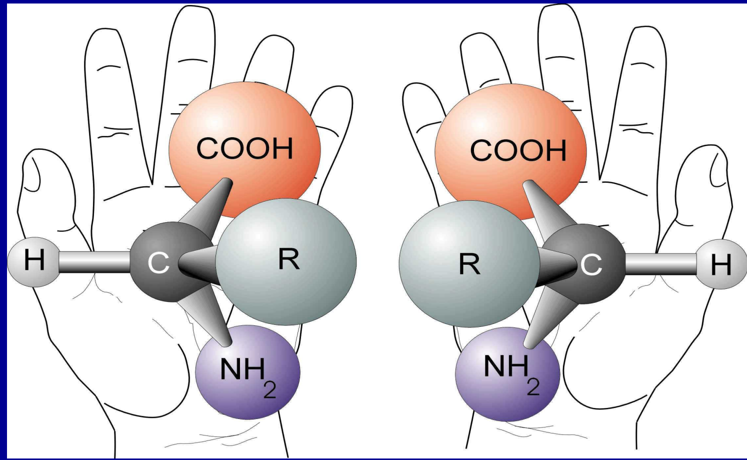
- Historical elements
- Main actors on the experimental side
- Experimental fingerprints
- Mass regions of interest

# Chirality in triaxial nuclei

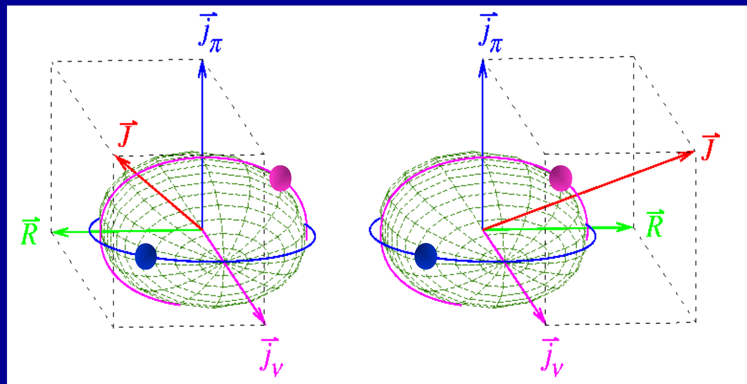
**1997**




## Static chirality




## Dynamic chirality

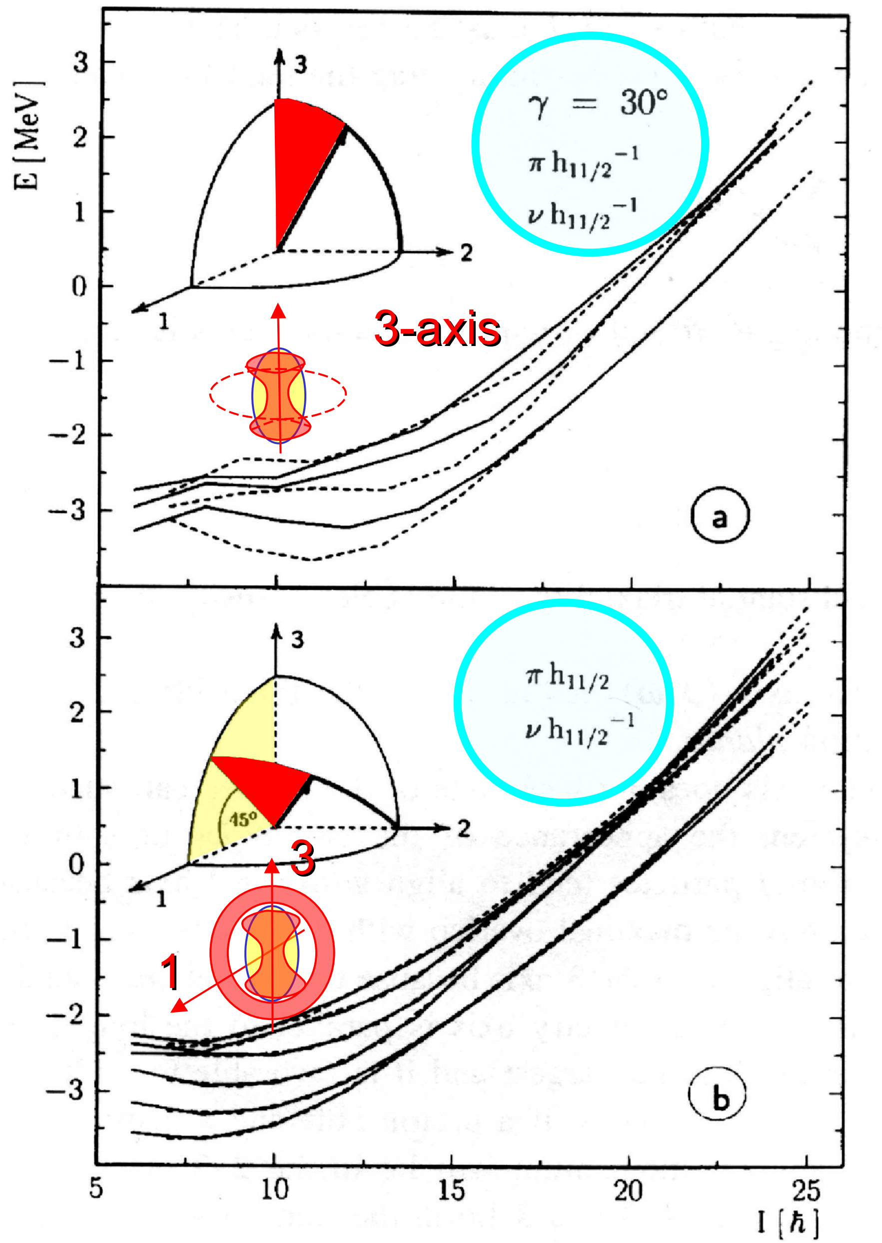



Frauendorf & Meng, NPA 617, 1997

C.P. et al, NPA 597, 1996

# Chirality in triaxial nuclei

1997




Theoretical paper

Frauendorf, Meng, Nucl. Phys. A 617

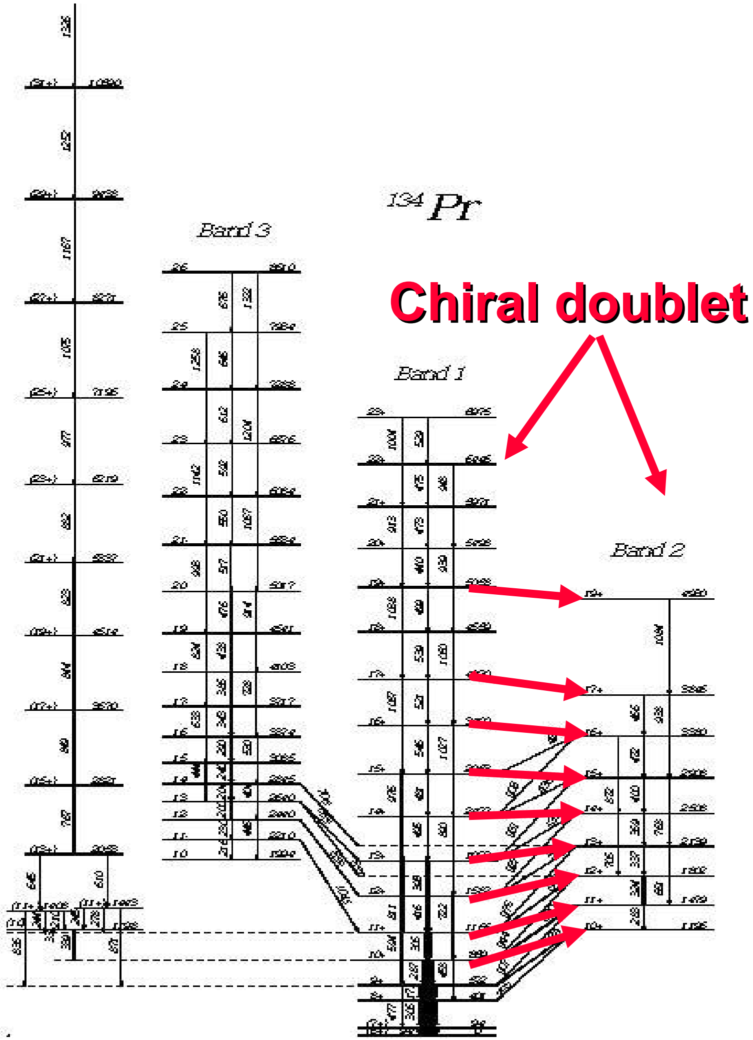
Tilted rotation of triaxial nuclei

($^{134}$Pr best candidate)

° ∩OIEEUII:

Conditions are discussed when the axis of rotation lies inside or outside the principal planes of the triaxial density distribution. The planar solutions represent ΔI=1 bands, whereas the aplanar solutions represent pairs of identical ΔI=1 bands with the same parity. The two bands differ by the chirality of the principal axes with respect to the angular momentum vector. The transition from planar to chiral solutions is evident in both the quantal and the mean field calculations. Its physical origin is discussed.

# First experimental evidence of chirality in 1996, ignoring the chiral interpretation which arrived in 1997



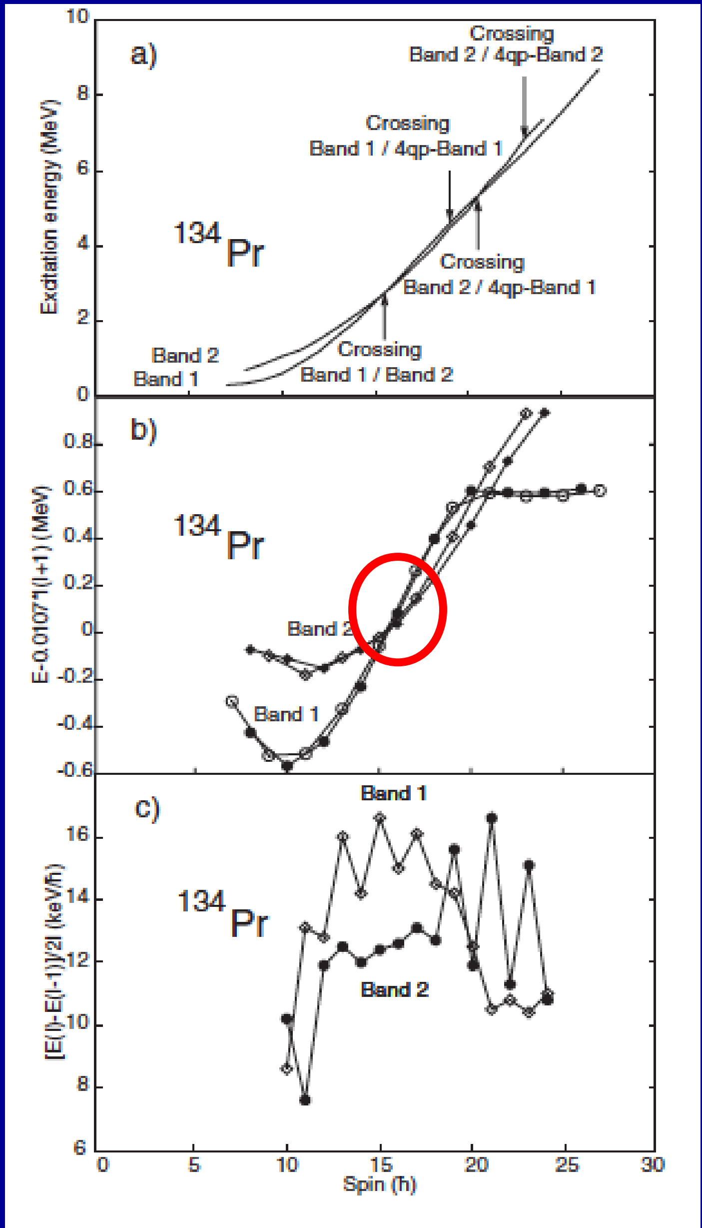

## Experimental paper

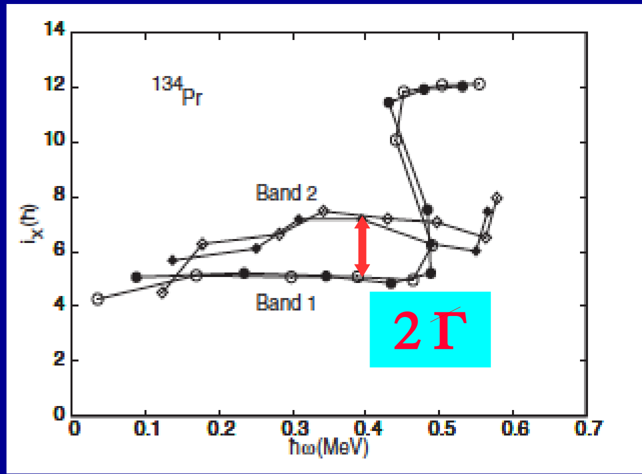
$^{134}$Pr - C.P. et al., Nucl. Phys. A 597

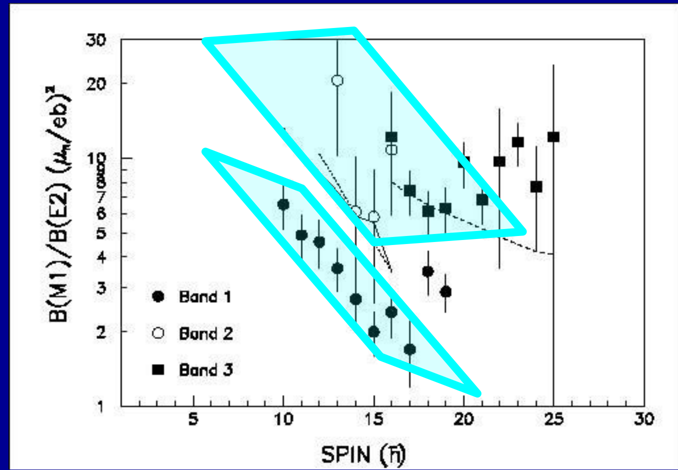
° ∩OIE∈UΠ:

Study of the $\pi h_{11/2}$[413]5/2 – $\nu h_{11/2}$[514]9/2 doublet bands.
The difference of 2 ħ in the experimental alignments and the B(M1)/B(E2) values are discussed in terms of shape coexistence and coupling with the $\gamma$ phonon, but no consistent interpretation could be found.

