



Institut de Physique Nucléaire de Lyon

# Backbending in the pear-shaped $^{223}_{90}Th$ : evidence of a high spin octupole to quadrupole shape transition in the actinides

Shapes and Symmetries in nuclei : from Experiment to Theory

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# Main lines of the talk

## ① Introduction : pear shaped nuclei

## ② Experimental conditions and results

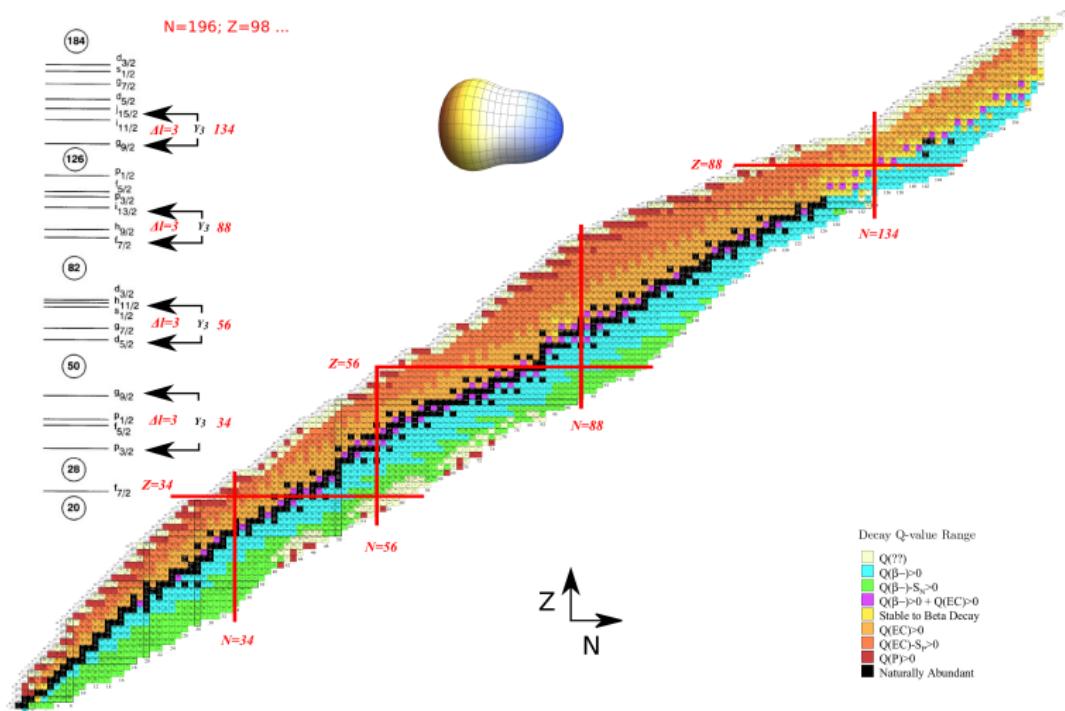
- ▶ The  $^{18}O + ^{208}Pb$  experiment
- ▶ New Level Scheme

## ③ Backbending in $^{223}Th$ : Shape Transition

- ▶ Low and medium spin structures
- ▶ Kinematic moment of inertia : The  $J^{(1)}$  accident
- ▶ Octupole to Quadrupole shape transition

