Two-phonon wobbling in ^{135}Pr

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February 13, 2018

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Introduction

A Spherical nucleus

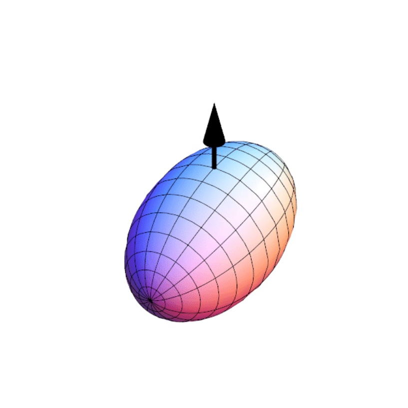
Courtesy Dr. J. T. Matta

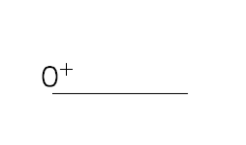
Bohr and Mottelson stated:

A common feature of systems that have rotational spectra is the existence of a 'deformation', by which is implied a feature of anisotropy that makes it possible to specify an orientation of the system as a whole.

Nuclear Structure Volume II: Nuclear Deformations (1975)

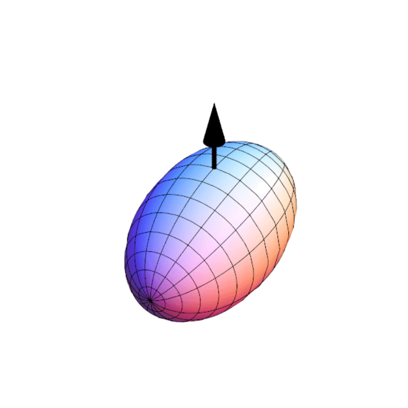
Deformed Nucleus

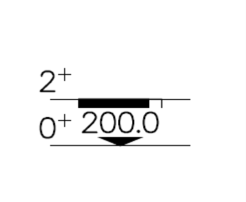




Rotational Band

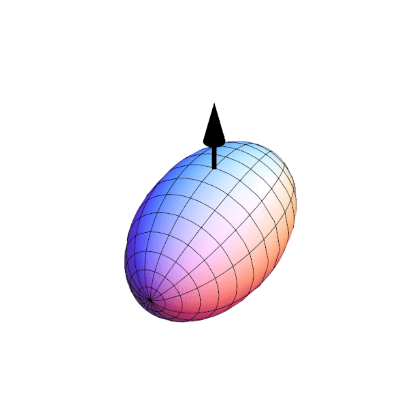
Deformed Nucleus

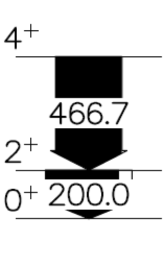




Rotational Band

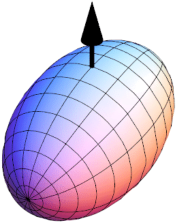
Deformed Nucleus

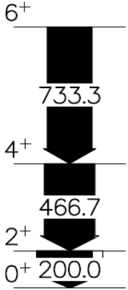




Rotational Band

Deformed Nucleus

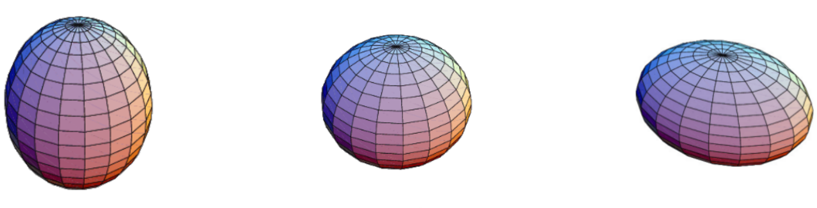


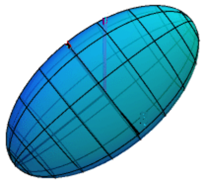


Rotational Band

Nuclear Shapes

Prolate | Spherical | Oblate

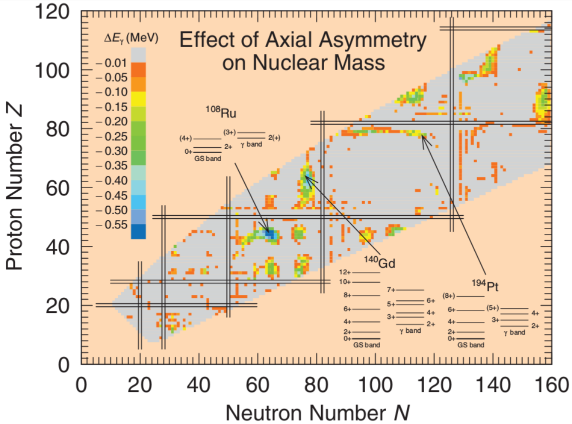




Triaxial Nucleus

Triaxiality - A rare phenomenon!