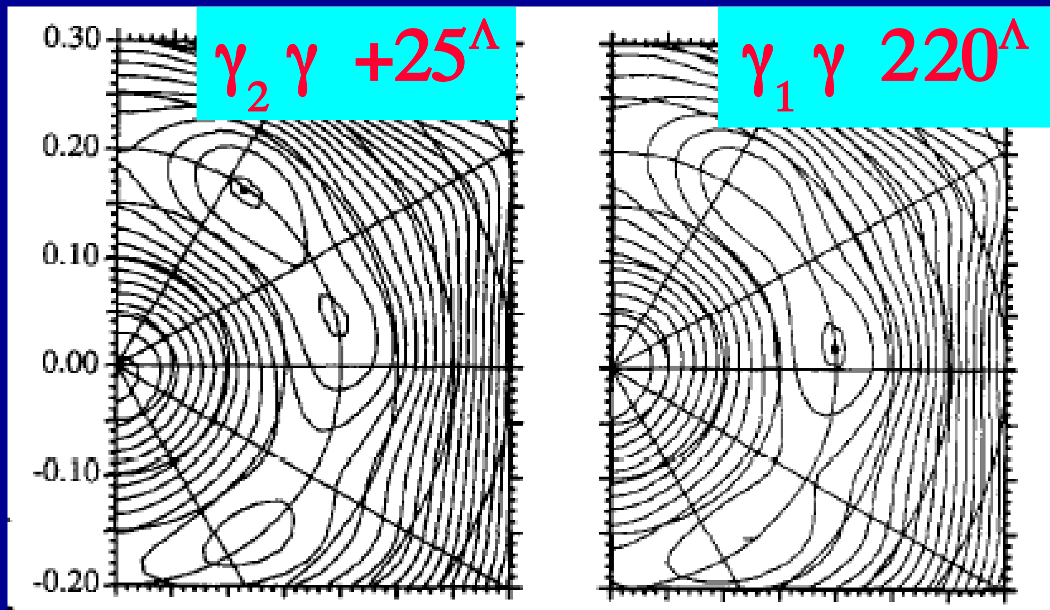
# $^{134}$Pr



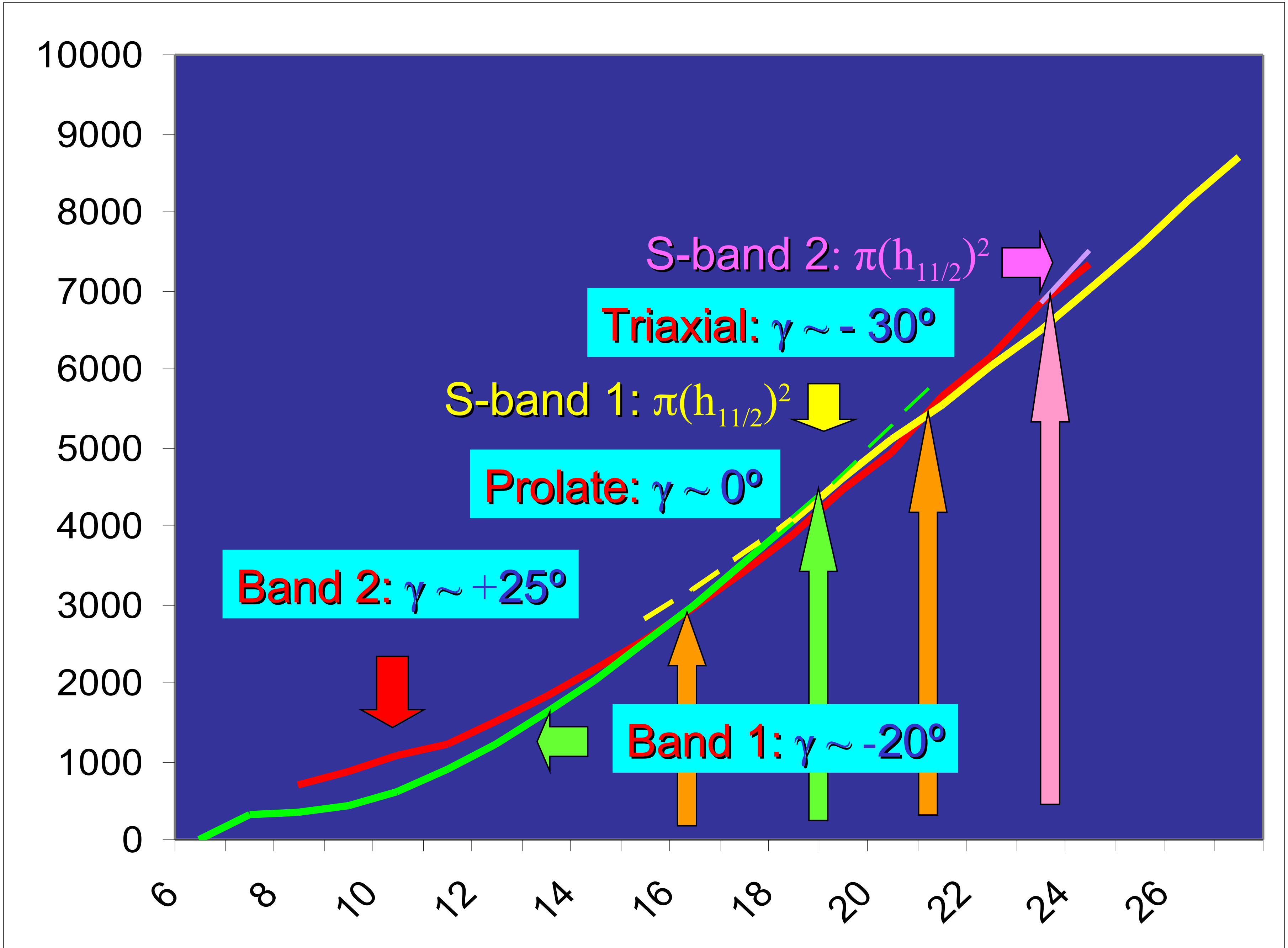

$$Q_{0,1}/Q_{0,2} \simeq 1.7$$

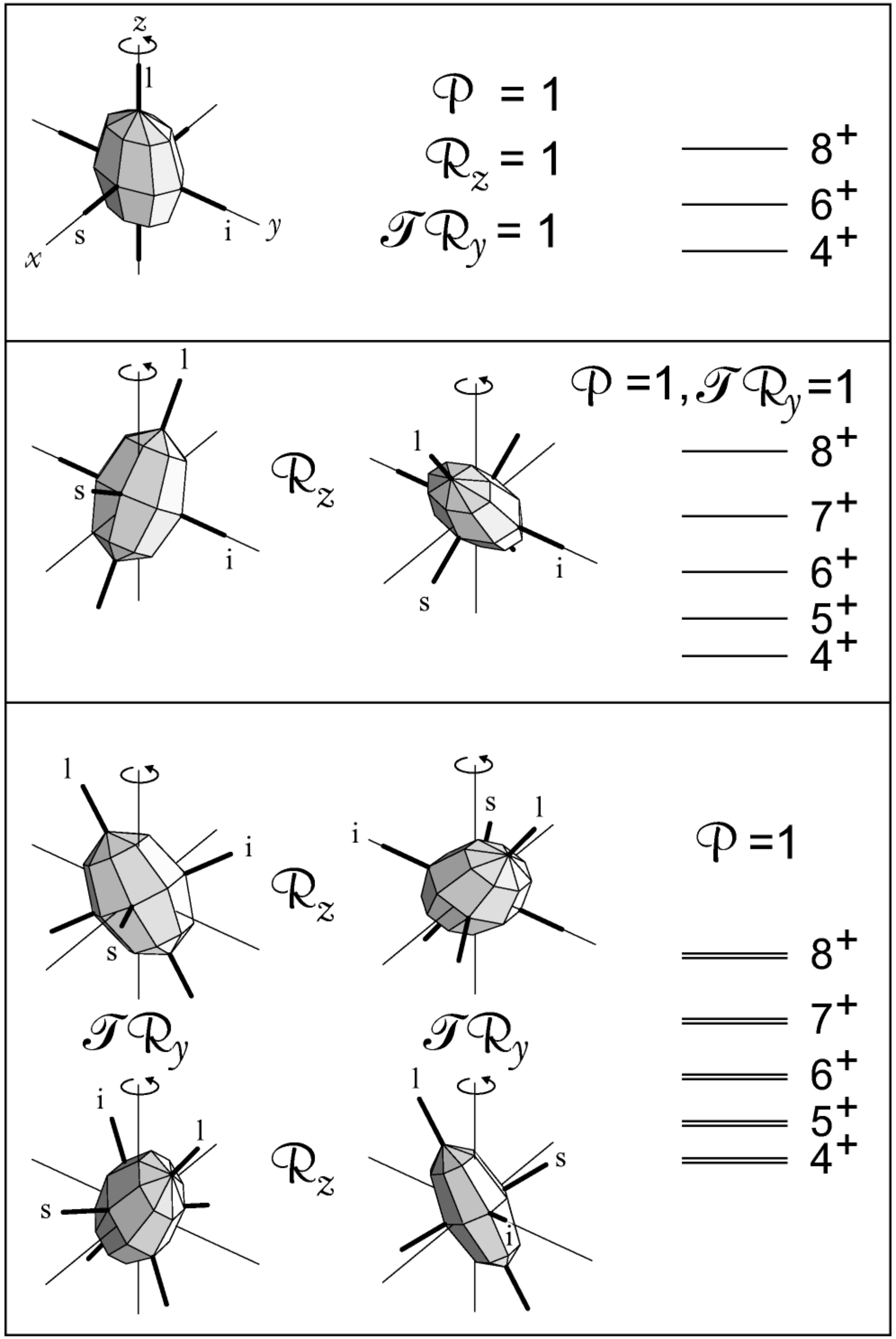



C.P. et al, PRL 96, 2006

C.P. et al, NPA 597, 1996

# Crossing bands in $^{134}Pr$






# 2000

Theoretical paper

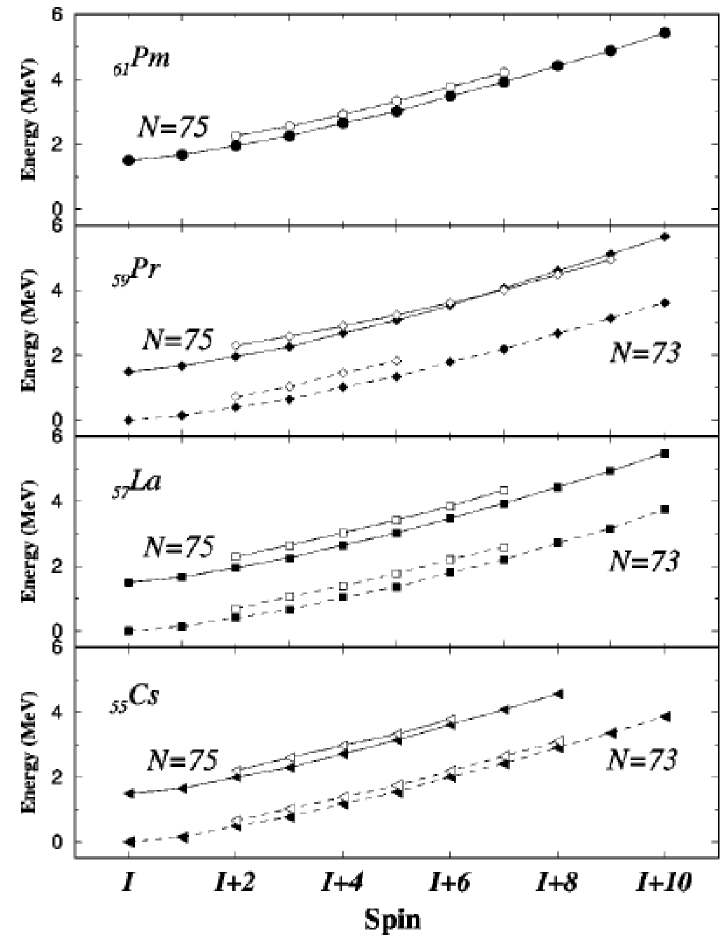
Dimitrov, Frauendorf, Dönau, PRL 84

Chirality of nuclear rotation

($^{134}$Pr best candidate)

° ∩ΟΙΕ∈∪Π:

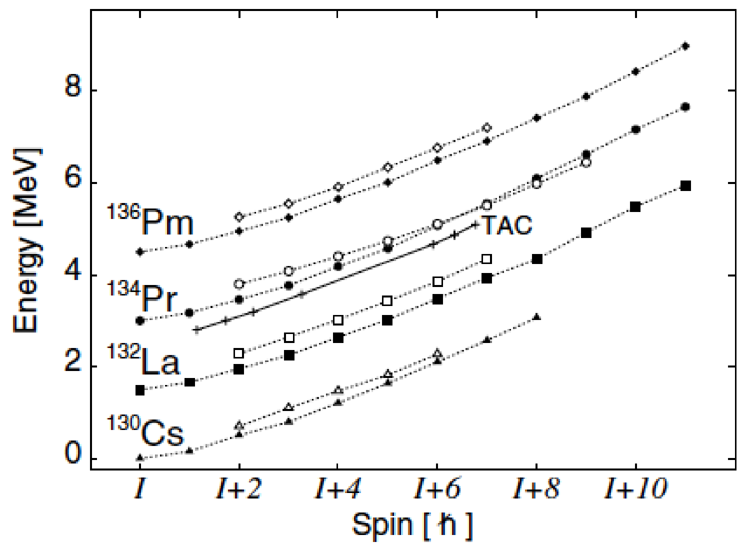
It is shown that the rotating mean field of triaxial nuclei can break the chiral symmetry. Two nearly degenerate ΔI=1 rotational bands originate from the left-handed and right-handed solutions.
The $^{134}$Pr and $^{188}$Ir are discussed.

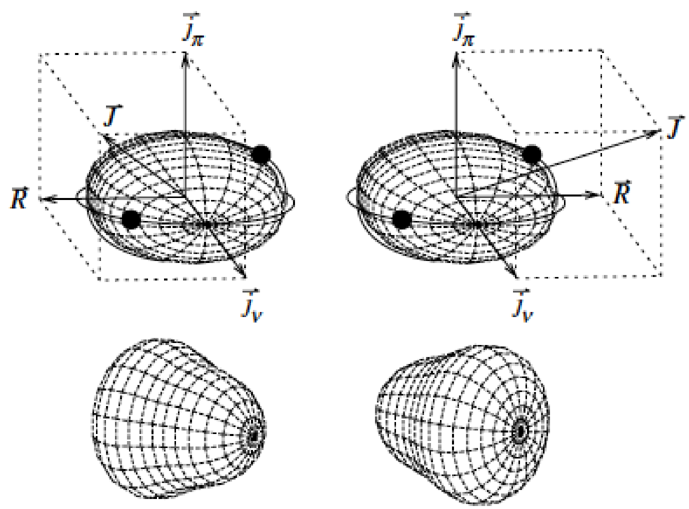



# 2001

**Experimental papers :**

- N=73 $^{128}$Cs, $^{130}$La, $^{132}$Pr
Koike, Starosta, et al., PRC 63
- N=75 $^{130}$Cs, $^{132}$La, $^{134}$Pr, $^{136}$Pm
Starosta, Koike et al., PRL 86
- N=75 $^{136}$Pm Hartley et al., PRC 64
- N=75 $^{138}$Eu Hecht et al., PRC 63
- N=77 $^{134}$La Bark et al., NPA 691



2002

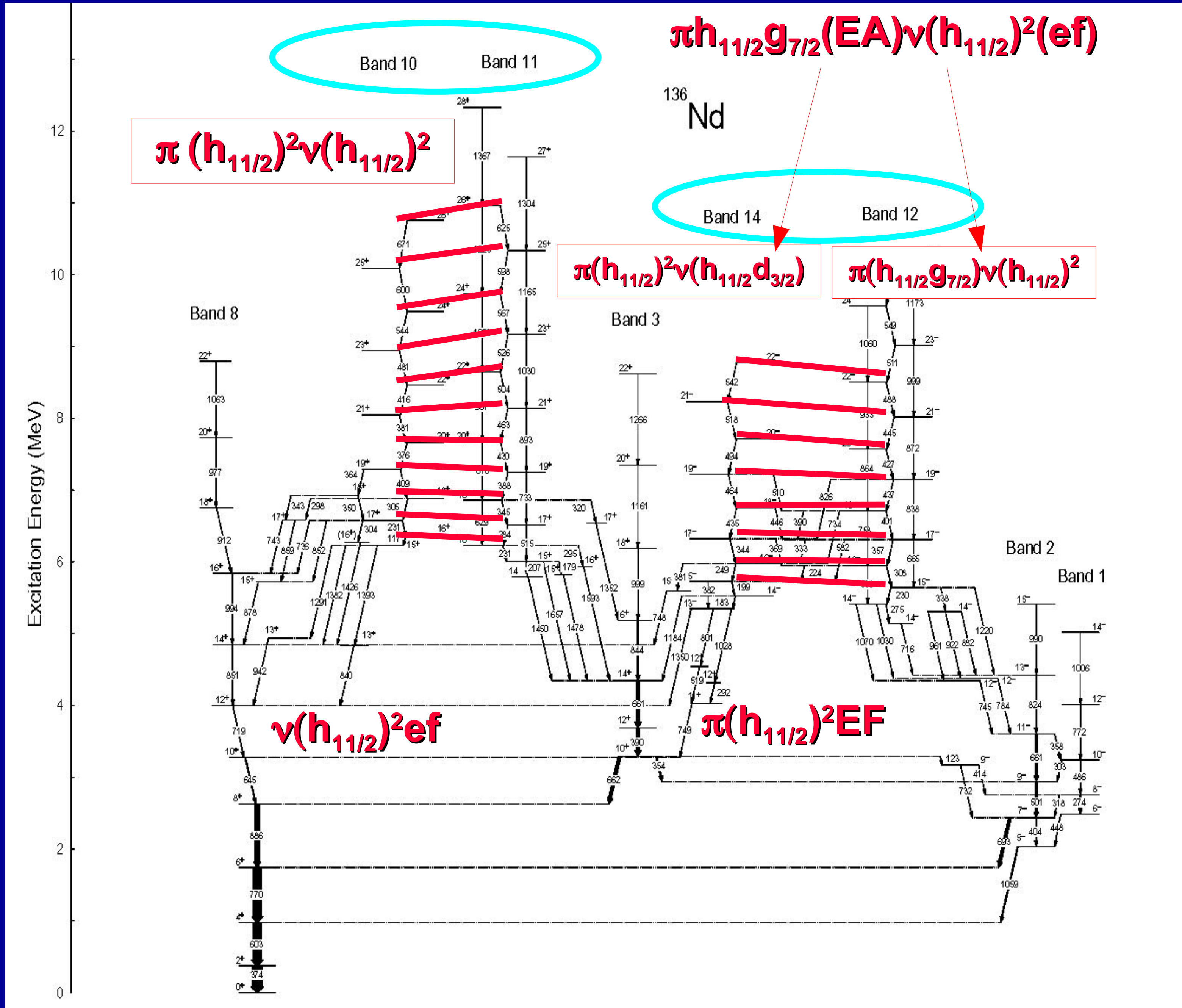
Experimental papers :

- $^{136}$Nd : candiate for chiral doublet bands

Mergel, Petrache et al., EPJA 15 –> not confirmed by lifetime measurements which show different transition rates implying two distinct configurations (Mukhopadhyay et al., PRC 78, 2008).

