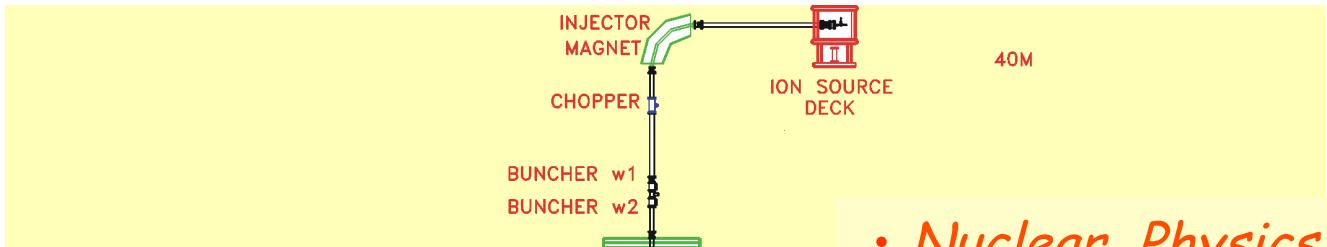


Rotation features of triaxial nuclei (Results from INGA)

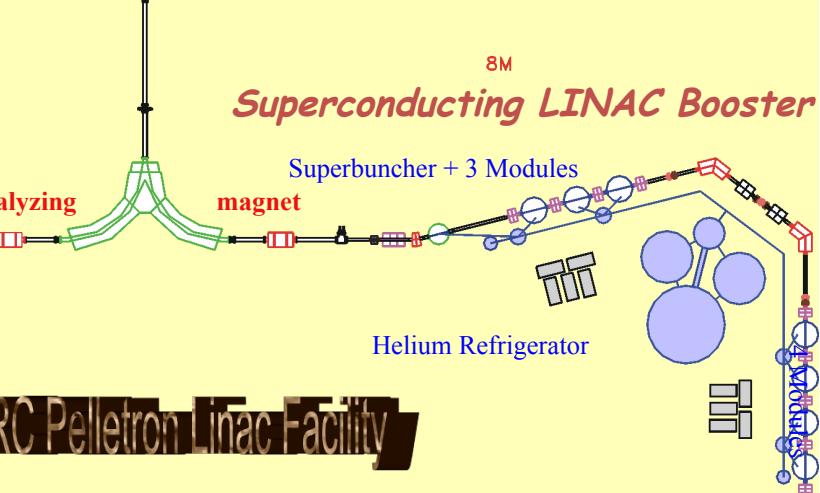
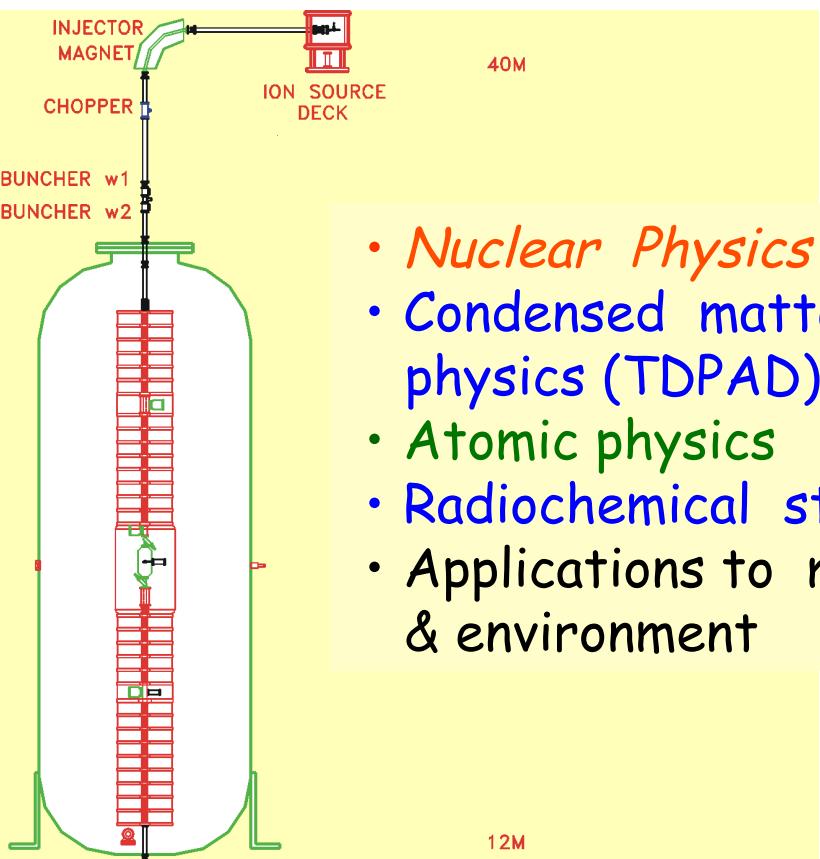
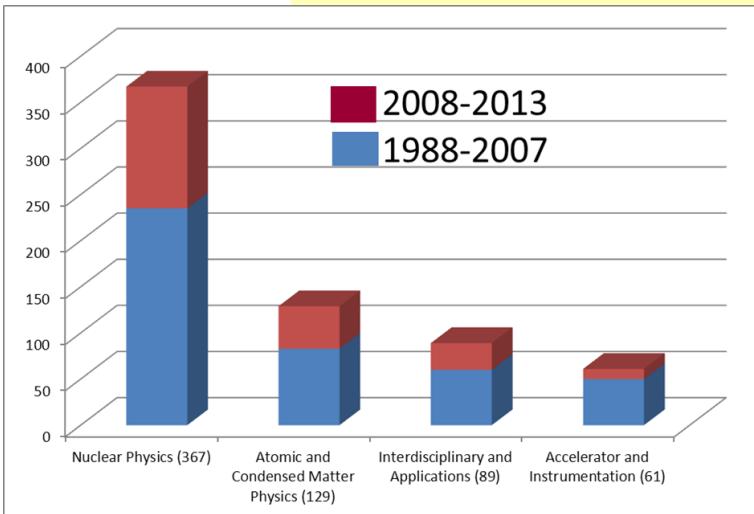
RUDRAJYOTI PALIT

Department of NUCLEAR AND ATOMIC Physics
Tata Institute of Fundamental Research
Mumbai, India

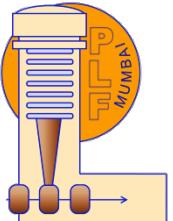




- Nuclear Physics
- Condensed matter physics (TDPAD)
- Atomic physics
- Radiochemical studies
- Applications to medicine & environment



TIFR-BARC Pelletron Linac Facility



Pelletron accelerator

- $E/A \sim 3\text{-}7 \text{ MeV}$, $\beta \sim 0.08\text{-}0.12$
- Heavy ions reactions upto $A \sim 40$

Superconducting Linac booster

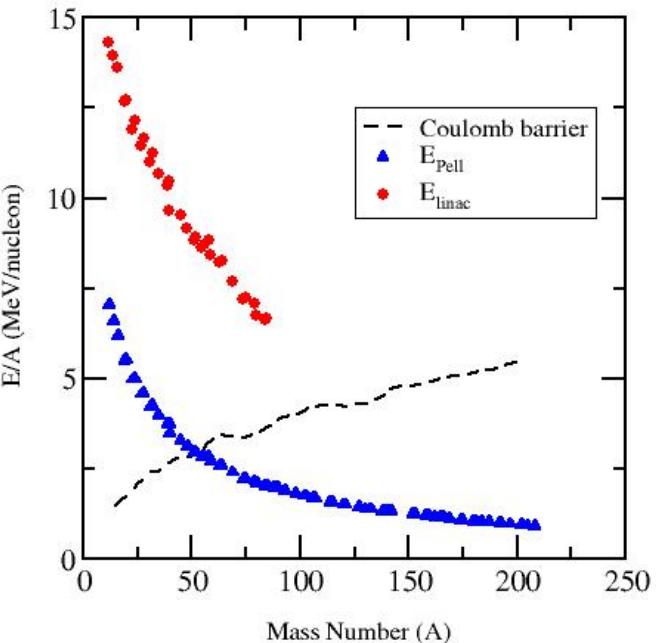
- $E/A \sim 5\text{-}10 \text{ MeV}$, $\beta \sim 0.10\text{-}0.16$
- Heavy ions reactions upto $A \sim 80$
(limited by pre-accelerator)
- Beam intensity: $0.1\text{-}10 \text{ pnA}$ ($10^{9\text{-}11} \text{ p/s}$)
(limited by ion source)

Beams accelerated through Pelletron

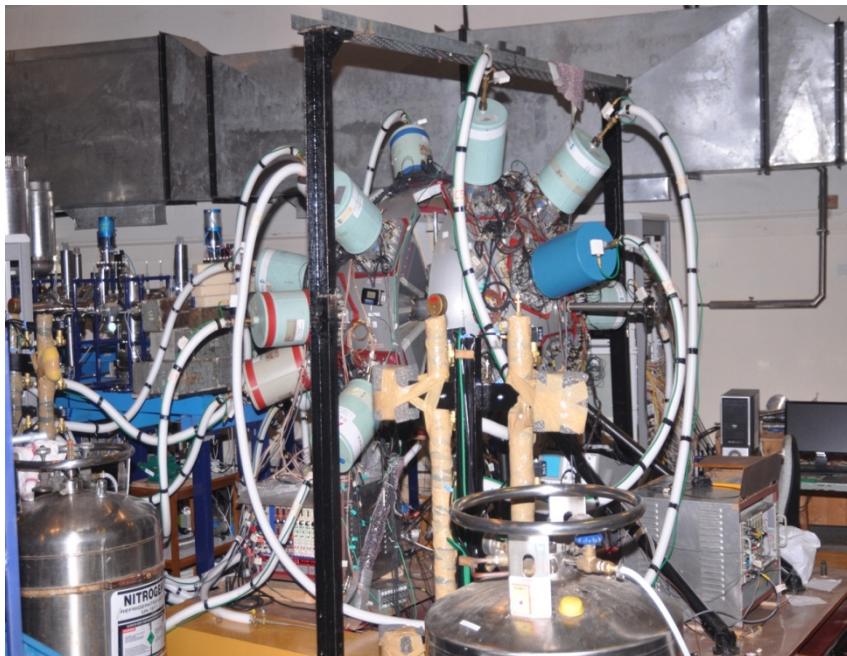
$^1H, ^4He, ^{6,7}Li, ^9Be, ^{10,11}B, ^{12,13}C, ^{16,18}O, ^{19}F, ^{28,30}Si, ^{32}S, ^{35}Cl, \dots Ag, ^{129}I$

Beams accelerated through Linac

$^7Li, ^{10,11}B, ^{12}C, ^{16,18}O, ^{19}F, ^{28,30}Si, ^{32}S, ^{35}Cl$



INGA campaign



DSP Implementation for INGA

- Up to ~200 channels
- Provision for Ancillary detectors
(CsI(Tl), Si and LaBr₃(Ce))

R. Palit, et al. NIMA 680 (2012) 90

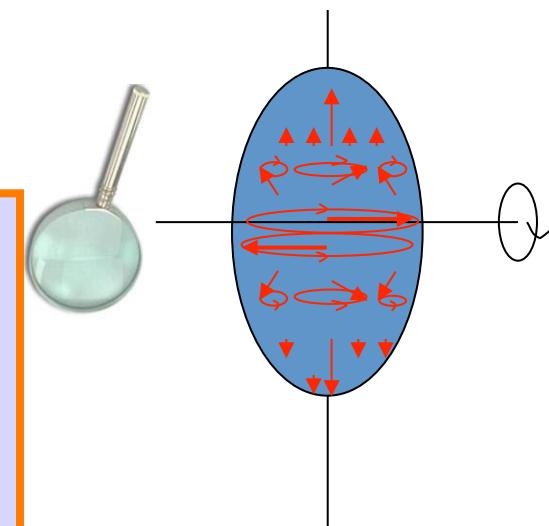
BARC, IUAC, IUC-KC, SINP, TIFR, VECC, IITs, Univ

Investing in the polarization measurements of gamma rays and “wide-range timing spectroscopy” proved to be a successful approach for creating our specific “niche” and complement research at large scale facilities.