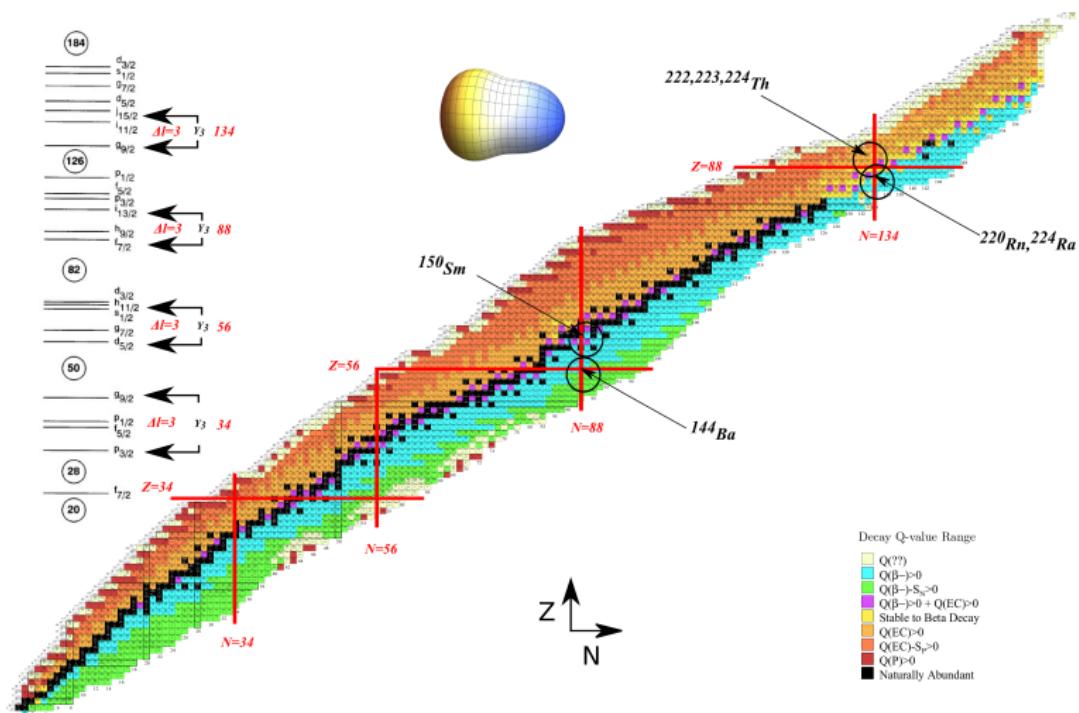


# Magic numbers for octupole shape





# Magic numbers for octupole shape





# Experimental conditions

Using the fusion-evaporation channel

- ▶  $^{18}_8O(85MeV) + ^{208}_{82}Pb \Rightarrow ^{226}Th^* \rightarrow ^{222,223,224}Th + xn$
- ▶ Dominant contribution of the ( $^{18}O, 3n$ ) channel ⇒ Evaporation residues centered around  $^{223}Th$

Two different experiments

- ▶ JUROGAM II 4 rings
- ▶ 39 Compton-suppressed Germanium detectors
- ▶ Building of cubes (Dim = 3)





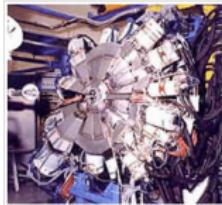
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## Two different experiments

- JUROGAM II 4 rings
- 39 Compton-suppressed Germanium detectors
- Building of cubes (Dim = 3)
- Euroball IV 13 rings → RADO
- 71 Compton-suppressed Germanium detectors
- Building of hypercubes (Dim = 4)

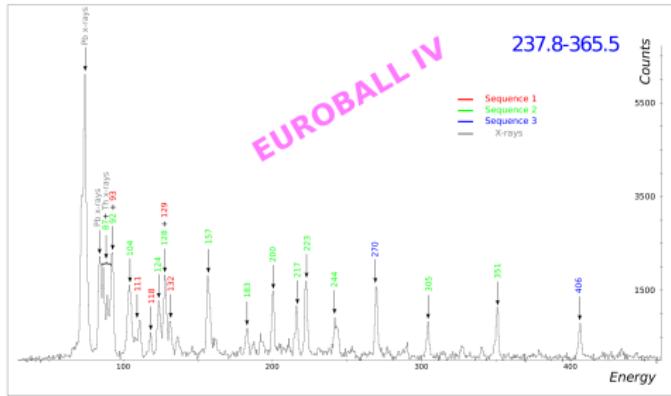
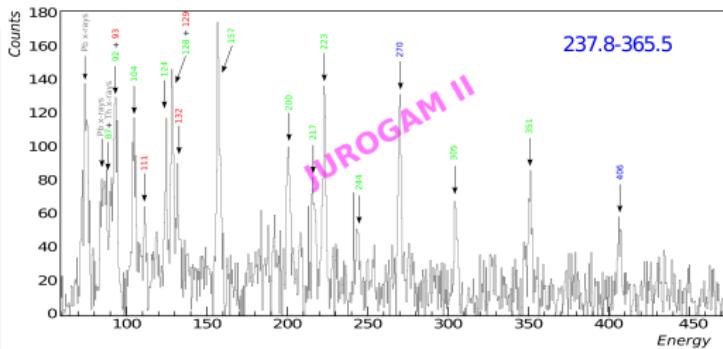