# Level scheme of $^{136}$Nd

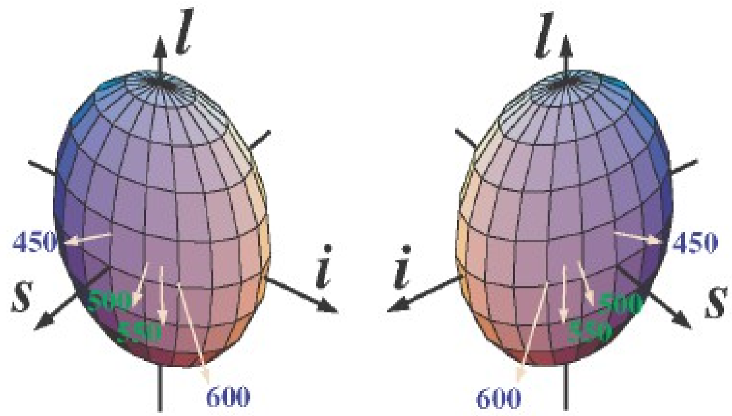
*E. Mergel et al.*
*EPJ **A15** (2002)*
*417 - 420*



# 2003

Eperimental papers :

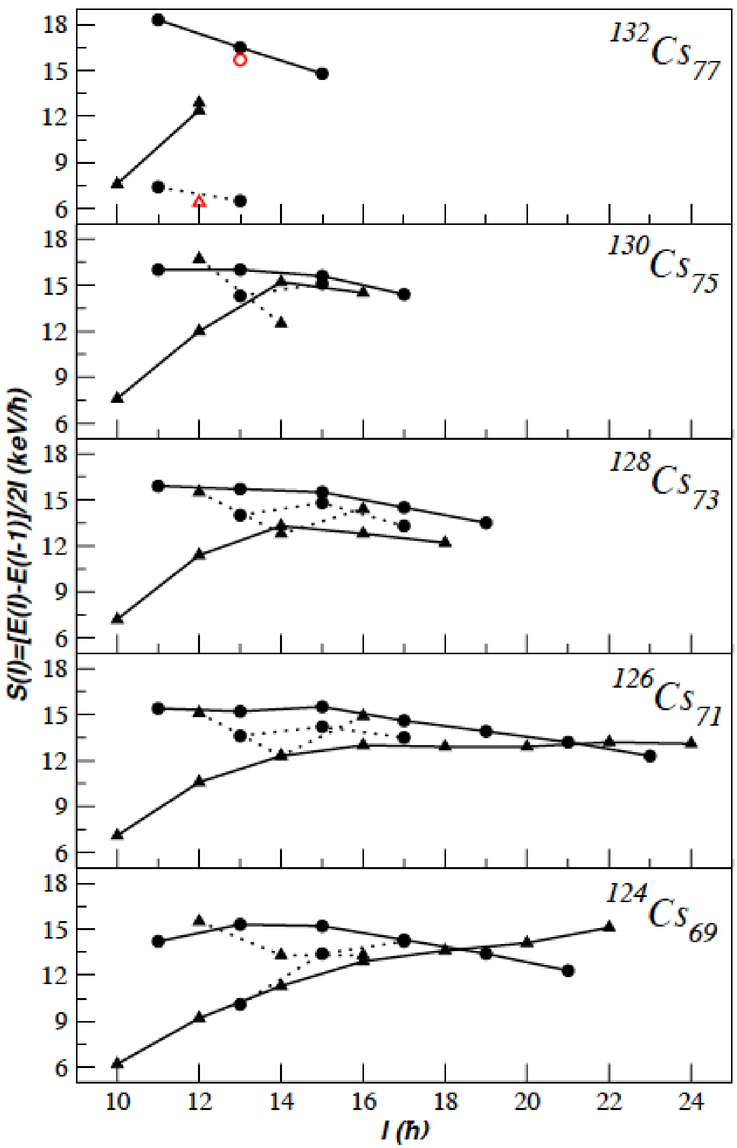
- $^{128-134}$Cs : Koike, Starosta et al., PRC 67
- $^{132}$Cs : Rainovski et al., PRC 68
- $^{134}$Pr : Roberts et al., PRC 67 – change of spins
- $^{140}$Eu : Hecht et al., PRC 68
- $^{135}$Nd : Zhu et al., PRL 91

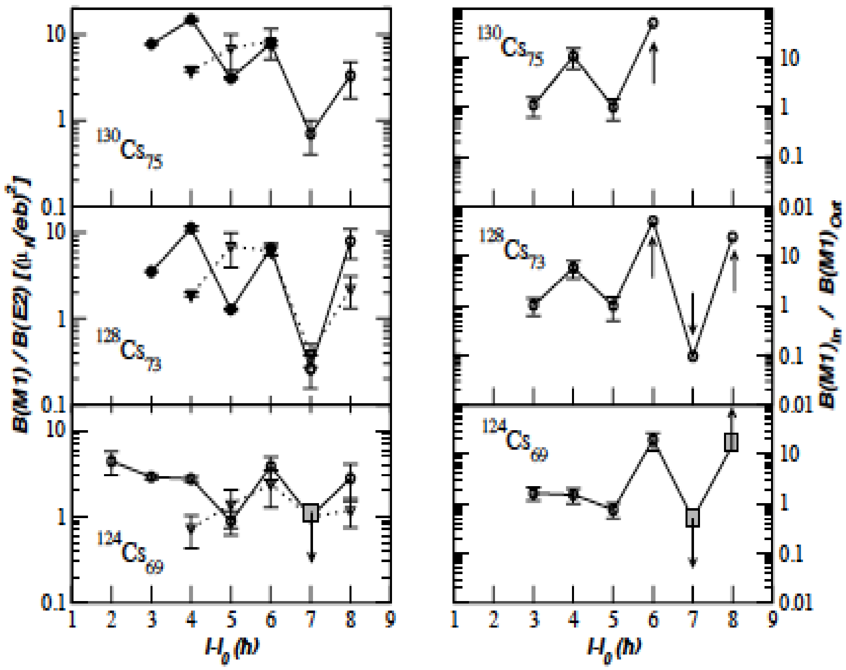


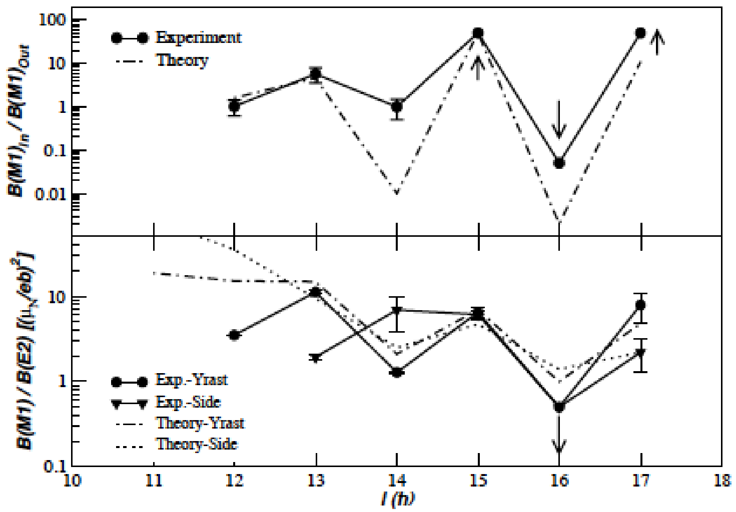

Theoretical paper :

- A~130 and A~100 : Peng, Meng, Zhang, PRC 68

# $^{128-134}$Cs : Koike, Starosta et al., PRC 67



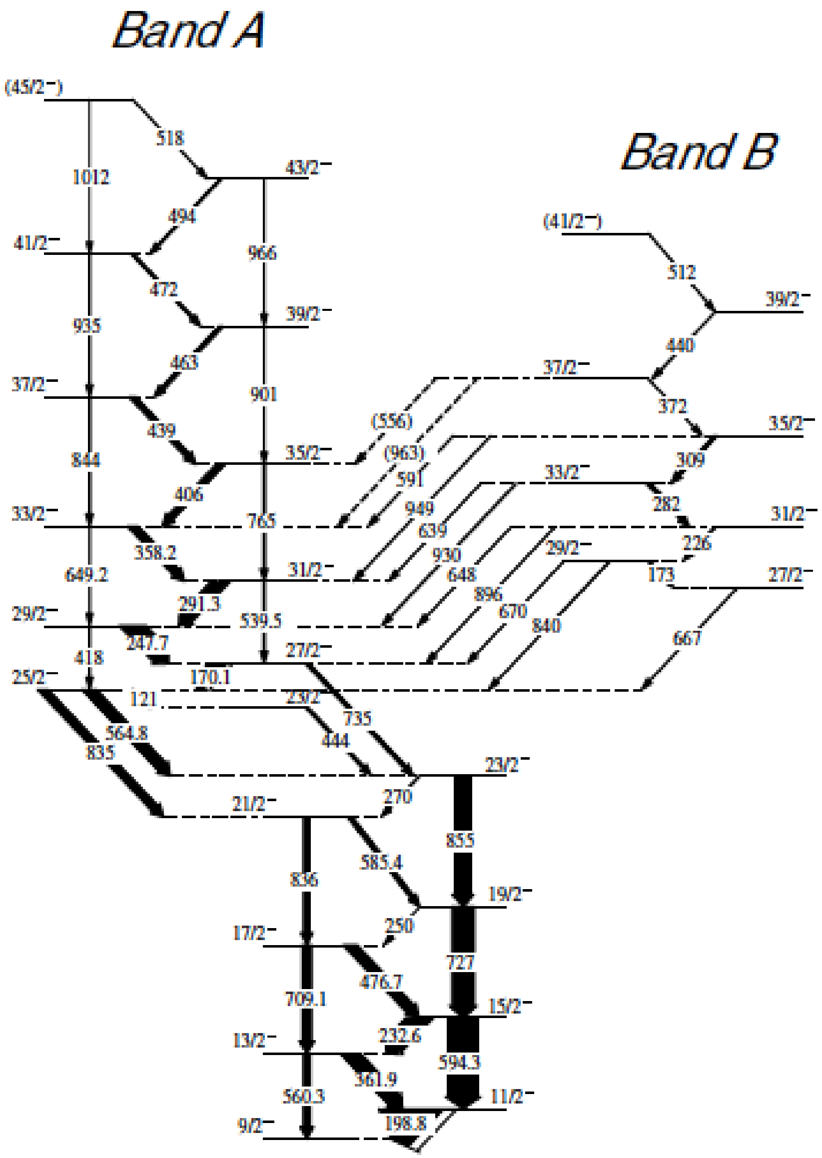



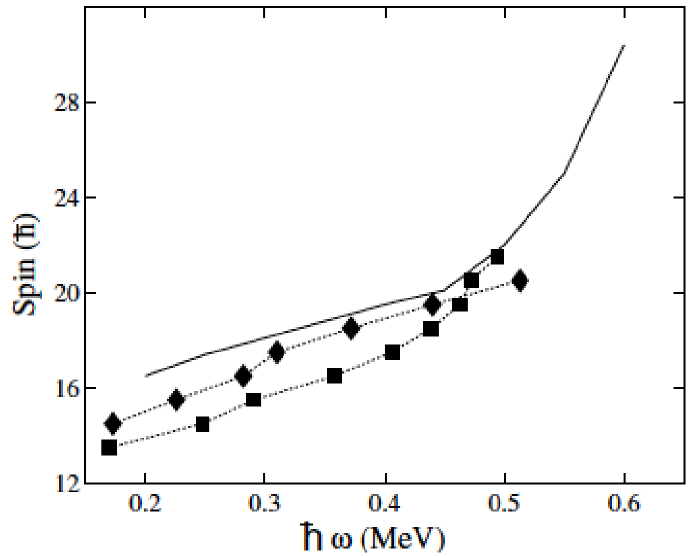



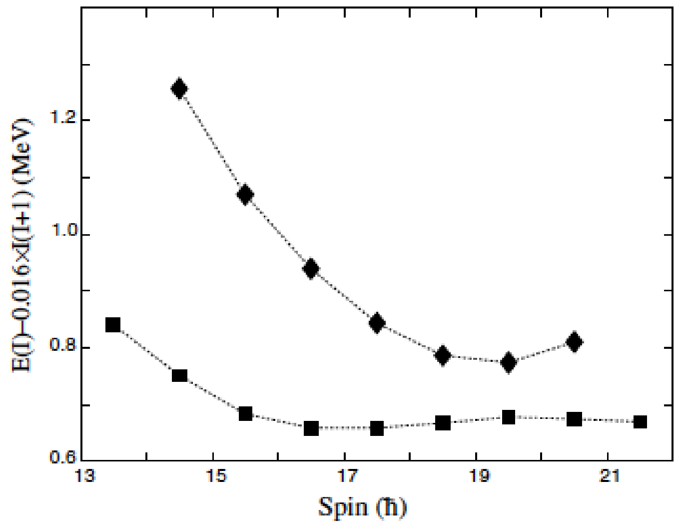
$^{135}$Nd : Zhu, Garg et al., PRL 91, 2003

composite chiral pair of rotational bands in $^{135}$Nd

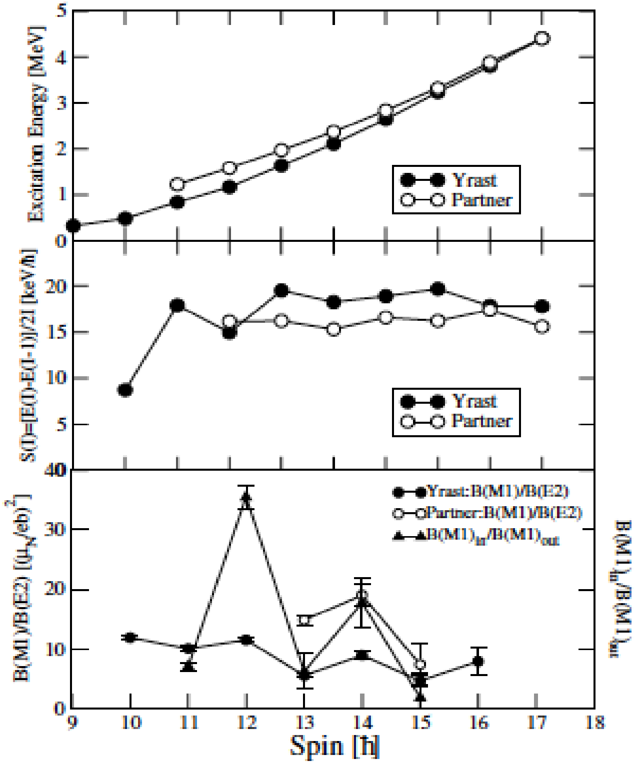
First odd-A chiral nucleus !



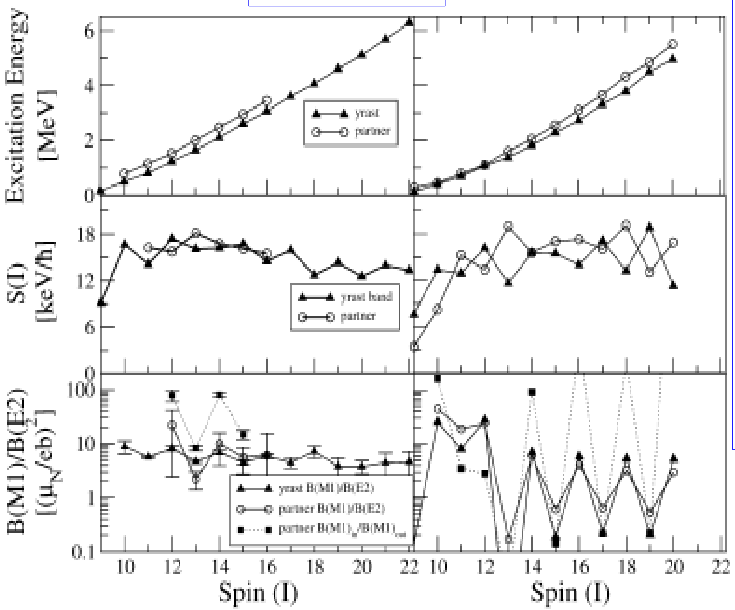



$^{104}$Rh




$^{106}$Rh




# 2004

## Experimental papers :

- $^{104}$Rh : Vaman, Koike, Starosta et al., PRL 92
- $^{105}$Rh : Alcantara et al., PRC 69
- $^{106}$Rh : Joshi et al., PLB 595

## Theoretical papers :

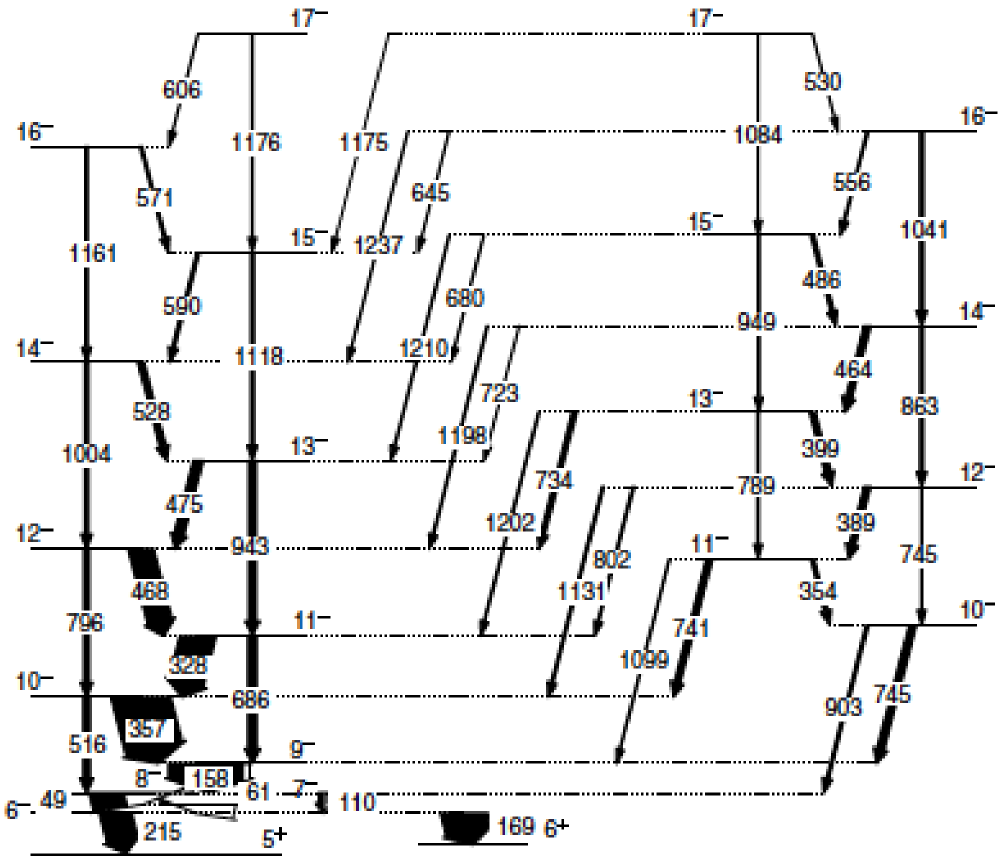
- Selection rules for electromagnetic transitions