Experiments: ~50 (Current experimental campaign 180 days)

60 researchers including 25 PhD students; 30 publications (2012-2015)

Moves between 3 accelerators (2001-2015) 120 publications; 50 PhDs



DSP based DAQ has Increased the data throughput by 10 times for INGA

Physics highlights of the INGA Campaign at TIFR

Antimagnetic rotation in ^{107}Cd , ^{105}Pd , ^{143}Eu
PRC87, 034304 (2013); PRC89, 061308(R) (2014);
PRC91, 014318(2015); ; PLB 748, 387 (2015);

Spectroscopy across isomers in ^{132}Te , ^{66}Cu
PRC93, 034324 (2016); PRC89, 044315 (2014);
Poster Purnima Singh

Degenerate dipole bands in ^{106}Ag , ^{108}Ag
PLB 725, 85 (2013); PRL 112, 202503 (2014);

Collectivity in ^{33}S
PRC90, 024328 (2014)

Octupole collectivity in ^{221}Th
PRC 87, 034319 (2013);

Shape co-existence and high- K in
 ^{188}Pt
PLB 739, 462 (2014);

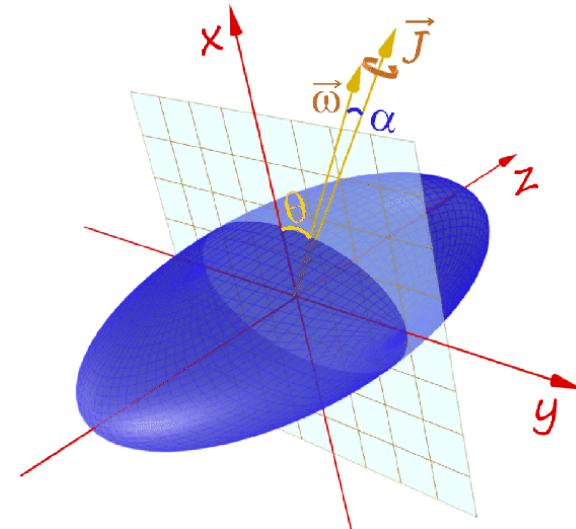
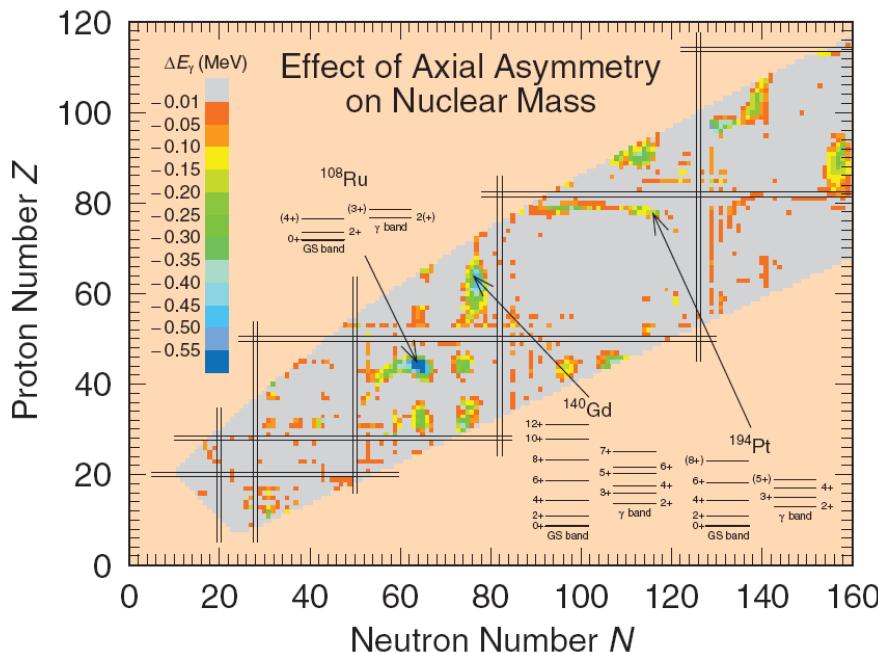
Wobbling bands in ^{135}Pr , ^{133}La
PRL 114, 082501 (2015); arXiv:1608.07840

Depletion of 413 yr isomer in ^{108}Ag
JPG43, 015103 (2016);

Shell model in ^{26}Mg , ^{28}Si , ^{30}Si , ^{34}Cl , ^{89}Zr , ^{89}Nb
PRC89, 024303 (2014); PRC90, 014306 (2014); PRC90, 014306 (2014);
PRC89, 024324 (2014); PRC91, 044306 (2015)

- Motivation
- Results from INGA on exotic rotations
 - Degenerate dipole bands & Chiral rotation
 - Wobbling rotation in ^{133}La an isotope of ^{135}Pr
- Future plans with INGA

Global Calculations of Ground-State Axial Shape Asymmetry of Nuclei

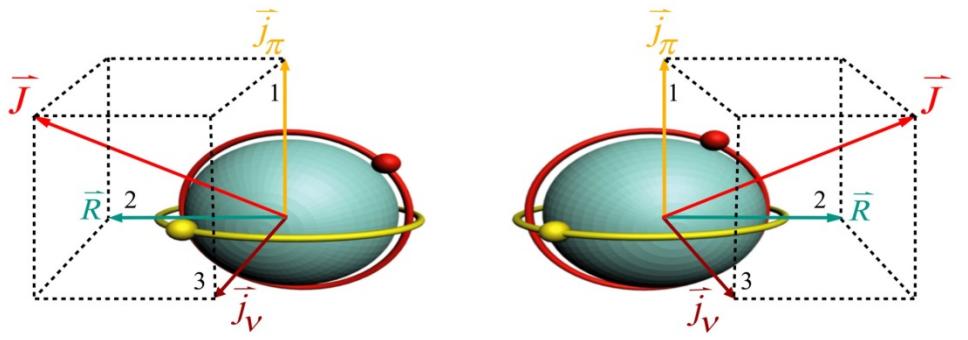
Peter Möller,^{1,*} Ragnar Bengtsson,² B. Gillis Carlsson,² Peter Olivius,² and Takatoshi Ichikawa³

Rotation of Triaxial Nuclei

Related phenomena: Gamma vibration, wobbling mode, chiral mode ...
 Wobbling mode was introduced by Bohr and Mottelson
 First experimentally observed in ^{163}Lu (PRL2001)
 Chirality was introduced by Frauendorf and Meng (NPA1997)
 Examples: ^{135}Nd (2007PRL), ^{128}Cs (2006PRL), ^{135}Pr (2001PRL)

Rotation of Triaxial Nuclei

Chiral Rotation



S. Frauendorf, J. Meng NPA617, 131 (1997)

Wobbling Mode

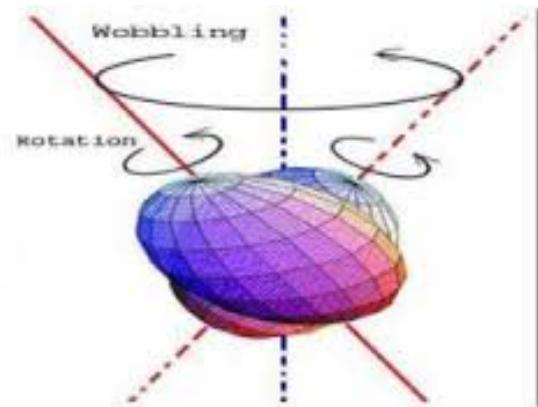


Figure 1.7. Nuclear wobbling motion

Frauendorf, Doenau, PRC 89, 014322 (201)
Y. Shimizu, et al. PRC 72, 014306 (2005)

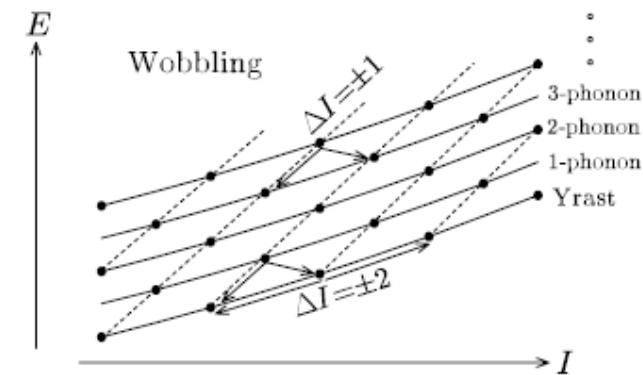
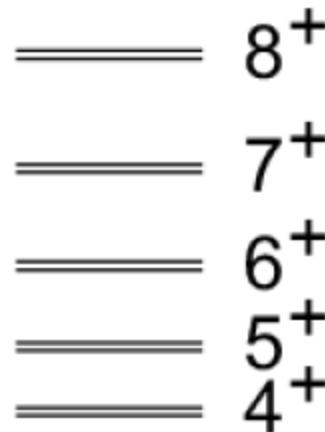
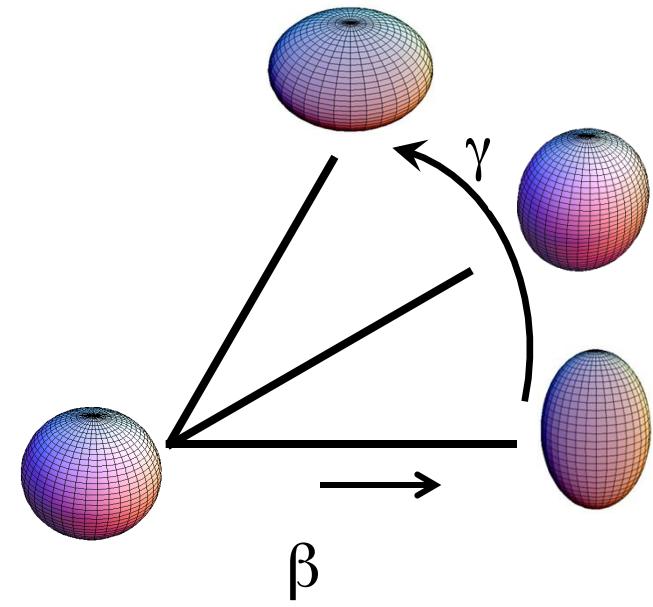
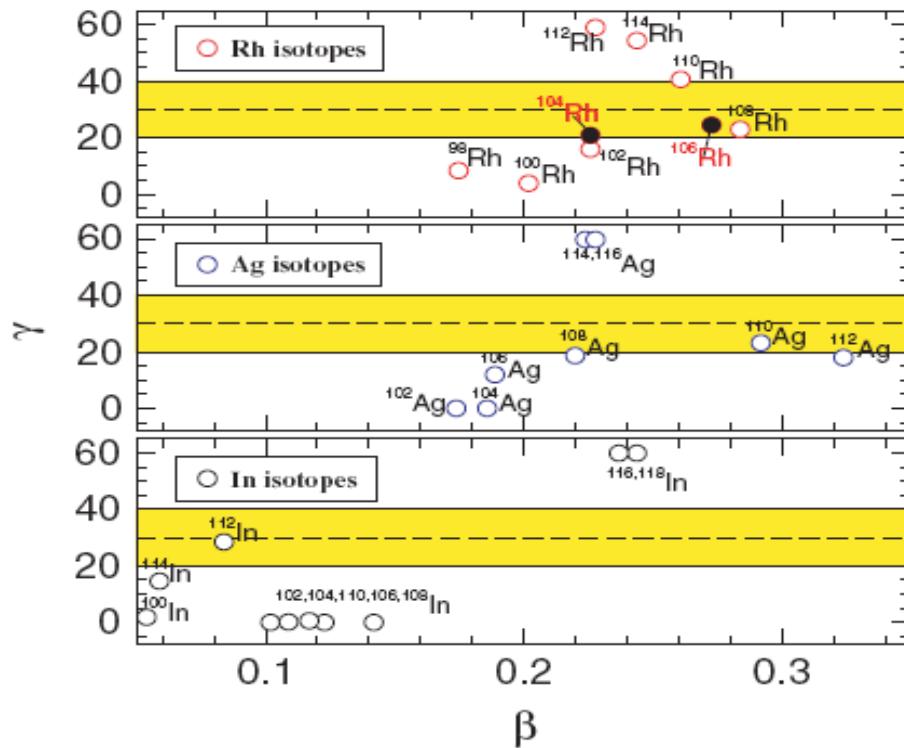


FIG. 1. Rotational spectra of a triaxial rotor Hamiltonian. Horizontal rotational bands are connected by solid lines; vertical phonon bands, by dotted lines.

Odd-odd Isotopes near $A \sim 110$

Meng et. al. PRC73 037303 (2006)



High spin Spectroscopy of ^{112}In , ^{108}Ag , ^{106}Ag isotopes have been carried out with Indian National Gamma Array (INGA).