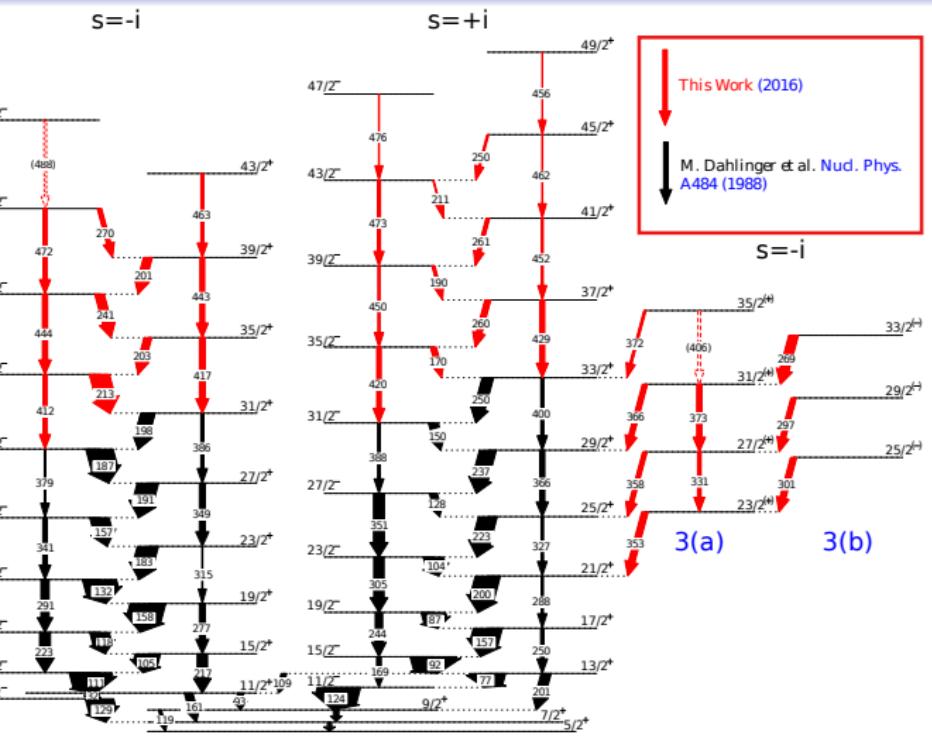
# Level scheme building

## $\gamma$ coincidences

- ▶ Comparisons
- JUROGAM II/EUROBALL IV
- ▶ Consistent data analysis
- ▶ More statistics with
- EUROBALL
- ▶ You can find more details and spectra in my poster



## Level scheme building



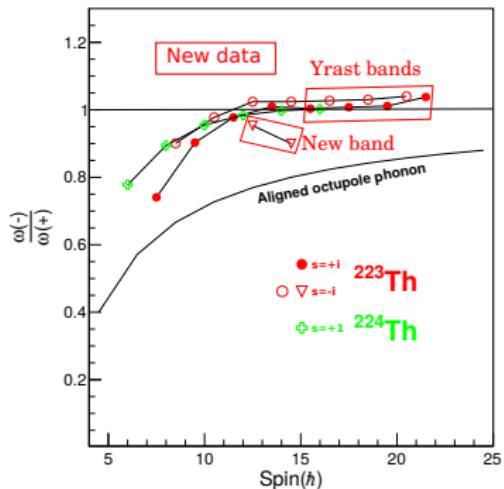
## New LS

- ▶ 14 new levels,
  - ▶ 33 new  $\gamma$
  - ▶ Level scheme  
extended up to  $\frac{49}{2} \hbar$
  - ▶ One new band
  - ▶ No parity doublets



# Characterization of octupole collectivity in $^{223}Th$ and Backbending

# Low-spin structures : differents configurations and behaviors



## Ratio of rotational frequencies

- $\frac{\omega^-(I)}{\omega^+(I)} = 2 \frac{E(I+1)^- - E(I-1)^-}{E(I+2)^+ - E(I-2)^+}$
- $\frac{\omega^-(I)}{\omega^+(I)} = 1 \rightarrow \text{Rigid Octupole Deformation}$
- $\frac{\omega^-(I)}{\omega^+(I)} < 1 \rightarrow \text{Vibrational behavior}$

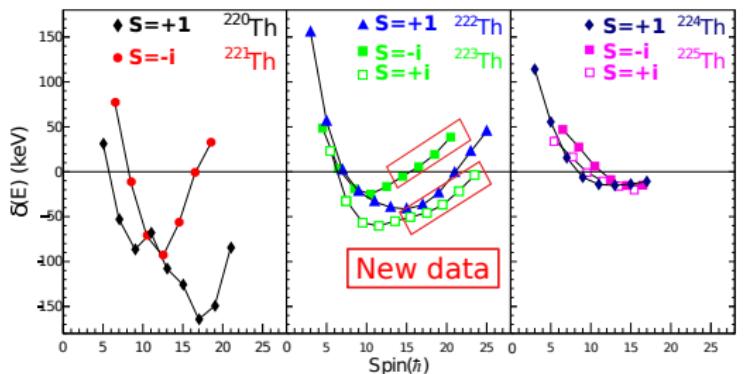
$^{223}\text{Th}$	Yrast	Non-yrast
Band-head	$K = 5/2$	$K = 1/2, E^* = 85 \text{ keV}$ [1]
$^{221}\text{Th}$	Yrast	Non-yrast
Band-head	$K = 1/2$	$K = 5/2, E^* = 186 \text{ keV}$ [1]