Koike, Starosta, Hamamoto, PRL 98

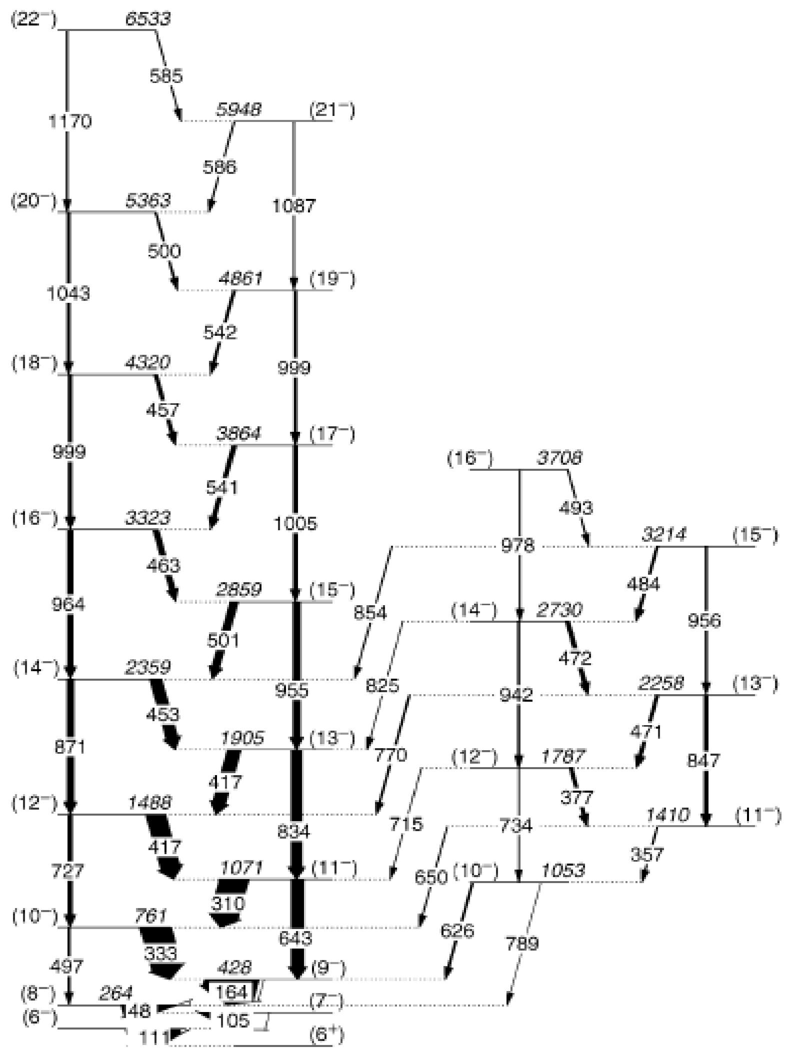
- Critical frequency in nuclear chiral rotation

Olbratowski Dobaczewski, Dudek, Plociennik, PRL 93

$^{104}$Rh : Vaman et al., PRL 92, 2004
First A~100 nucleus !

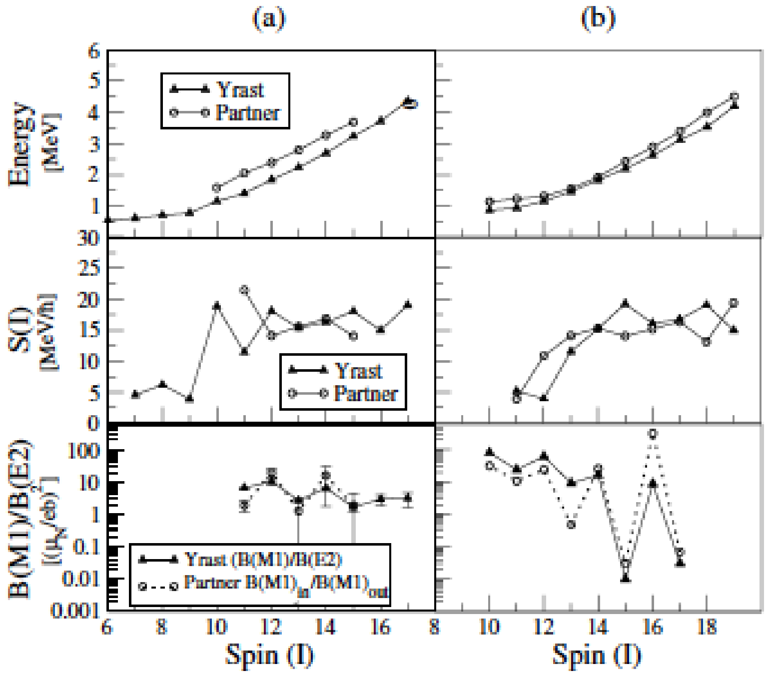



$^{104}$Rh : Joshi et al., PLB 595, 2004



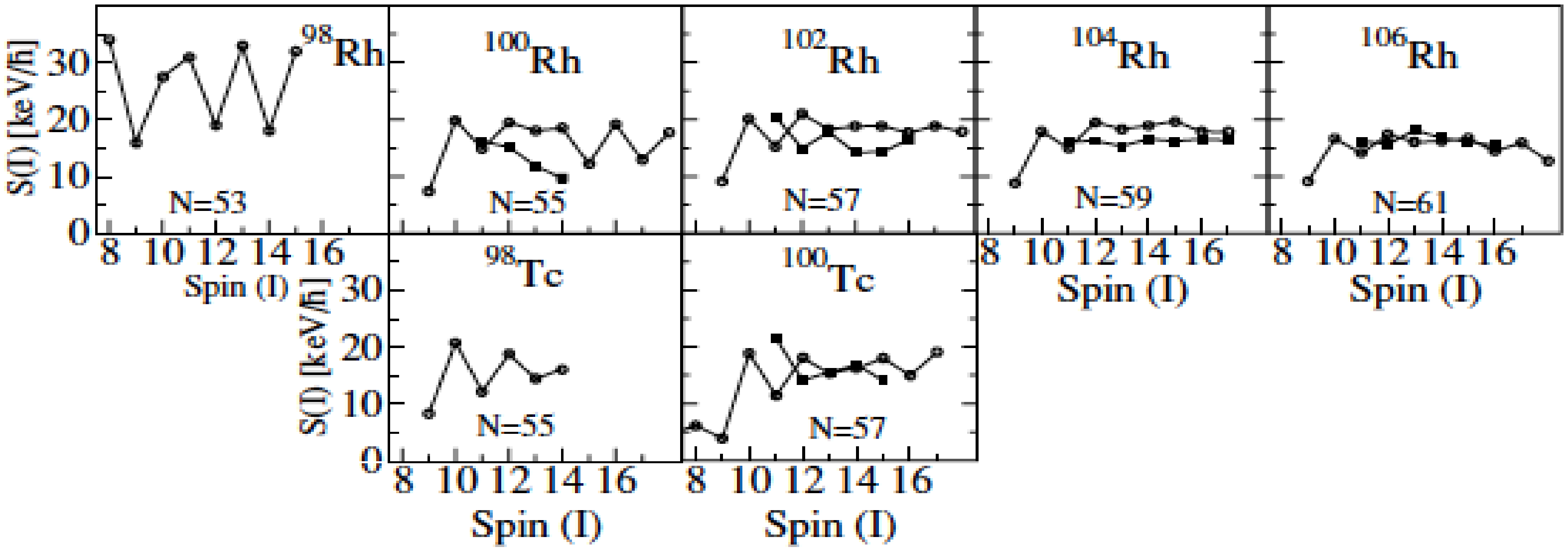
$^{100}$Tc

2005




Experimental papers :

- $^{100}$Tc : Joshi et al., EPJA 24
- $^{106}$Ag : Joshi et al., JPG 31
- $^{104}$Rh, $^{130}$Cs, $^{134}$Pr : Koike et al., JPG 31

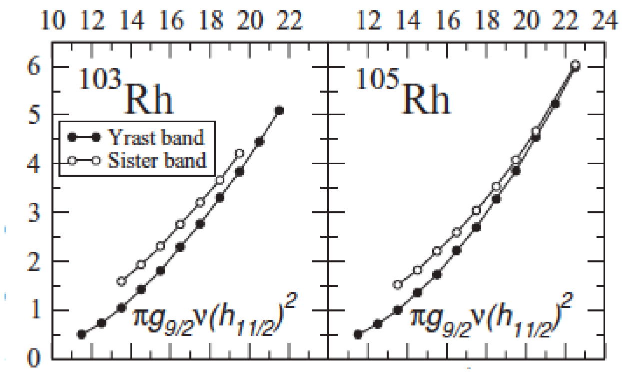


# 2006

Experimental papers :

- $^{134}$Pr – transition probabilities : Tonev et al., PRL 96
- $^{134}$Pr – quadrupole moments : Petrache et al., PRL 96
- $^{128}$Cs – transition probabilities : Grodner et al., PRL 97

- $^{126}$Cs : Wang et al., PRC 74
- $^{103}$Rh : Timar et al., PRCR 73

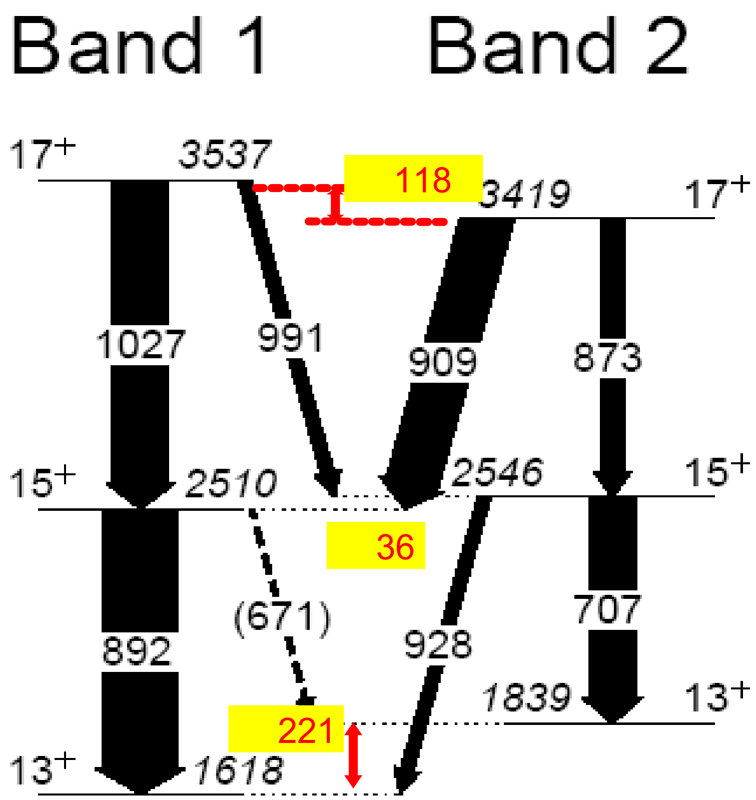



..ΓJΛΞJΠΕ⊎ΘΜΕΜJΞΟ :

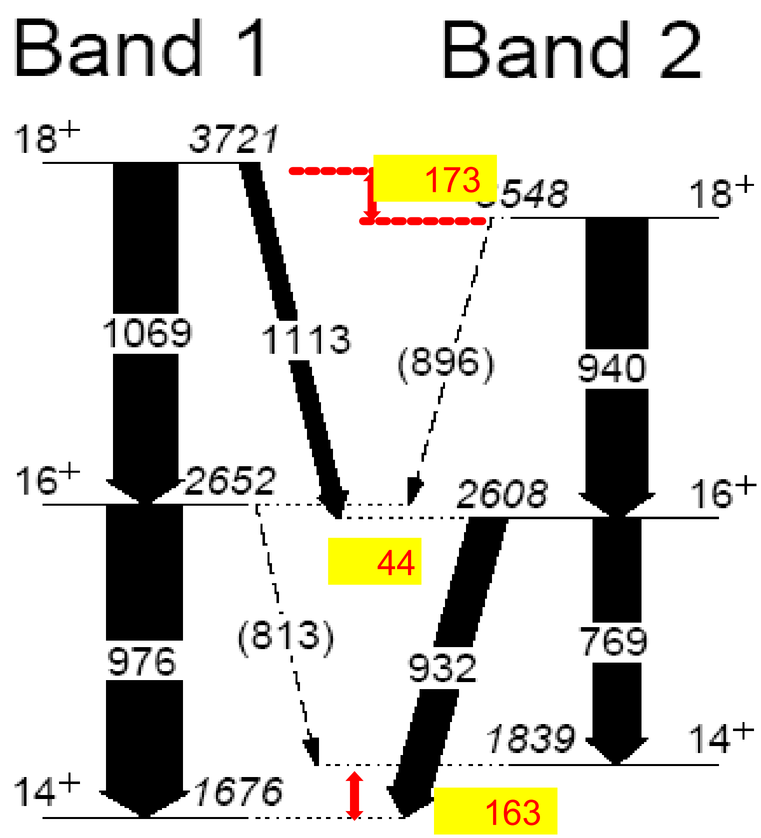
- multiple chiral doublets in $^{106}$Rh : Meng et al., PRC 73
- Skyrme-Hartree-Fock : Olbratowski, Dobczewski, Dudek, PRC 73

# Analysis of interaction between the bands in the crossing region of $^{134}Pr$

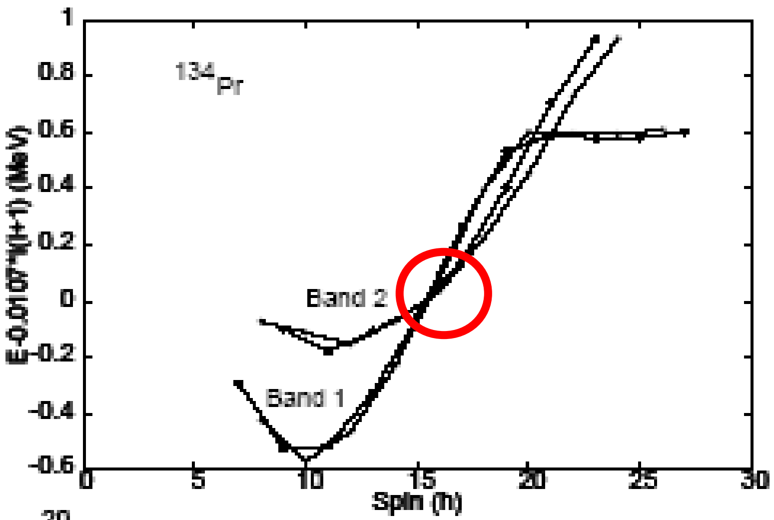
## Odd spins

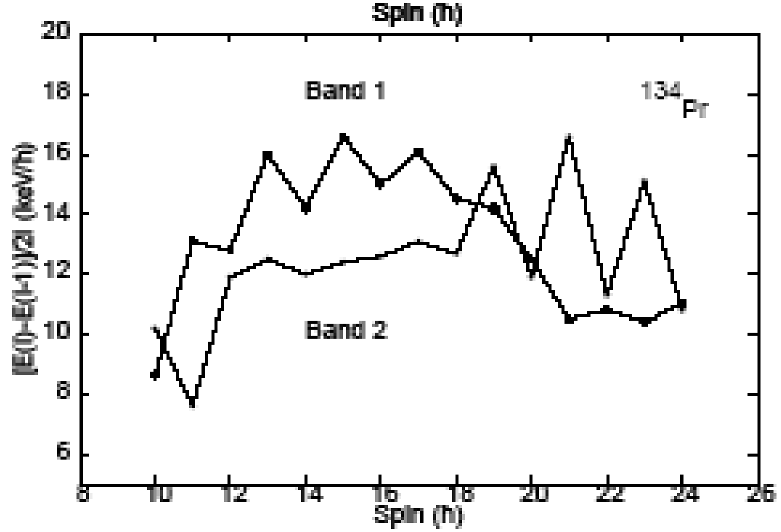



## Even spins



# Analysis of interaction between the bands in the crossing region of $^{134}$Pr




$$|y\rangle = \alpha_I|1\rangle + \sqrt{1-\alpha_I^2}|2\rangle$$

$$|ny\rangle = \sqrt{1-\alpha_I^2}|1\rangle - \alpha_I|2\rangle,$$

$$\frac{2V}{\Delta E_I} = \sin[2\sin^{-1}(\alpha_I)].$$

$$\frac{B[E2, I^{ny} \to (I-2)^y]}{B[E2, I^{ny} \to (I-2)^{ny}]} = \left(\frac{Q_{0,1}\alpha_{I-2}\sqrt{1-\alpha_I^2} - Q_{0,2}\alpha_I\sqrt{1-\alpha_{I-2}^2}}{Q_{0,1}\sqrt{1-\alpha_{I-2}^2}\sqrt{1-\alpha_I^2} + Q_{0,2}\alpha_I\alpha_{I-2}}\right)^2$$