T. Trivedi, R. Palit et al., PRC 85 014327 (2012)

J. Sethi, R. Palit et al., PLB 725 85 (2013)

N. Rather et al., PRL 112, 202503(2014)

^{108}Ag : Experimental Details

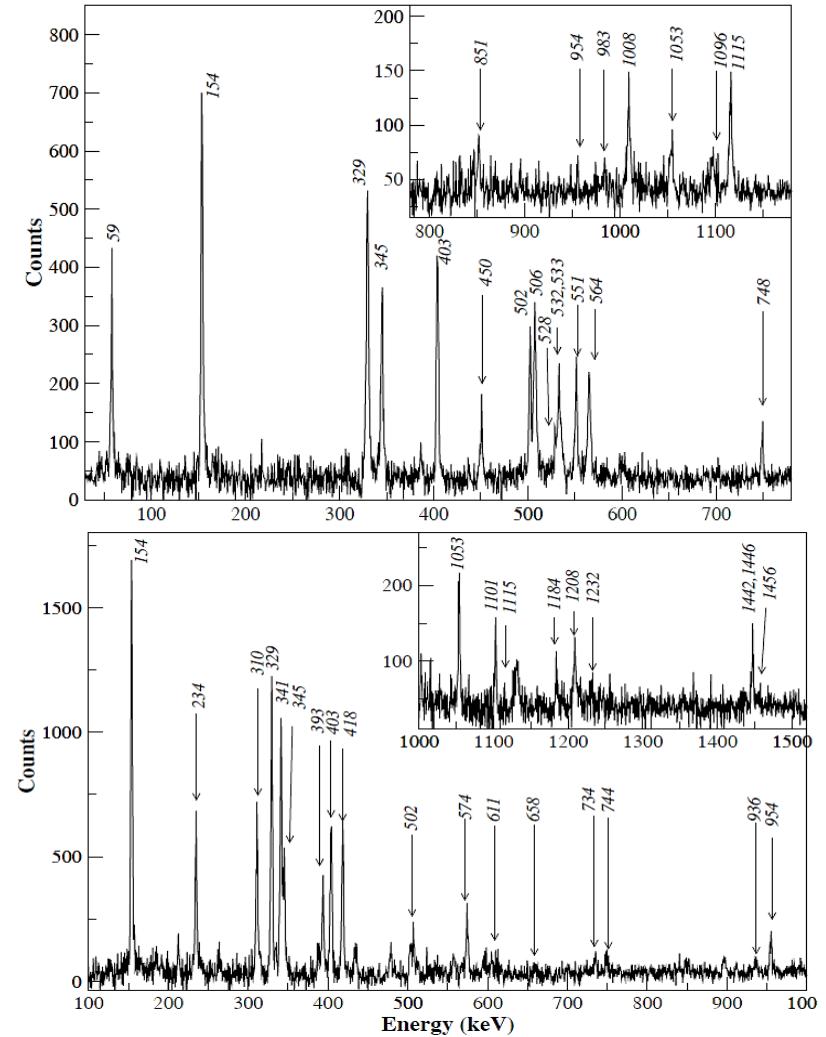
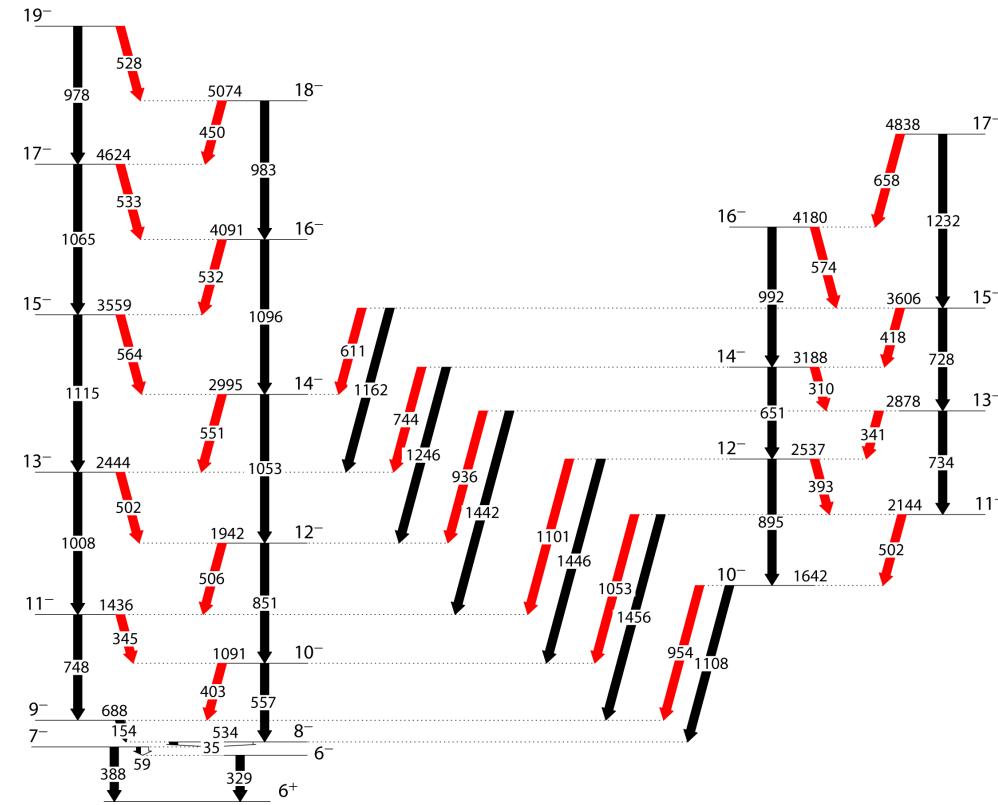
- Reaction for level scheme:
 $^{100}\text{Mo}(^{11}\text{B}, 3n\gamma) ^{108}\text{Ag}$
- Set up : INGA @ TIFR
18 Compton suppressed HPGe Clover detectors
- Pixie-16 DDAQ from XIA
- Target :
 ^{100}Mo (10 mg/cm²) self supported.
- Beam : ^{11}B at 39 MeV.



- Reaction for lifetime : $^{94}\text{Zr}(^{18}\text{O}, p3n\gamma) ^{108}\text{Ag}$
- Detector set-up : INGA at TIFR with 21 Compton suppressed HPGe Clover detectors
- Pixie-16 DDAQ from XIA
- Target : ^{94}Zr (0.9 mg/cm²) backed with 10 mg/cm² ^{197}Au .
- Beam : ^{18}O at 72 MeV.

Twin Bands of ^{108}Ag

Partial Level Scheme and double gated spectra



Triaxial Projected Shell Model

1. The quasi particle states are generated by triaxial Nilsson+ BCS Hamiltonian.

$$\hat{H} = \hat{H}_0 - \frac{1}{2}\chi \sum_{\mu} \hat{Q}_{\mu}^{\dagger} \hat{Q}_{\mu} - G_M \hat{P}^{\dagger} \hat{P} - G_Q \sum_{\mu} \hat{P}_{\mu}^{\dagger} \hat{P}_{\mu}$$

2. Angular momentum projected basis are obtained from the intrinsic Nilsson states.
3. The projected angular momentum basis states are used to diagonalize the Shell model Hamiltonian.

Recent work:

J.A. Sheikh, G.H. Bhat, R. Palit, Z. Naik, Y. Sun, Nucl. Phys. A 824 (2009) 58.

J. A. Sheikh, G. H. Bhat, Y. Sun, R. Palit, Phys. Lett. B 688, 305 (2010).

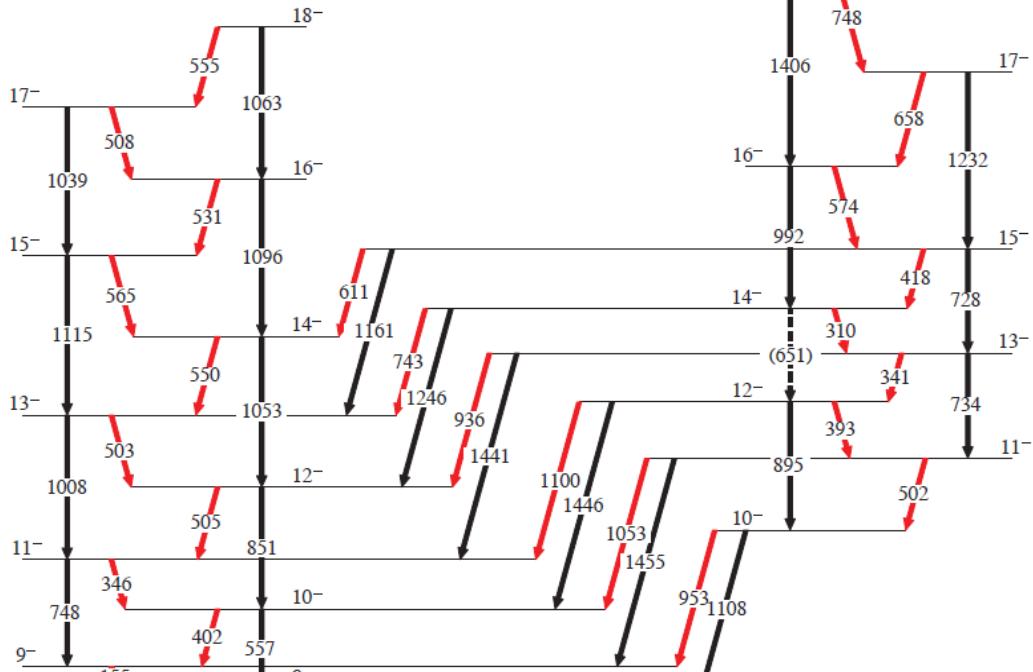
G.H. Bhat, J.A. Sheikh, R. Palit, Phys. Lett. B 707, 237 (2012).

G.H. Bhat, J.A. Sheikh, W.A. Dar, S. Jehangir, R. Palit, P. Ganai, Phys. Lett. B 738, 218 (2014).

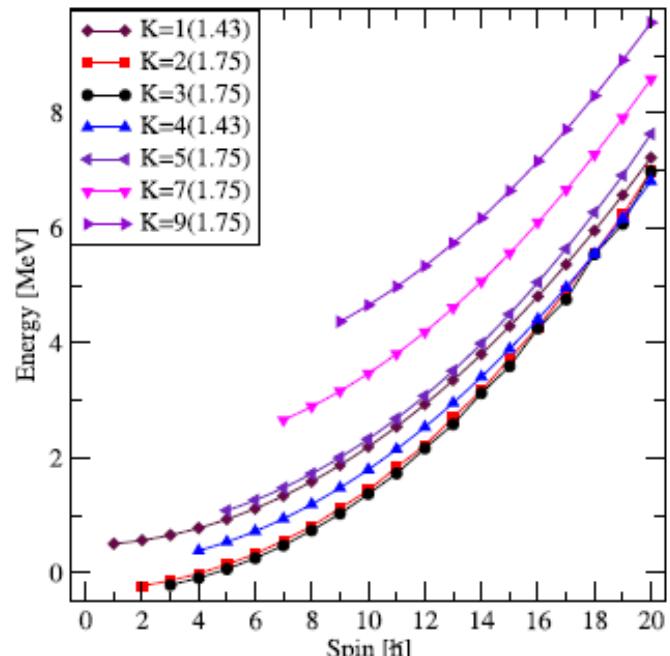
Structure of nearly degenerate dipole bands in ^{108}Ag 

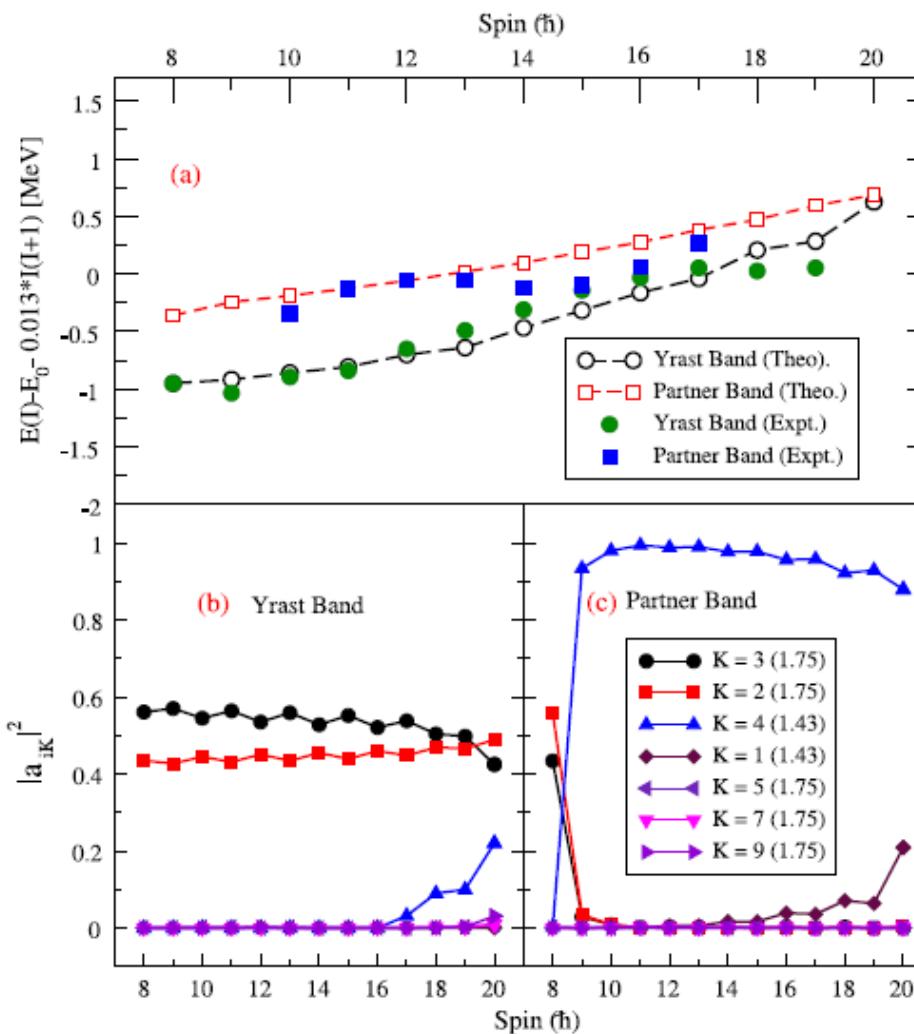
J. Sethi^a, R. Palit^{a,*}, S. Saha^a, T. Trivedi^a, G.H. Bhat^b, J.A. Sheikh^b, P. Datta^c, J.J. Carroll^d, S. Chattopadhyay^e, R. Donti^a, U. Garg^f, S. Jadhav^a, H.C. Jain^a, S. Karamian^g, S. Kumar^h, M.S. Litz^d, D. Mehtaⁱ, B.S. Naidu^a, Z. Naik^j, S. Sihotraⁱ, P.M. Walker^k

$$\hat{H} = \hat{H}_0 - \frac{1}{2}\chi \sum_{\mu} \hat{Q}_{\mu}^{\dagger} \hat{Q}_{\mu} - G_M \hat{P}^{\dagger} \hat{P} - G_Q \sum_{\mu} \hat{P}_{\mu}^{\dagger} \hat{P}_{\mu}$$