[1] Predictions from S. Cwiok et al. Nucl. Phys. A529 (1991)

## Configurations and behavior in octupole band of $^{223}\text{Th}$

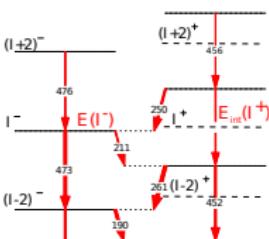
- New-band : no parity doublets  $\rightarrow$  analogous to  $^{221}\text{Th} g - \text{band}$
- More *vibrational character* in the new-band

## Medium-spin structures



## Parity splitting

►  $\delta E = E(I^-) - E_{Int}(I^+)$



Large parity splitting  $\delta E \simeq 100$  keV

- ### ► More vibrational behavior

### Small parity splitting $\delta E \leq 50$ keV

- #### ► Static octupole deformation

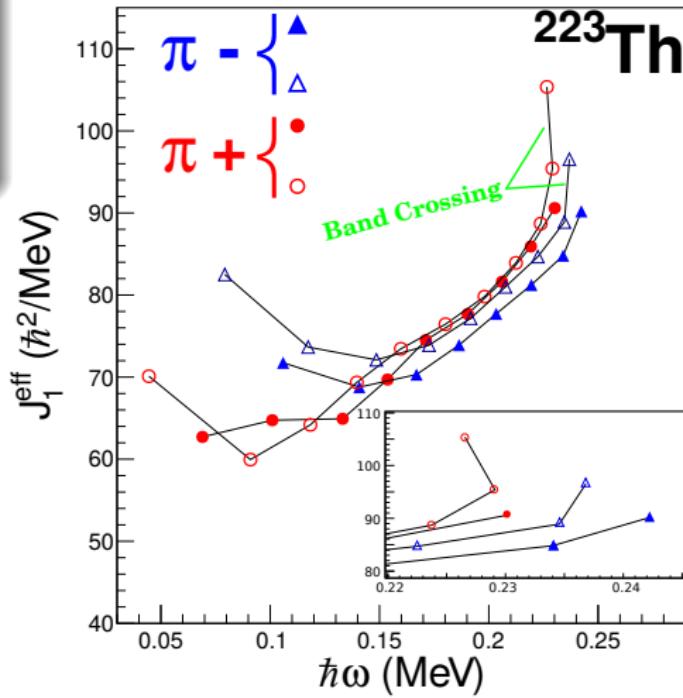
Behavior of  $\delta E$  interpreted in terms of rotational octupole-phonons

- ▶  *Oscillations* arise from consecutive crossing and mixing of different *phonons bands* S. Frauendorf Phys. Rev. C 77 (2008)
  - ▶  <sup>222,223</sup>*Th* intermediate behavior

# Kinematic moment of inertia : *Backbending*

Calculated  $J_1^{\text{eff}}$

- ▶  $\blacktriangle, \bullet \rightarrow s = -i$
- ▶  $\blacktriangle, \circ \rightarrow s = +i$
- ▶  $\blacktriangle$  Upbend  $\simeq 0.23$  MeV
- ▶  $\circ$  Backbend  $\simeq 0.23$  MeV



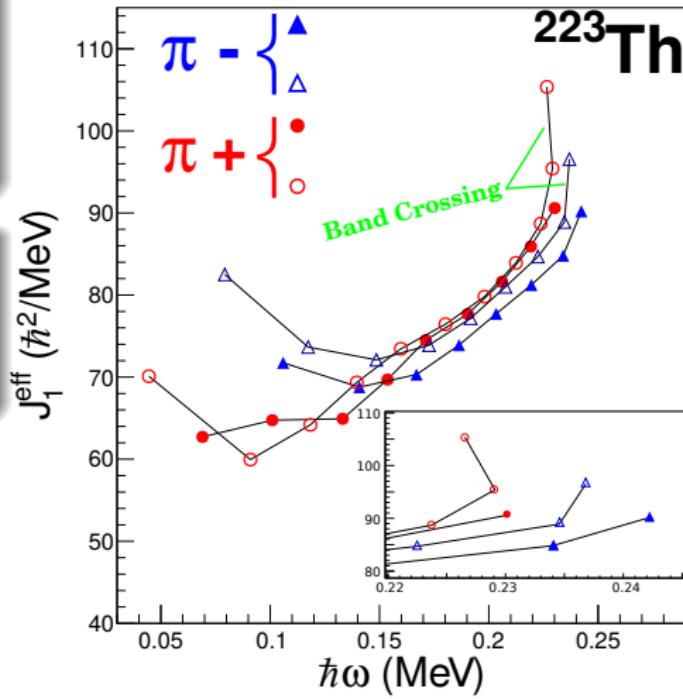
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Scenario for  $^{223}\text{Th}$

