Novel excitation modes of nuclei using INGA: Results and Opportunities

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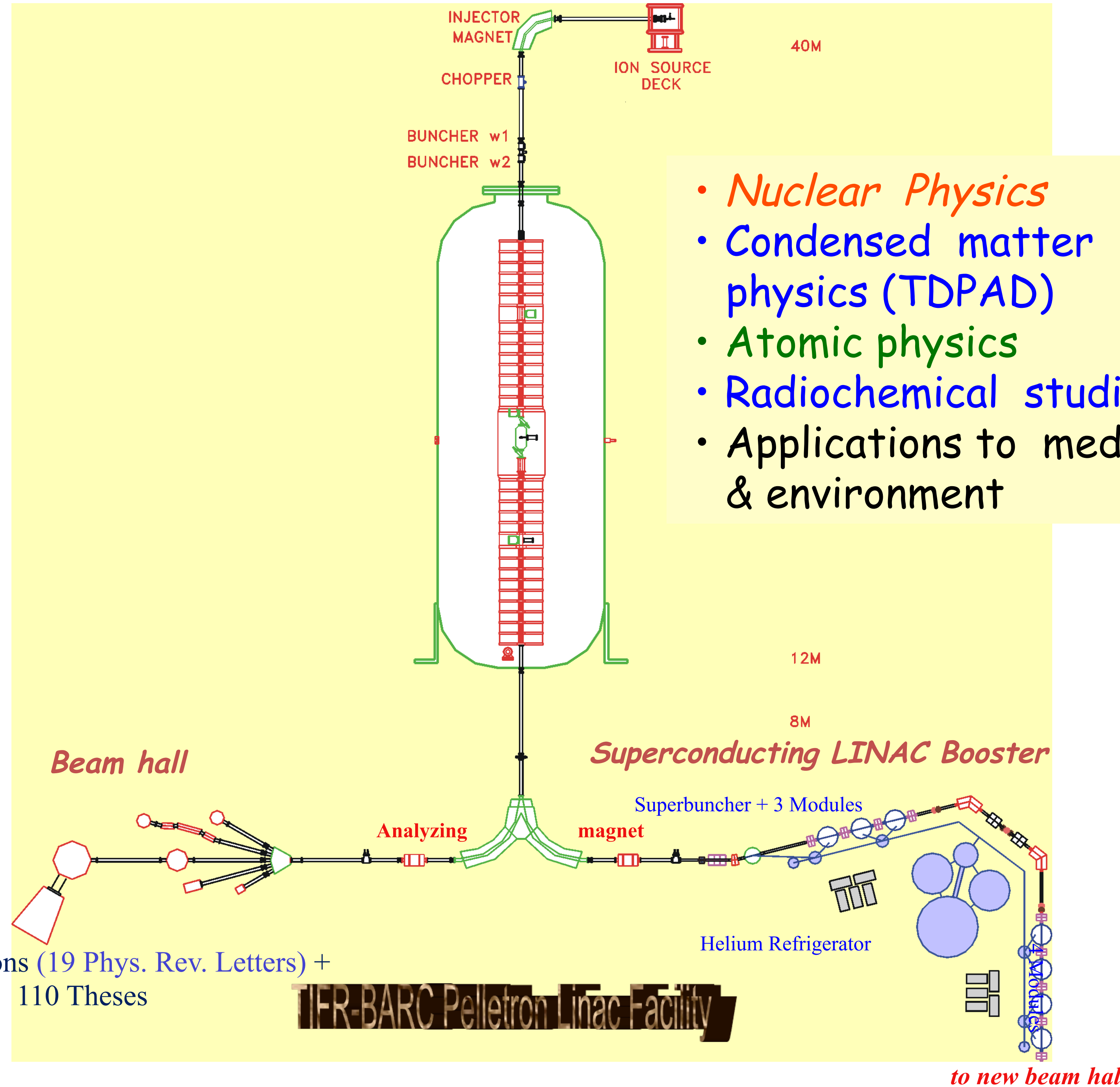
COMEX6, Cape Town, 29 Oct – 2 Nov 2018

INGA Collaboration



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

700 publications (19 Phys. Rev. Letters) +
110 Theses

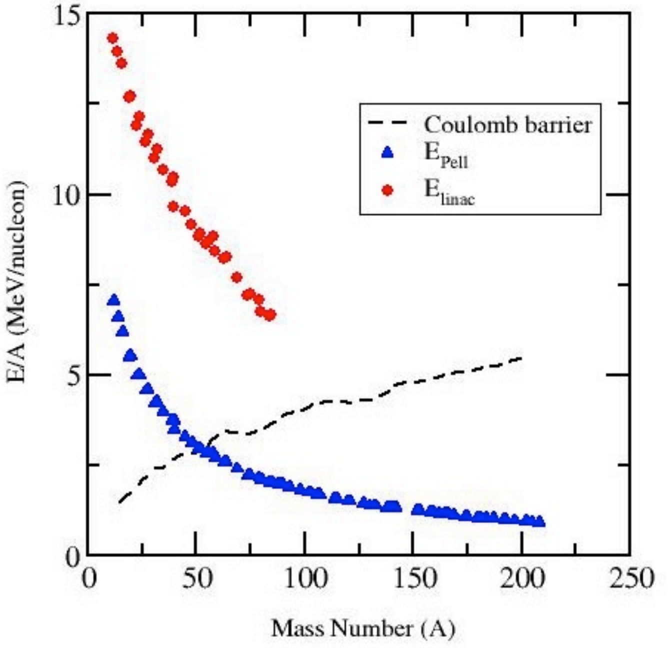
TIFR-BARC Pelletron Linac Facility

TIFR-BARC Pelletron Linac Facility

Pelletron accelerator

– E/A ~ 3-7 MeV, β ~ 0.08-0.12

– Heavy ions reactions upto A ~ 40



Superconducting Linac booster

– E/A ~ 5-10 MeV, β ~ 0.10-0.16

– Heavy ions reactions upto A ~ 80

(limited by pre-accelerator)

– Beam intensity: 0.1-10 pnA (10^{9-11} p/s)

(limited by ion source)

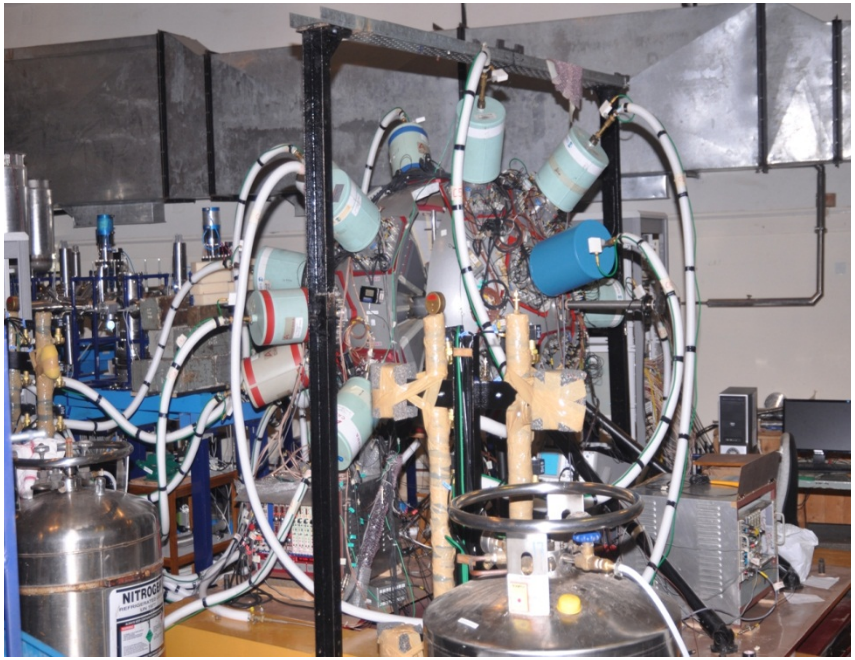
Beams accelerated through Pelletron

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

Beams accelerated through Linac

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

INGA campaign



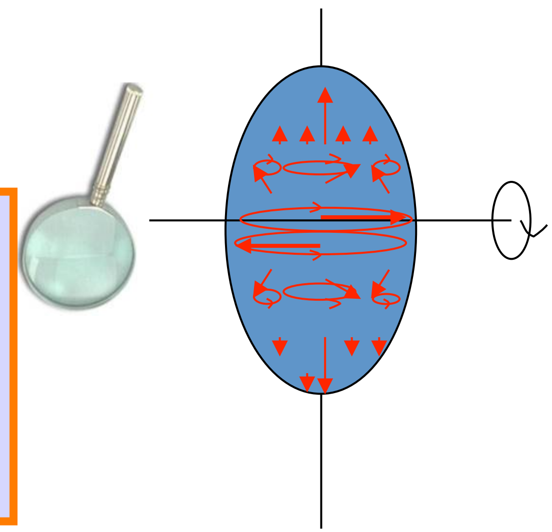
DSP Implementation for INGA

- Up to ~200 channels
- Provision for Ancillary detectors (CsI(Tl), Si and $LaBr_3$(Ce))