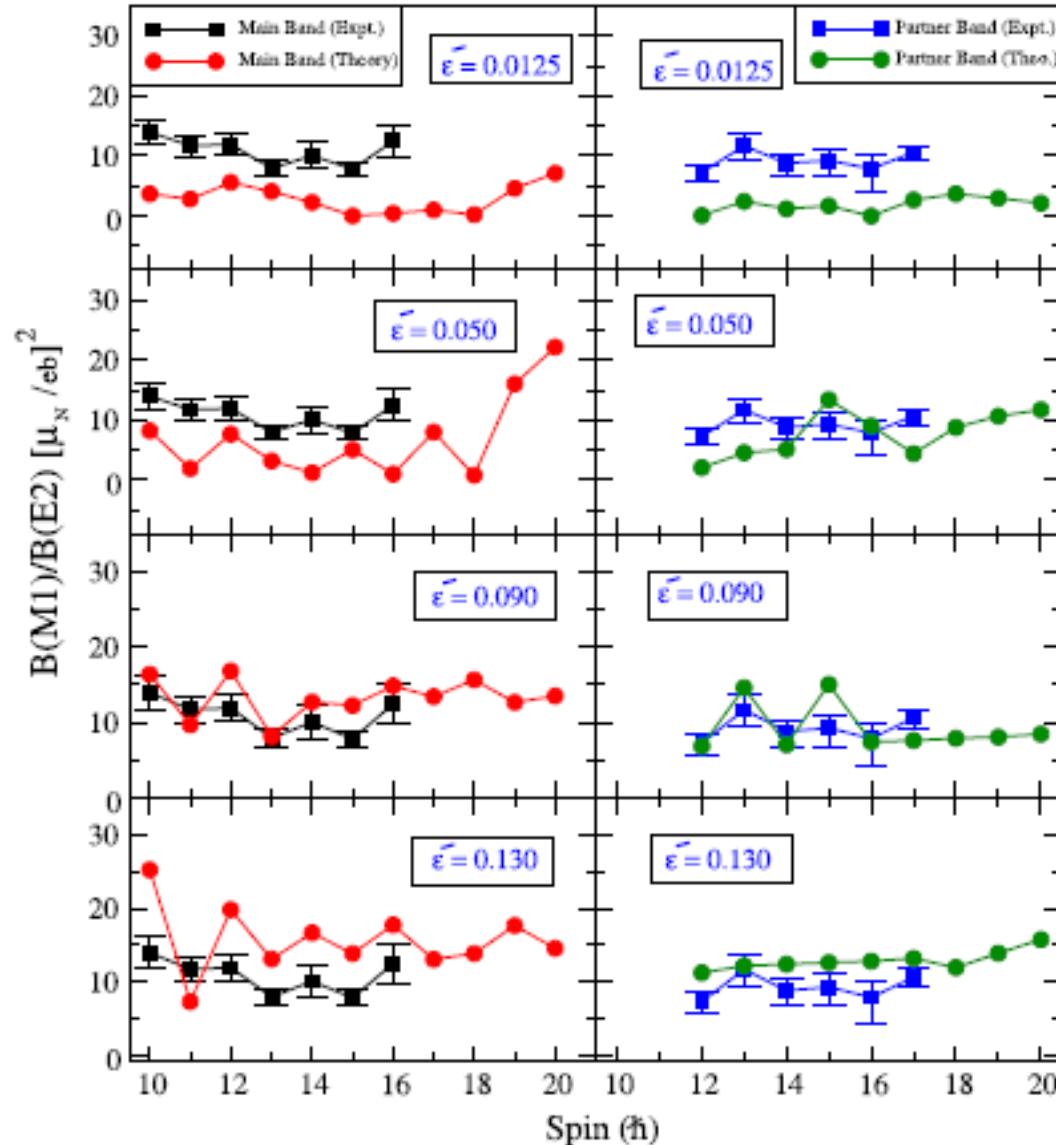
$$\pi g_{9/2}^{-1} \times v h_{11/2}$$





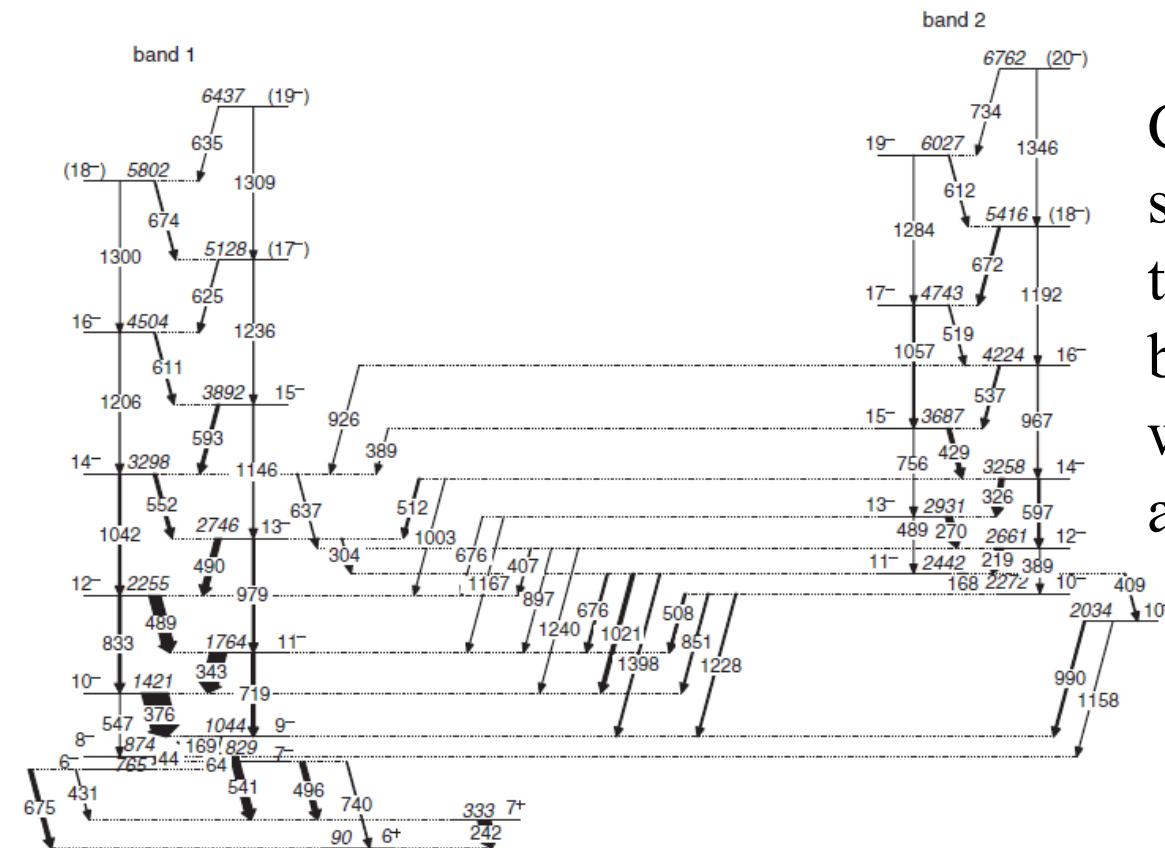
Degenerate bands reproduced with triaxial deformations
 $\varepsilon_2 = 0.265$ and $\varepsilon' = 0.09$

Comparison of ratio of transition strengths



Triaxial deformation for ^{108}Ag

Degenerate dipole bands in ^{106}Ag



Comparison with systematics suggested yrast band has triaxial shape, while partner band possesses properties which can be explained by axial shape.

Exploring the Origin of Nearly Degenerate Doublet Bands in ^{106}Ag

N. Rather,¹ P. Datta,^{2,*} S. Chattopadhyay,¹ S. Rajbanshi,¹ A. Goswami,¹ G. H. Bhat,³ J. A. Sheikh,³ S. Roy,⁴ R. Palit,⁴ S. Pal,⁴ S. Saha,⁴ J. Sethi,⁴ S. Biswas,⁴ P. Singh,⁴ and H. C. Jain⁴

¹Saha Institute of Nuclear Physics, Kolkata 700064, India

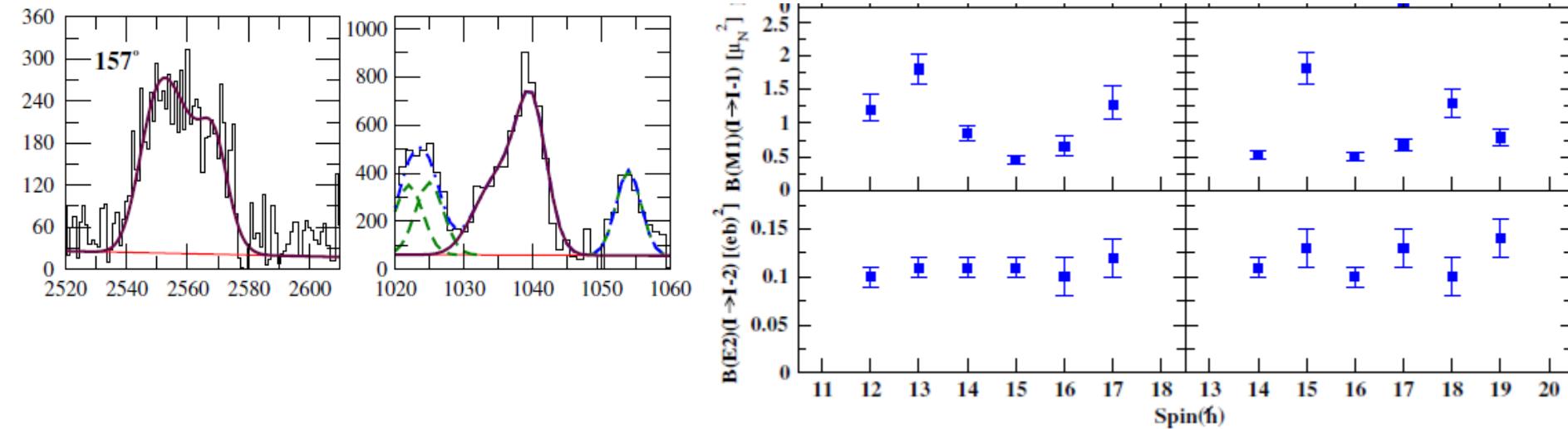
²Ananda Mohan College, Kolkata 700009, India