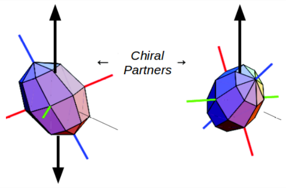
P. Möller et. al. PRL 97, 162502 (2006)

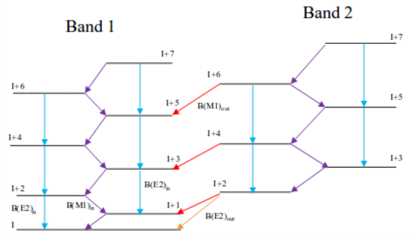


Predicted regions $\rightarrow Z = 60, N = 76$ and $Z = 46, N = 66$

Triaxiality - Fingerprints (1/2)

Chirality



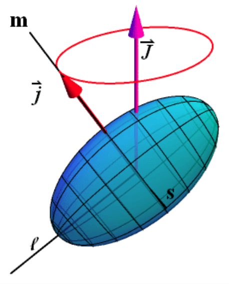


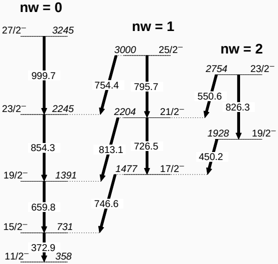
- $\vec{J}$ lies outside of all principal planes.
- Two $\Delta\mathrm{I} = 1$ bands of same parity with nearly same energy.
- Opposite chirality bands.

Standard fingerprints for chiral bands:

- Close excitation energies
- Constant Staggering parameter
- Identical B(M1)/B(E2) ratios

Wobbling





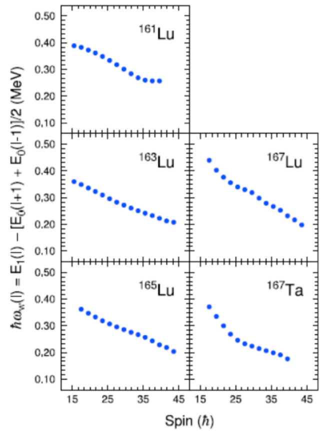
- Analog of the spinning motion of an asymmetric top.
- Oscillation of a principal axis about the space fixed $\vec{J}$.

Standard fingerprints for Wobbling bands:

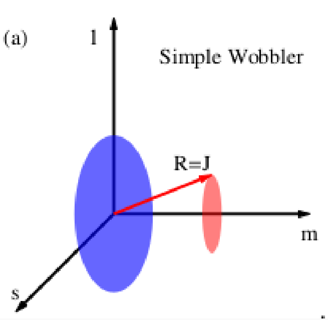
- Rotational bands corresponding to n_w = 0, 1, 2, ...
- Transitions from $n_{w+1} \rightarrow n_w$ ($\Delta n_w = +1$)
- Interband Transitions are ΔI = 1, E2

Previous cases of wobbling

- Until 2015, only five wobblers discovered: ^{161}Lu, ^{163}Lu, ^{165}Lu, ^{167}Lu and ^{167}Ta.
- All in A$\sim$160 region.
- Wobbling energy (E_{wobb})- energy associated with wobbling excitations.
- E_{wobb} vs. spin - did not agree with the **Standard Wobbler** theory!



Simple wobbler

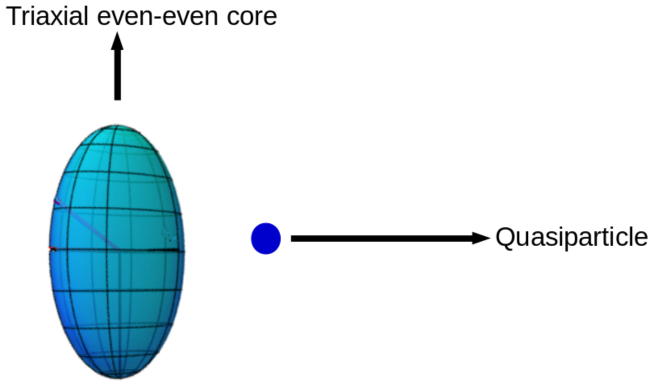


- Wobbling motion in triaxial even-even nuclei.
- Moment of Inertia (MOI) order: $\mathcal{J}_m > \mathcal{J}_s > \mathcal{J}_l$
- Wobbling excitations - small amplitude oscillations of $\vec{J}$ about the m-axis.

$$E(n_w, J) = \frac{\hbar^2}{2\mathcal{J}_1} J(J+1) + (n_w + \frac{1}{2})\hbar\omega_{\text{wobb}}$$

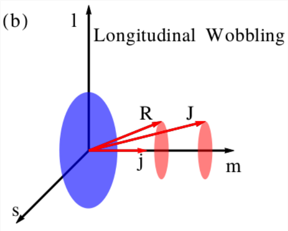
$$\hbar\omega_{\text{wobb}} = \frac{J}{\mathcal{J}_1}\sqrt{\frac{(\mathcal{J}_1 - \mathcal{J}_2)(\mathcal{J}_1 - \mathcal{J}_3)}{\mathcal{J}_2\mathcal{J}_3}}$$

Quasiparticle Triaxial Rotor (QTR) model



Triaxiality in odd-mass nuclei: High-j unpaired proton/neutron couples with the triaxial core $\Longrightarrow$ Modified wobbling motion.

