Experimental Study of excited bands in ^{160}Yb : Theoretical context of Exotic Shape-Coexistence

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Shapes and Symmetries in Nuclei: from Experiment to Theory (SSNET16)

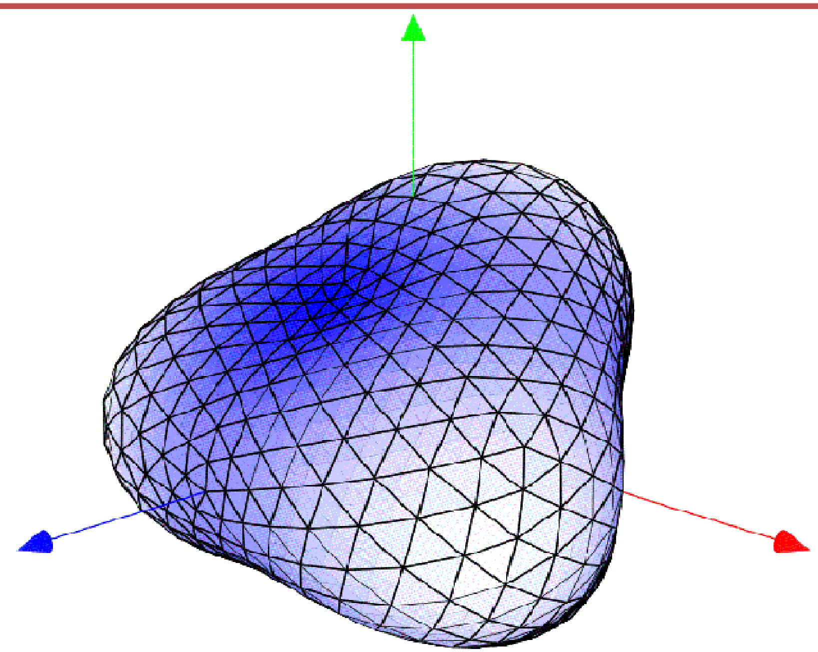
Introduction

- The great majority of nuclei known experimentally are non-spherical.

- Whereas tetrahedral symmetry has been observed abundantly in molecular physics, its observation in nuclear structure physics remains a challenge.

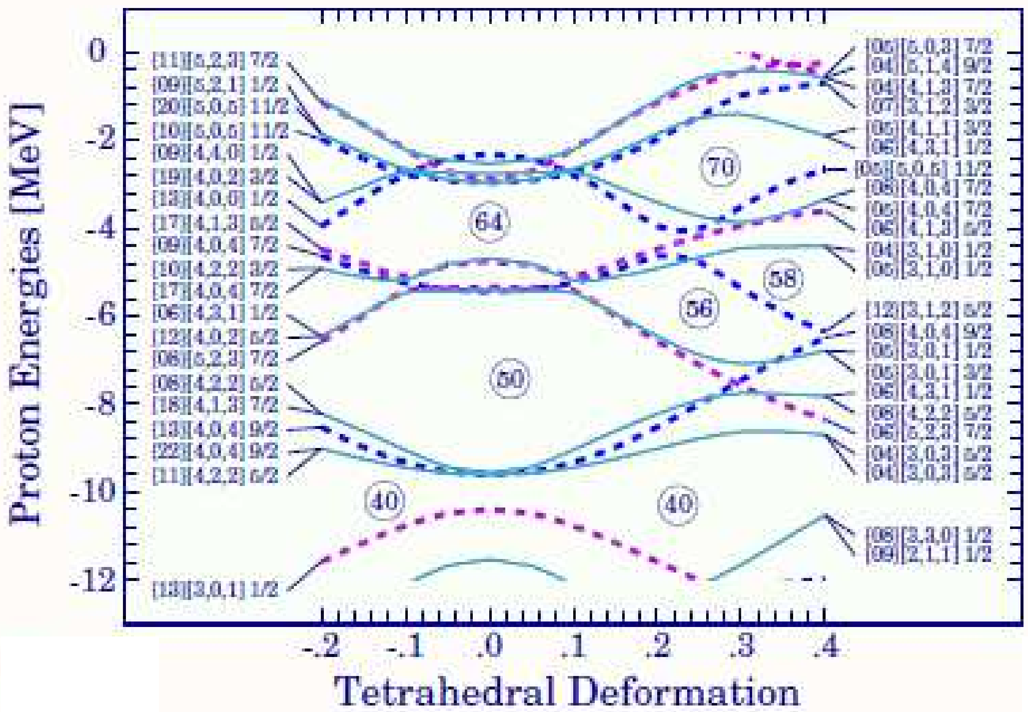
- The tetrahedral-symmetry nuclear-surfaces can be represented with the help of the non-zero α_{32} deformation parameter.

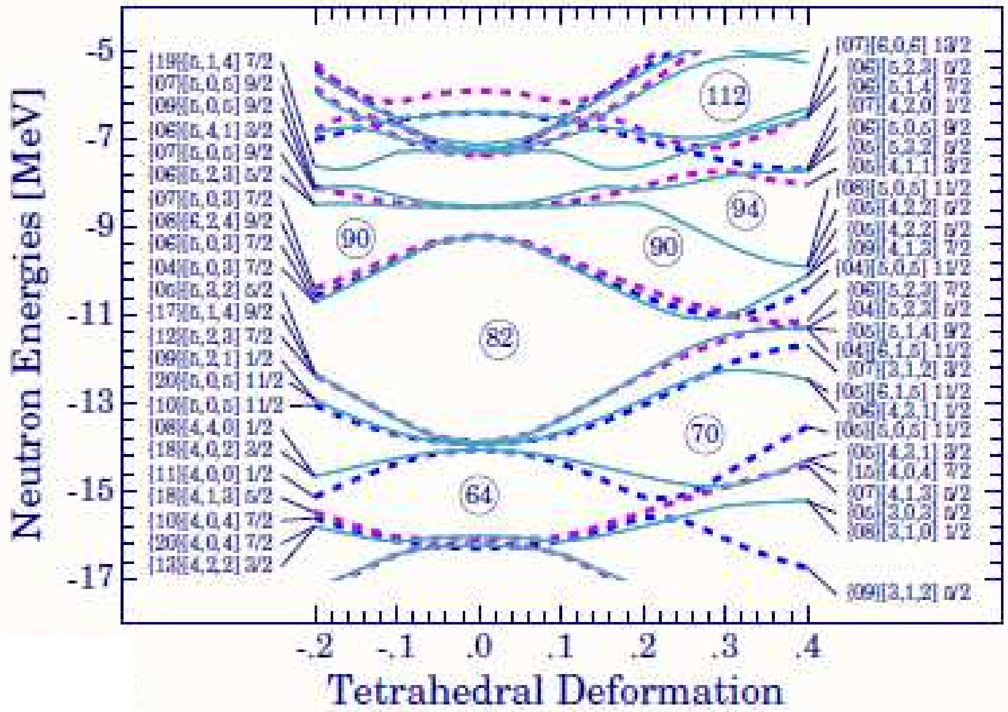
- Calculations by J. Dudek suggests that nuclei with a Tetrahedral deformation may exist at a low excitation in Nuclear landscape.