³Department of Physics, University of Kashmir, Srinagar 190006, India

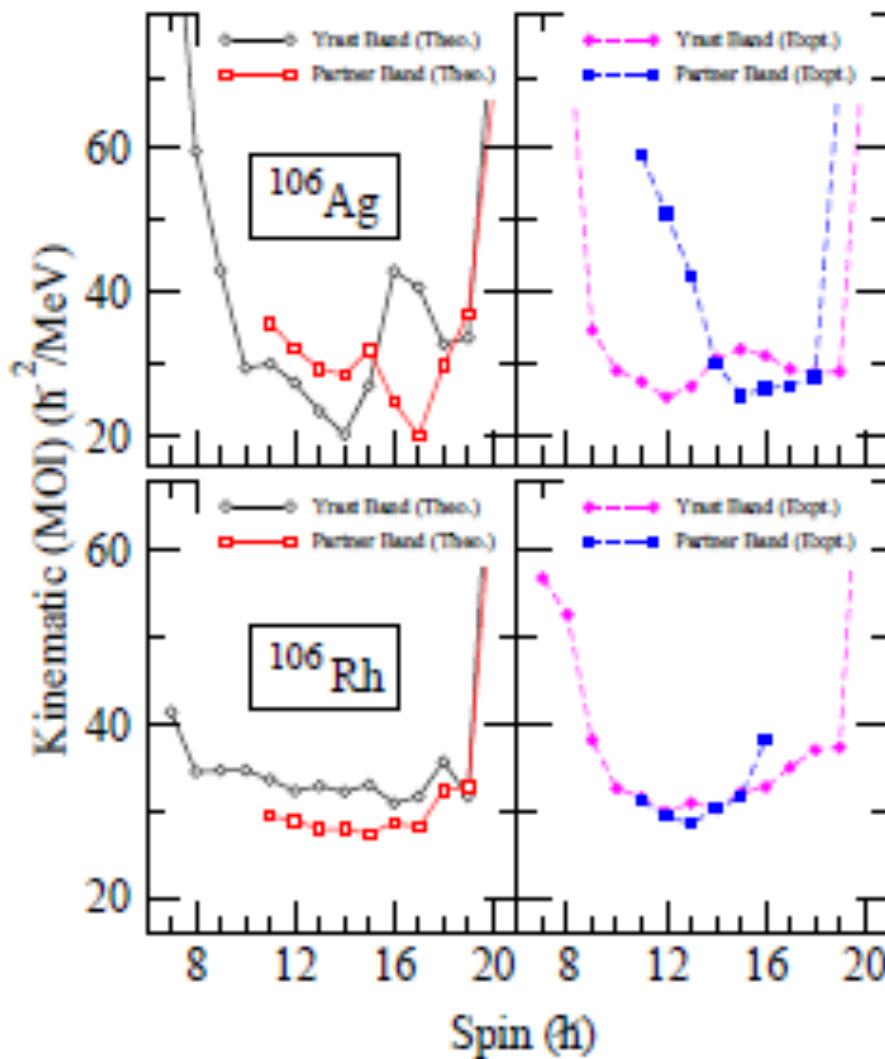
⁴Tata Institute of Fundamental Research, Mumbai 400005, India

(Received 28 October 2013; revised manuscript received 16 April 2014; published 20 May 2014)

The lifetimes of the excited levels for the two nearly degenerate bands of ^{106}Ag have been measured using the Doppler-shift attenuation method. The deduced $B(E2)$ and $B(M1)$ rates in the two bands are found to be similar, except around the band crossing spin, while their moments of inertia are quite different. This is a novel observation for a nearly degenerate doublet band.



Related work: Lieder et al., Phys.Rev.Lett. 112, 202502 (2014)

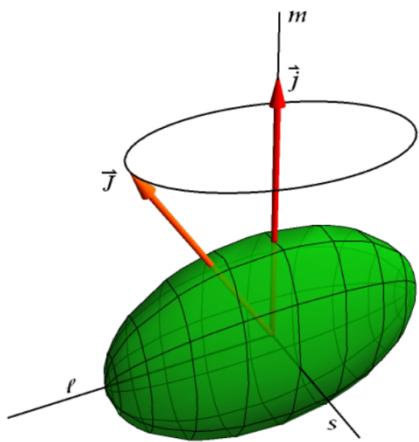


Degenerate bands in odd-odd Ag isotopes are from different configuration contrary to Odd-odd Rh isotopes.

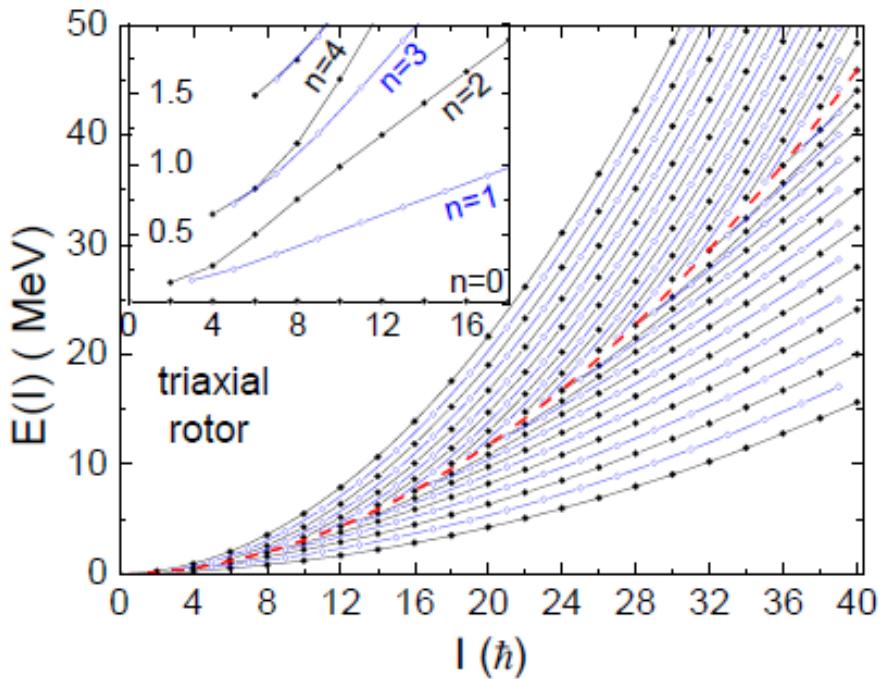
NPA 933, 123 (2015).

Microscopic study of chiral rotation in odd-odd $A \sim 100$ nuclei

Wobbling mode in odd- A triaxial nuclei



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



$$\hbar\omega_w =$$

$$\frac{j}{J_3} \left[\left(1 + \frac{J}{j} \left(\frac{J_3}{J_1} - 1 \right) \right) \left(1 + \frac{J}{j} \left(\frac{J_3}{J_2} - 1 \right) \right) \right]^{1/2}.$$

- Induces sequences of rotational bands.
- Inter-band transitions are $\Delta I=1$ E2 in nature

Transverse Wobbling in ^{135}Pr

J. T. Matta, U. Garg, W. Li, S. Frauendorf, A. D. Ayangeakaa,[†] D. Patel, and K. W. Schlax
Physics Department, University of Notre Dame, Notre Dame, Indiana 46556, USA

R. Palit, S. Saha, J. Sethi, and T. Trivedi[‡]
Tata Institute of Fundamental Research, Mumbai 400 005, India

S. S. Ghugre, R. Raut, and A. K. Sinha
UGC-DAE Consortium for Scientific Research, Kolkata 700 098, India

R. V. F. Janssens, S. Zhu, M. P. Carpenter, T. Lauritsen, and D. Seweryniak
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

C. J. Chiara
Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA and Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

F. G. Kondev
Nuclear Engineering Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

D. J. Hartley
Department of Physics, United States Naval Academy, Annapolis, Maryland 21402, USA

C. M. Petrache
Centre de Sciences Nucléaires et Sciences de la Matière, Université Paris—Sud and CNRS/IN2P3, F-91405 Orsay, France

S. Mukhopadhyay
Bhabha Atomic Research Centre, Mumbai 400 085, India

D. Vijaya Lakshmi, M. Kumar Raju,[§] and P. V. Madhusudhana Rao
Department of Nuclear Physics, Andhra University, Visakhapatnam 530 003, India

S. K. Tandel
UM-DAE Centre for Excellence in Basic Sciences, Mumbai 400 098, India

S. Ray[¶]
Saha Institute of Nuclear Physics, Kolkata 700 064, India

F. Dönau^{*}
Institut für Strahlenphysik, Helmholtz-Zentrum Dresden-Rossendorf, 01314 Dresden, Germany

Longitudinal Wobbling in ^{133}La

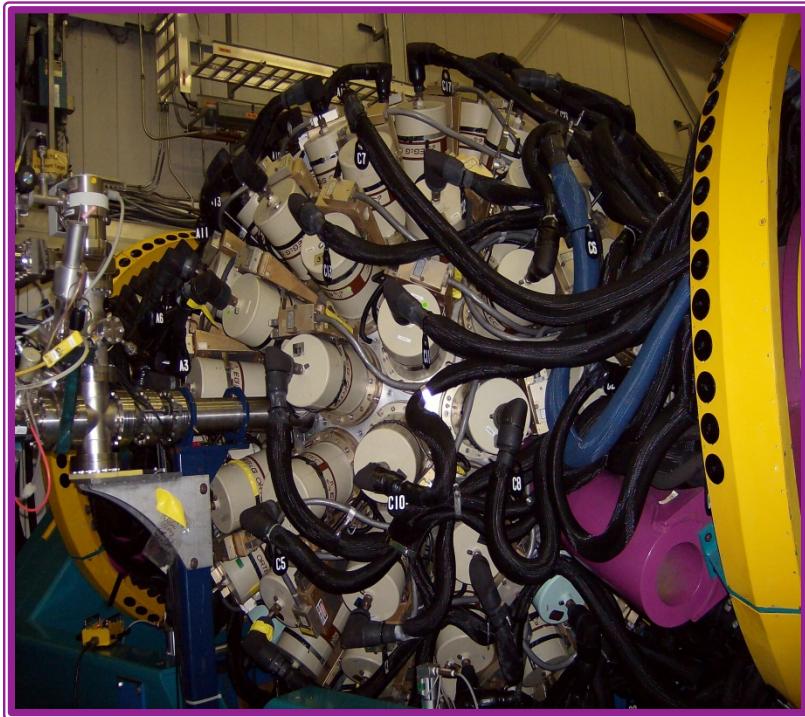
S. Biswas,¹ R. Palit,¹ U. Garg,² G. H. Bhat,³ S. Frauendorf,² W. Li,² J. A. Sheikh,³ J. Sethi,¹ S. Saha,¹ Purnima Singh,¹ D. Choudhury,¹ J. T. Matta,² A. D. Ayangeakaa,² W. A. Dar,³ V. Singh,⁴ S. Sihotra⁴

¹*Department of Nuclear and Atomic Physics, Tata Institute of Fundamental Research, Mumbai 400005, India*

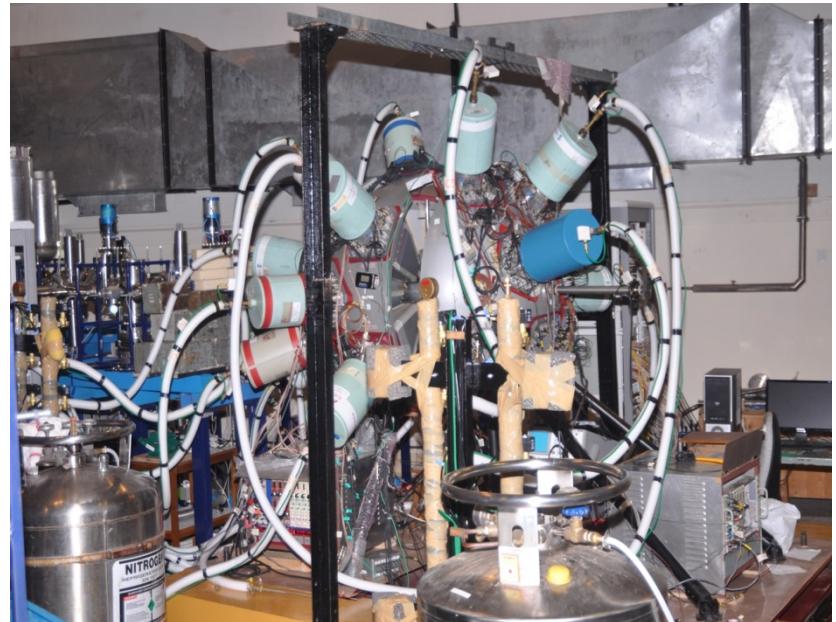
²*University of Notre Dame, Indiana 46556, USA*