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

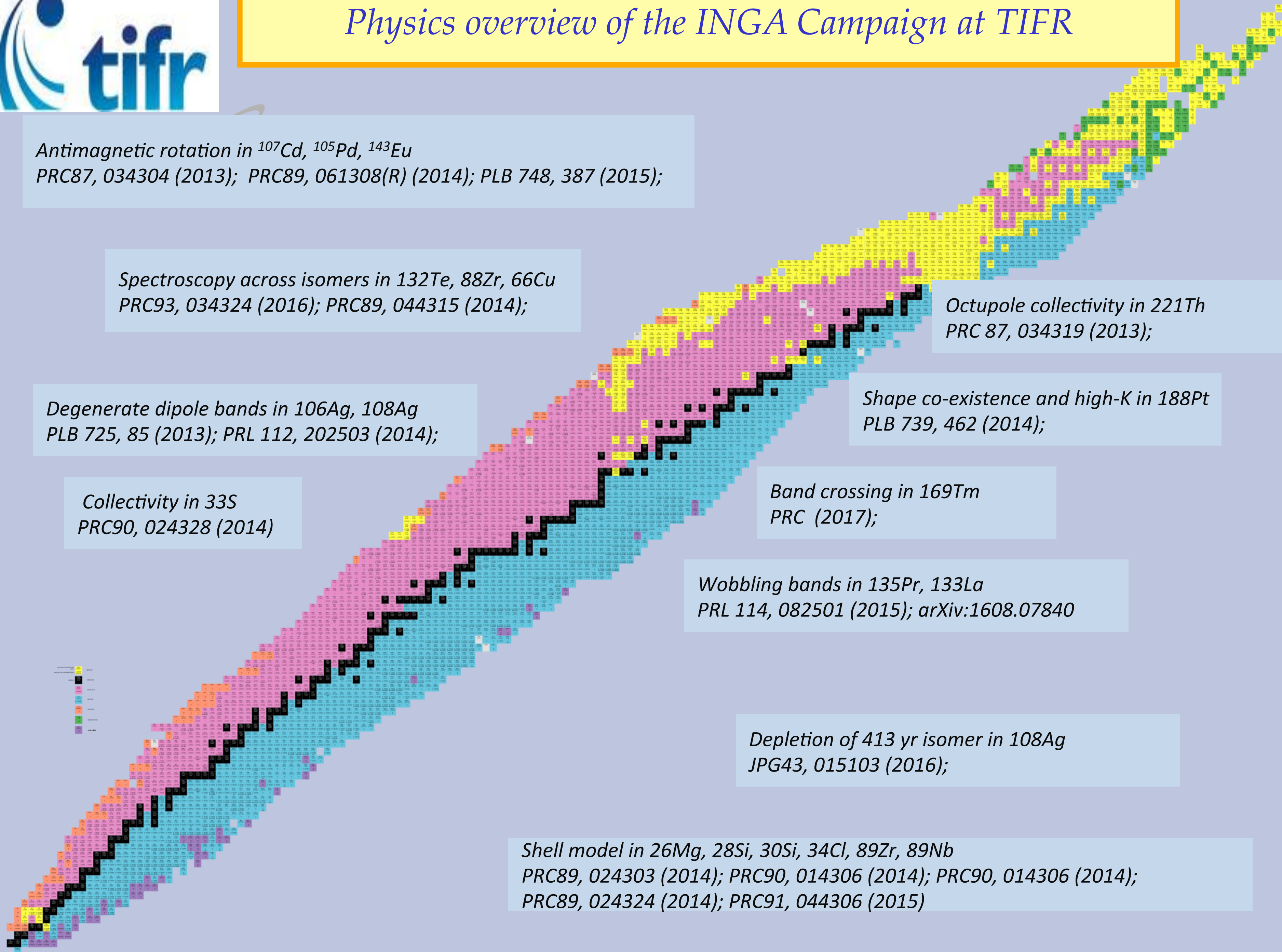
BARC, IUAC, IUC-KC, SINP, TIFR, VECC, IITs, Univ

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; 40 publications (2012-2017)



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

Physics overview of the INGA Campaign at TIFR



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

Spectroscopy across isomers in 132Te, 88Zr, 66Cu
PRC93, 034324 (2016); PRC89, 044315 (2014);

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

Collectivity in 33S
PRC90, 024328 (2014)

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

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

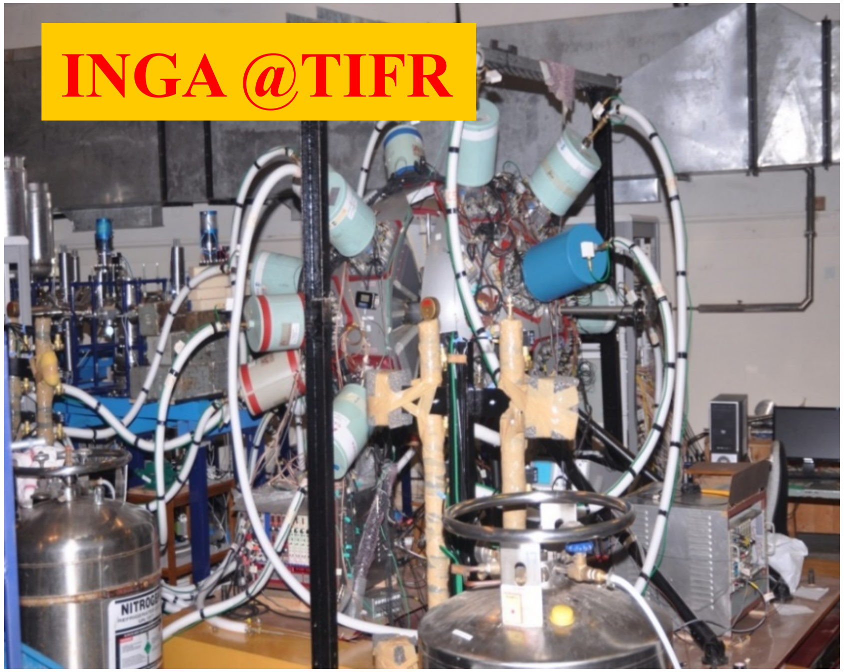
Band crossing in 169Tm
PRC (2017);

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

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

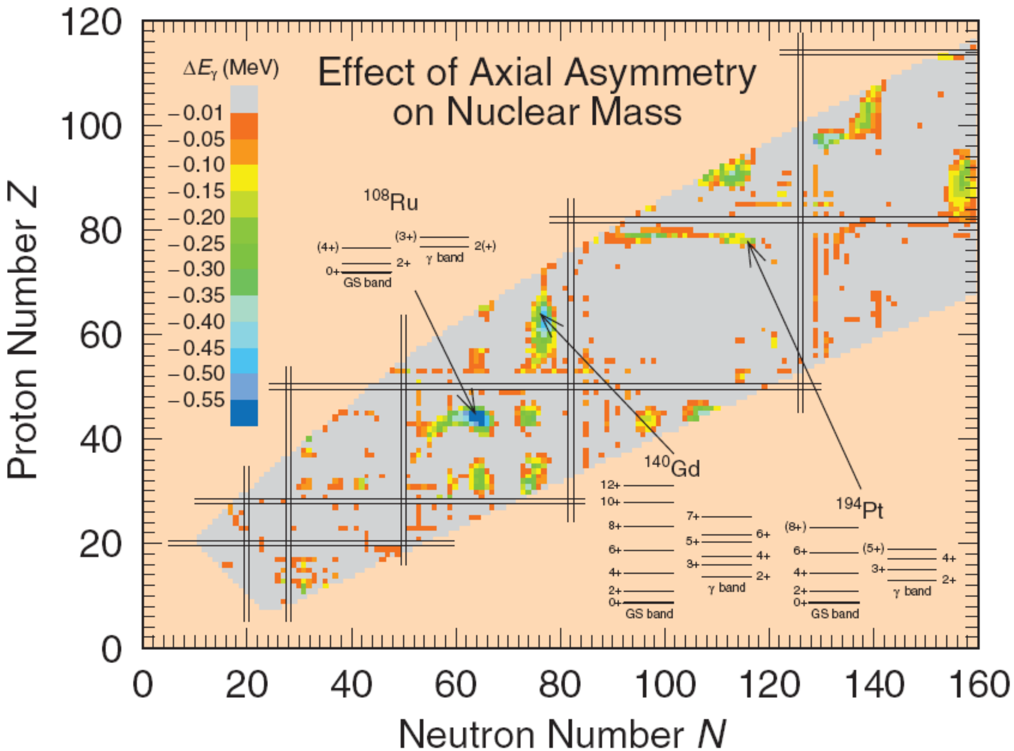
Shell model in 26Mg, 28Si, 30Si, 34Cl, 89Zr, 89Nb
PRC89, 024303 (2014); PRC90, 014306 (2014); PRC90, 014306 (2014);
PRC89, 024324 (2014); PRC91, 044306 (2015)

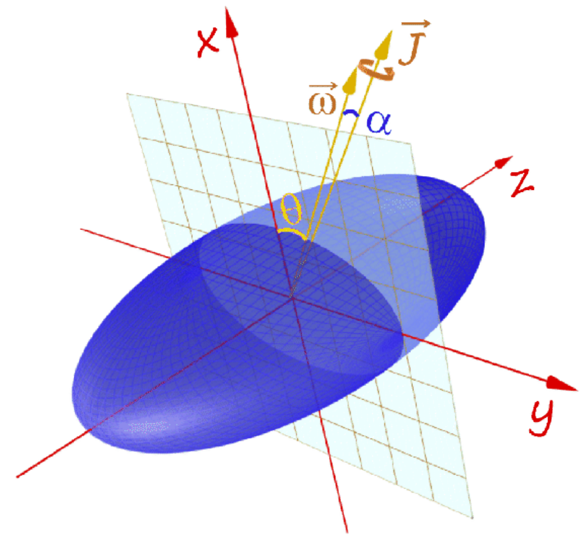
Physics highlights of the INGA Campaign at TIFR