$$R(\theta,\phi) = R_o\left[1 + \sum_{\lambda=0}^{\infty}\sum_{\mu=-\lambda}^{\lambda}\alpha_{\lambda\mu}Y_{\lambda\mu}(\theta,\phi)\right]$$

Tetrahedral Shell Gaps

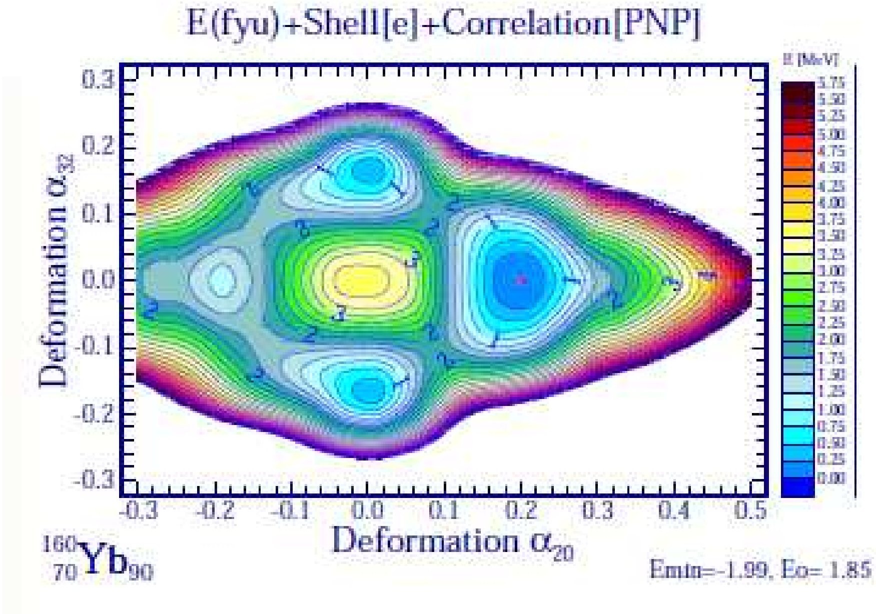


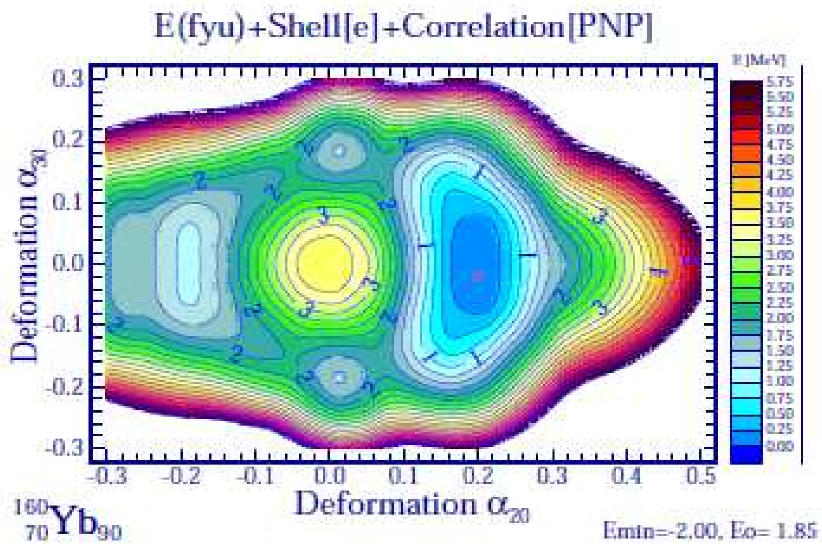


Realistic calculations with the phenomenological Woods-Saxon potential illustrating the mechanism of creating strong 'tetrahedral' gaps in the single-particle spectra.

J. Dudek et al., Phys. Rev. Lett. 97, 072501(2006)

Total Energy Calculations for ^{160}Yb





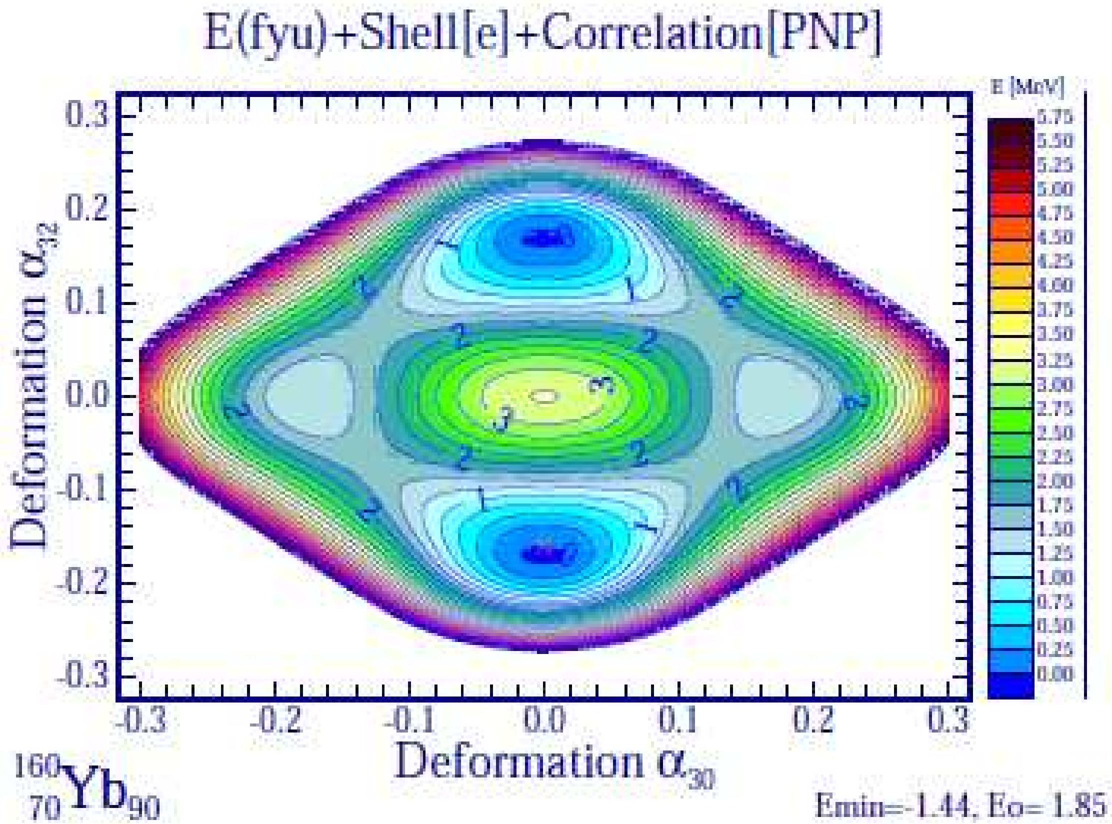
Microscopic Macroscopic method and deformed Wood-Saxon potential are used for calculation.

Two symmetric minima at α_{32}~ $\pm$ 0.18 represent the exotic shape co-existing configuration with tetrahedral symmetry.