³*Department of Physics, University of Kashmir, Srinagar 190006, India*

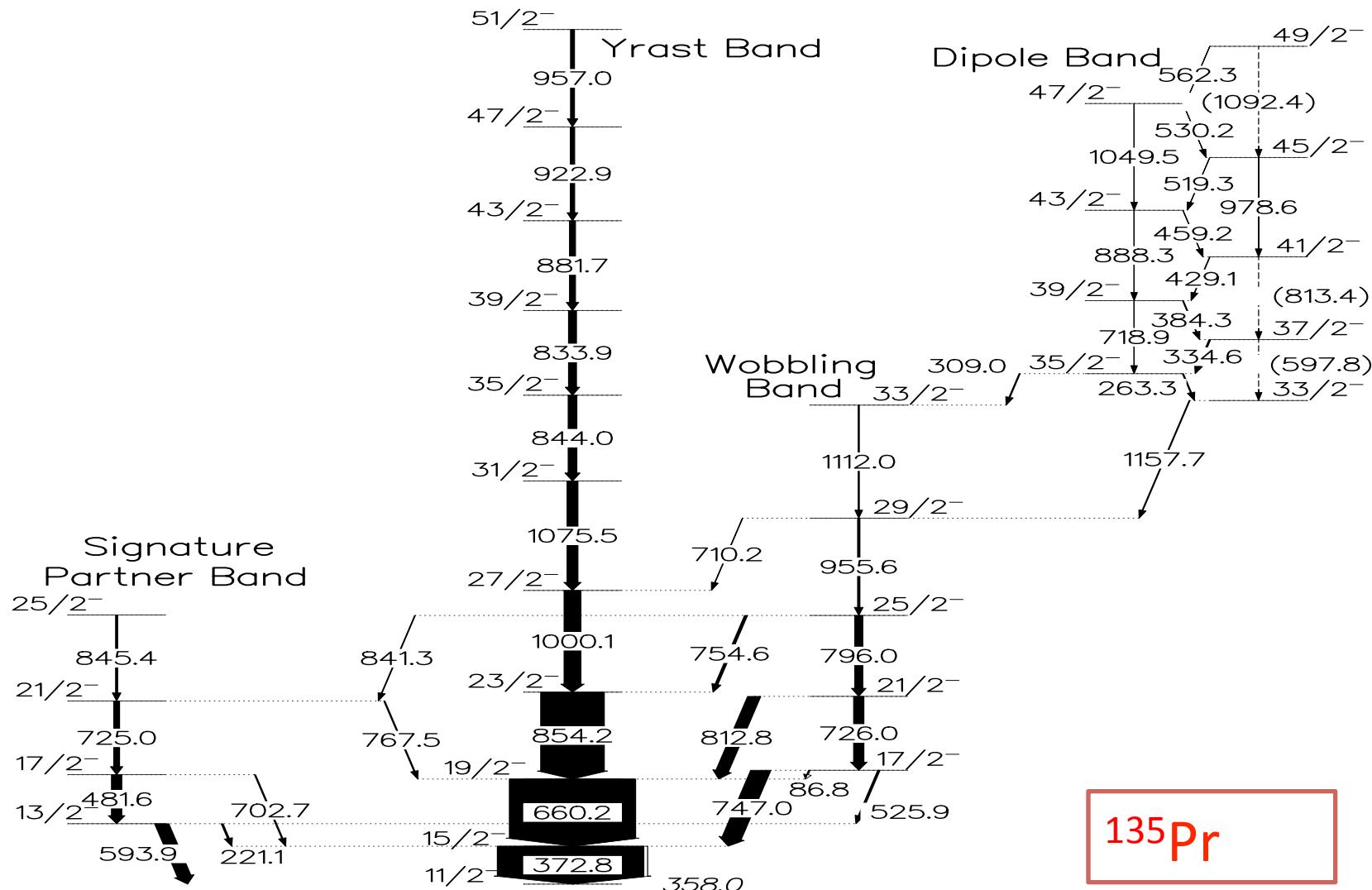
⁴*Department of Physics, Panjab University, Chandigarh 160014, India*

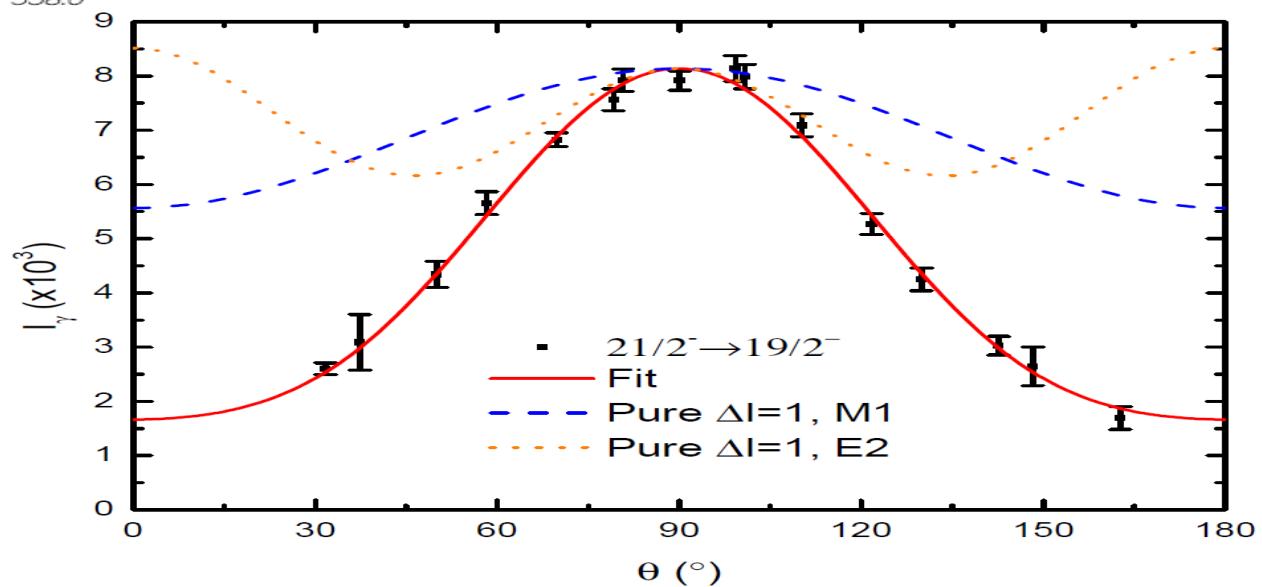
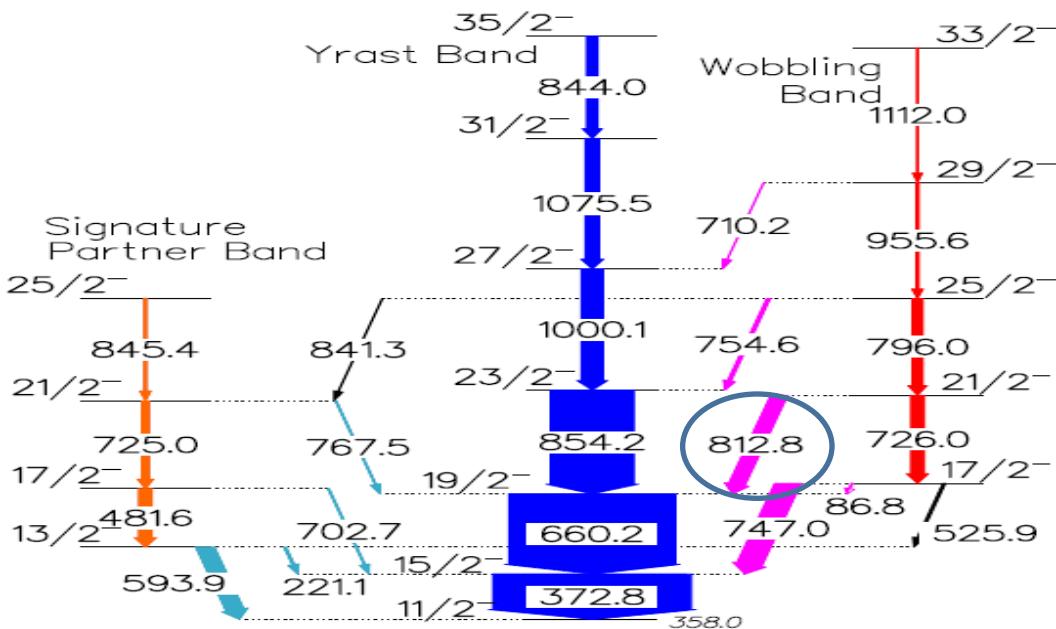


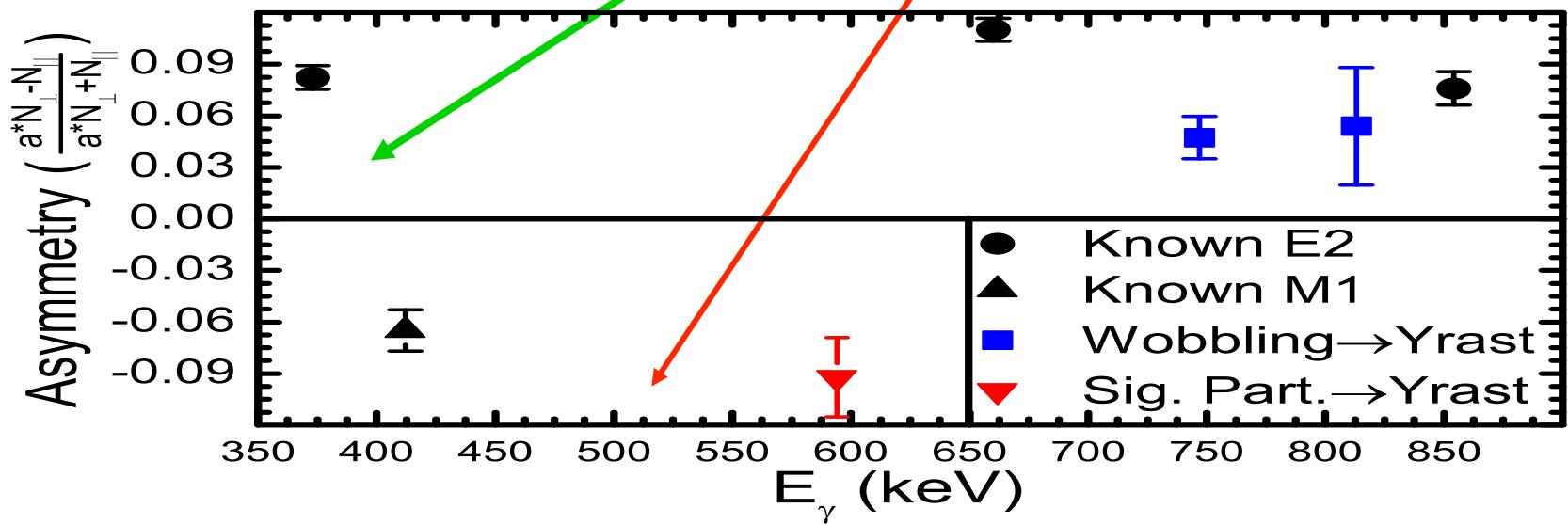
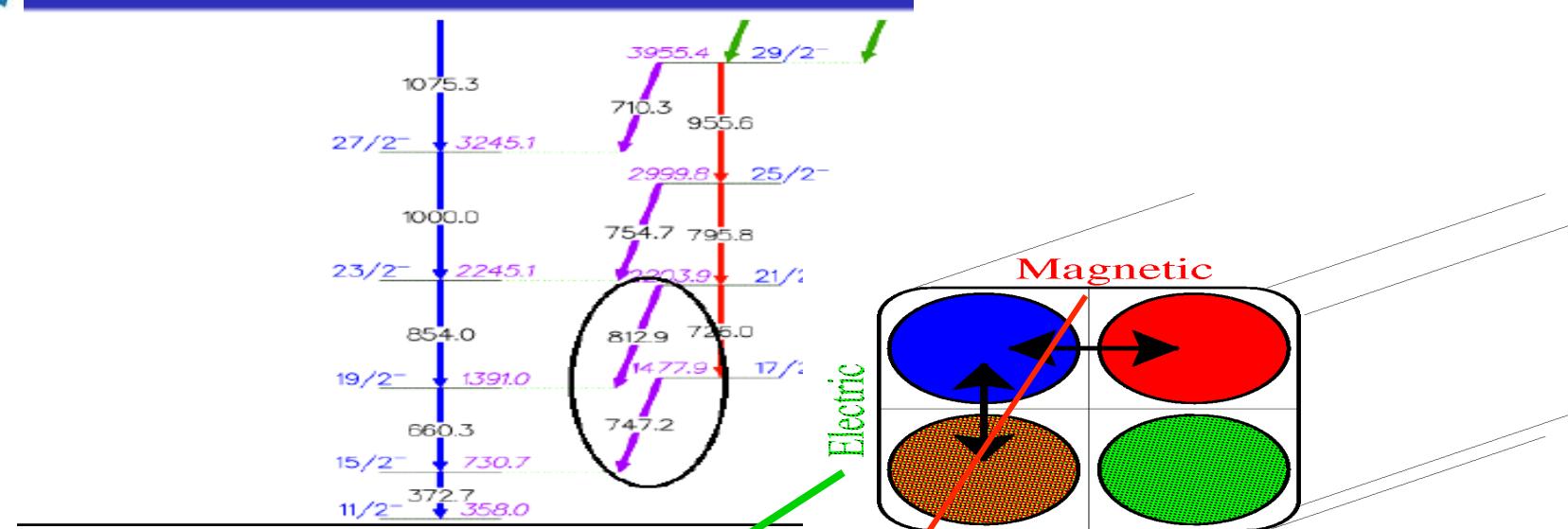
^{123}Sb ($^{16}\text{O}, 4\text{n}$) ^{135}Pr @ 80 MeV
Gammasphere at ATLAS
(100 CSGe detectors)
 γ - γ - γ coincidences
angular correlations