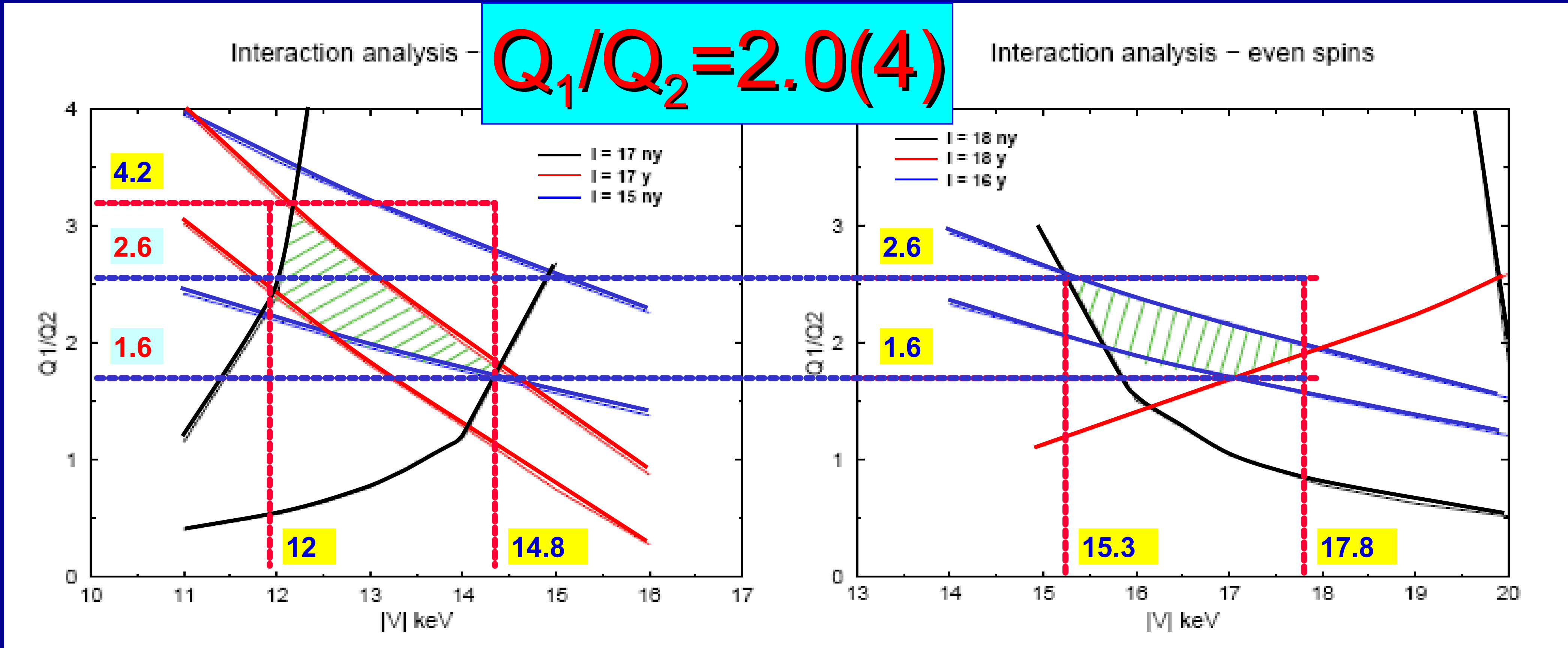
$$\frac{B[E2, I^y \to (I-2)^{ny}]}{B[E2, I^y \to (I-2)^y]} = \left(\frac{Q_{0,1}\alpha_I\sqrt{1-\alpha_{I-2}^2} - Q_{0,2}\alpha_{I-2}\sqrt{1-\alpha_I^2}}{Q_{0,1}\alpha_I\alpha_{I-2} + Q_{0,2}\sqrt{1-\alpha_I^2}\sqrt{1-\alpha_{I-2}^2}}\right)^2$$

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

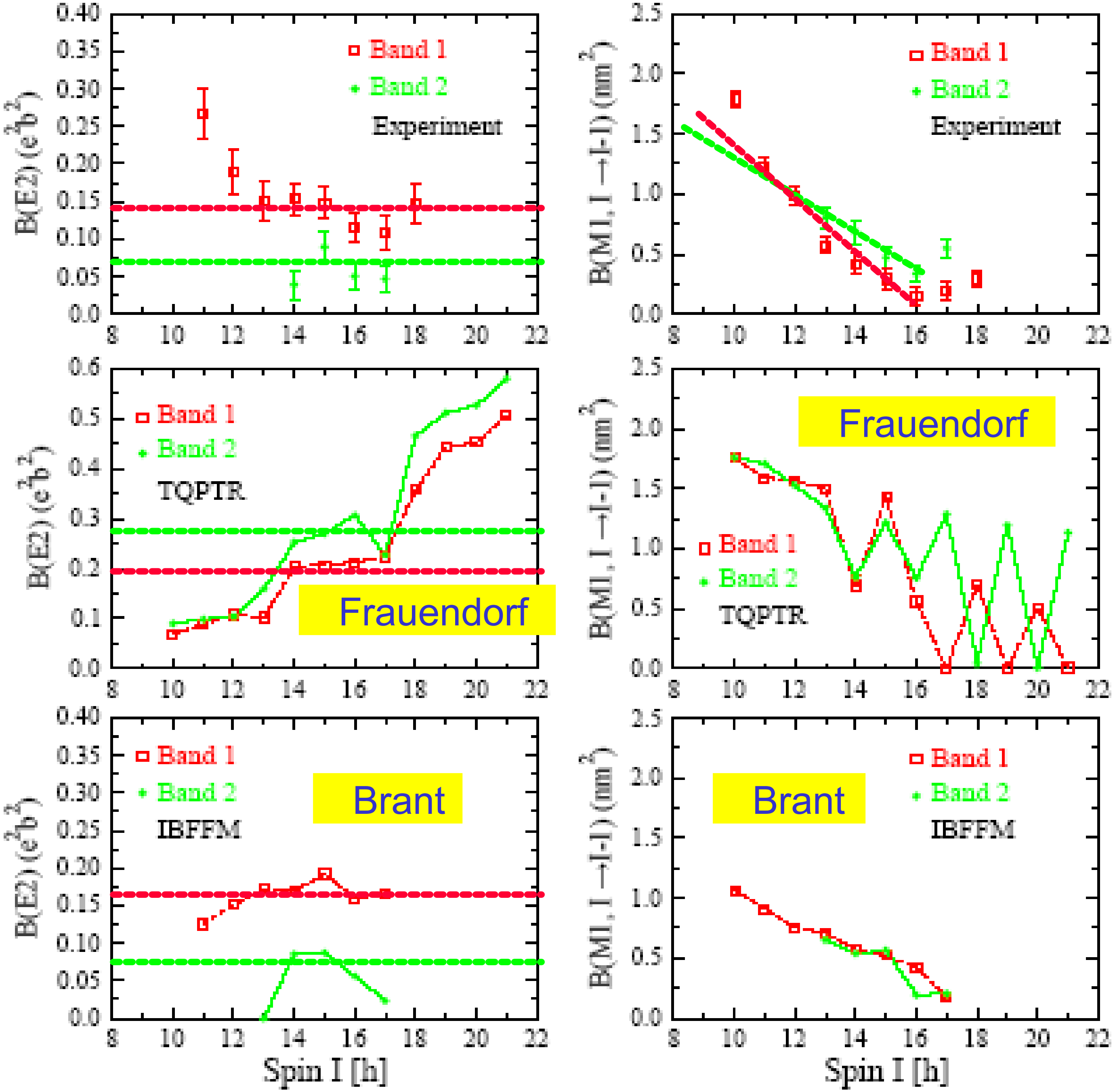
C. M. Petrache,[1] G. B. Hagemann,[2] I. Hamamoto,[3,2] and K. Starosta[4]

## Plot of the ratio $Q_1/Q_2$ of unperturbed quadrupole moments vs the interaction strength |V| in the crossing region



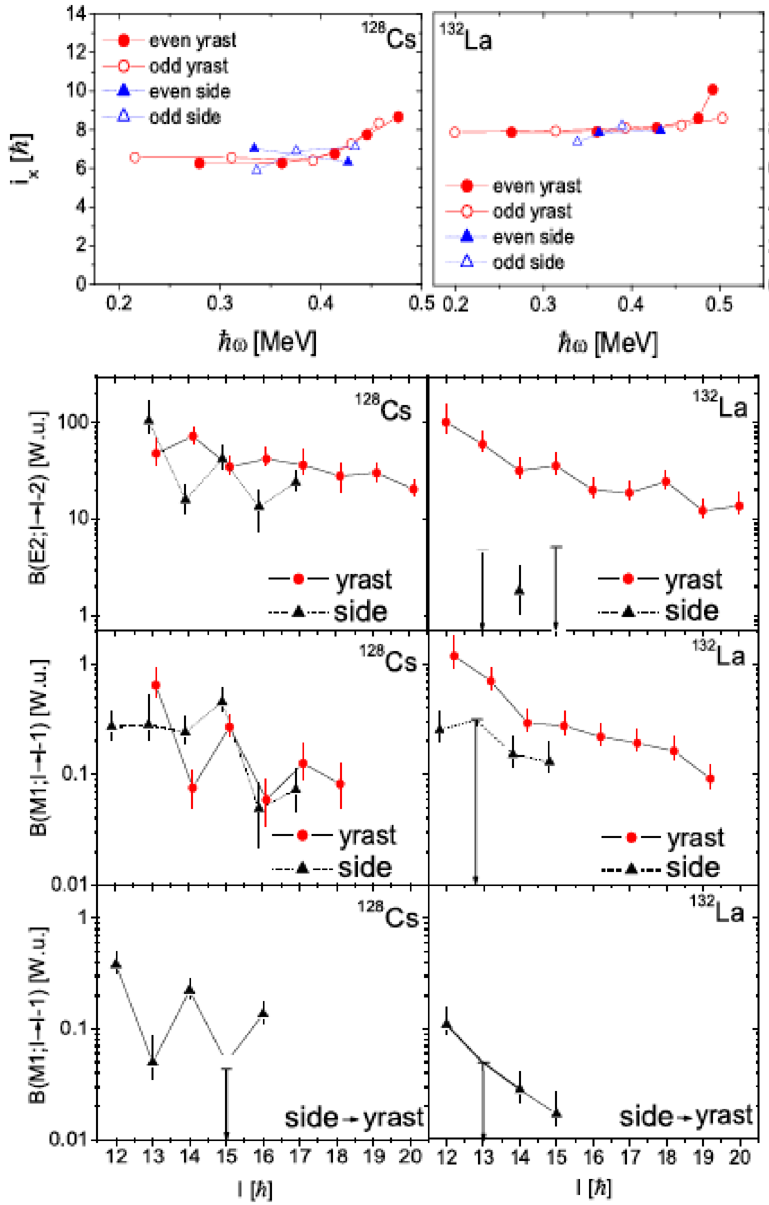
Experimental and calculated absolute B(E2) & B(M1) for the transitions in $^{134}$Pr

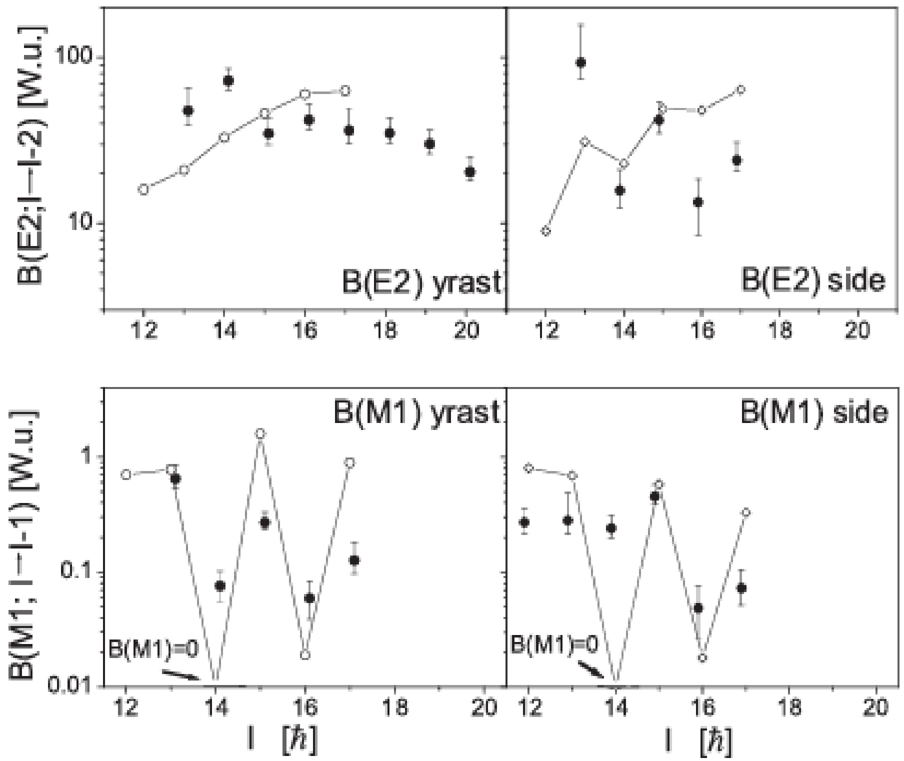
Tonev et al., PRL 96 (2006)

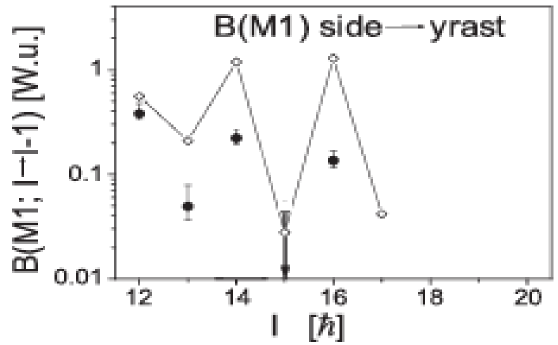


# 2006

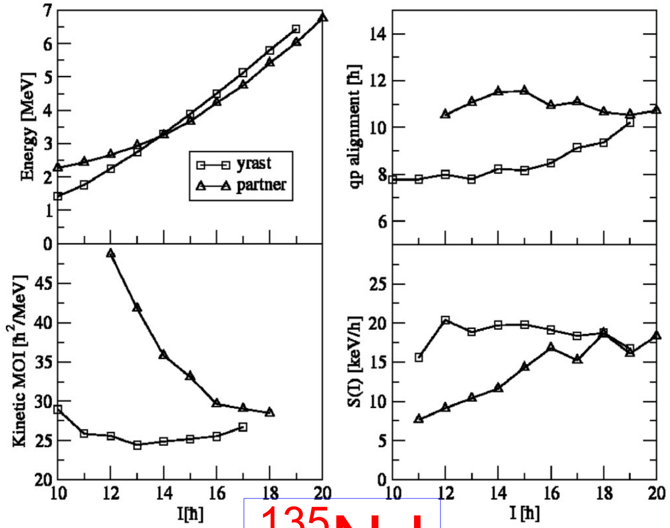
## $^{128}$Cs – transition probabilities : Grodner et al., PRL 97



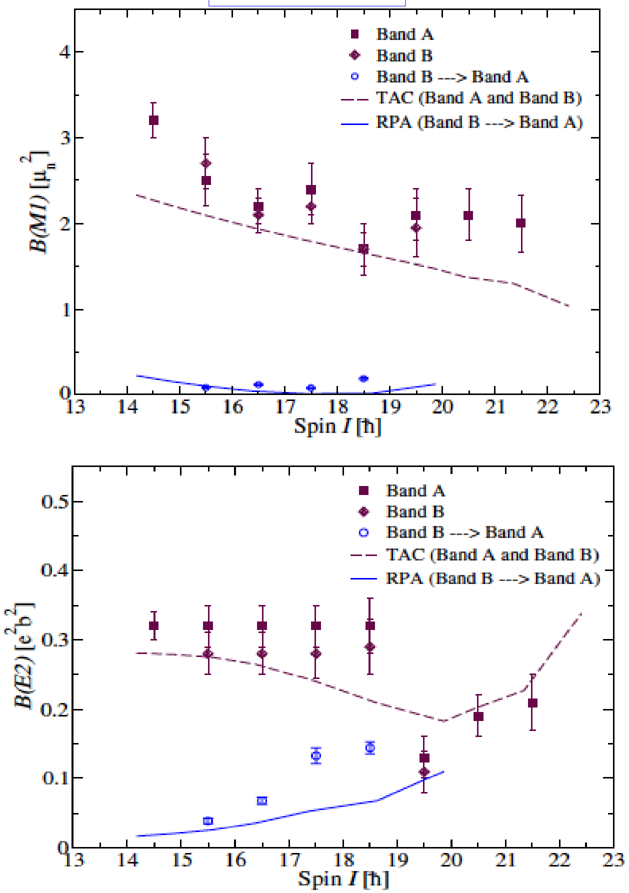



$^{106}$Ag




$^{135}$Nd




# 2007

## Experimental papers :

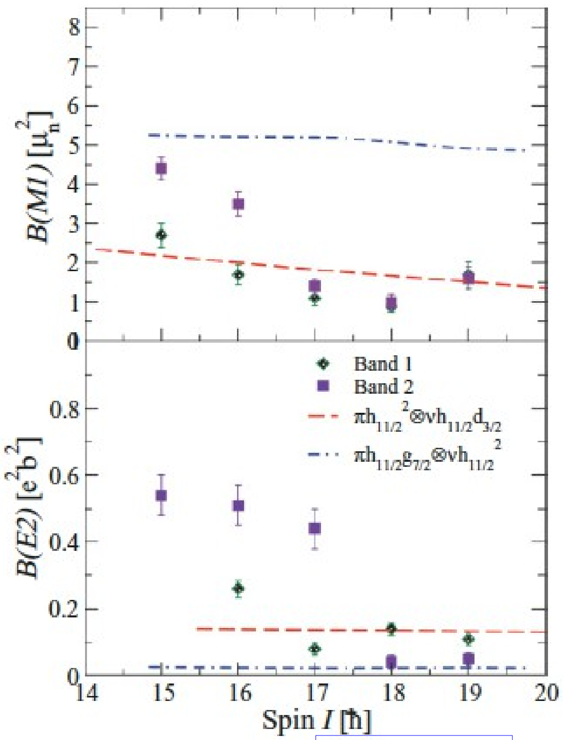
- $^{105}$Ag : Timar et al., PRC 76
- $^{106}$Ag : Joshi et al., PRL 98
- $^{134}$Pr : Tonev et al., PRC 76
  lifetimes, IBFFM
- $^{135}$Nd : Mukhopahyay et al., PRL 99
  TAC+RPA calculations