- ▶ *Band Crossing* at high spin :  
Switch of the yrast line at  
 $I \simeq 24\hbar, \hbar\omega \simeq 0.23 \text{ MeV}$





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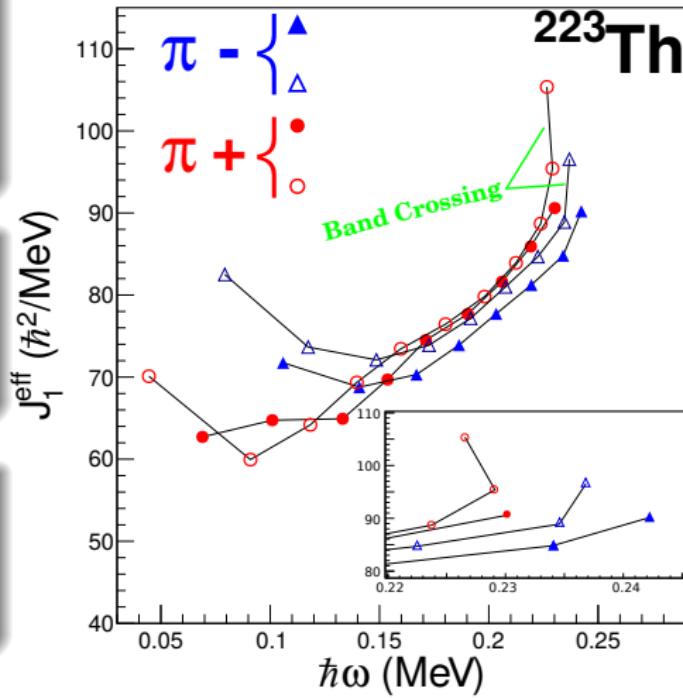
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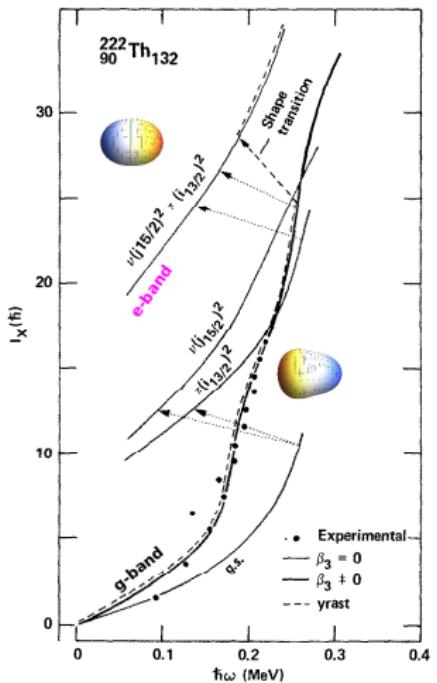
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Hints of such band termination

- Abrupt loss of intensity in  
yrast-band in  $^{221}\text{Th}$
- Same feeding pattern in  $^{222}\text{Th}$



# Calculations for $^{222}Th$ and heavier even-even thorium nuclei



## Calculation results for $^{222}Th$

- ▶ + Octupole band structure remains yrast up to  $I \simeq 24\hbar$
- ▶ + Backbending above  $\hbar\omega = 0.23$  MeV, crossing with reflection-symmetric band ( $e$ -band),  
 $(\beta_3 = 0, \beta_2 = 0.120)$ .

W. Nazarewicz et al. NPA 467



# Conclusions and perspectives



## Future prospects of shape transition in Th

### Summary about $^{223}Th$

- ▶ Strong experimental evidence about band crossing around  $\hbar\omega \simeq 0.23\text{MeV}$
  - ▶ New data consistent with theoretical calculations that predict a **backbending** at **high spin** and an **octupole to quadrupole shape transition**.
  - ▶ To reach the fully aligned band ***e – band***, we need to probe higher spins → Experimental challenge
  - ▶ Note : Work to be submitted

- ▶  Open the way to new research of shape transition in odd-mass actinides
  - ▶  Look for recent theoretical prediction for odd-mass actinides including the octupole degree of freedom
  - ▶  Where is the starting point of octupole collectivity in light Th?