Longitudinal Wobbler



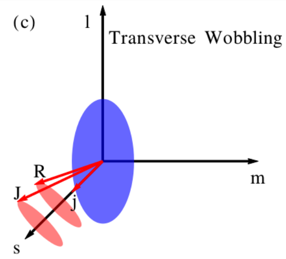
- Odd-particle aligned with axis with max. MOI (m-axis).
- $\mathcal{J}_3 > \mathcal{J}_2$ and $\mathcal{J}_3 > \mathcal{J}_1$
- Longitudinal wobbling: $\mathcal{J}_3 = \mathcal{J}_m$

$$\hbar\omega_w = \frac{j}{\mathcal{J}_3}\left[\left(1+\frac{J}{j}\left(\frac{\mathcal{J}_3}{\mathcal{J}_1}-1\right)\right)\left(1+\frac{J}{j}\left(\frac{\mathcal{J}_3}{\mathcal{J}_2}-1\right)\right)\right]^{1/2}$$

$\Longrightarrow$ E_{wobb} increases with J.

S.Frauendorf and F.Dönau, Phys. Rev. C 89, 014322 (2014).

Transverse Wobbler



- Odd-particle aligned perpendicular to axis with max. MOI (s- or l-axis).
- $\mathcal{J}_3 < \mathcal{J}_2$ and $\mathcal{J}_3 > \mathcal{J}_1$
- Transverse wobbling: $\mathcal{J}_3 = \mathcal{J}_s$

$$\hbar\omega_w = \frac{j}{\mathcal{J}_3}\left[\left(1+\frac{J}{j}\left(\frac{\mathcal{J}_3}{\mathcal{J}_1}-1\right)\right)\left(1+\frac{J}{j}\left(\frac{\mathcal{J}_3}{\mathcal{J}_2}-1\right)\right)\right]^{1/2}$$

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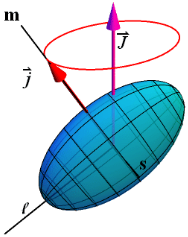
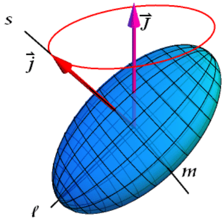
Longitudinal wobbler



Courtesy Dr. J. T. Matta

Transverse wobbler



Courtesy Dr. J. T. Matta

Confirmation of Wobbling bands

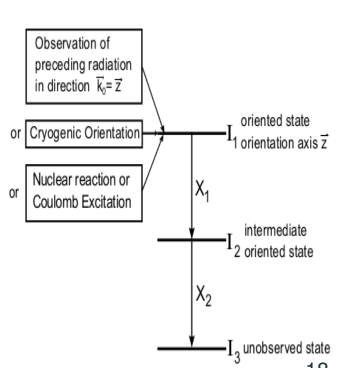
ΔI = 1, E2 interband transitions between wobbling band are verified by:

- **Angular Distributions**

Observation of the intensity distribution of a single γ-ray transition relative to an orientation axis.

$$W(\theta) = A_0(1 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta))$$

Mixing ratio: $\delta = \sqrt{\frac{I_\gamma(L')}{I_\gamma(L)}}$



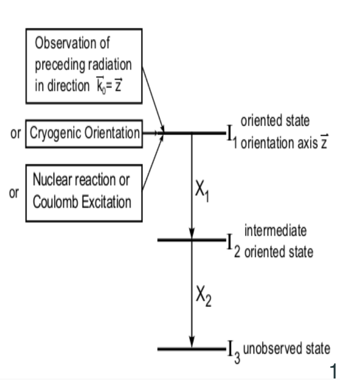
Confirmation of Wobbling bands

$\Delta\mathrm{I}$ = 1, E2 interband transitions between wobbling band are verified by:

- **Directional Correlation of Oriented states (DCO) Ratios**

$$R_{\mathrm{DCO}} = \frac{I^{\gamma_2}_{\theta_1}(\mathrm{Gate}^{\gamma_1}_{\theta_2})}{I^{\gamma_2}_{\theta_2}(\mathrm{Gate}^{\gamma_1}_{\theta_1})}$$

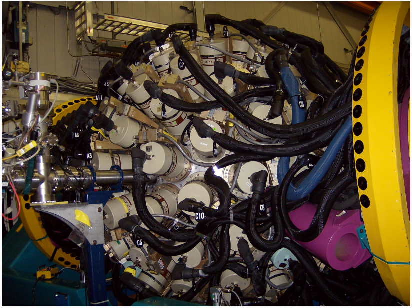
- Calculated for weak transitions to establish their multipolarities.
- Distinguishes between pure $\Delta\mathrm{I} = 1$ and pure $\Delta\mathrm{I} = 2$.



Experiment

Experiment

Gammasphere at Argonne National Laboratory, USA



- 110 Compton suppressed HpGe detectors arranged in spherical geometry.
- Compton suppression achieved with large BGO scintillators.
- Honeycomb suppression scheme.
- Operated in Anti-coincidence mode.
- Detectors arranged in 17 different angular rings around the beamline.

Experiment (cont..)

Initial Observation

- J.T. Matta et. al. (2015)
- ^{135}Pr identified as first case of wobbling in A$\sim$130 region.
- Reaction Used: ^{123}Sb(^{16}O,4n)^{135}Pr. E_{beam} = 80 MeV
- Indication of a second wobbling band but insufficient statistics.

Experiment (cont..)