INGA @ TIFR
20 CS “clover” detectors
polarization measurements





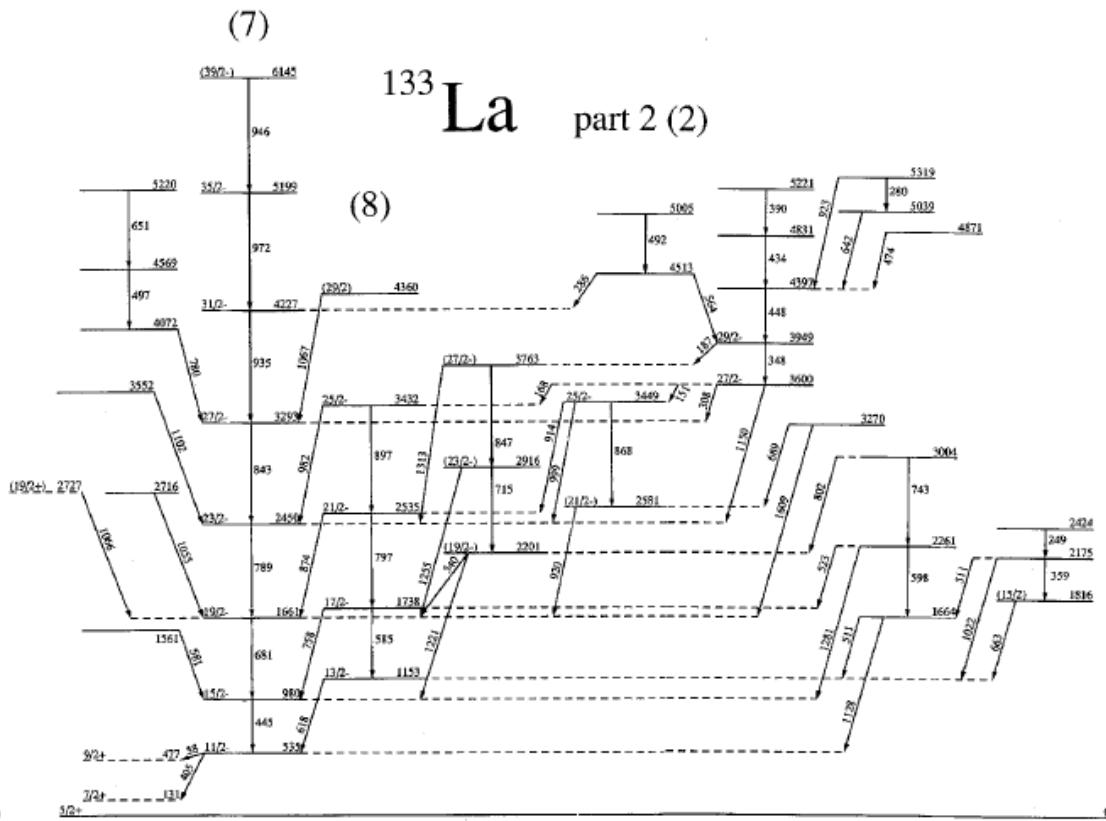


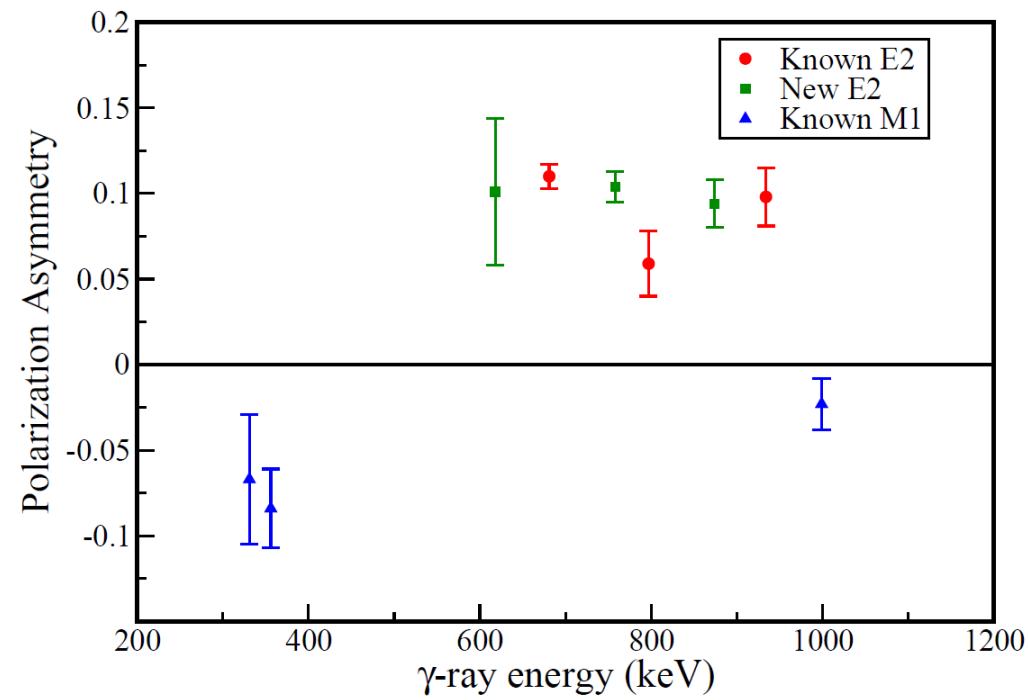
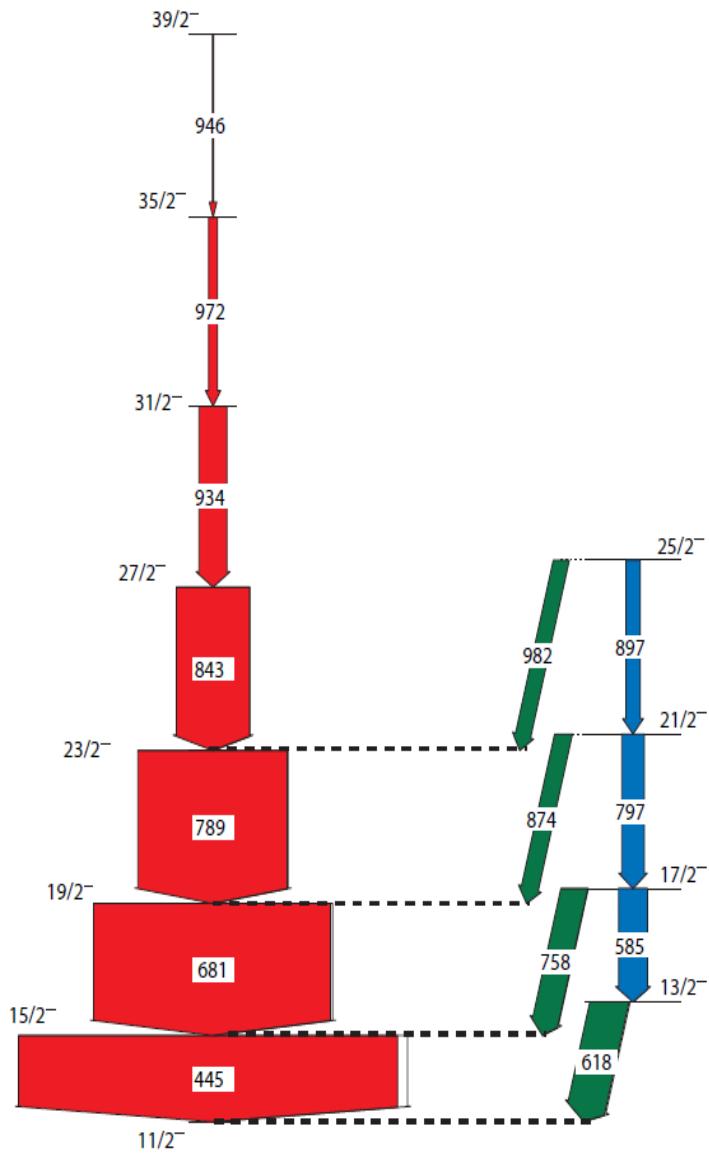
Neutron $h_{11/2}$ alignments in the triaxial nucleus ^{133}La

L. Hildingsson¹, W. Klamra¹, Th. Lindblad¹, C.G. Lindén¹, G. Sletten², and G. Székely^{1*}

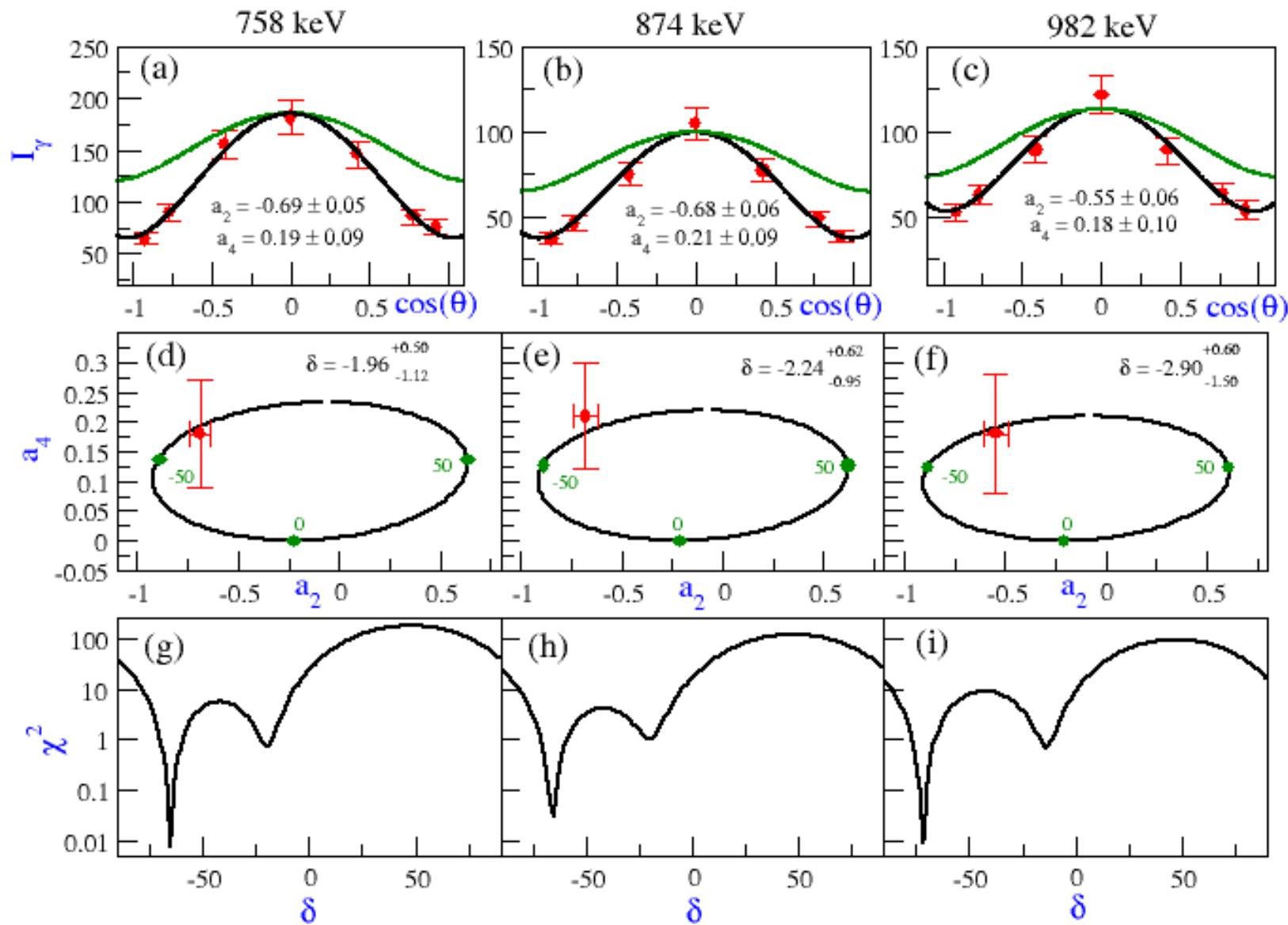
¹ Manne Siegbahn Institute of Physics, Tresladvägen 24, S-104 05 Stockholm, Sweden