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## Prospects

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- ▶ + Where is the starting point of octupole collectivity in light Th?



Pear shaped nuclei



Experimental results

Charaterization of Octupole Collectivity in  $^{223}Th$ 

CCL &amp; Perspectives



Thanks for your attention



# Angular distribution ratios : Spins confirmed

## Process for ADO

- ▶ Angular distribution ratio ( $R_{ADO}$ ) with respect to the beam axis
- ▶ 13 discrete angles (from  $13^\circ$  to  $163^\circ$ )
- ▶ 2 main angles T+C( $39.3^\circ$ ) et Q( $76.6^\circ$ ) for weaker  $\gamma - rays$

## Calculation methods



Tapered + Cluster



Tapered + Cluster + I+2 → I -&gt; I+2



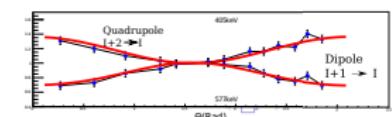
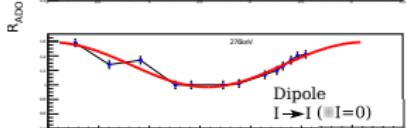
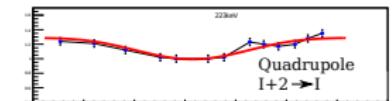
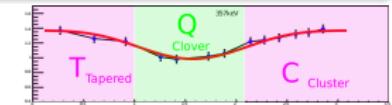
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Uncertainties - Statistic and systematic



Tapered + Cluster + I+2 → I -&gt; I+2 + Syst





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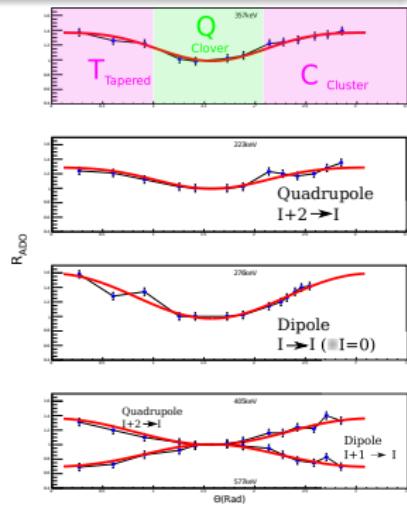
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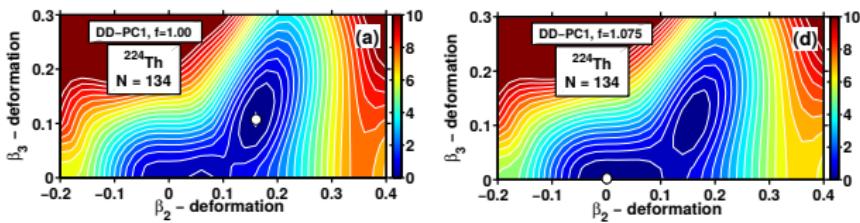
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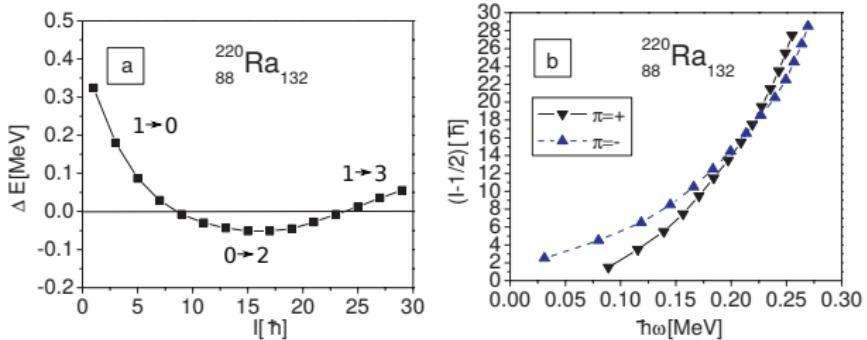
## Calculation methods

- ▶  $R_{ADO} = \frac{I(39.3)}{I(76.6)}$
- ▶  $R_{ADO} > 1 \Rightarrow \Delta I = 2$     $R_{ADO} < 1 \Rightarrow \Delta I = 1$
- ▶ Uncertainties : Statistic and systematic
- ▶  $\frac{\Delta(R_{ADO})}{R_{ADO}} = \frac{\Delta(TC)}{TC} + \frac{\Delta(Q)}{Q} + 5\%$