- Structure near closed shell
- Chiral bands in rotating nuclei
- First observation of wobbling mode at low spin
- Magnetic and Anti-magnetic rotation
- Depletion of long lived isomer in ^{108}Ag

Rotation of triaxial nuclei and symmetries





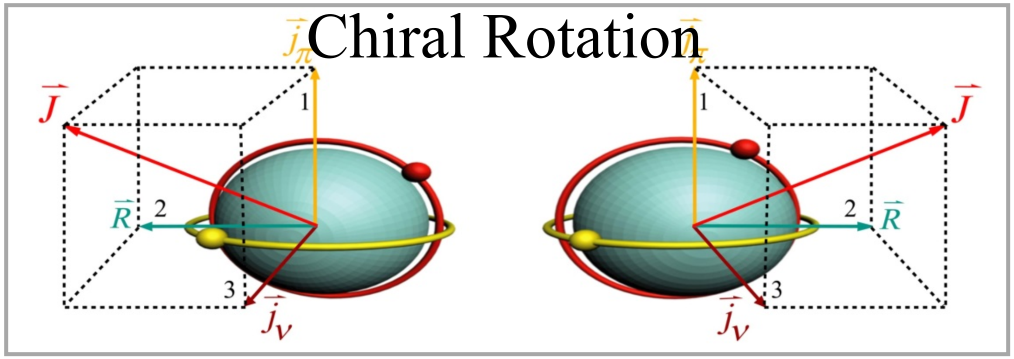
Rotation of Triaxial Nuclei

P. Moller et al., Phys. Rev. Lett. 97 (2006) 162502.

Triaxiality in nuclei had been a longstanding prediction of theory, but had proved very difficult to establish experimentally.
Chirality and Wobbling bands (TSD) are generally considered as the bes signatures of nuclear triaxiality.

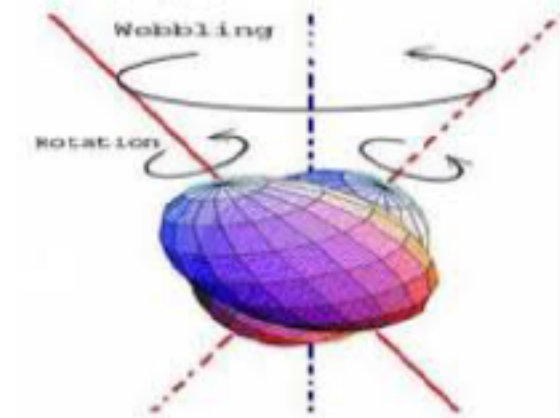
Rotation of triaxial nuclei and symmetries

Chiral Rotation



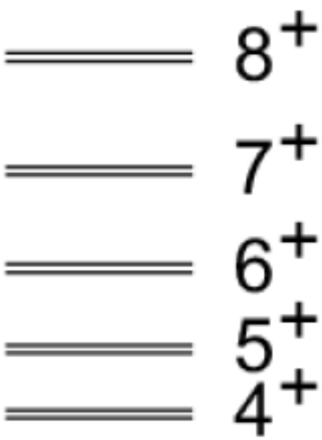
SF, JM NPA (1997)

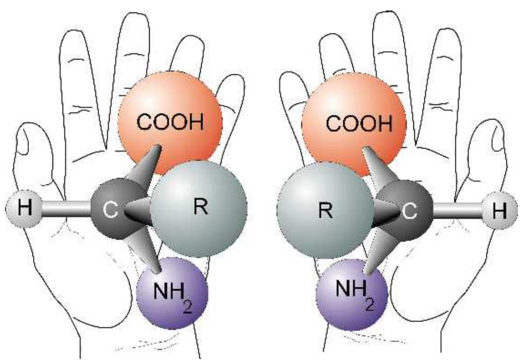
Wobbling Mode

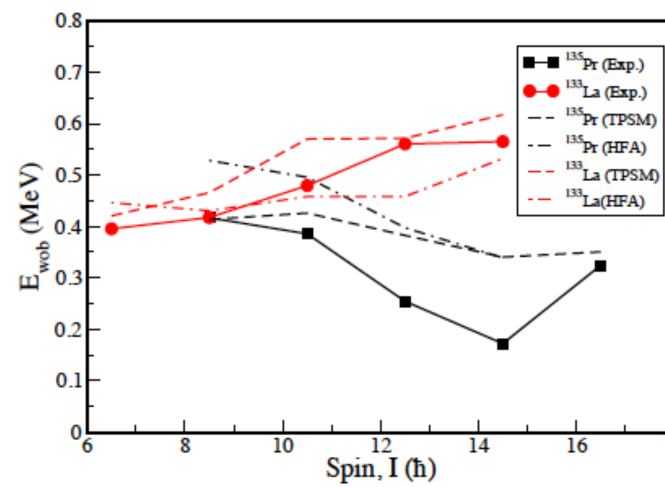


SF, FD PRC (2014)

Polarization, Angular distribution, $T_{1/2}$





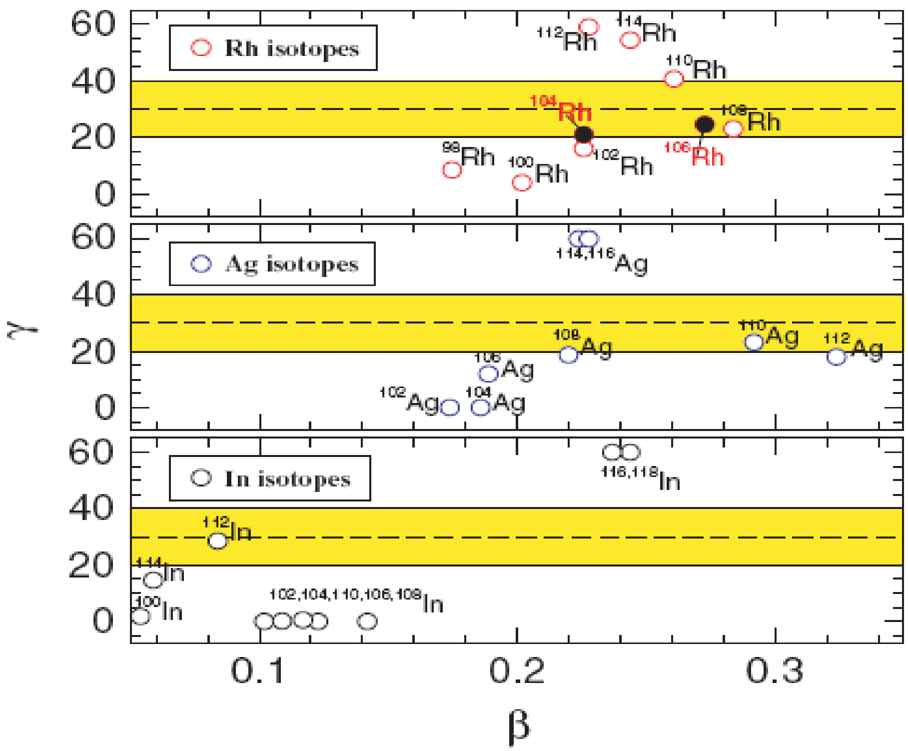


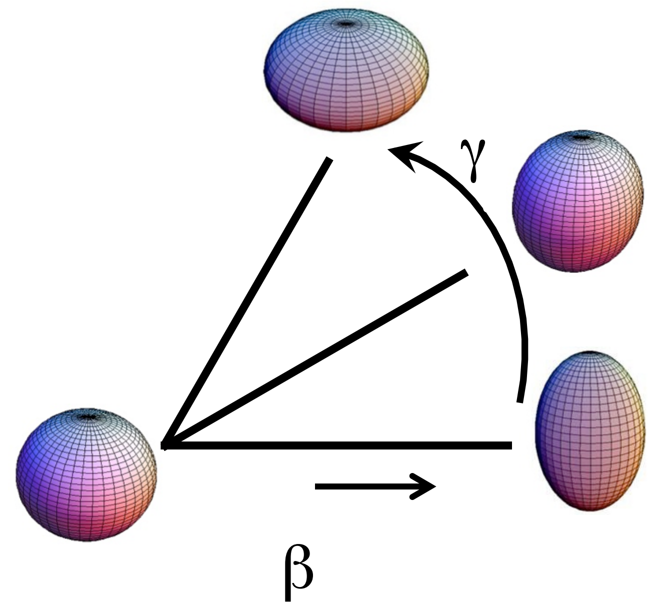
T. Roy et al. PLB 782, 768 (2018)
N. Rather, etal.,PRL112,202503(2014)
J. Sethi, et al., PLB 725, 85 (2013)

J. Matta et al., PRL 114 082501 (2015) ^{135}Pr
S. Biswas, et al., arXiv:1608.07840 ^{133}La

Odd-odd Isotopes near A ~ 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).