² The Niels Bohr Institute, Risø, Denmark

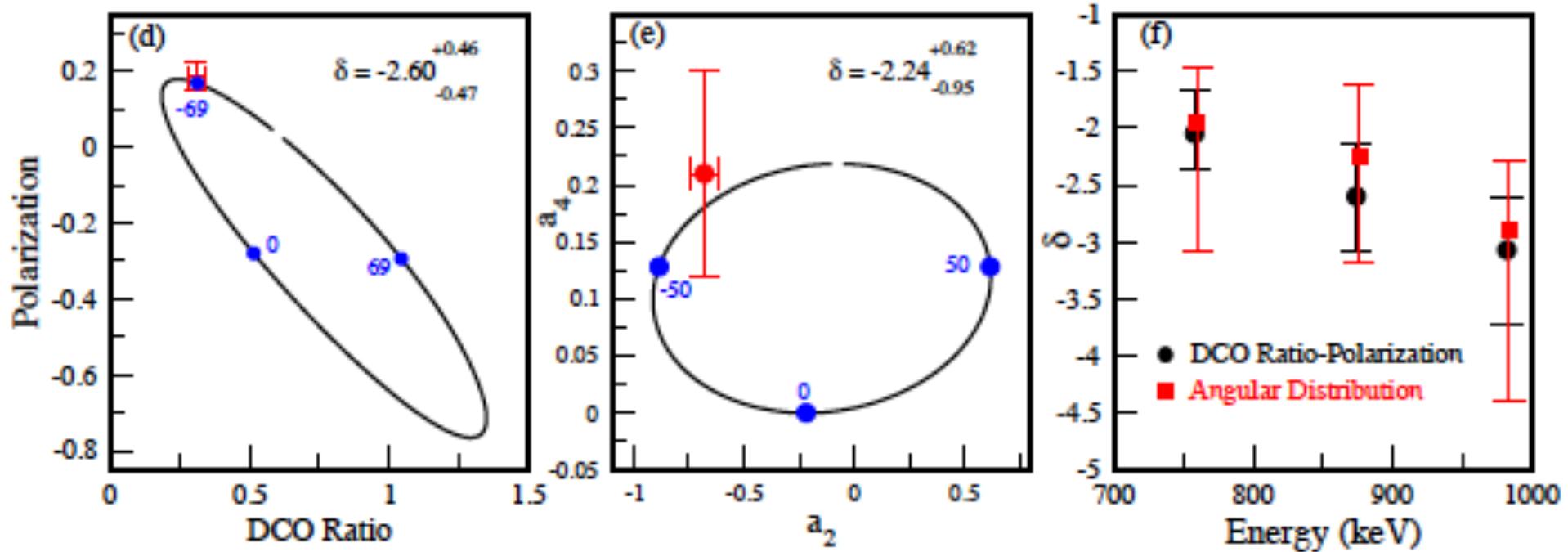


Search for wobbling mode in ^{133}La at low spin

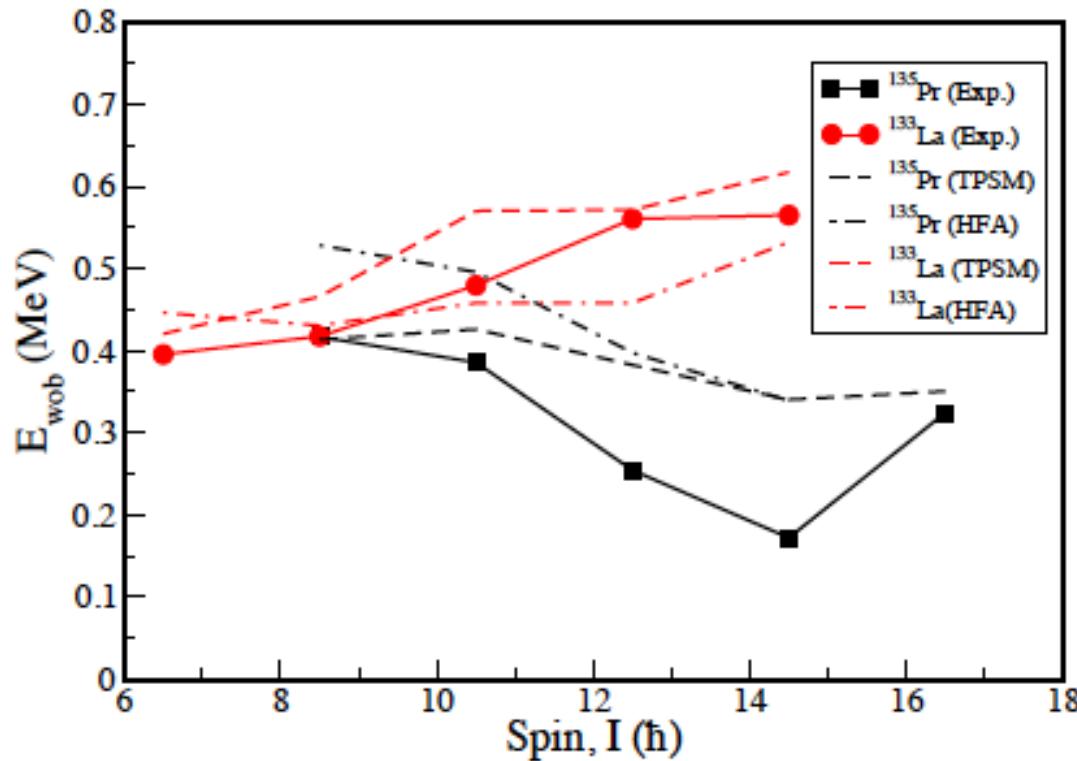
Angular distribution for wobbling mode in ^{133}La



Angular distribution, DCO, Polarization for linking transitions for wobbling mode in ^{133}La at low spin



*Transverse and longitudinal wobbling mode
in ^{135}Pr and ^{133}La*



TPSM: ^{133}La , ^{135}Pr

$\epsilon = 0.15, 0.16$ and $\epsilon' = 0.11$

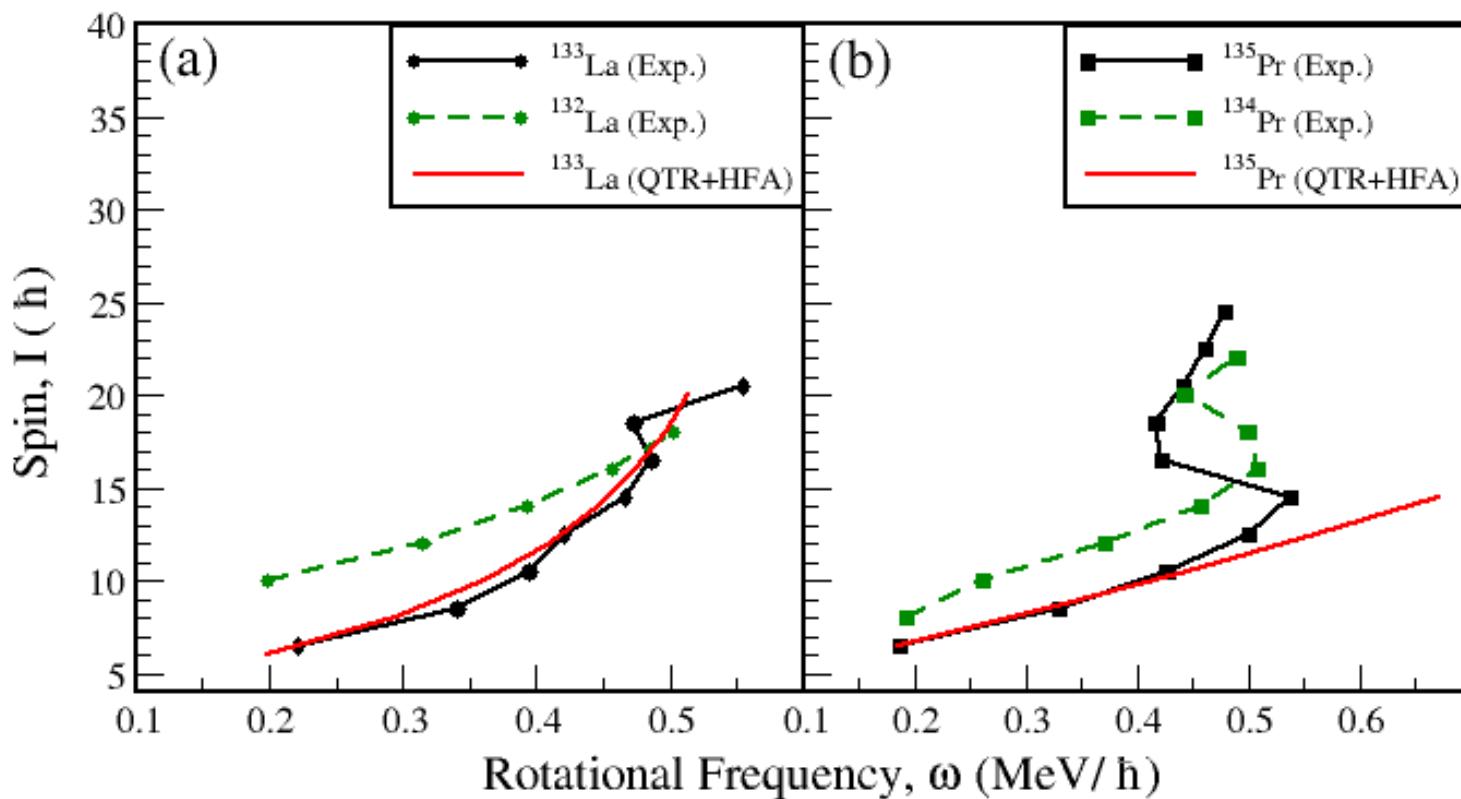
QTR+HFA

$\mathcal{J}_m / \mathcal{J}_s / \mathcal{J}_l$

$^{135}\text{Pr}: 21/15.4/4$

$^{133}\text{La}: 21/19/4$

*Transverse and longitudinal wobbling mode
in ^{135}Pr and ^{133}La*



Continuous gap in ^{134}Pr and ^{135}Pr unlike ^{132}La and ^{133}La

Spin dependent M.I. for short axis in QTR+HFA

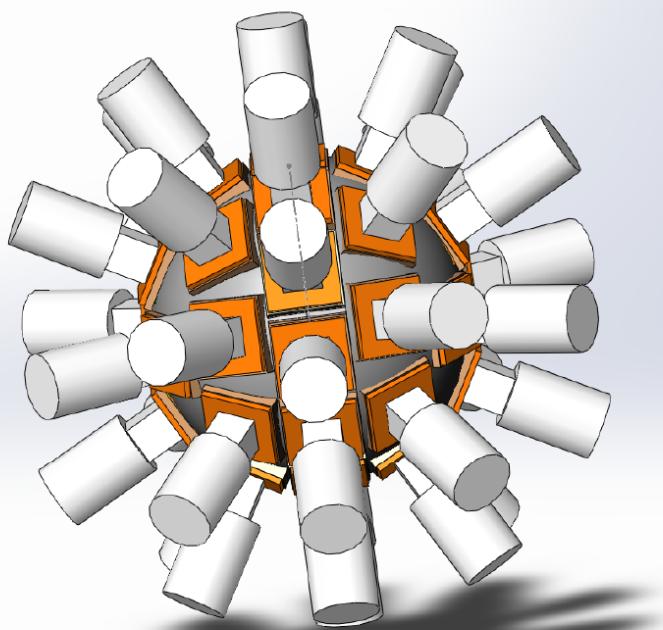
^{135}Pr : MoI of shorter axis is smaller than medium axis

^{133}La : MoI of shorter axis is similar to medium axis

Future plan for INGA

Proposal for complete array in 3 accelerator facilities in near future.
TIFR, IUAC, VECC

Conceptual Design of ~40 CS HPGe Clover array with ~8% Efficiency



**Enhance the solid angle to 40%;
Gamma multiplicity filter;
Ancillary detectors;**

Summary

- Structure of degenerate dipole bands in ^{108}Ag and nearby nuclei
- Longitudinal wobbling in ^{133}La at low spin and comparison with its isotope ^{135}Pr a transverse wobbler.

INGA coupled to a DDAQ and other ancillary detectors will provide opportunities to probe various exotic modes of nuclear rotation and excitation.

INGA will remain a competitive facility for nuclear structure investigation with stable beams.

Investing in the polarization measurements of gamma rays and “wide-range timing spectroscopy” proved to be a successful approach for creating our specific “niche” and complement research at large scale facilities



Thank You

*INGA Collaboration meeting at TIFR
Hosted by IUAC, UGC-CSR-DAE-KC and TIFR
9th – 11th March 2013*