E [keV]	I	R <sub>ADO</sub>	I	I <sub>i</sub>	I <sub>f</sub>	Localization
268.7	16.1(43)	0.80(9)	1	$\frac{33(-)}{2}$	$\frac{31(+)}{2}$	3b - 3a
269.8	7.8(22)	0.64(9)	1	$\frac{41}{2}$	$\frac{39(+)}{2}$	1a - 1b
276.9	10.7(25)	1.31(8)	2	$\frac{19(+)}{2}$	$\frac{15(+)}{2}$	1b - 1b
288.4	3.9(9)	1.43(11)	2	$\frac{21(+)}{2}$	$\frac{17(+)}{2}$	2b - 2b
290.5	15(2)	1.30(7)	2	$\frac{21}{2}$	$\frac{17}{2}$	1a - 1a







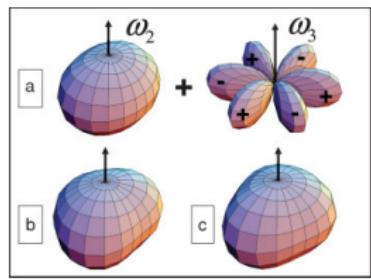


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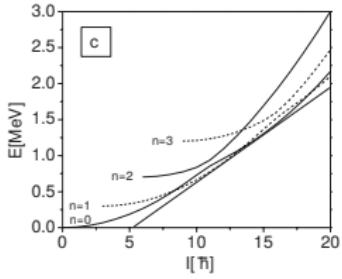
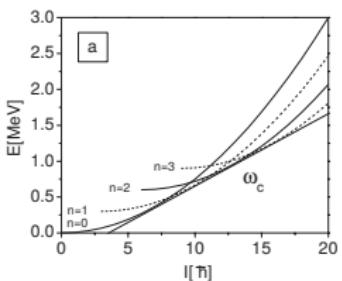
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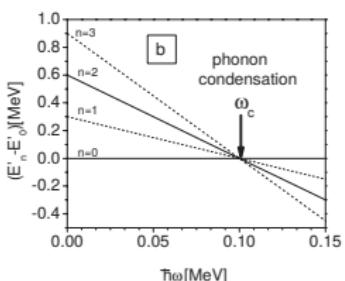
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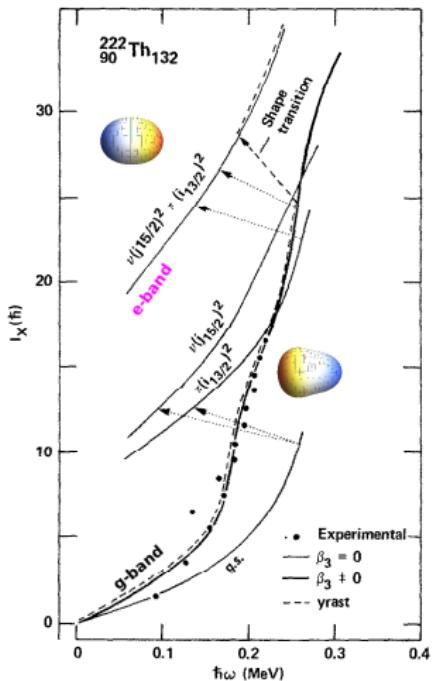
(a1)



(b1)



# Calculations for $^{222}Th$ and heavier even-even thorium nuclei

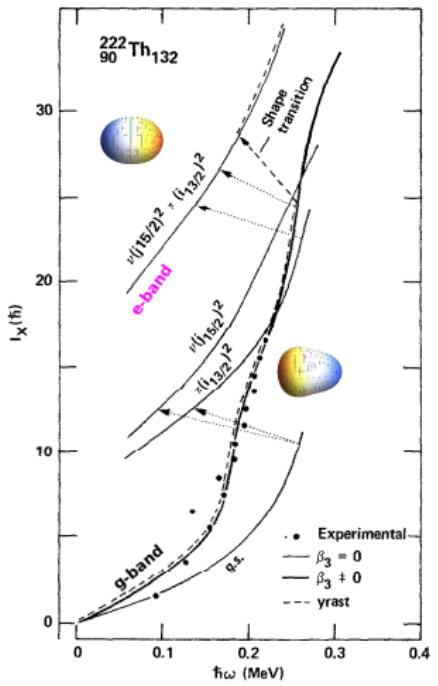


## Calculation results for $^{222}Th$

- ▶ Woods-Saxon Bogolyubov Cranking calculations
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- ▶ + Backbending above  $I \geq 24\hbar$ , crossing with reflection-symmetric band ('e - band').  
( $\beta_3 = 0, \beta_2 = 0.120$ )