Prolate-oblate shape minima at α_{20}~ $\pm$ 0.20 and the presence of two shallow symmetric minima at α_{30}~ $\pm$ 0.20 → superposition of the pear-shapes with the surface of the sphere.

Courtesy : J. Dudek and his collabolators

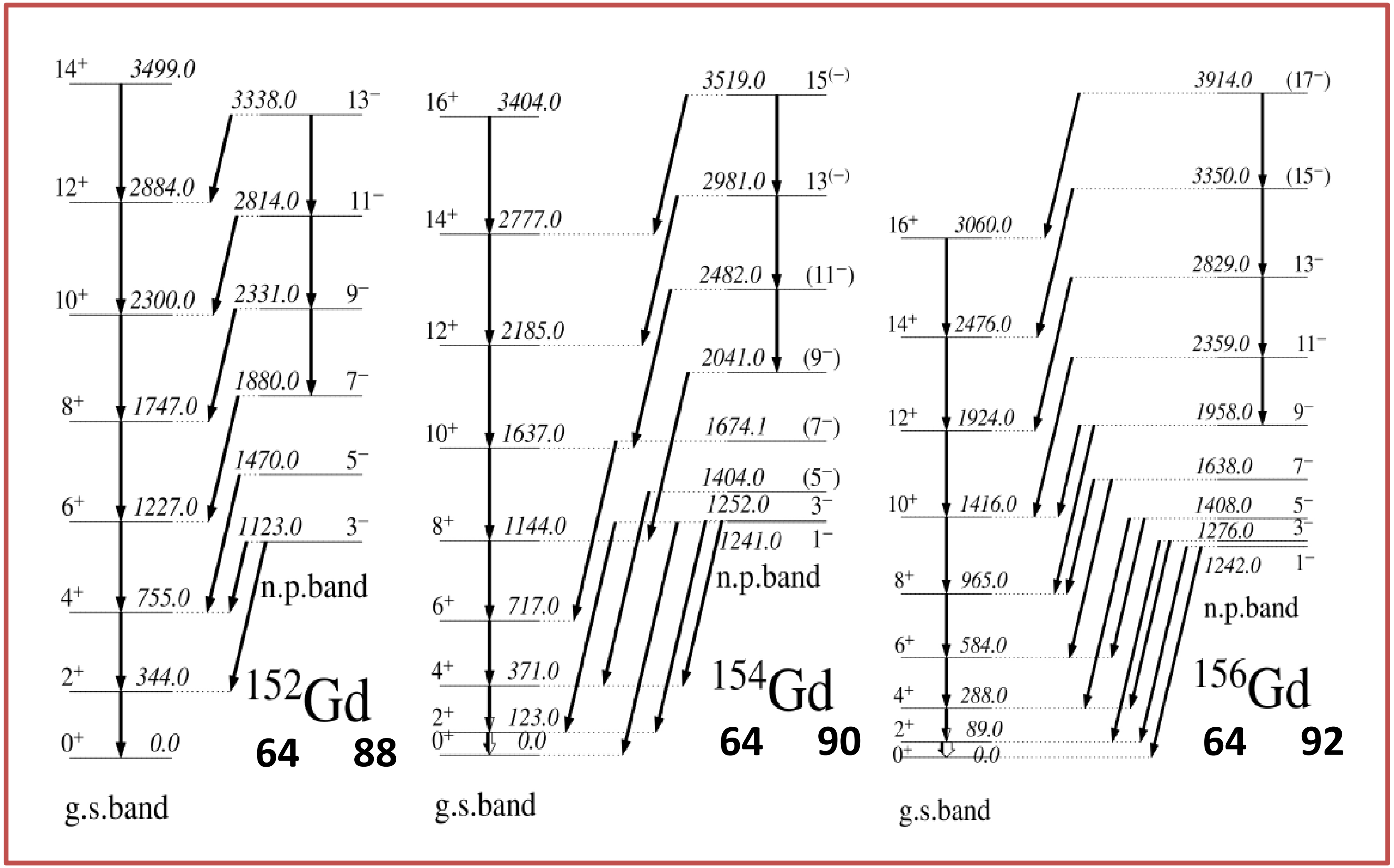
Competition between α_{32} and α_{30} in ^{160}Yb



Courtesy : J. Dudek and his collaborators

Quadrupole deformation is set to zero in this particular discussion. Tetrahedral minima with α_{32}~ $\pm$ 0.18 lie approximately 1.5 MeV lower than the competing shallow pear-shape minima with α_{30}~ $\pm$ 0.18.

Historical scenario



B (E2; I → I-2) / B (E1; I →I-1) → 0 as I → 0

B(E2)/B(E1) ratio in 10^6 fm^2

Spin	$^{152}_{64}Gd_{88}$	$^{156}_{64}Gd_{92}$	$^{154}_{66}Dy_{88}$	$^{160}_{68}Er_{92}$	$^{164}_{68}Er_{96}$	$^{162}_{70}Yb_{92}$	$^{164}_{70}Yb_{94}$
19^-	-	50.2(9.4)	-	-	-	-	-
18^-	-	-	-	-	-	-	-
17^-	-	16.0(2.7)	-	-	-	-	-
16^-	-	-	-	-	-	-	-
15^-	-	6.1(1.1)	12.2(0.5)	60.5(?)	23.9(12.9)	-	-
14^-	-	-	-	74.0(28)	-	-	-
13^-	13.5(?)	6.8(0.4)	26.9(18.3)	18.4(0.8)	22.9(12.0)	-	16.6(8.1)
12^-	-	-	-	148 (?)	-	-	-
11^-	3.6(?)	14.6(7.4)	10.0(?)	9.5(?)	-	10.4 (?)	10.5(5.6)
10^-	30.0(?)	-	256.5(?)	813 (95)	-	209 (19)	279.3(48.6)
9^-	3.9(?)	-	-	-	-	11.1(0.3)	10.0(3.7)
8^-	-	311.8(43.9)	-	181 (?)	-	-	558.0(91.8)
7^-	-	-	-	-	-	-	-
6^-	-	160.7(49.2)	-	1349 (?)	-	-	908.1(217.2)
5^-	-	-	-	-	-	-	-
4^-	-	123.1(11.5)	-	-	-	-	-

Rare Earth Elements

B (E2; I → I-2) / B (E1; I →I-1) → 0 as I → 0 :