## Theoretical papers :

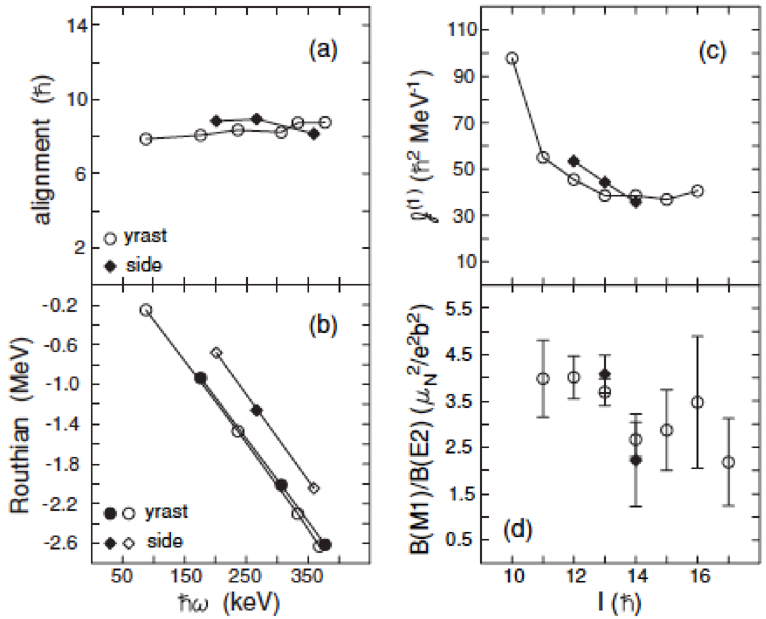
- PRM calculations :

Zhang, Qi, Wang, Meng, PRC 75

$^{136}$Nd




$^{198}$Tl




# 2008

## Experimental papers :

- $^{103,104}$Rh : Suzuki et al., PRCR 78
  lifetimes
- $^{136}$Nd : Mukhopahyay et al., PRC 78
  lifetimes → no chiral doublets
- $^{198}$Tl : Lawrie et al., PRCR 78
  region of oblate nuclei γ ~44$^o$

## Theoretical papers :

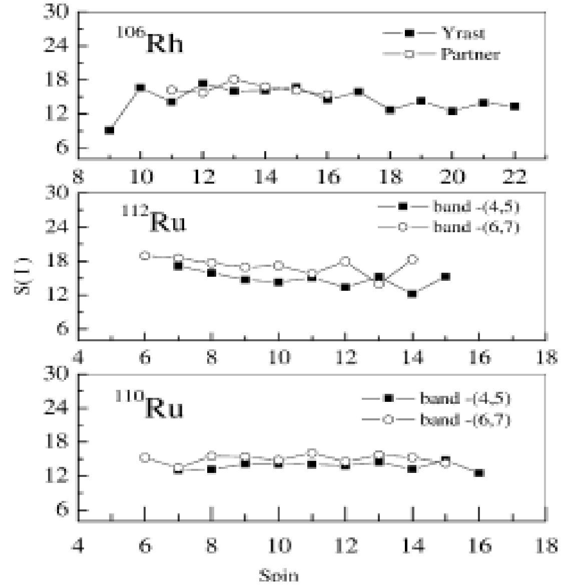
-IBFFM calculations

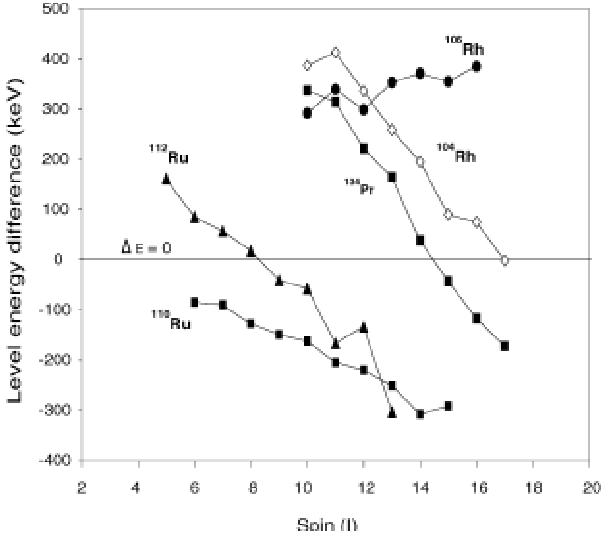
Brant et al., PRC 78

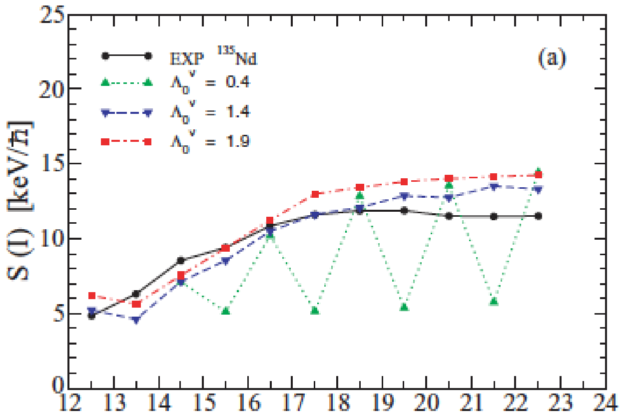
- RMF calculations for multiple chiral doublets in Rh isotopes

Peng et al., PRC 77

# 2009



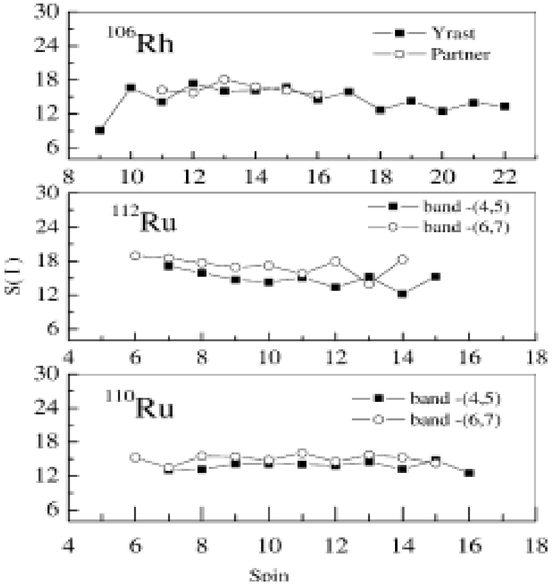



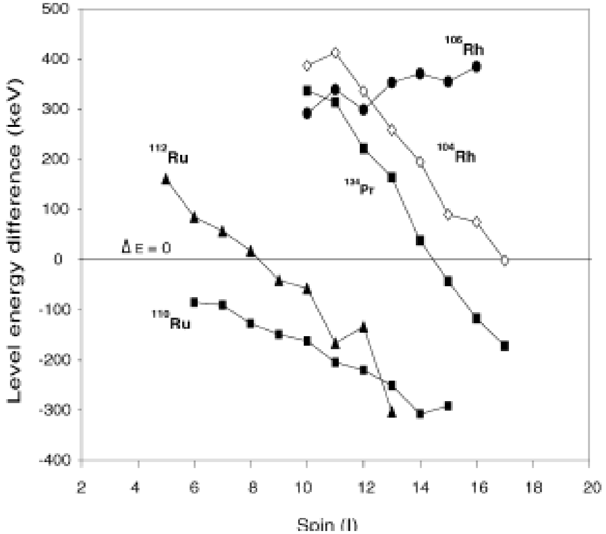

## Experimental papers :

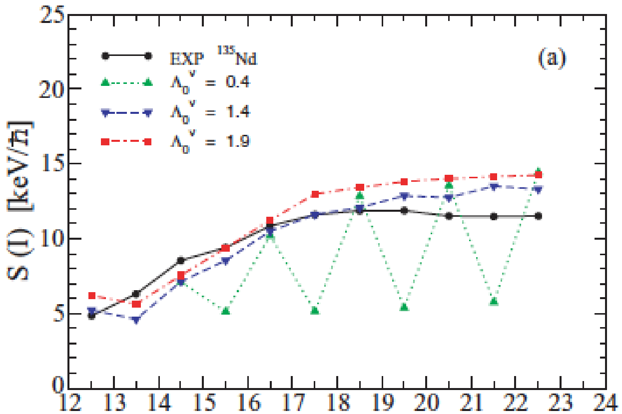
- $^{108,110,112}$Rh : Luo et al., PLB 670
  chiral vibrations, TAC+RPA

## Theoretical papers :

- IBFM calculations for $^{135}$Nd, $^{137}$Nd
  Brant, Petrache, PRC 79
- IVBM calculations for $^{126}$Pr, $^{134}$Pr, $^{132}$La
  Ganev et al., PRC 79
- CPHC calculations : Droste et al., EPJA 42
- PRM calculations for $^{135}$Nd : Qi et al., PLB 675
- B(M1) staggering : Qi et al., PRCR 79
- multiple chiral doublets in $^{106}$Rh
  Yao et al., PRC 79




# 2009

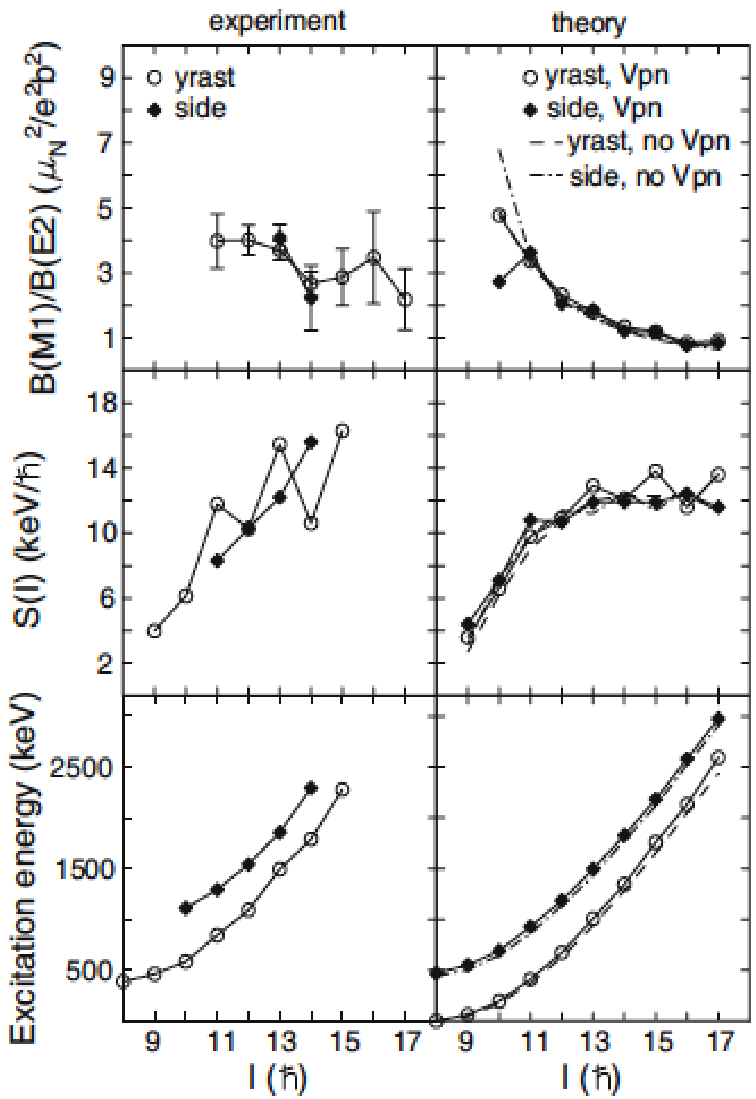
## Experimental papers :

- $^{108,110,112}$Rh : Luo et al., PLB 670
  chiral vibrations, TAC+RPA

## Theoretical papers :

- IBFM calculations for $^{135}$Nd, $^{137}$Nd
  Brant, Petrache, PRC 79
- IVBM calculations for $^{126}$Pr, $^{134}$Pr, $^{132}$La
  Ganev et al., PRC 79
- CPHC calculations : Droste et al., EPJA 42
- PRM calculations for $^{135}$Nd : Qi et al., PLB 675
- B(M1) staggering : Qi et al., PRCR 79
- multiple chiral doublets in $^{106}$Rh
  Yao et al., PRC 79

# 2010



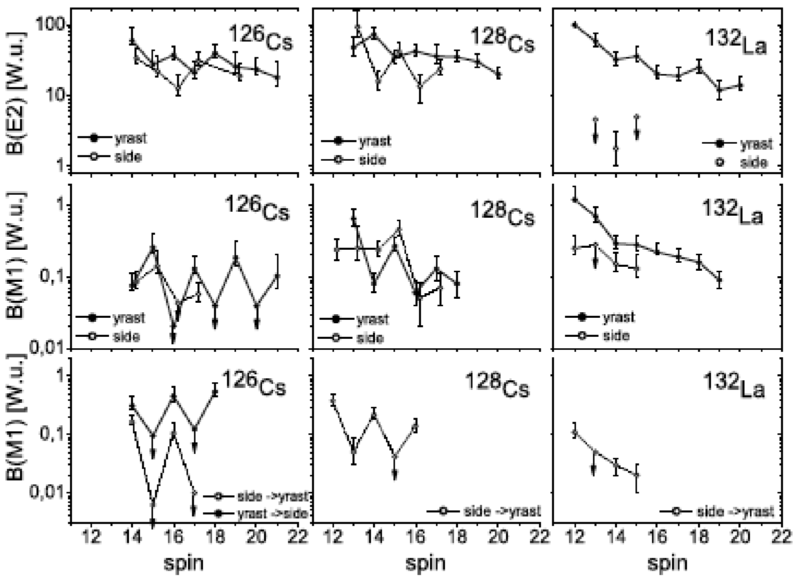

Experimental papers :

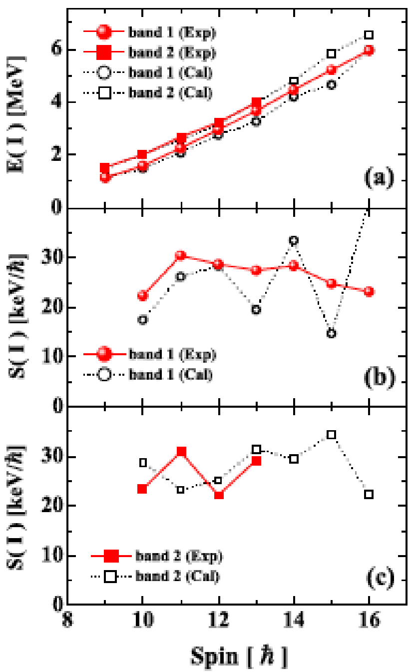
- $^{198}$Tl : Lawrie et al., EPJA 45

..Γ∫ΛΞ∫ΠΕ⊂ΘΜΕΜ∫ΞΟ:

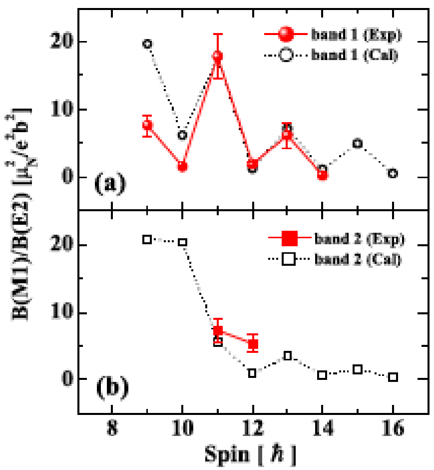
- PRM calculations
Lawrie, Shirinda, PLB 689
- multiple chiral doublets with CMI and VMI
Chen et al., PRC 82

# 2011




$^{80}$Br



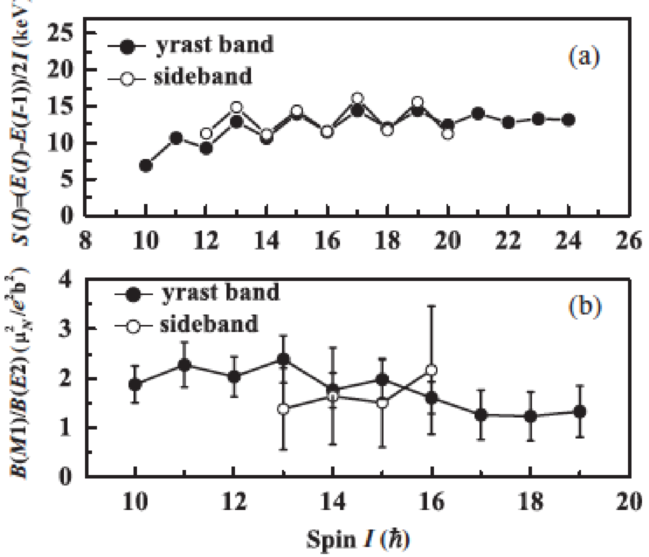

Experimental papers :

- $^{126}$Cs : Grodner et al., PLB 703
  chiral transition rules
- $^{80}$Br : Wang et al., PLB 703
  chiral vibration
- $^{134}$Pr : Timar et al., PRC 84
  new chiral candidate