W. Nazarewicz and al. NPA 467

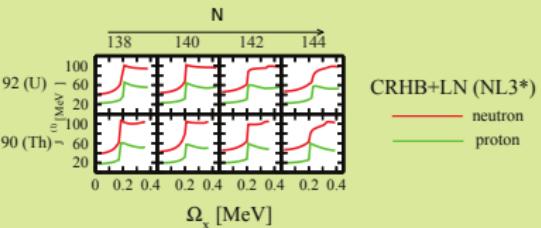
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## Simultaneous alignements in the $\pi$ and $\nu$ orbitals



A. V. Afanasjev et al., Phys. Rev. C (2013)

- For  $U$  and  $Th$  isotopes :
  - Alignment of the  $\pi i_{13/2}$  and  $\nu j_{15/2}$  orbitals
  - Sharp transition is predicted around  $\Omega_x \simeq 0.2\text{MeV}$

W. Nazarewicz and al. NPA 467

G. Maquart et al. (UCBL)

## Shape transition in $^{223}Th$

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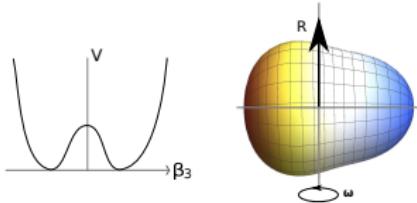
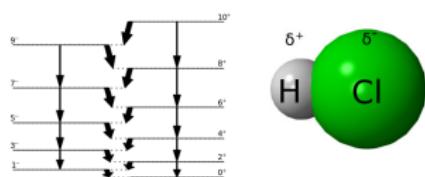
# Reflection-asymmetric shapes & consequences in nuclei

## Generalized Rayleigh shape

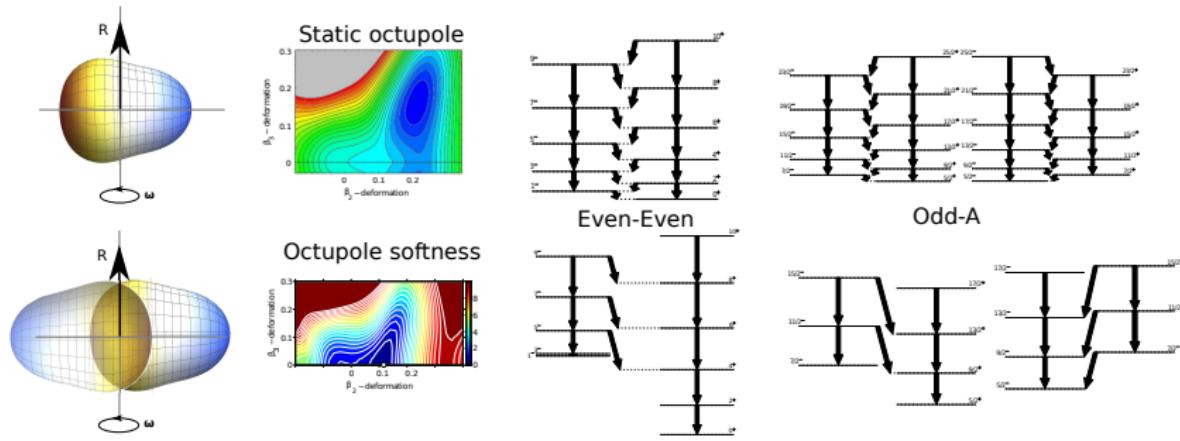
- ▶  $R(\theta, \phi) = c(\alpha)[1 + \sum_{\lambda=2}^{\infty} \sum_{\mu=-\lambda}^{\mu=+\lambda} \alpha_{\lambda\mu} Y_{\mu}^{\lambda}(\theta, \phi)]$
- ▶ For axial symmetries :  
 $\beta_{\lambda} = \alpha_{\lambda,0}$   
other values of  $\alpha_{\lambda\mu}$  are zero.
- ▶ if  $\alpha_{\lambda\mu} \neq 0$  for odd  $\lambda$  the nucleus becomes reflection-asymmetric
- ▶  $\alpha_{3,0} \neq 0 \rightarrow$  Octupole component, pear shape

## HCl molecule

- ▶ Spectroscopic consequences of reflection asymmetry well known in molecules



## Reflection-asymmetric shapes & consequences in nuclei



PES from Z.P. Li et al. and S.E. Agbemava et al.

- ▶ Static Octupole deformation  $\rightarrow$  deep octupole potential well at  $\beta_3 \neq 0$ , saddle point at  $\beta_3 = 0$
  - ▶ Octupole softness  $\rightarrow$  the nucleus is in average *reflection-symmetric*, vibration between the two pear shapes