Is a Necessary but NOT Sufficient condition

Recent theoretical calculation suggests

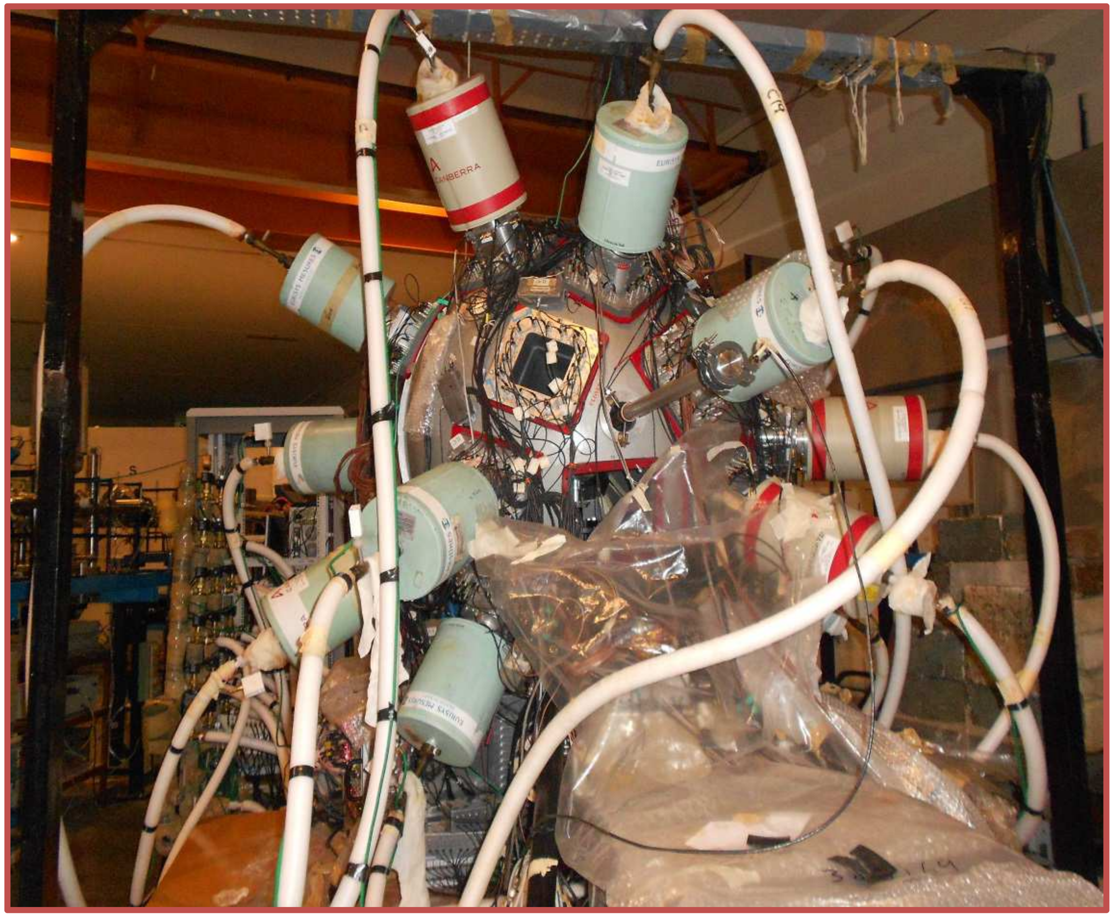
B (E2; I→I-2) → 0 as I →0 :

as an experimental signature also necessary for the tetrahedral symmetry

S. Tagami, Y. R. Shimizu and J. Dudek, Phys. Rev. C **87**,054306 (2013)

S. Tagami, Y. R. Shimizu and J. Dudek, J. Phys. G **42**, 015106 (2015).

Experiment on ^{160}Yb



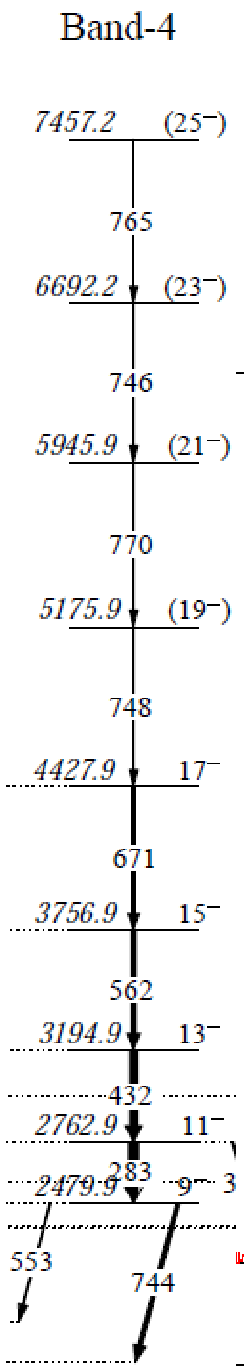
Indian National Gamma Array (INGA),
TIFR, Mumbai, India

- Total no. of detectors = 20
- Angles of detectors … $\pm$23, $\pm$40, $\pm$65 and 90 degree.
- Gathered statistics ~ 6 x 10^9 γ-γ events.
- Coincidence time window = 200 ns
- Target thickness = 900 μg/cm^2
- Baking density= 3 mg/cm^2 ^{nat}Pb

^{148}Sm(^{16}O, 4n)^{160}Yb; E_{beam}=90 MeV

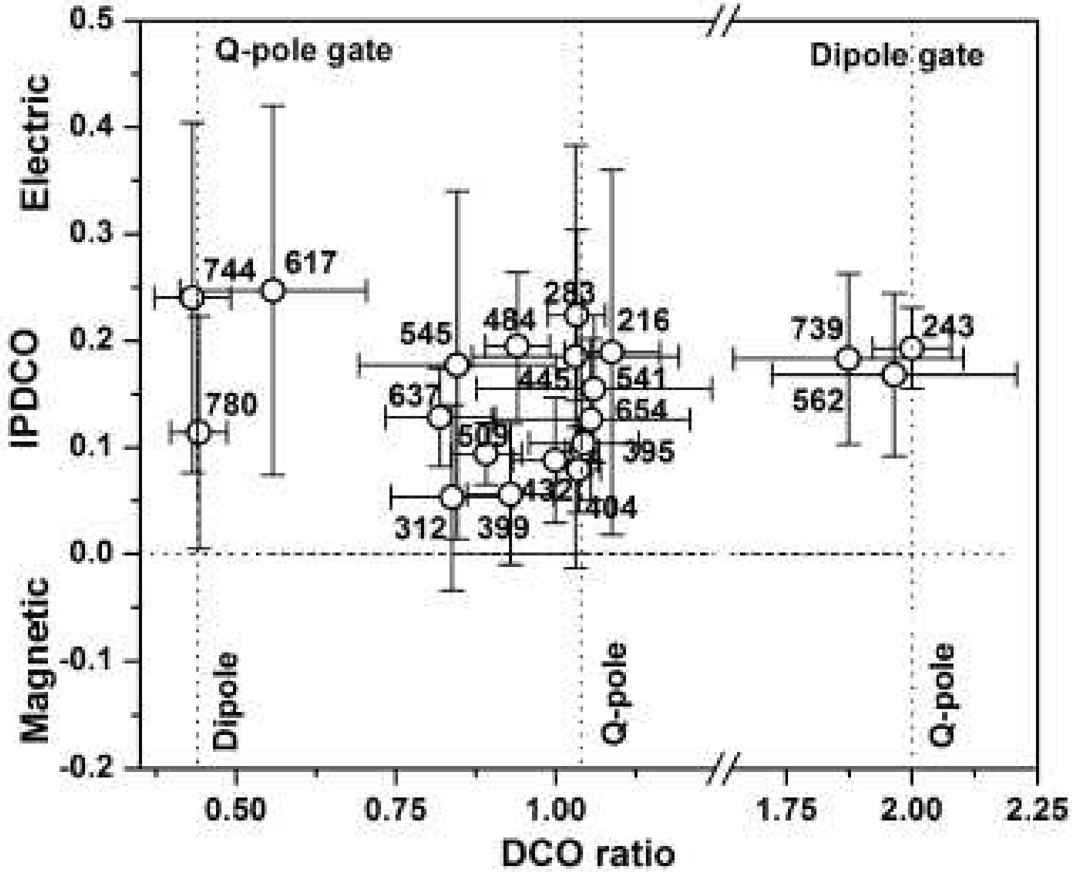
Efficiencies for the detection of γ, γ-γ and γ-γ-γ events → 1.12, 1.45 and 2.01 times higher compared to the latest experiment on ^{160}Yb.