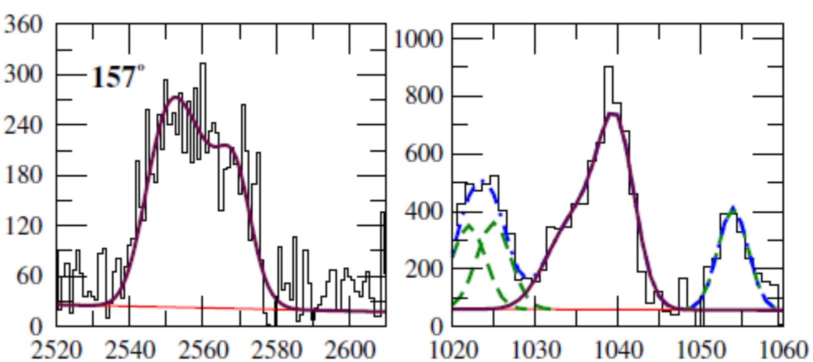
T. Trivedi, R. Palit et al., PRC 85 014327 (2012)
J. Sethi, R. Palit et al., PLB 725 85 (2013)
N. Rather et al., PRL 112, 202503(2014)

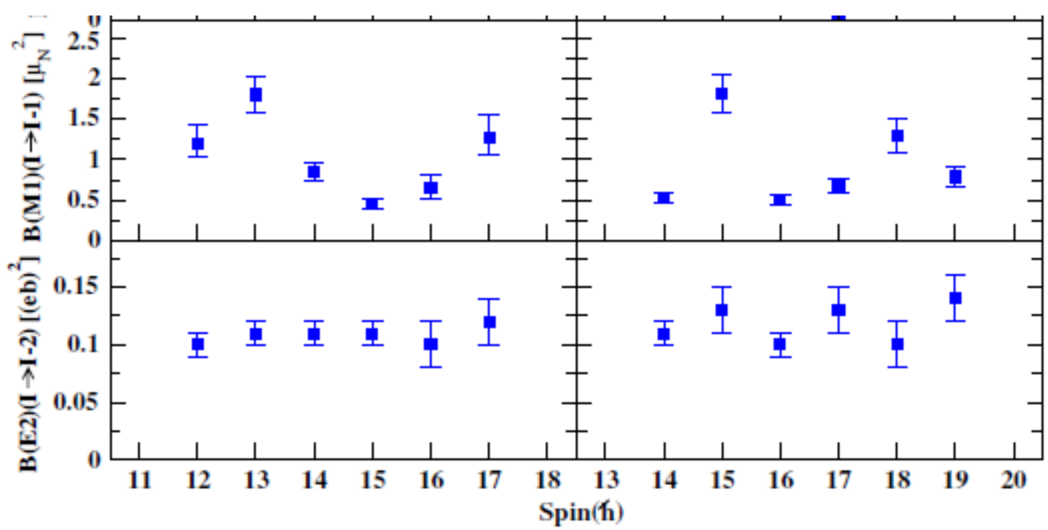
PRL 112, 202503 (2014) PHYSICAL REVIEW LETTERS week ending 23 MAY 2014

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. Jain[4]
[1]Saha Institute of Nuclear Physics, Kolkata 700064, India
[2]Ananda Mohan College, Kolkata 700009, India
[3]Department of Physics, University of Kashmir, Srinagar 190006, India
[4]Tata Institute of Fundamental Research, Mumbai 400005, India
(Received 28 October 2013; revised manuscript received 16 April 2014; published 20 May 2014)

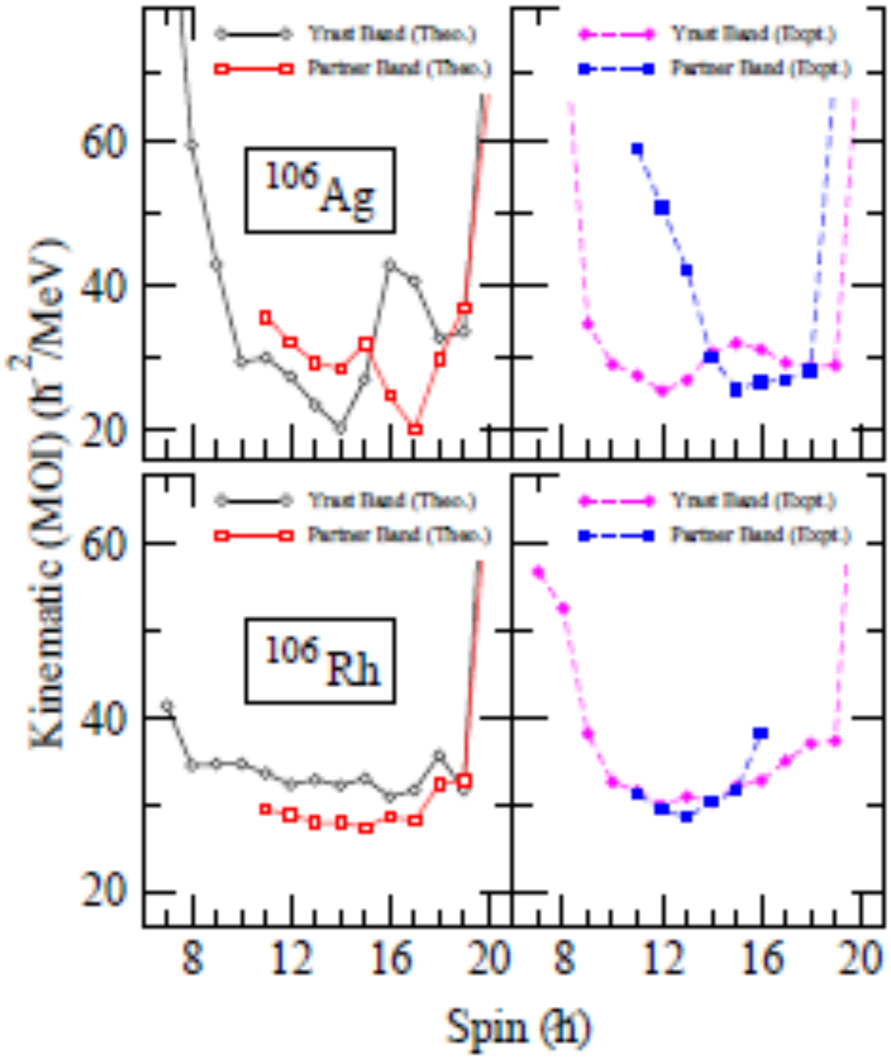
The lifetimes of the excited levels for the two nearly degenerate bands of ^{106}Ag have been measured using the Doppler-shift attenuation method. The deduced $B(E2)$ and $B(M1)$ rates in the two bands are found to be similar, except around the band crossing spin, while their moments of inertia are quite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





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

Comparison of energy of levels for odd-odd isotopes



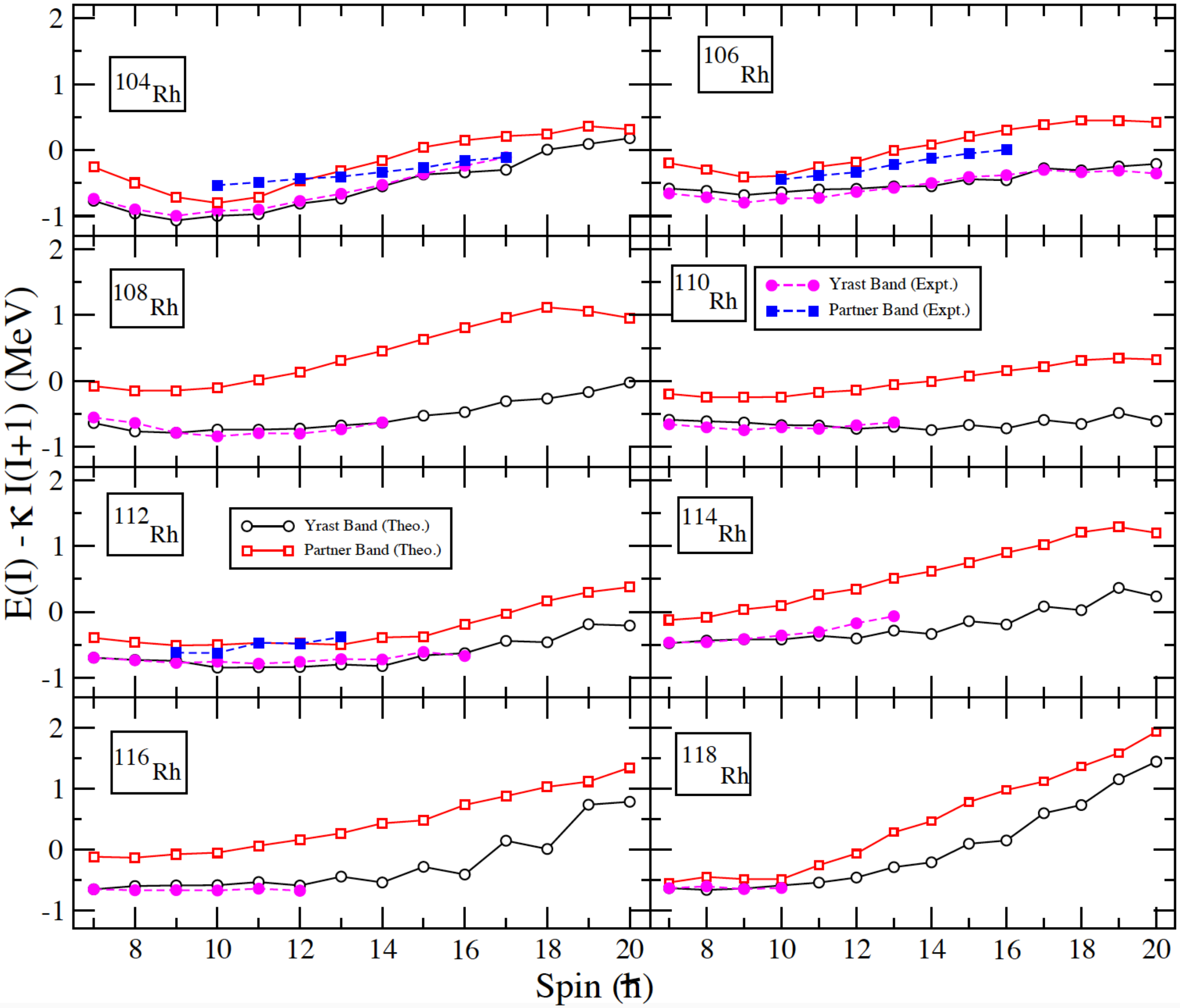
Degenerate bands in ^{106}Ag isotope are from different configuration contrary to ^{106}Rh isotopes.