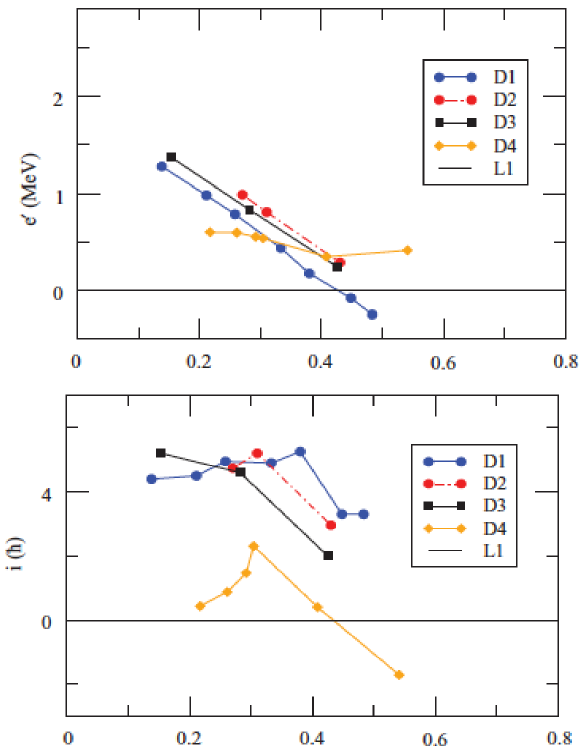
..ΓJΛΞJΠEЄΘMΞMJΞO :

- RMF calculations in $^{105}$Rh
Li, Zhang, Meng, PRC 83
- chiral vibrations in A=135
Almehed, Dönau, Frauendorf, PRC 83

$^{128}$La




$^{138}$Nd




# 2012

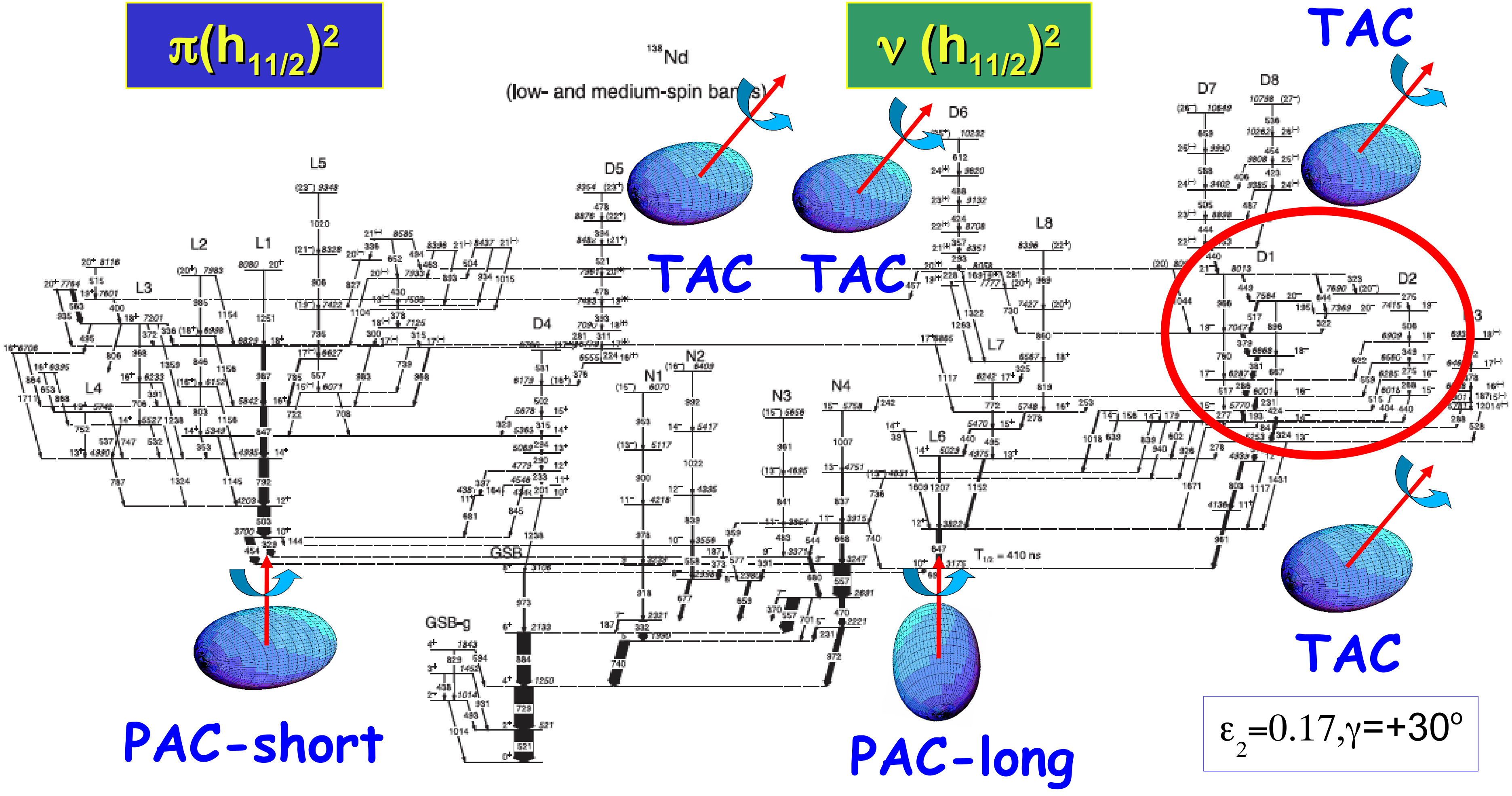
Experimental papers :

- $^{138}$Nd : Petrache et al., PRC 86
- $^{128}$La : Ma et al., PRC 85

..ΓЈΛΞЈΠΈΘΜΕΜЈΞΟ :

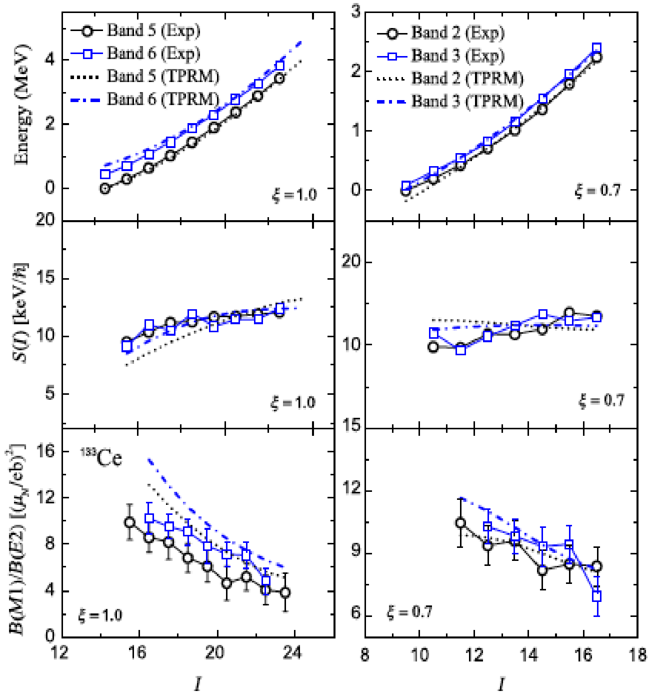
- TPSM calculations for $^{128}$Cs
 Bhat, Sheikh, Palit, PLB 707
- chirality in real nuclei
Shirinda, Lawrie, EPJA 48

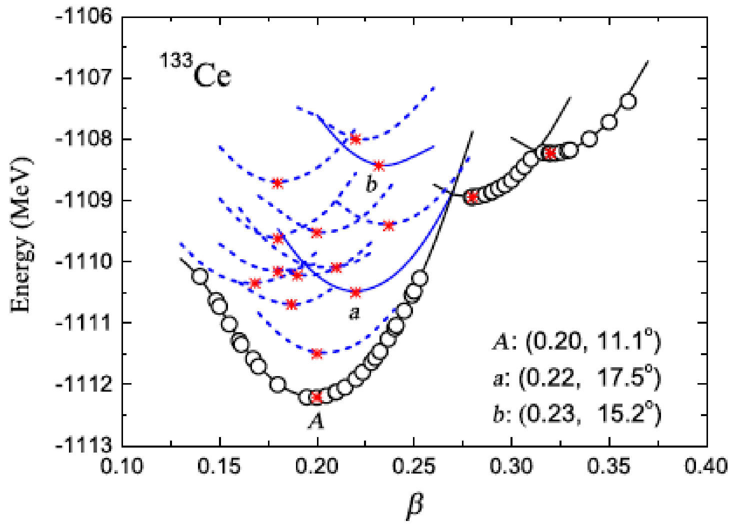
# $^{138}$Nd – 21 bands at medium spins !




C. Petrache et al., PR C86, 044321 (2012)

# 2013




Potential energy curves

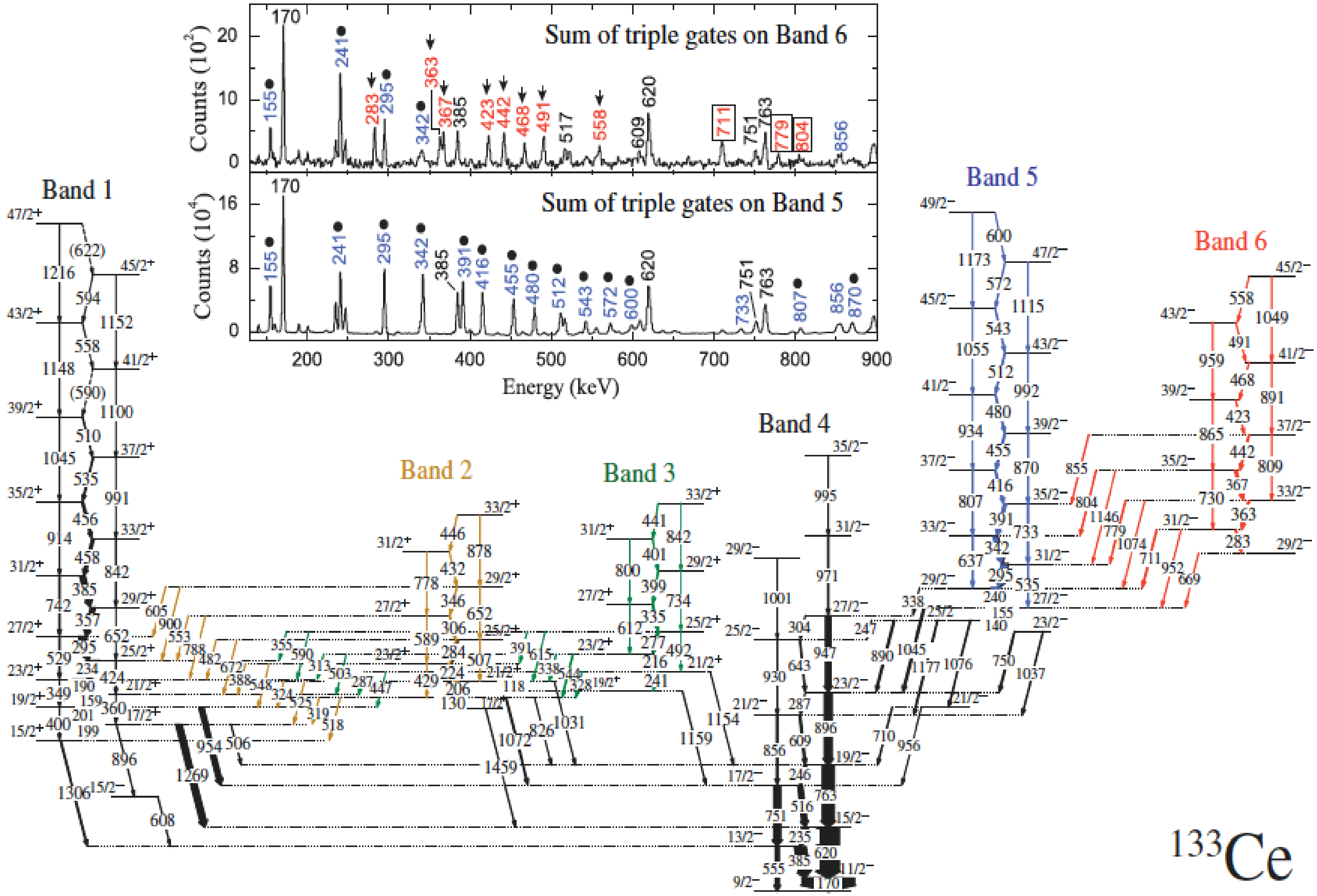
Experimental papers :

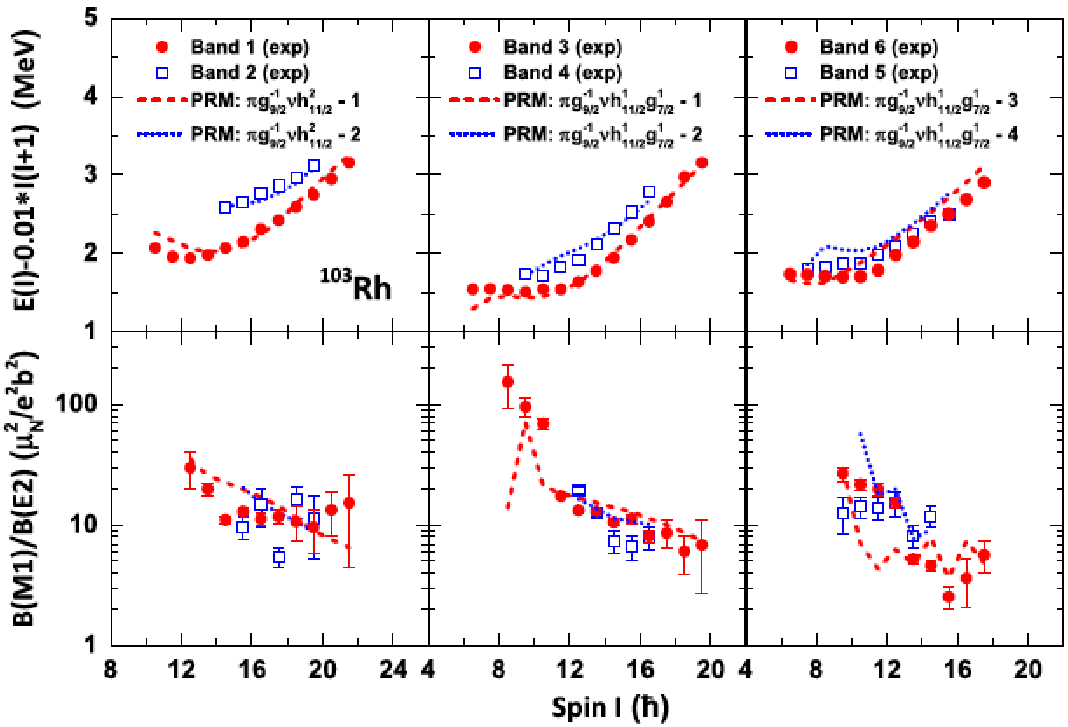
- $^{133}$Ce : Ayageankaa et al., PRL 110
  multiple chiral bands
- $^{132}$La : Kuti et al., PRC 87
- $^{194}$Tl : Masiteng et al., PLB 719

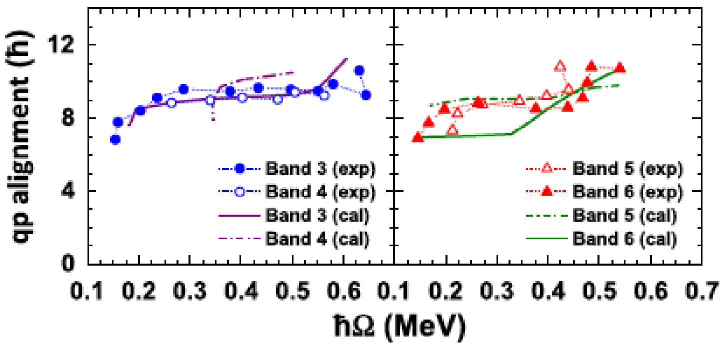
..Γ ϳΛΞϳΠΕ∪ΕΘΜΕΜϳΞΟ :

- multi-chiral-pair bands
Hamamoto, PRC 88
- collective Hamiltonian for chiral modes
Chen et al., PRC 87
- risk of chiral interpretation in $^{103,105,106,107}$Ag
Ma et al., PRC 88
- multiple chiral doublet bands in $^{107}$Ag
Qi et al., PRC 88