Results & Discussions : I_γ, DCO & IPDCO ratio



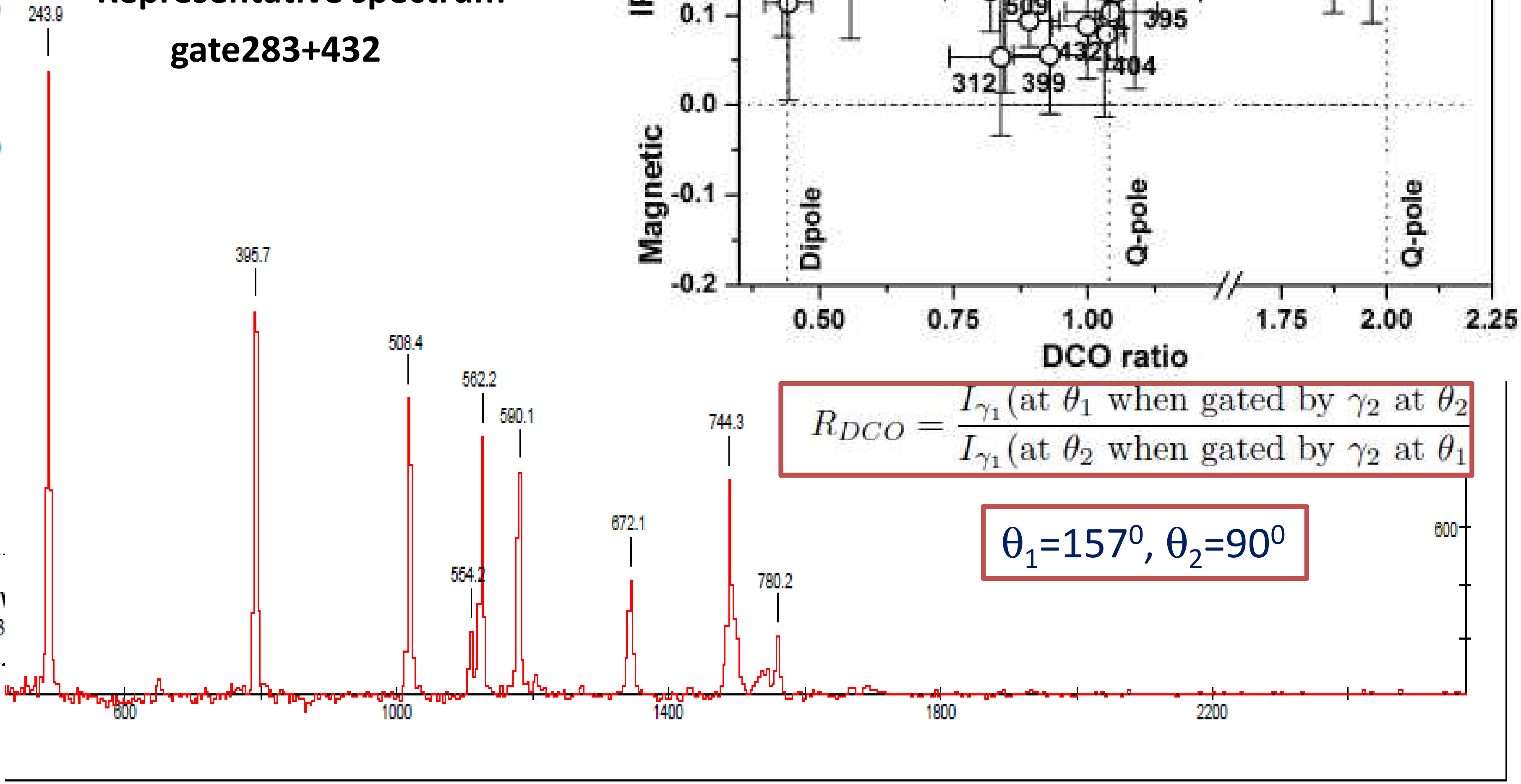
$$\Delta_{\text{IPDCO}} = \frac{a(E_\gamma)N_\perp - N_\parallel}{a(E_\gamma)N_\perp + N_\parallel},$$

$$a(E_\gamma) = \frac{N_\parallel \text{ (unpolarised)}}{N_\perp \text{ (unpolarised)}},$$