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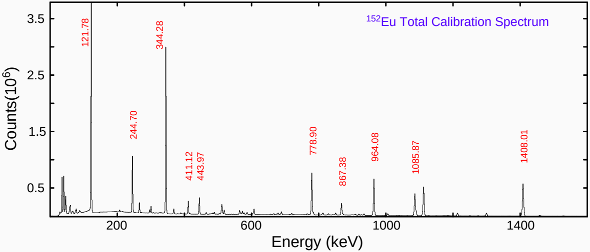
- Reaction Used: ^{123}Sb(^{16}O,4n)^{135}Pr. E_{beam} = 80 MeV
- Indication of a second wobbling band but insufficient statistics.

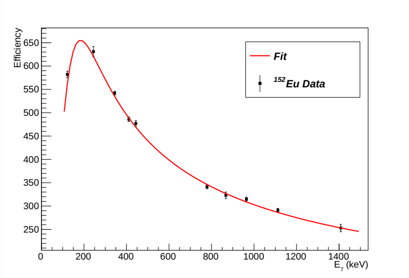
Second experiment

- Performed in October, 2015.
- Same reaction used.
- Gammasphere updated to the digital system.
- Data acquired in triple γ-coincidences.
- 4 times more data as compared to the previous experiment collected.

Data Analysis

Gammasphere Calibration

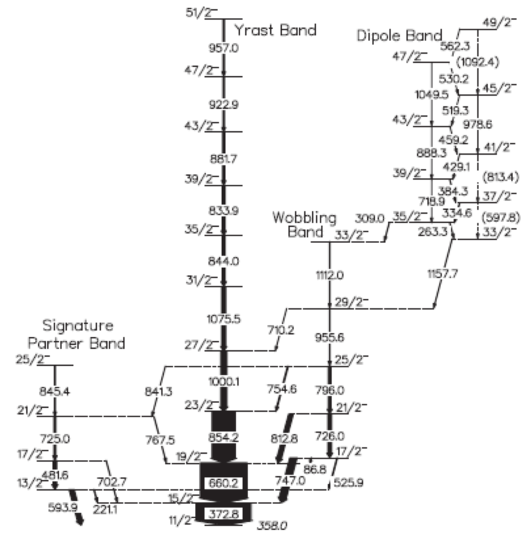




- Data analyzed using `RADWARE` suite of codes.
- Energy and efficiency calibration using standard ^{152}Eu source.
- Data sorted into $\gamma - \gamma$ matrices and $\gamma - \gamma - \gamma$ cubes.

^{135}Pr Level Scheme

What we know so far.. (*J.T. Matta et. al., PRL 114, 082501 (2015)*)



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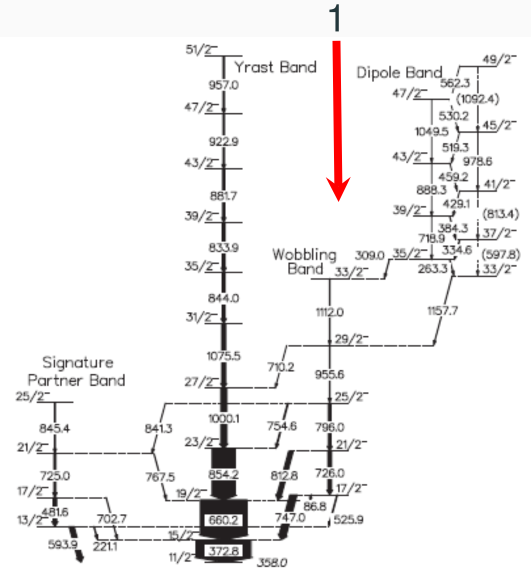


$(n_w = 1)$

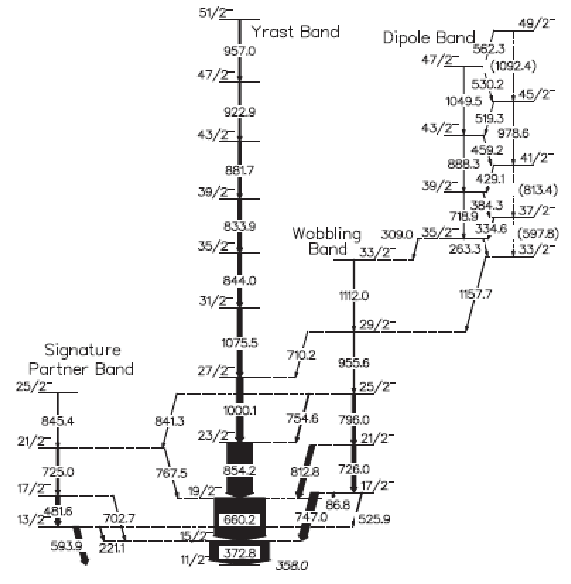
Wobbling Band

^{135}Pr Level Scheme

What we know so far.. (*J.T. Matta et. al., PRL 114, 082501 (2015)*)