# $^{133}$Ce : Ayageankaa, Garg, Frauendorf et al., PRL 110, 2013
## multiple pairs of chiral doublet bands (MχD)






# 2014

## Experimental papers :

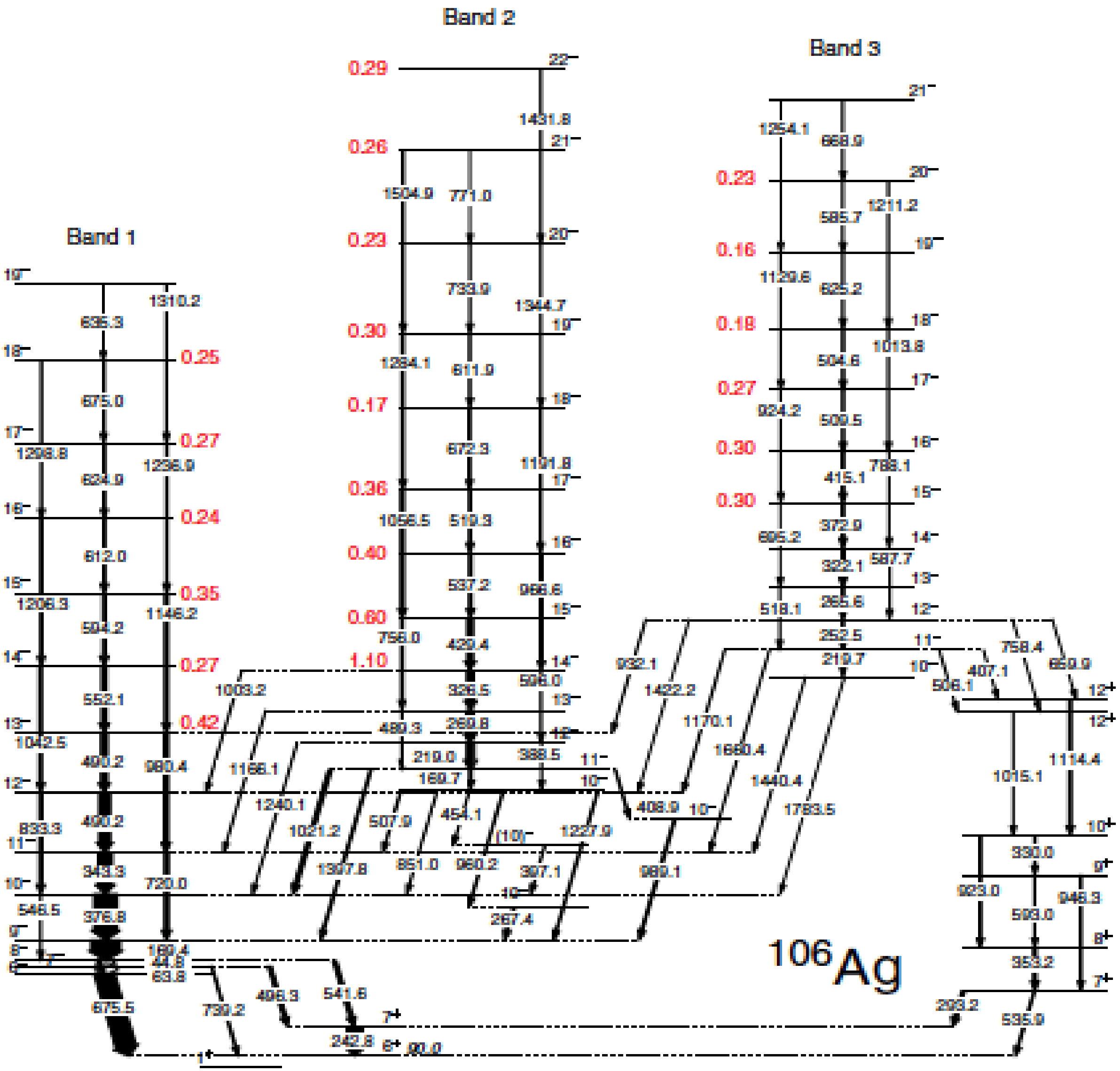
- $^{103}$Rh : Kuti et al., PRL 113
  multiple chiral bands
  1 excited chiral doublet !
- $^{106}$Ag : Rather et al., PRL 112
- $^{106}$Ag : Lieder et al., PRL 112

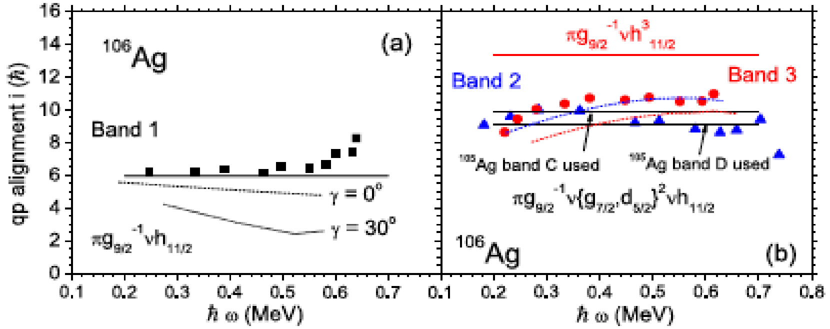
- $^{102}$Rh : Tonev et al., PRL 112
  lifetimes → chiral vibrations

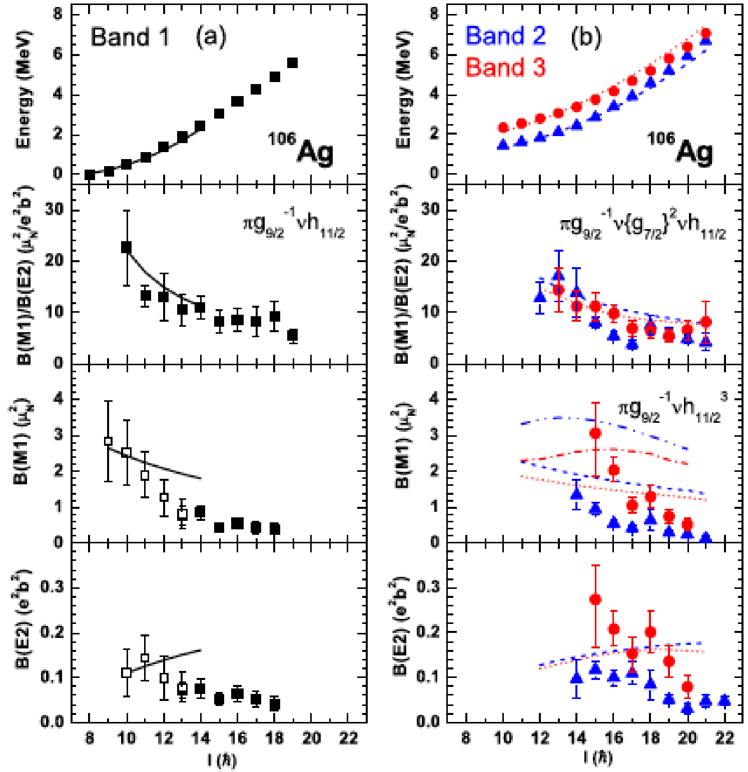
..ΓJΛΞJΠΕ∈ΘΜ∈ΜJΞΟ :

- collective Hamiltonian for chiral modes
Chen et al., PRC 87

# $^{106}$Ag : Lieder et al., PRL 112, 2014
## Resolution of chiral conundrum in $^{106}$Ag



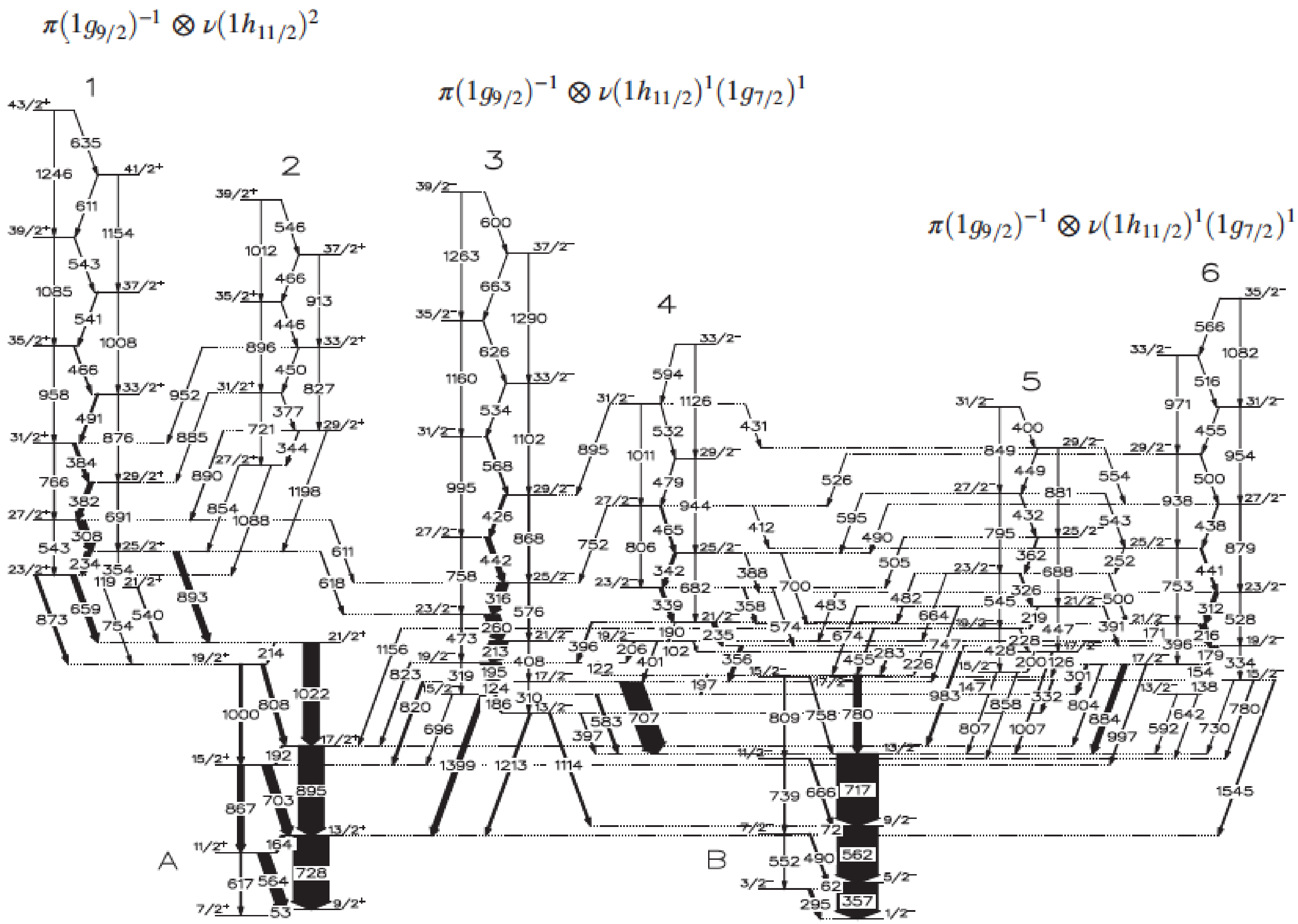



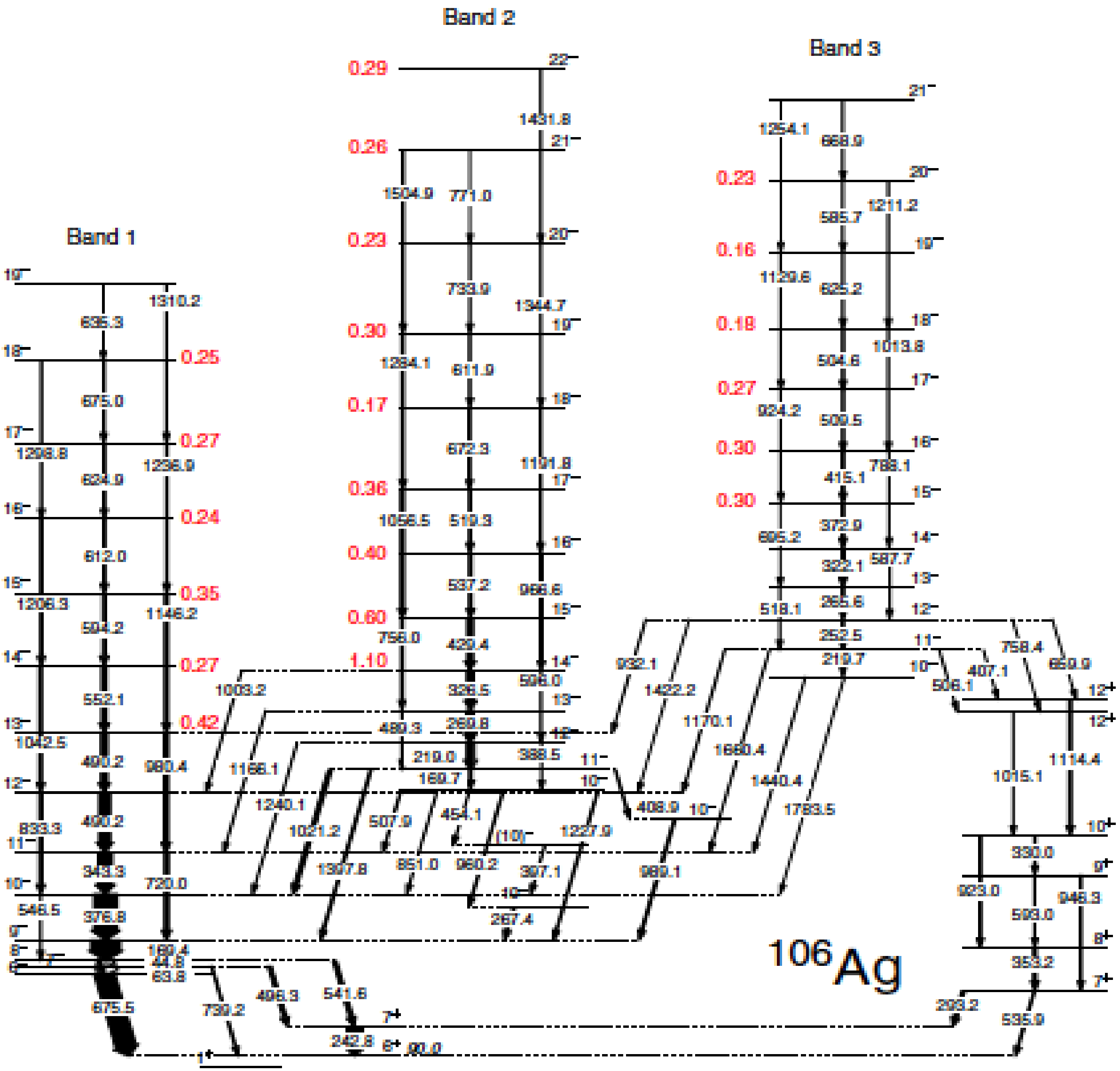
$^{103}$Rh : Kuti et al., PRL 113, 2014

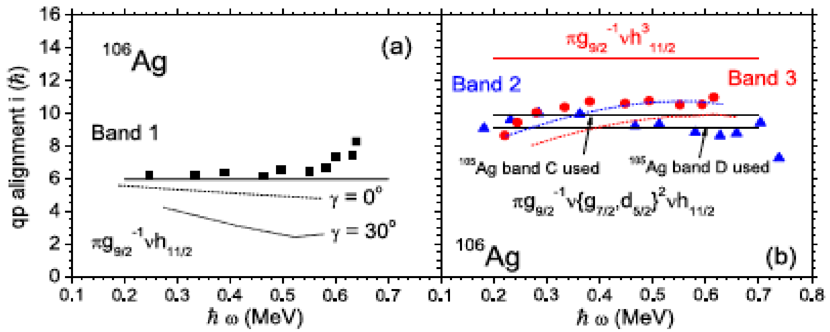
multiple chiral doublet bands with identical configuration

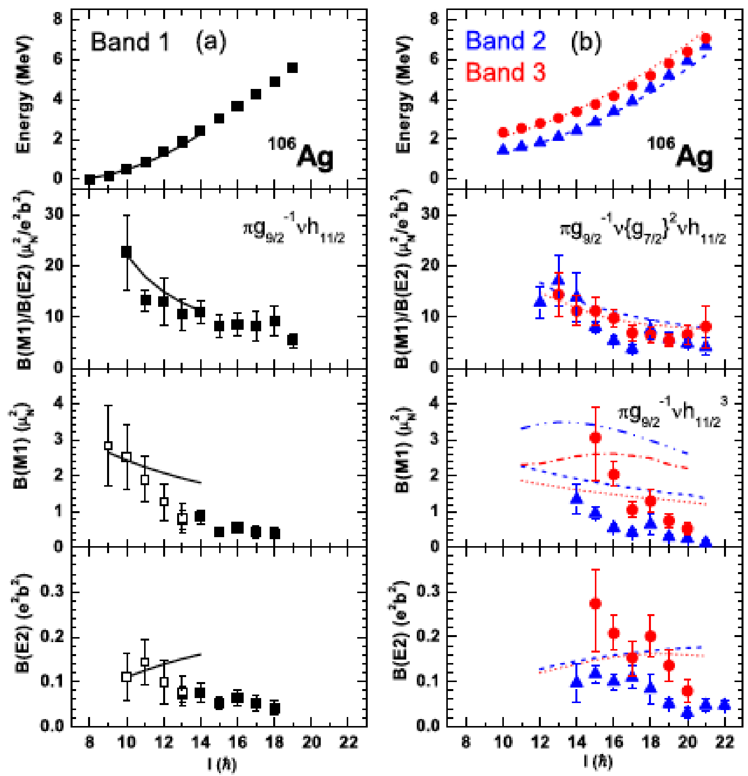
1 excited chiral doublet ! (MχD)



# $^{106}$Ag : Lieder et al., PRL 112, 2014
## Resolution of chiral conundrum in $^{106}$Ag



# Conclusions

20 years of intense life, 100 articles (30 letters and Rapid Comm.) !

Regions of chirality : 80, 100, 130, 180, 200

Experimental fingerprints :
- almost constant energy difference between partners
- similar intraband transitions probabilities
- similar single-particle alignments
- attenuated energy staggering
- B(M1) staggering (why only in Cs nuclei?)
- present in odd-odd, odd-A and even-even nuclei ($^{136}$Nd,$^{138}$Nd?)

Theoretical fingerprints :
- similar expectation values of the squared angular momenta
- similar spin aligned along two perpendicular axes
- near maximal triaxiality
- only above a critical rotational frequency
- degeneracy over a limited spin range