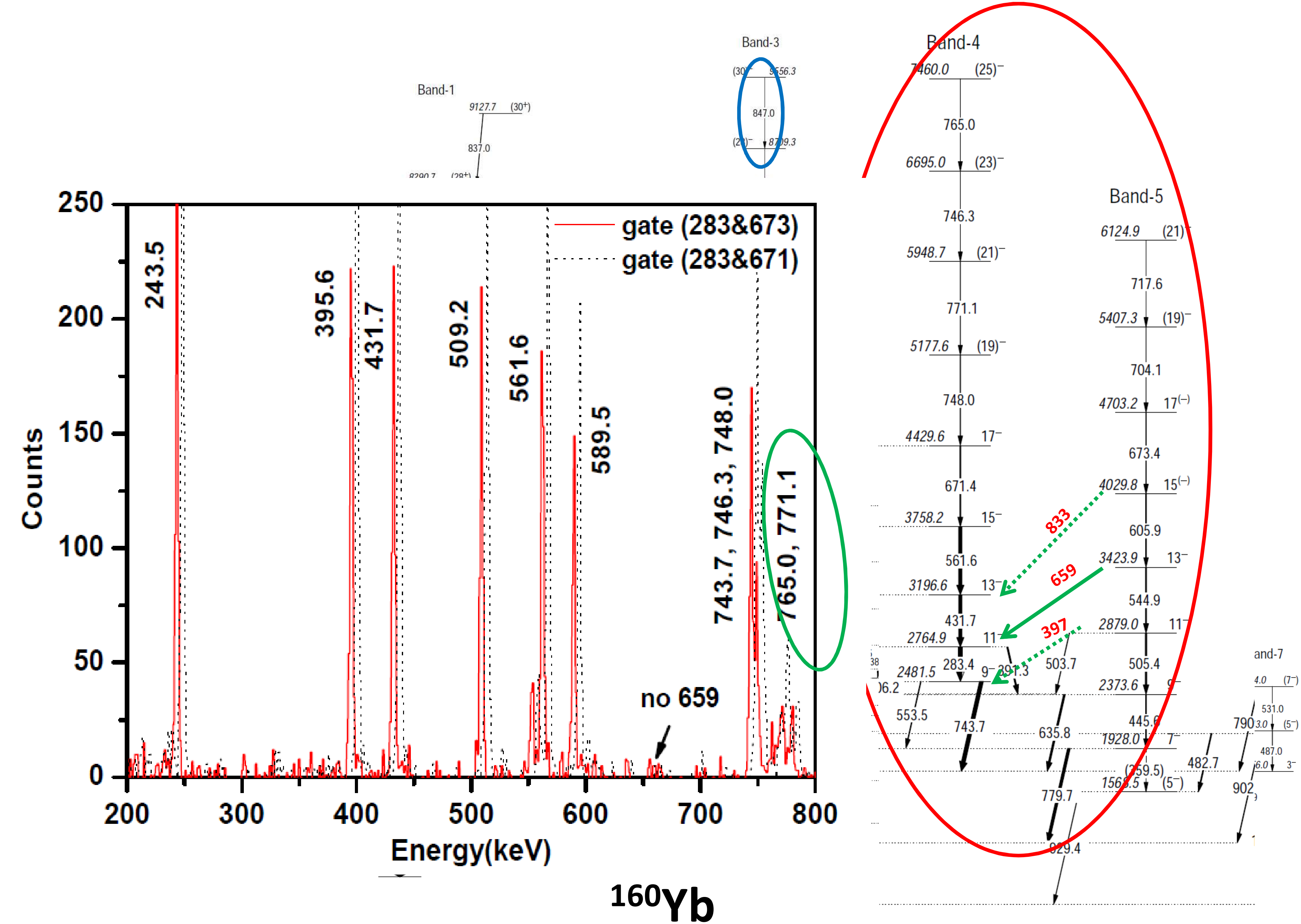
Representative spectrum

gate283+432



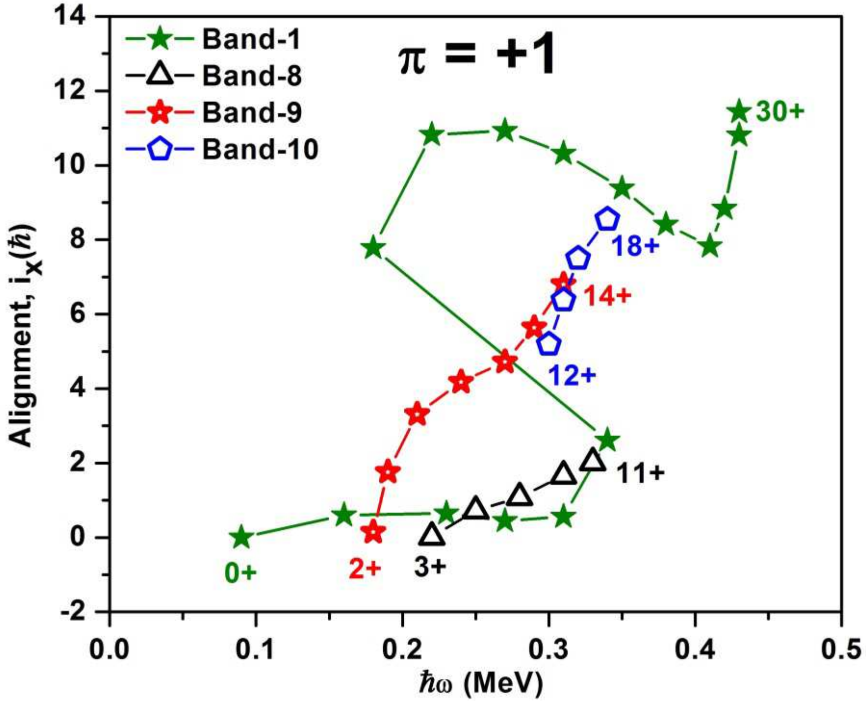
$$R_{DCO} = \frac{I_{\gamma_1}(\text{at } \theta_1 \text{ when gated by } \gamma_2 \text{ at } \theta_2)}{I_{\gamma_1}(\text{at } \theta_2 \text{ when gated by } \gamma_2 \text{ at } \theta_1)}$$

$\theta_1 = 157^0$, $\theta_2 = 90^0$



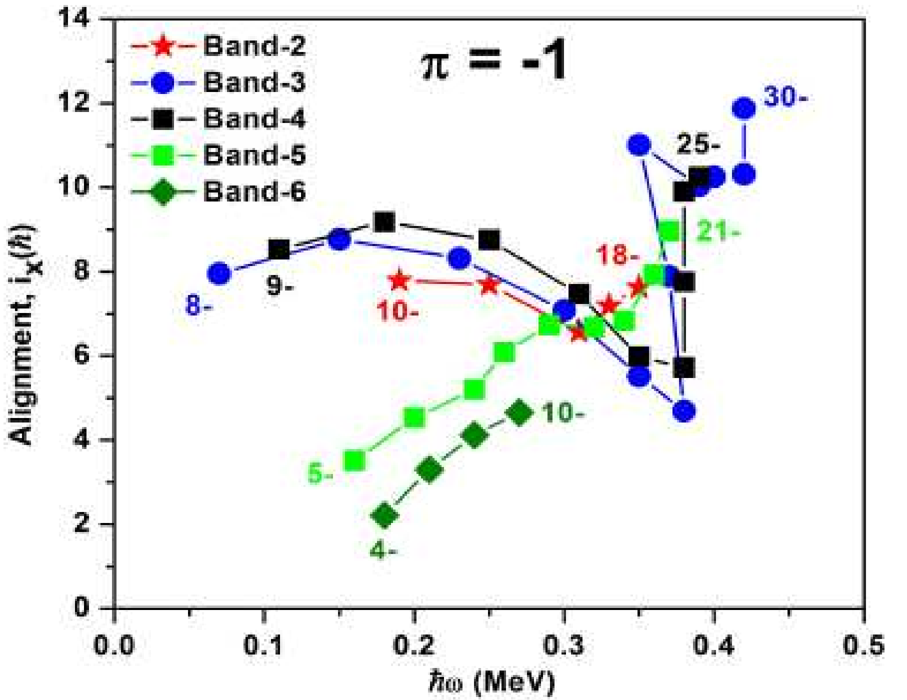
Previous work : Phys. Rev. Lett. 104, 022501 (2010)