ΔI $=$ 2 sequences of alternate signatures

2 →



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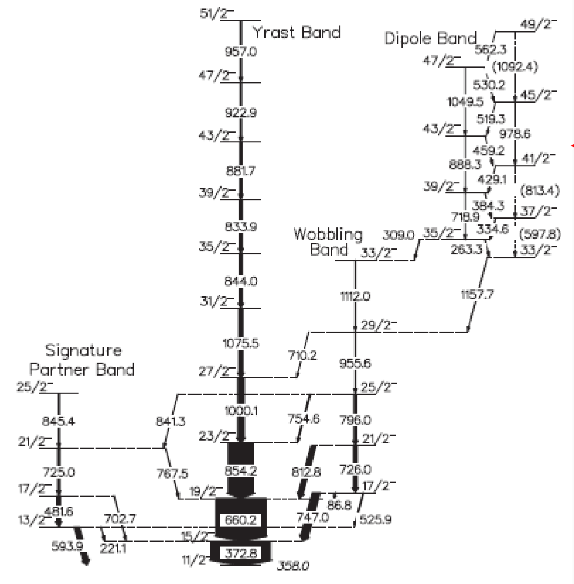
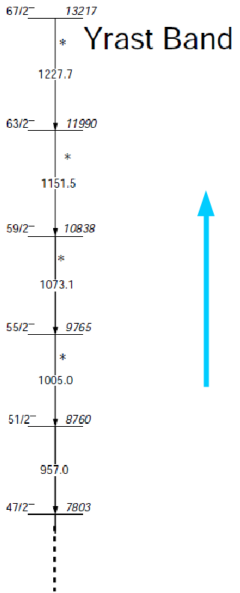


3

Strong $\Delta I = 1$

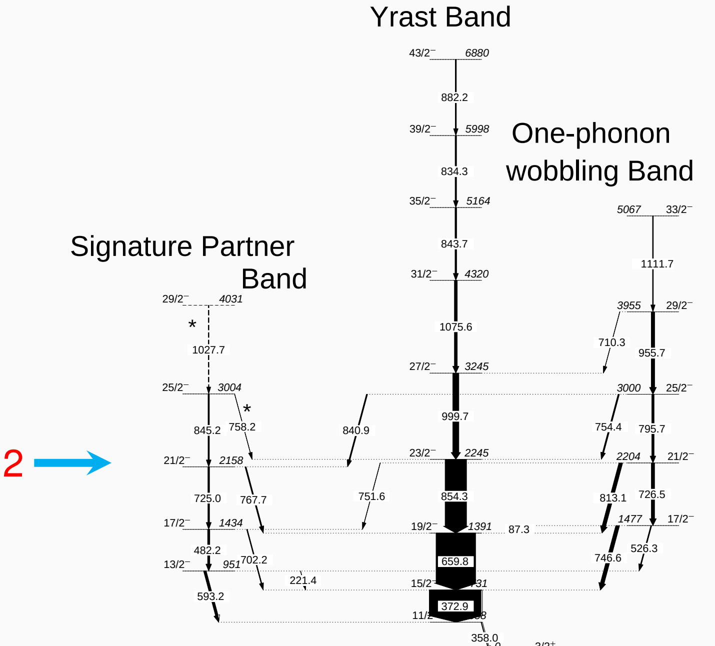
M1 transitions

^{135}Pr Level Scheme (extended)