NPA 933, 123 (2015).

Microscopic study of chiral rotation in odd-odd A ∼ 100 nuclei

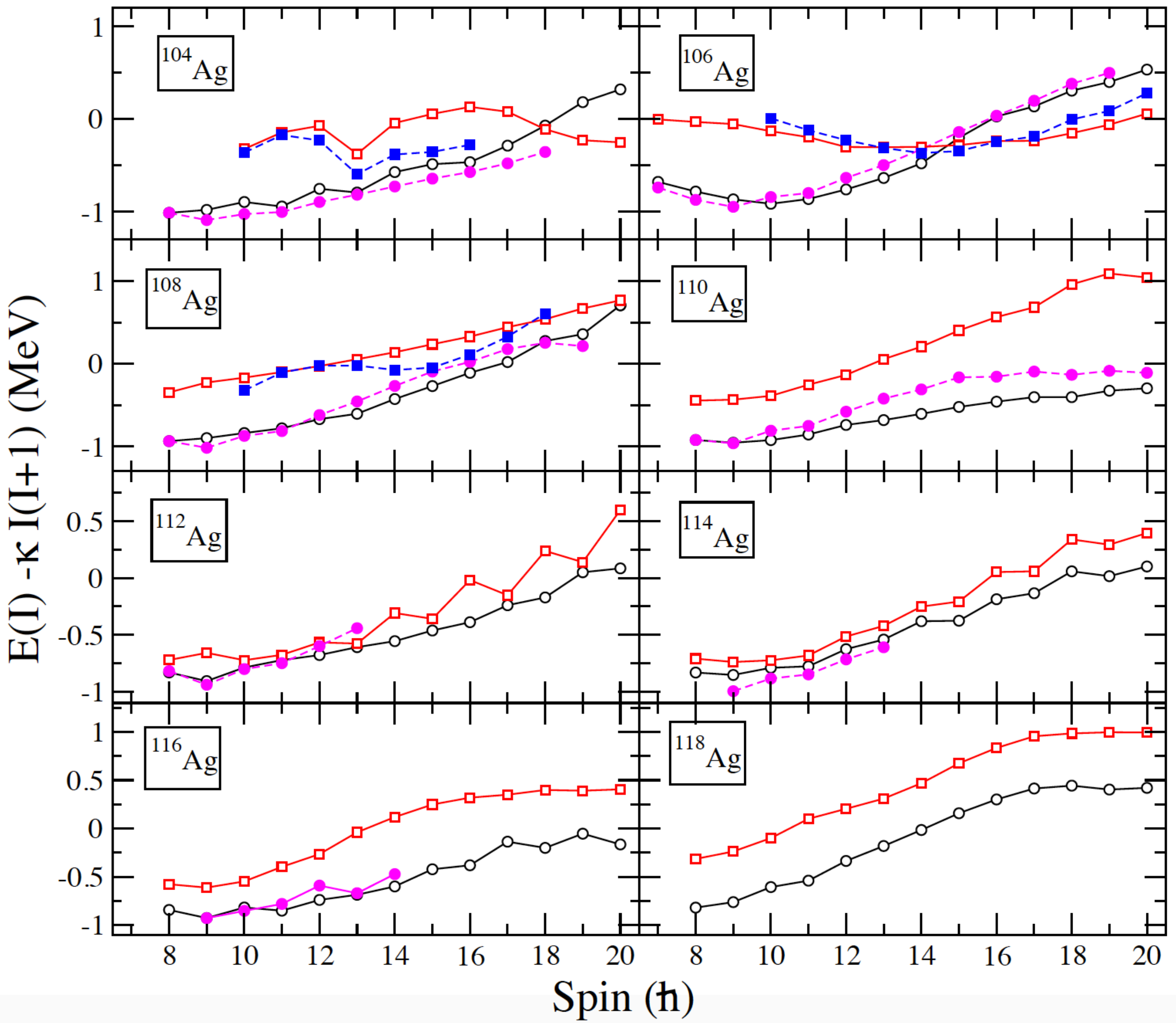
W.A. Dar[1], J.A. Sheikh[1,2], G.H. Bhat[1], R. Palit[3] and S. Frauendorf[4]

Structure and symmetries of odd-odd triaxial Rh isotopes

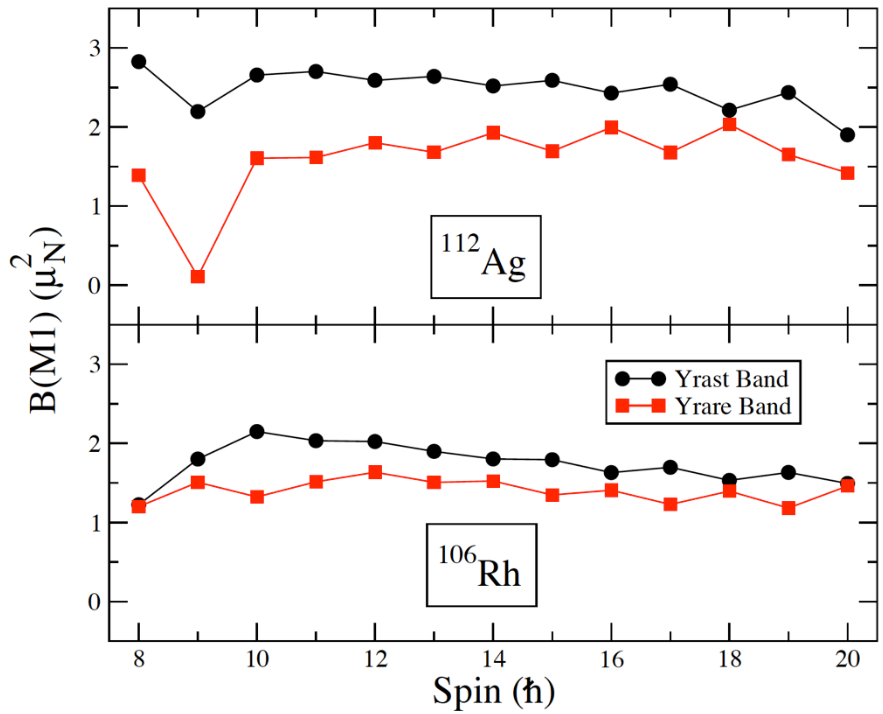


RP, GB, JS, Eur.Phys.J. A 53, 90 (2017)

Structure and symmetries of odd-odd Ag isotopes



Best candidates for chiral bands for odd-odd isotopes in A~110



^{104}Ag	^{106}Ag	^{108}Ag	^{110}Ag	^{112}Ag	^{114}Ag	^{116}Ag	^{118}Ag
^{102}Pd $\gamma=23^0$	^{104}Pd $\gamma=25^0$	^{106}Pd $\gamma=26^0$	^{108}Pd $\gamma=27^0$	^{110}Pd $\gamma=27^0$	^{112}Pd $\gamma=27^0$	^{114}Pd $\gamma=27^0$	^{116}Pd $\gamma=27^0$
^{104}Rh	^{106}Rh	^{108}Rh	^{110}Rh	^{112}Rh	^{114}Rh	^{116}Rh	^{118}Rh
^{102}Ru $\gamma=25^0$	^{104}Ru $\gamma=24^0$	^{106}Ru $\gamma=22^0$	^{108}Ru $\gamma=23^0$	^{110}Ru $\gamma=24^0$	^{112}Ru $\gamma=26^0$	^{114}Ru $\gamma=27^0$	^{116}Ru $\gamma=28^0$

^{106}Rh and ^{112}Ag are the best candidates for 2-qp chiral bands in this region for which more experimental efforts are required.