Results & Discussions : Alignment

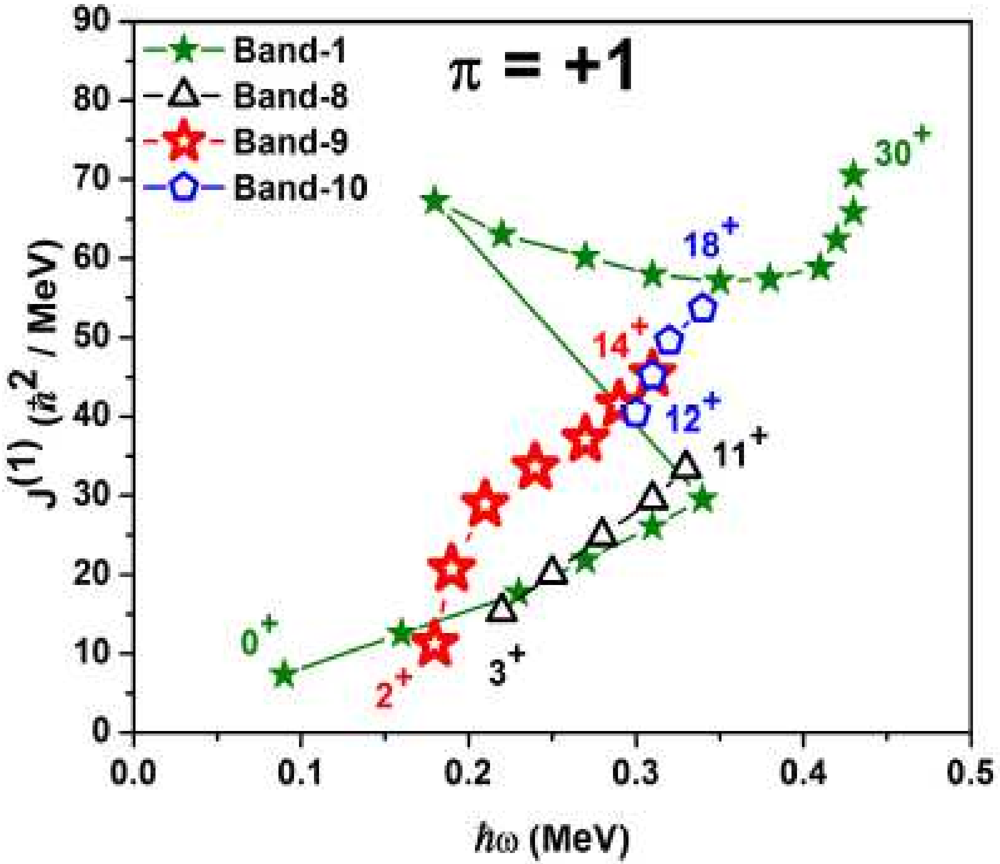


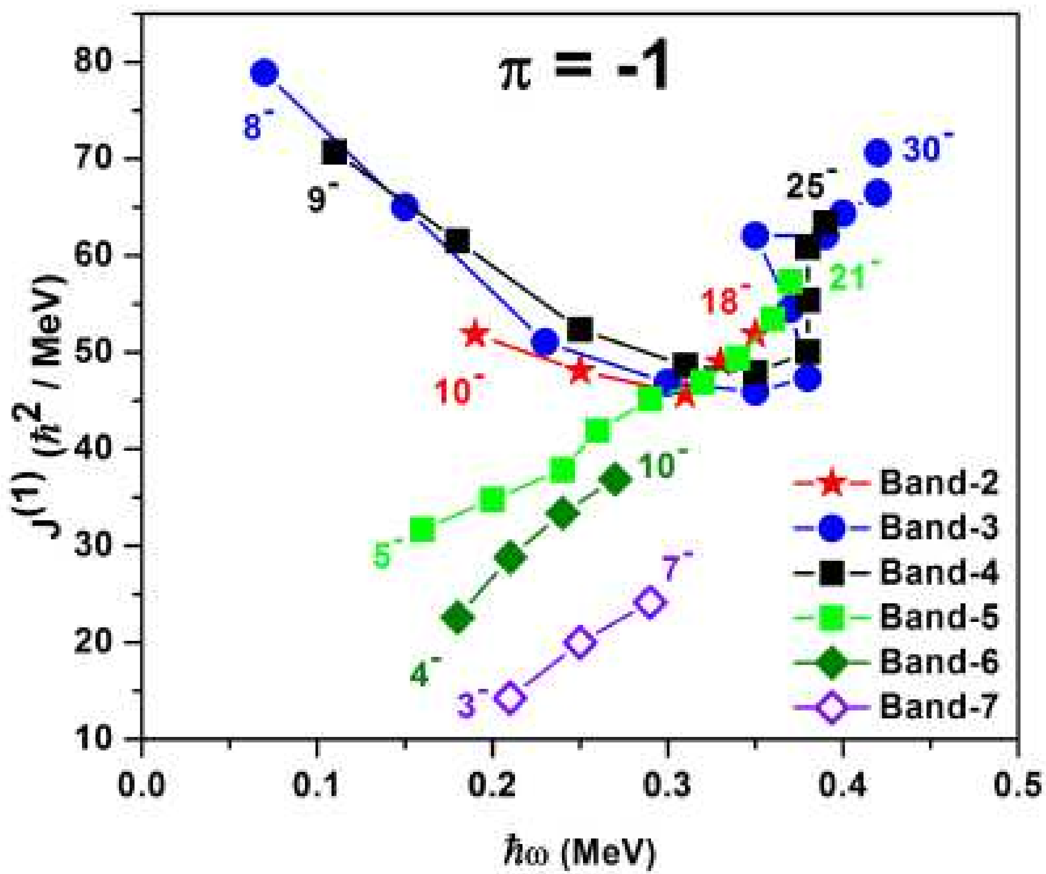
- Alignment plot for positive-parity bands shows the well-known two-quasi-neutron and two-quasi-proton alignment mechanism for Band-1.
- Band-8 shows similar alignment values as that of Band-1.
- Also indicates that structure of Band-9 changes with increase in rotational frequency.

- Band-3 and Band-4 carry from the beginning an alignment ~ $8\hbar$. They undergo another crossing at higher angular momenta at $\hbar\omega$~ 0.38 MeV bringing in an extra alignment of about $6\hbar$.
- Alignment of Band-5 and Band-6 are very different from that of other negative-parity bands. Alignment of Band-5 is slightly higher compared to Band-6.