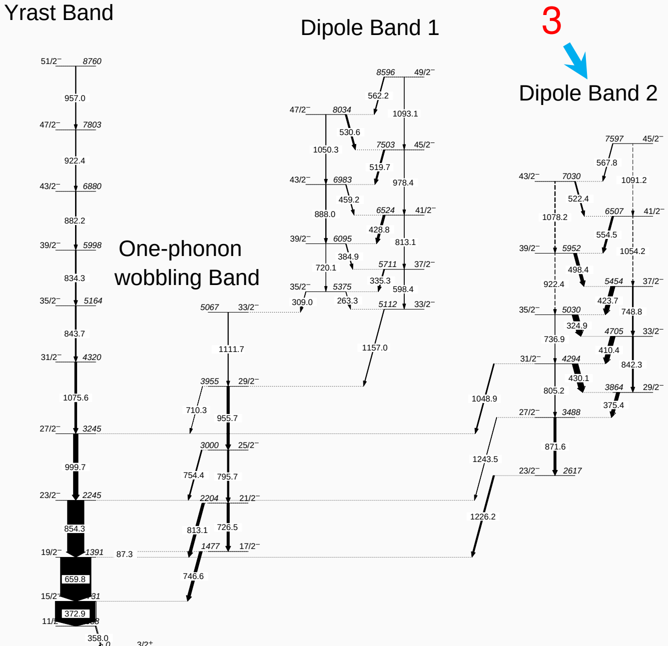


Extended up to spin $67/2^{-}$

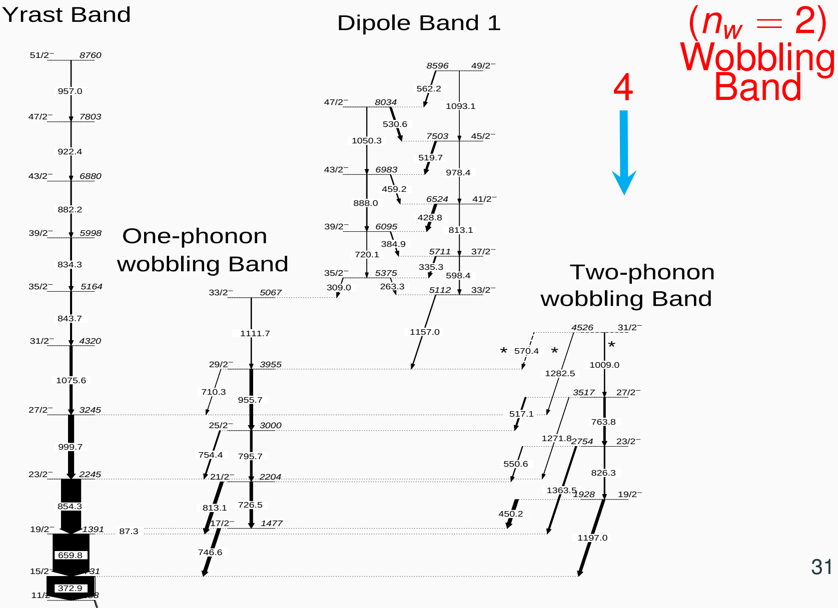
^{135}Pr Level Scheme (extended)



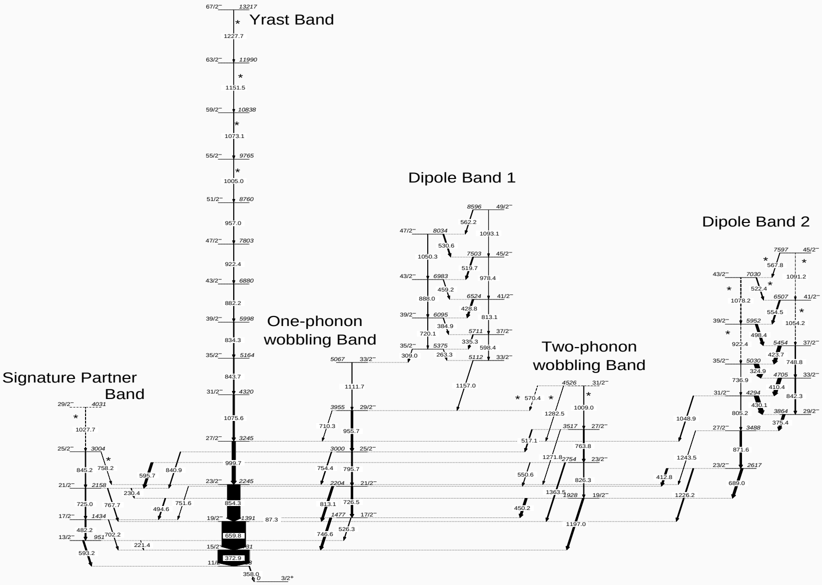
^{135}Pr Level Scheme (extended)



^{135}Pr Level Scheme (extended)



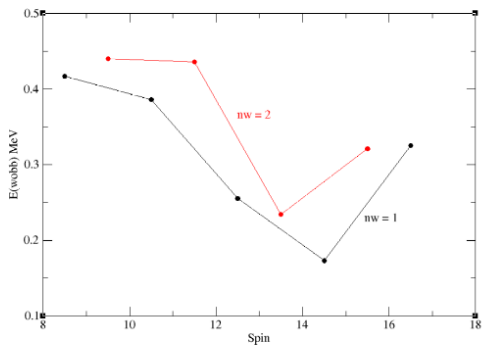
^{135}Pr Level Scheme (all together)



Preliminary Results

Results (E_{wobb} vs. Spin)

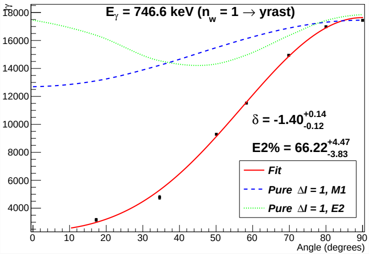
$$E_{wobb}(I) = E(I, n_w = 1) - [E(I-1, n_w = 0) + E(I+1, n_w = 0)]/2$$

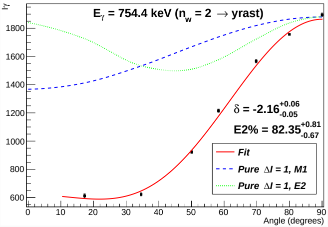


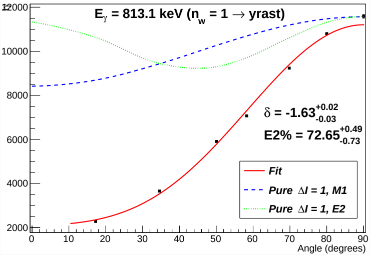
Confirms Transverse Wobbling in ^{135}Pr!