RP, GB, JS, Eur.Phys.J. A 53, 90 (2017)

Physics Letters B 782 (2018) 768–772

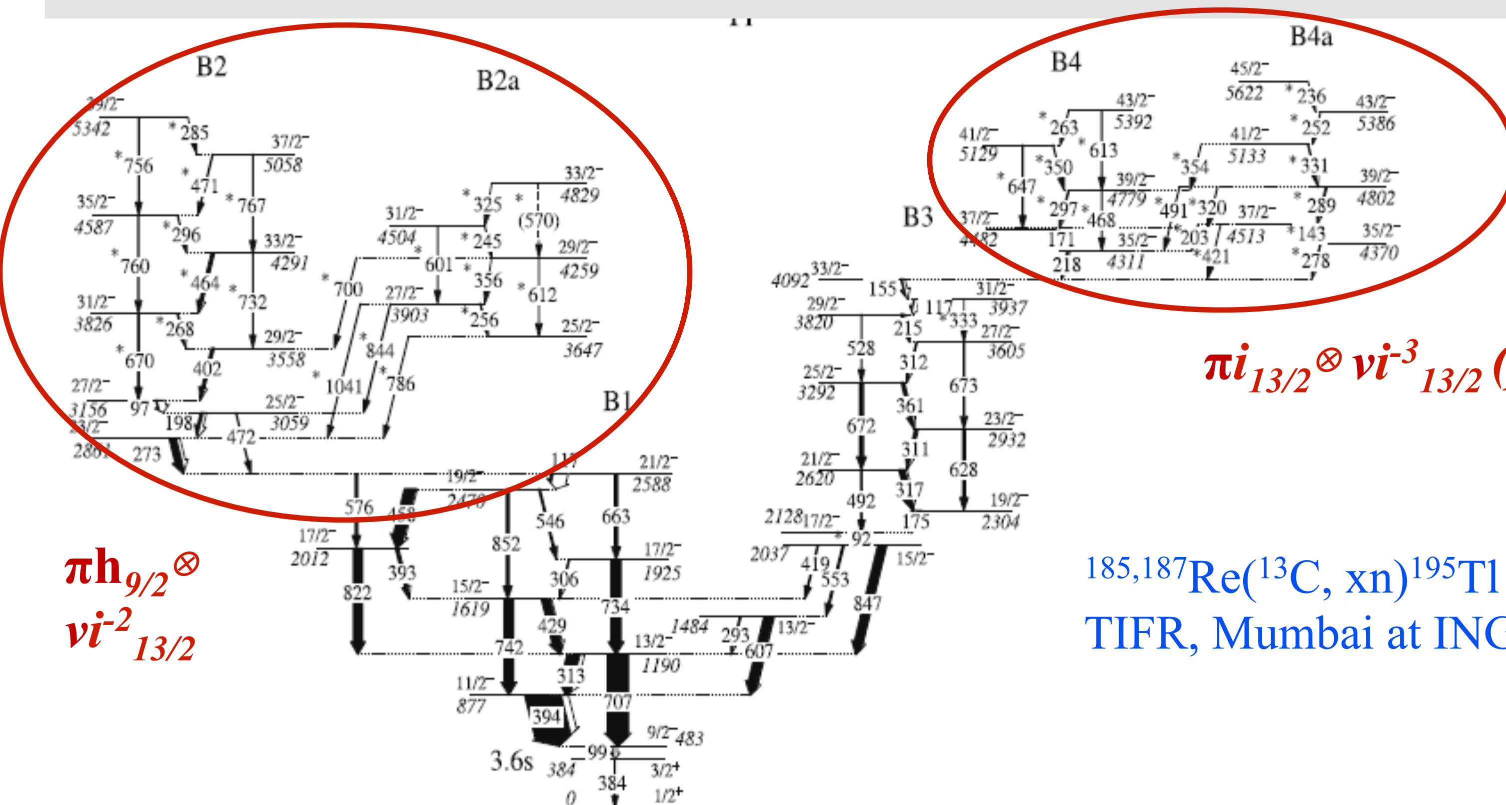
Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of multiple doubly degenerate bands in ^{195}Tl

T. Roy [a,b], G. Mukherjee [a,b,*], Md.A. Asgar [a,b], S. Bhattacharyya [a,b], Soumik Bhattacharya [a,b], C. Bhattacharya [a,b], S. Bhattacharya [a,1], T.K. Ghosh [a,b], K. Banerjee [a,b,c], Samir Kundu [a,b], T.K. Rana [a], P. Roy [a,b], R. Pandey [a,b], J. Meena [a], A. Dhal [a], R. Palit [d], S. Saha [d], J. Sethi [d], Shital Thakur [d], B.S. Naidu [d], S.V. Jadav [d], R. Dhonti [d], H. Pai [e], A. Goswami [e]



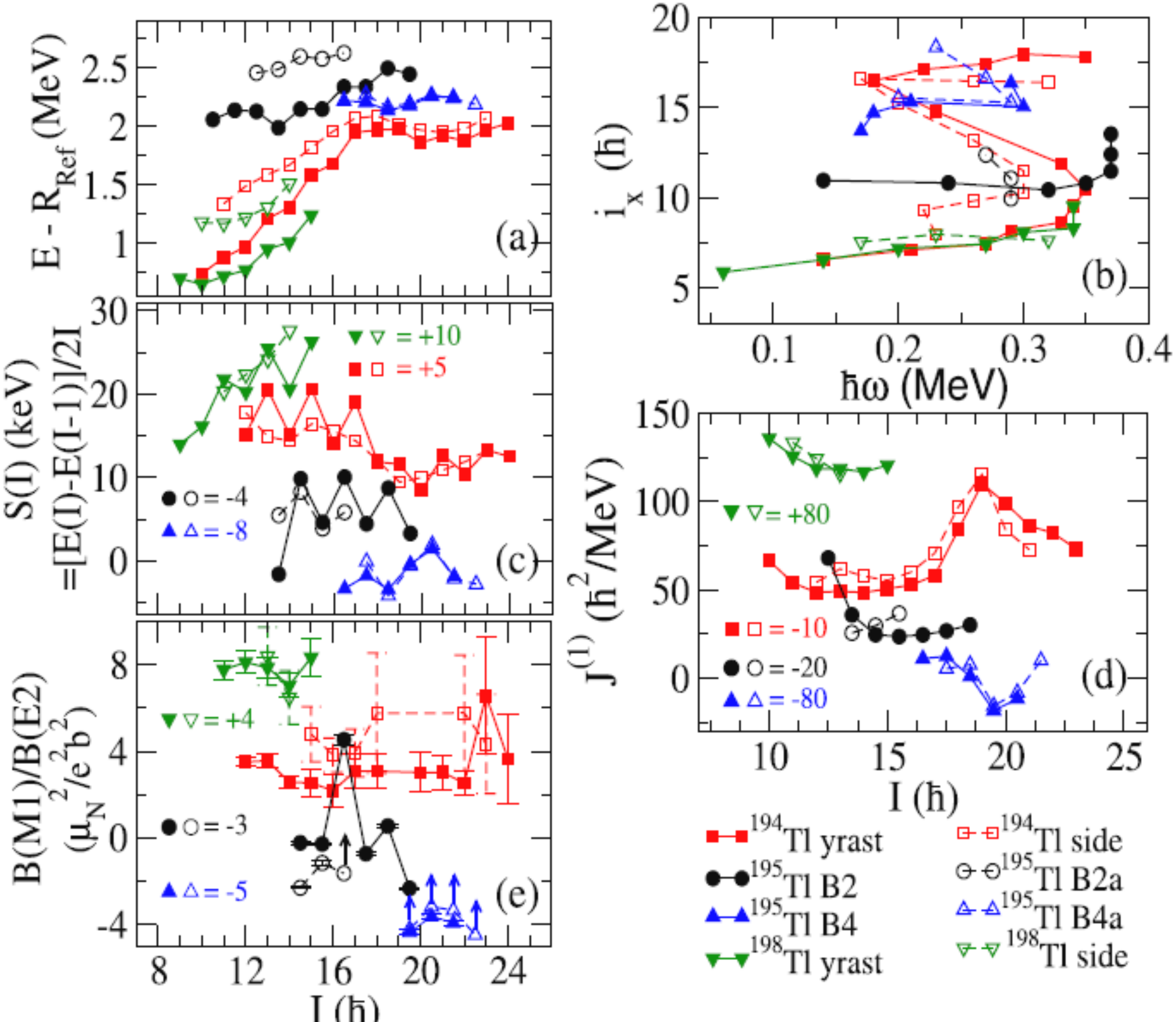
$\pi h_{9/2} \otimes \nu i^{-2}_{13/2}$

$\pi i_{13/2} \otimes \nu i^{-3}_{13/2} (p_{3/2} f_{5/2})^{-1}$

^{185,187}Re(^{13}C, xn)^{195}Tl @ 75 MeV

TIFR, Mumbai at INGA with 15 Clovers

Comparison of the Bands B2-B2a and B4-B4a with other Chiral partner bands

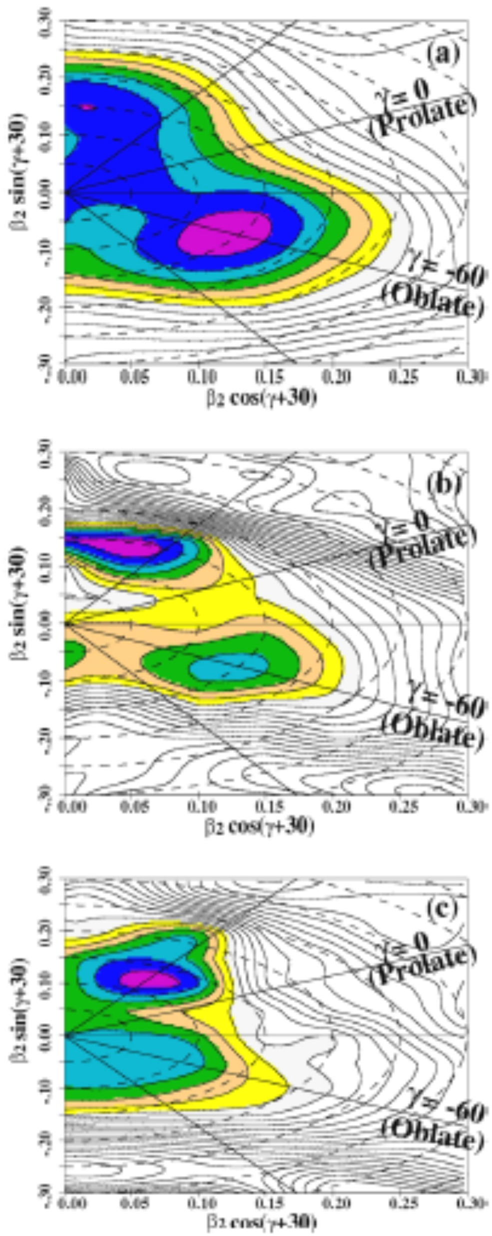


- **First observation of MχD in A = 190 region.**
- **First observation of doublet bands with configuration involving as large as 5 quasiparticles.**
- **ΔE_{av} ~25 keV (Δe_{max} = 59 keV) for B4-B4a represents one of the best degenerate bands.**