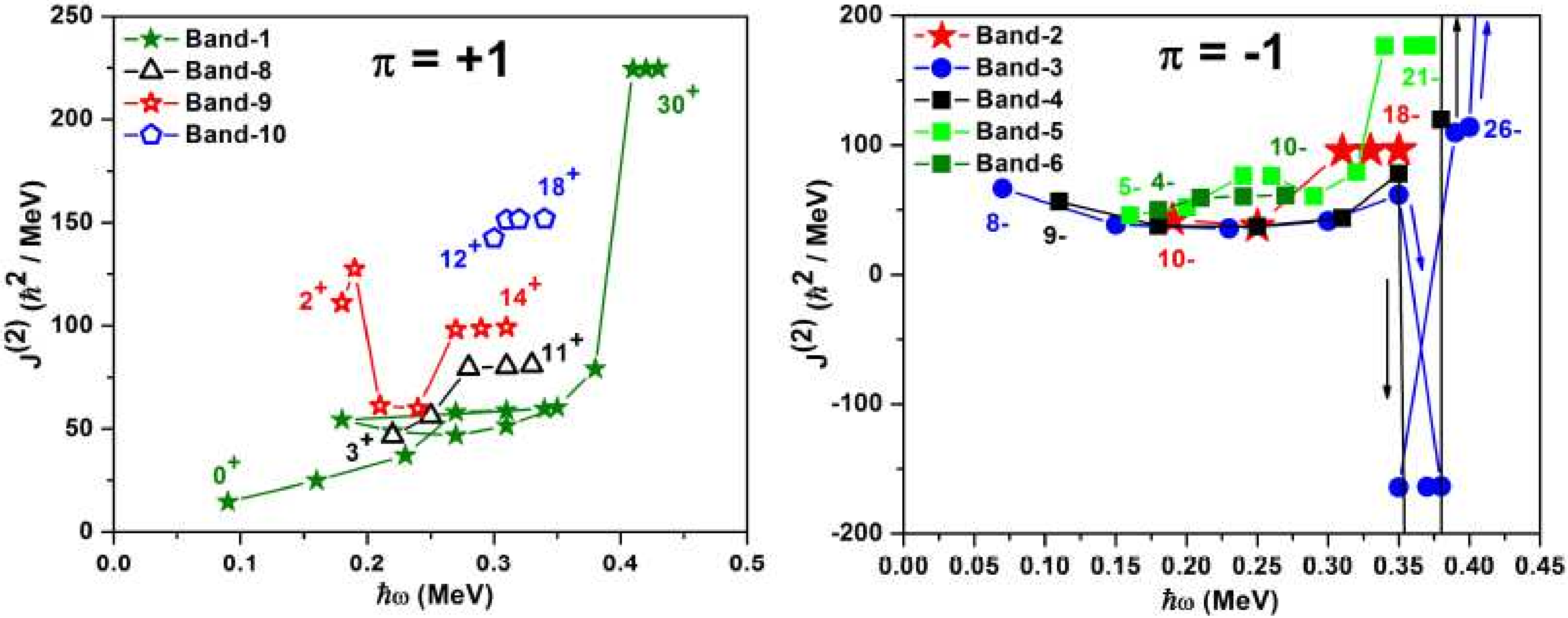
Results & Discussions : $J^{(1)}$





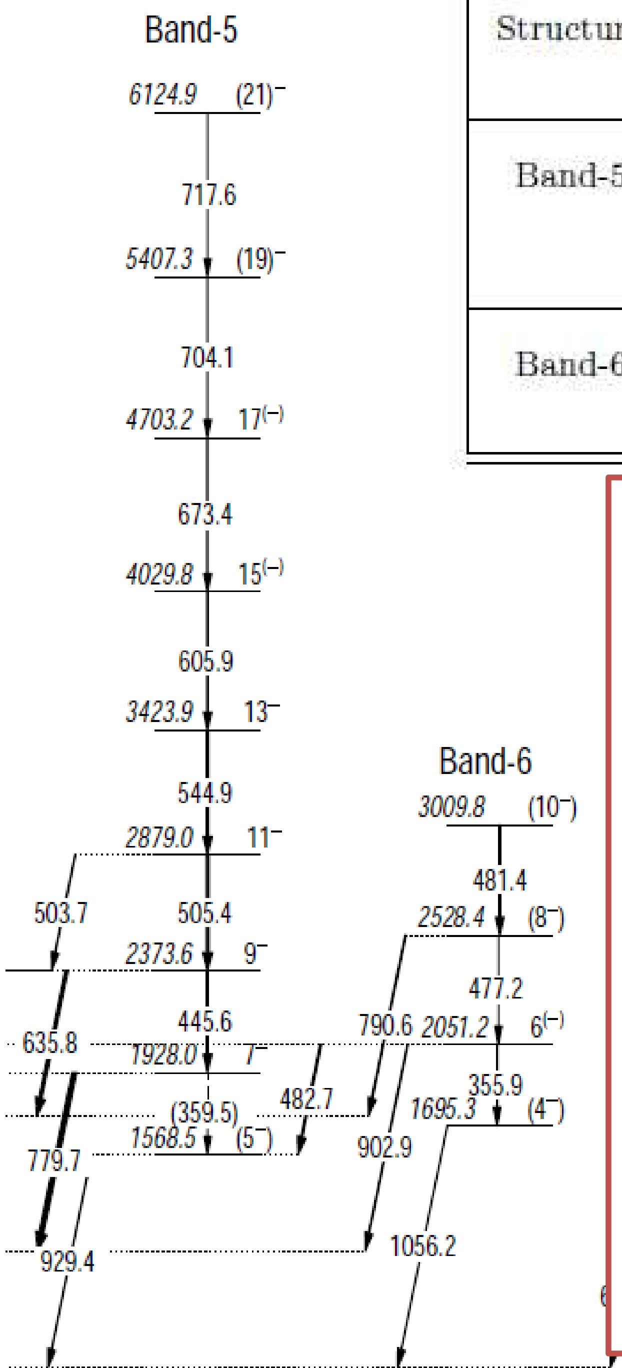
- Band-3 and Band-4 behave in a very similar manner and are conjectured to be signature partners as they have the same moment of Inertia.
- Here also, we see that Band-5 and Band-6 behaves in a very different manner than the other negative-parity sequences with respect to their kinematic moment.
- The backbending phenomenon occurring in Band-1 is reflected from the $J^{(1)}$ plot too.

Results & Discussions : $J^{(2)}$



- Band-6 manifests at its bottom the properties similar to those of Band-5.
- As in the case of alignment and $J^{(1)}$ plots, Band-8 shows similar dynamic moment values as that of Yrast band.
- Band-9 manifests a complicated structure.

Results & Discussions : B(E2)/B(E1) ratio



Structure	I_i^π	E_i	E_γ(E2) (keV)	E_γ(E1) (keV)	I_γ(E2)	I_γ(E1)	I_γ(E2)/I_γ(E1)	B(E2)$_{in}$/B(E1)$_{out}$ $10^6 \cdot$fm^2
Band-5	7^-	1928.0	359.5	779.7	0.44(0.10)	8.91(4.22)	0.05(0.03)	5.11(2.68)
	9^-	2373.6	445.6	635.8	2.90(0.68)	5.94(1.52)	0.49(0.17)	9.36(3.25)
	11^-	2879.0	505.4	503.7	5.25(1.25)	1.44(0.47)	3.65(1.47)	18.47(7.46)
Band-6	$6^{(-)}$	2051.2	355.9	902.9	0.61(15)	1.81(43)	0.34(12)	56.41(19.29)
	(8^-)	2528.4	477.2	790.6	1.48(37)	2.19(52)	0.68(23)	17.60(6.10)

•In case of Band-5, ratio decrease slowly with decreasing angular momentum.

•Ratios for Band-6 are significantly higher compared to Band-5.

Band-5 → Conjectured as Octupole Vibrational Band
Band-6 → Conjectured as Tetrahedral Vibrational Band

•Not much can be said about the trend in variation of B(E2)/B(E1) with spin for Band-6, because too few transitions observed.

Collaborators

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MERCI BEAUCOUP!!

Theoretical Predictions

•Theoretical studies by Strasbourg-Fukuoka collaboration suggest that the tetrahedral symmetry solution allows for the precisely restricted spin sequences:

$0^{+},3^{-},4^{+},6^{\pm},7^{-},8^{+},9^{\pm},10^{\pm}$

•$\pm$ indicates the presence of degenerate opposite-parity states.

•The two characteristic sub-sequences of opposite parity form a common $E_I \propto I*(I+1)$ parabola.

•A surprising element on the list of exotic features is the total absence of 4- and 5- states in the negative-parity sub-sequence and presence of $\Delta I=3$ band members with I^{π}=3-,6-,9-,...

•The vanishing quadrupole and dipole moments hinder the population of the tetrahedral symmetry states via collective transitions.