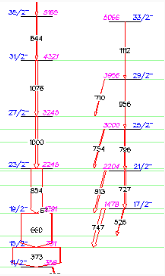
Angular distributions (1/3)

$n_W = 1 \rightarrow$ Yrast linking transitions



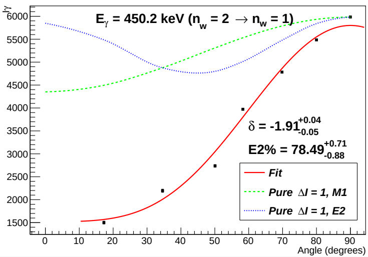


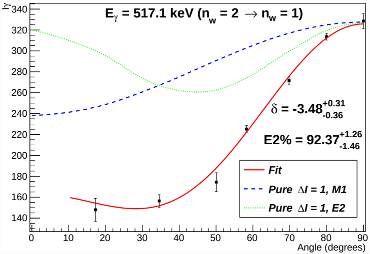


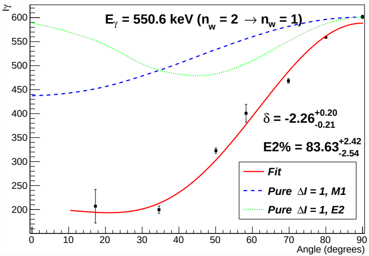


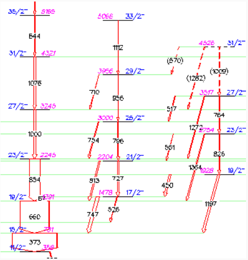
Angular distributions (2/3)

$n_w = 2 \rightarrow n_w = 1$ linking transitions

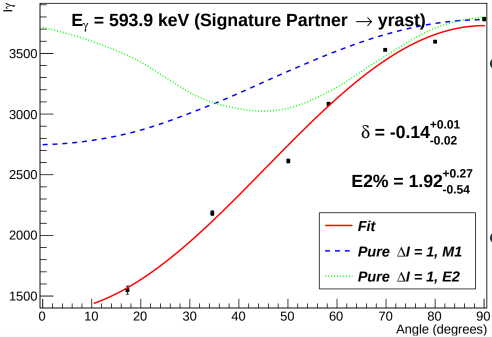






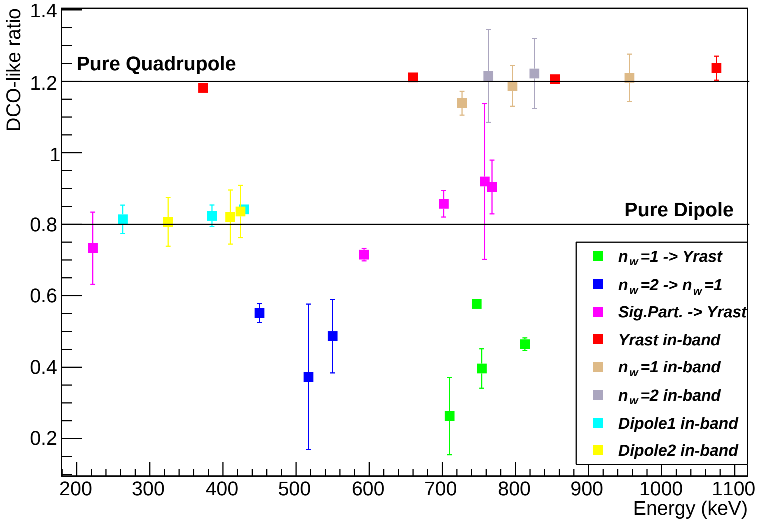


Signature Partner → Yrast linking transitions



- Exhibited a predominant **dipole** character.
- Differentiating factor between proposed wobbling bands and the signature partner.
- Higher linking transitions too weak to extract angular distributions.

DCO-like ratios



Conclusion and Future Work

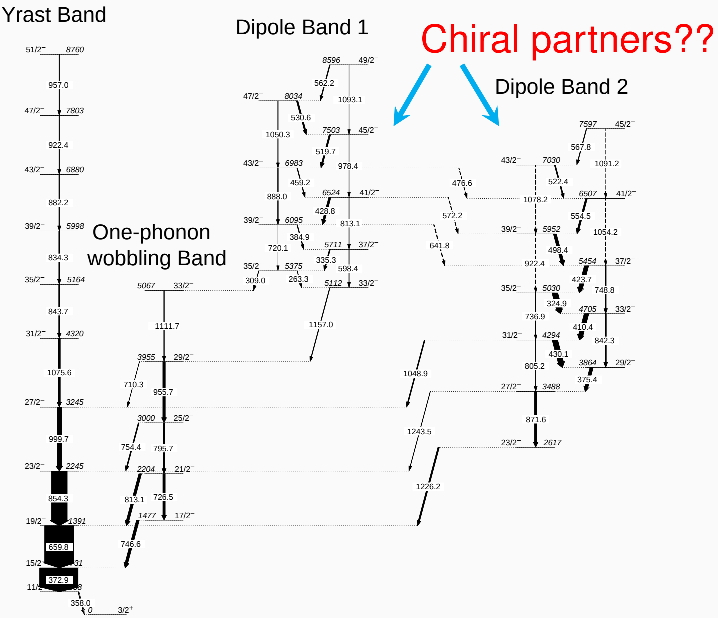
Conclusion and Future Work (1/3)

- Transverse wobbling has been investigated in the A$\sim$130 region.
- The proposed two-phonon wobbling band has been identified.
- ΔI = 1, E2 interband transitions between wobbling band verified by:
  - Angular Distributions
  - DCO-like ratios
- This is only the third such case after ^{163,165}Lu.