T. Roy et al., PLB 782 (2018) 768.

M.L. Masiteng, et al., PLB 719 (2013) 83; E.A. Lawrie, et al., PRC 78 (2008) 021305(R).

Total Routhian Surface (TRS) Calculations: Shape of ^{195}Tl For different configuration

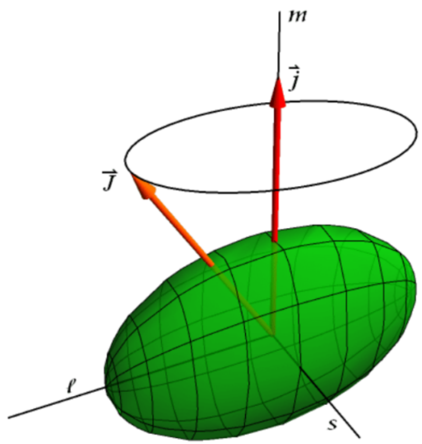


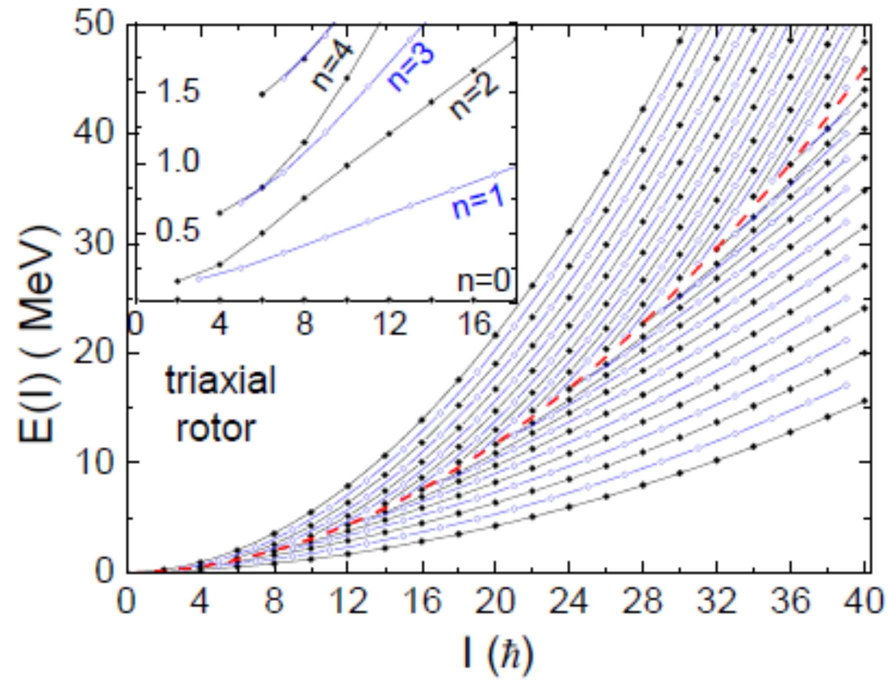
The Oblate shape for 1-qp configuration changes to a triaxial shape with $\gamma \sim +39^{o}$ for 3-qp configuration.

More number of neutrons in $i_{13/2}$ orbital gives stable triaxiality.

T. Roy et al., Phys. Lett. B 782 (2018) 768

Wobbling mode in odd-A triaxial nuclei





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

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

- Induces a sequences of rotational bands.
- Inter-band transitions are ΔI=1 E2 in nature

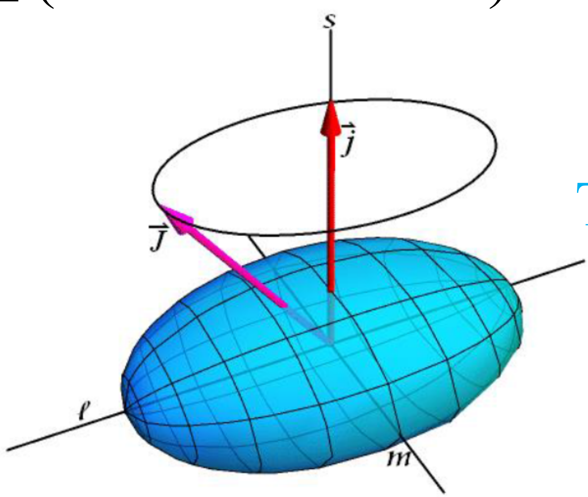
Frauendorf, Doenau, PRC 89, 014322 (2014)

Transverse and longitudinal wobbling

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

$$\boldsymbol{E_{wobb} = E\,(I,\, n_T{=}1) - \tfrac{1}{2}\,[E\,(I{+}1,\, n_T{=}0) + E\,(I{-}1,\, n_T{=}0)]}$$

j ⊥ (Max. M.I m-axis)



Transverse

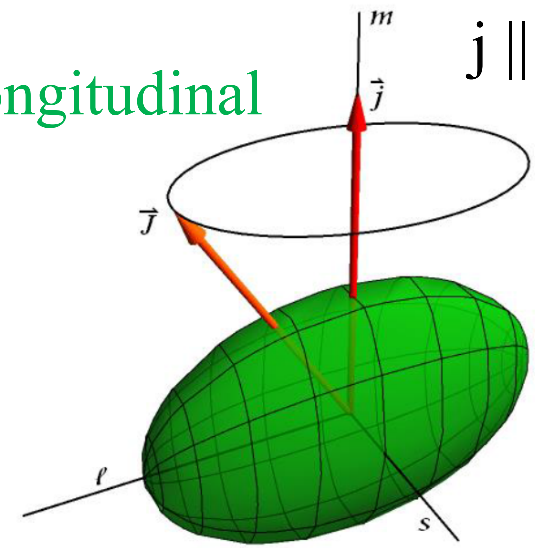
$\mathfrak{I}_3 < \mathfrak{I}_2$; $\mathfrak{I}_3 > \mathfrak{I}_1$

→ E_ω decreases with J

reaching 0 at $J_c = j\,\mathfrak{I}_2/(\mathfrak{I}_2 - \mathfrak{I}_3)$

Longitudinal

j ∥ m-axis



$\mathfrak{I}_3 > \mathfrak{I}_2$; $\mathfrak{I}_3 > \mathfrak{I}_1$

→ E_ω increases with J

Courtesy: J. Matta, U. Garg

PRL 114, 082501 (2015) PHYSICAL REVIEW LETTERS week ending 27 FEBRUARY 2015

Transverse Wobbling in ^{135}Pr

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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. Sihotra[4]