Conclusion and Future Work (2/3)

- QTR model calculations to support the experimental findings need to be done.
- Once confirmed, it would firmly establish wobbling in A$\sim$130 region.
- Possibility of the two dipole bands to be chiral partners of each other being explored.

Conclusion and Future Work (3/3)



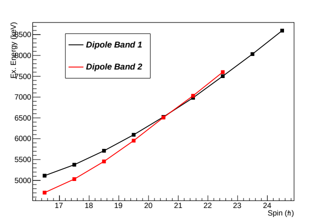
Conclusion and Future Work (3/3)

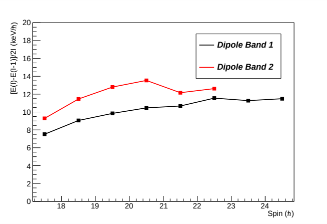
Possible chirality of the two dipole bands

Remember?

Standard fingerprints for chiral bands:

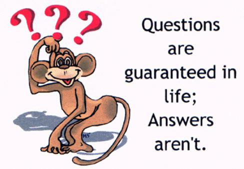
- Close excitation energies
- Constant Staggering parameter
- Identical B(M1)/B(E2) ratios



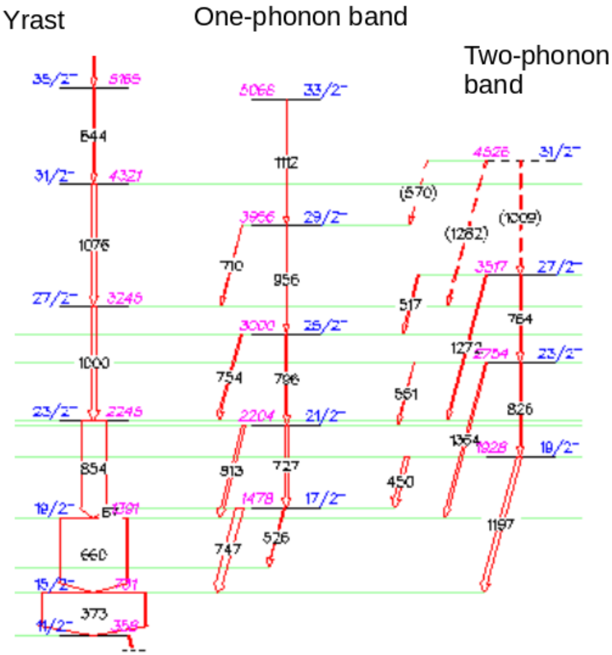


This would be the first ever case of a nucleus to exhibit both fingerprints of triaxiality - chirality and wobbling!


Thank you for your attention!
Any questions?!


Questions are guaranteed in life; Answers aren't.

BACKUP


Yrast
One-phonon band
Two-phonon band
35/2⁻
5165
644
31/2⁻
4321
1076
27/2⁻
3245
1000
23/2⁻
2245
854
19/2⁻
1391
67
660
15/2⁻
731
373
11/2⁻
358
5066
33/2⁻
1112
3956
29/2⁻
710
956
3000
25/2⁻
754
796
2204
21/2⁻
913
727
1478
17/2⁻
747
526
4526
31/2⁻
(570)
(1282)
(1009)
3517
27/2⁻
517
764
1272
2754
23/2⁻
561
826
1364
1928
19/2⁻
450
1197

Signature Partner Band

- If rotation is about a principal axis of the nucleus - mean field invariant w.r.t $\mathcal{R}_z(\pi)$

$$\mathcal{R}_z(\pi)\,|\rangle = \exp^{-i\alpha\pi}\,|\rangle$$

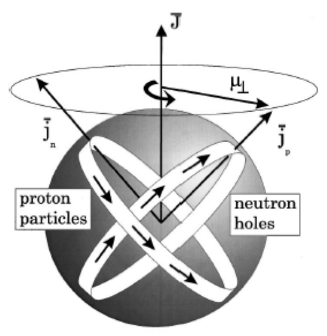
where α is the signature quantum number and leads to a selection rule for I:

$$I = \alpha + 2n; n = 0, \pm 1, \pm 2, ...$$

- For odd-A nuclei, α takes values $\pm 1/2$.
- A principal axis rotation leads to sequences of $\Delta \mathrm{I} = 2$ bands having alternate signatures.

Magnetic Rotation

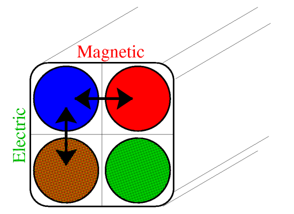
- A sequence of strong $\Delta \mathrm{I}$ =1, M1 transitions.
- j_p and j_n get lined up separately.
- This gives rise to a large transverse magnetic dipole moment $\mu_\perp$ that rotates and gives rise to magnetic radiation.
- $\mathcal{R}_z(\psi)$ **symmetry is broken - A rotational band is a consequence!**



S. Frauendorf, Reviews of Modern Physics, Volume 73 (2001)

Polarization Measurements

- Distinguishes between the electric and magnetic nature of γ-rays.
- Investigated from the observed asymmetry of the Compton scattering of γ-rays.
- Clover detectors used to measure polarization.



Polarization Measurements - Previous Results

Performed at the Indian National Gamma Array (INGA) using Clover detectors.