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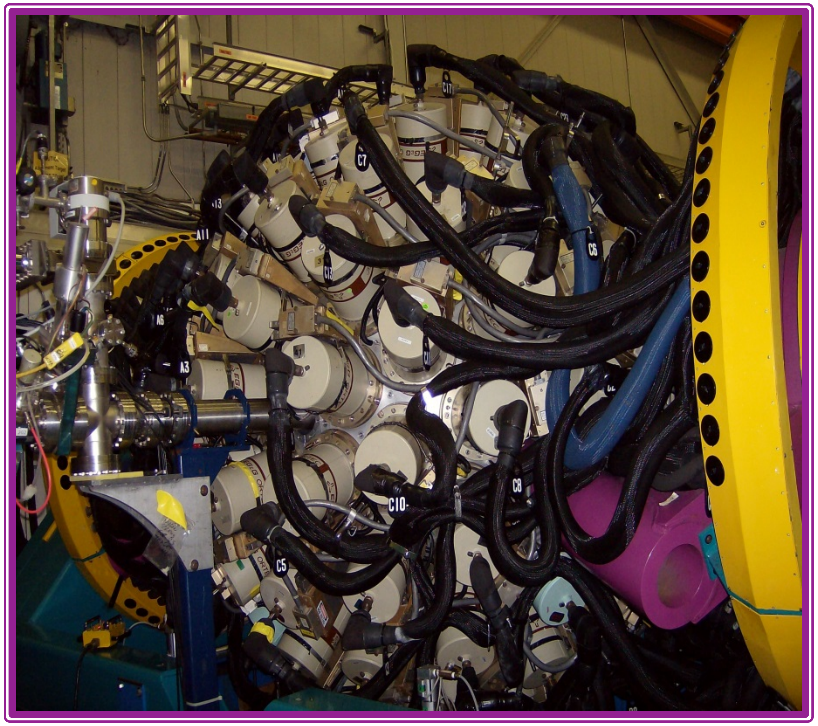
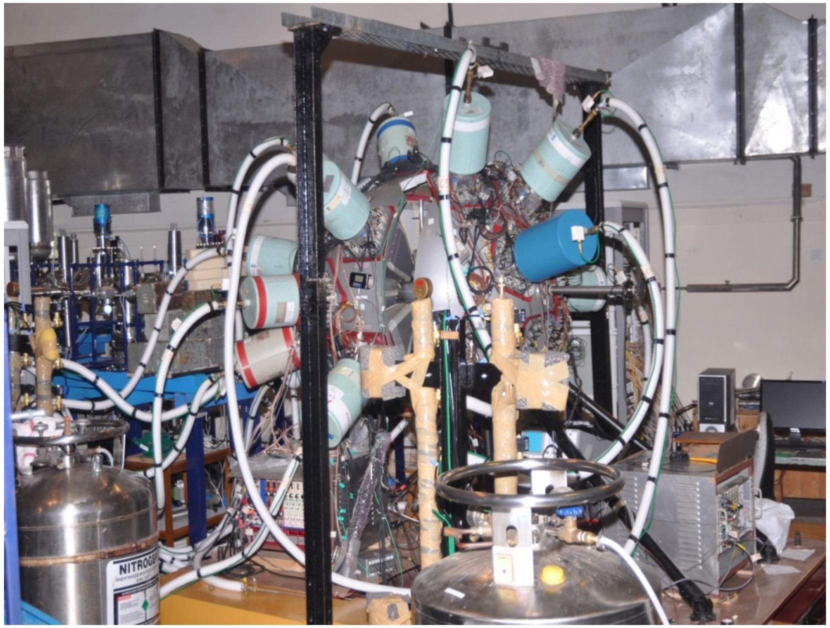
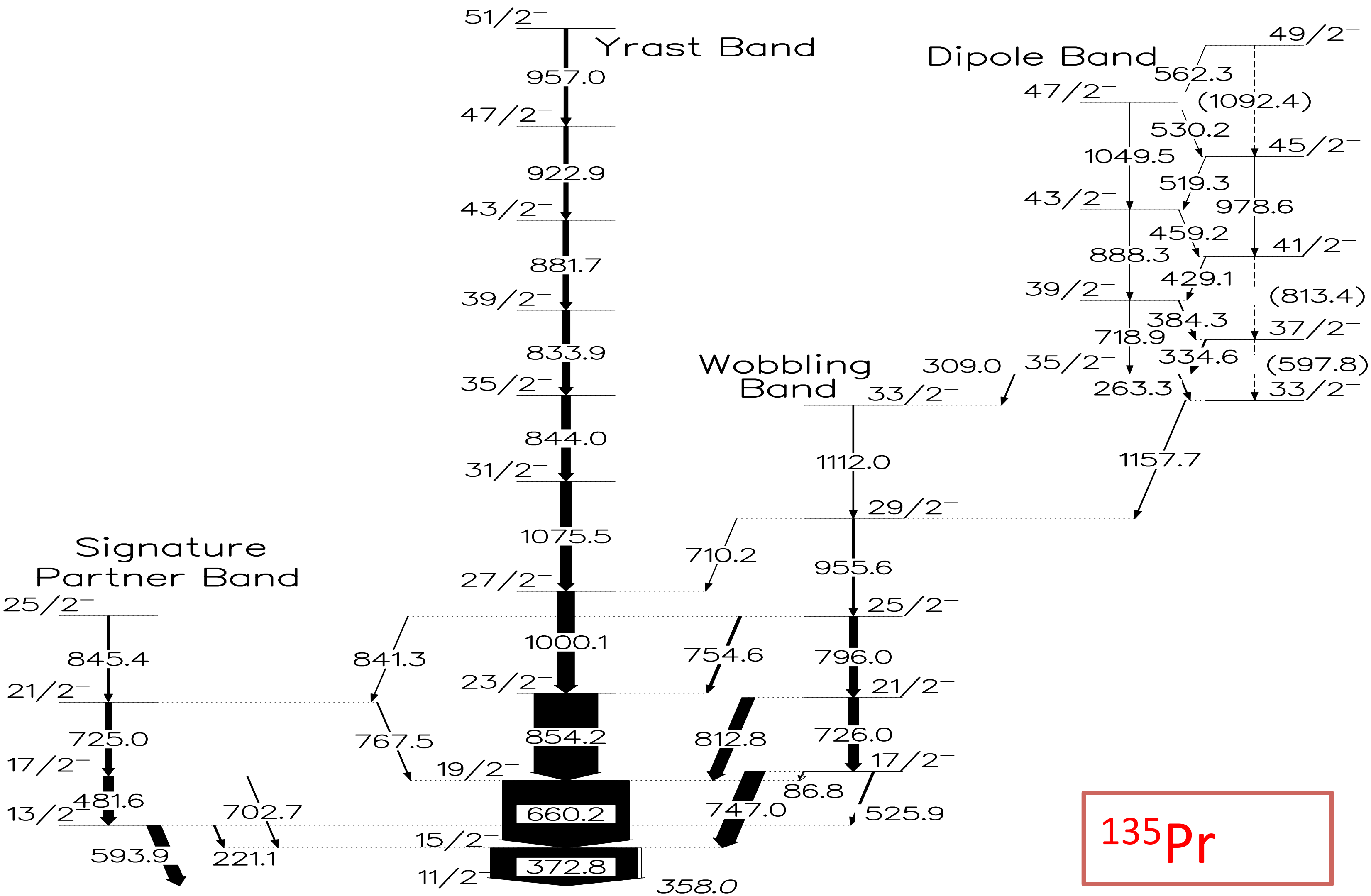
arXiv:1608.07840





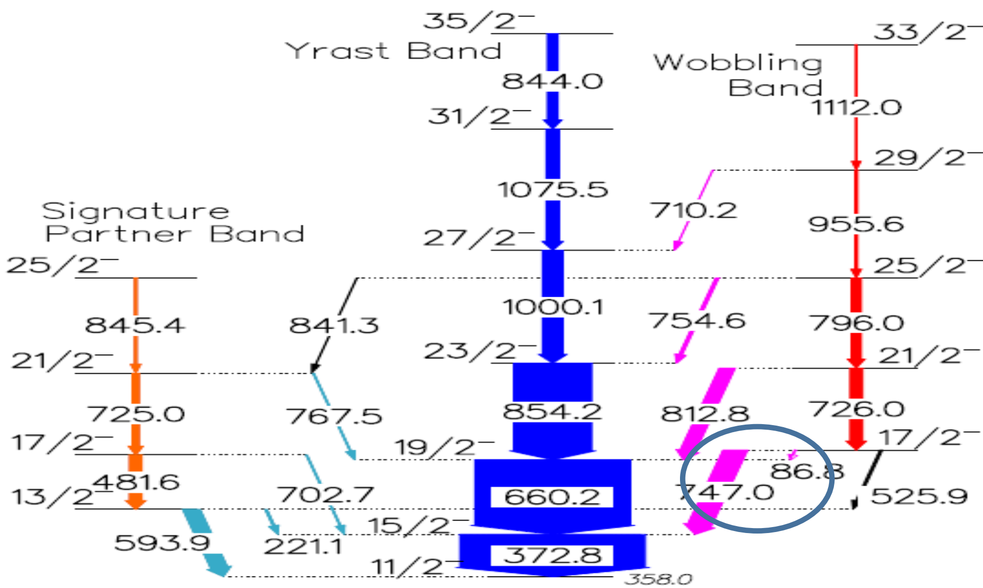
^{123}Sb (^{16}O, 4n)^{135}Pr @ 80 MeV
Gammasphere at ATLAS
(100 CSGe detectors)
γ−γ−γ coincidences
angular correlations

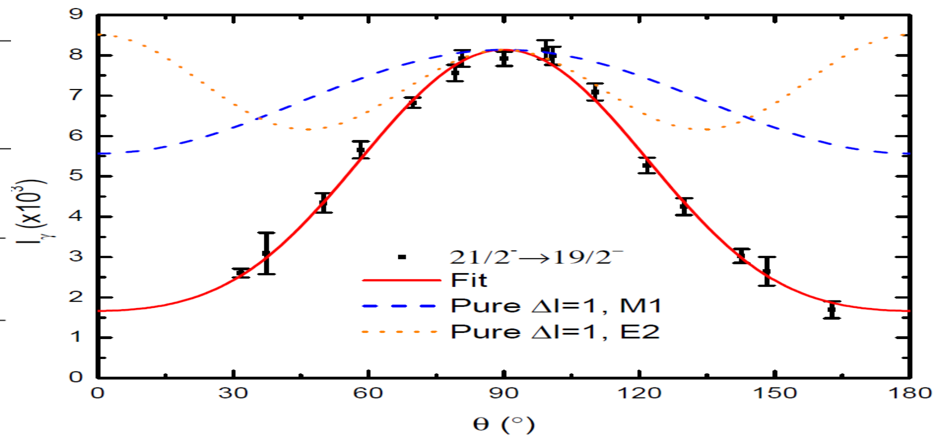
INGA @ TIFR
20 CS “clover” detectors
polarization measurements

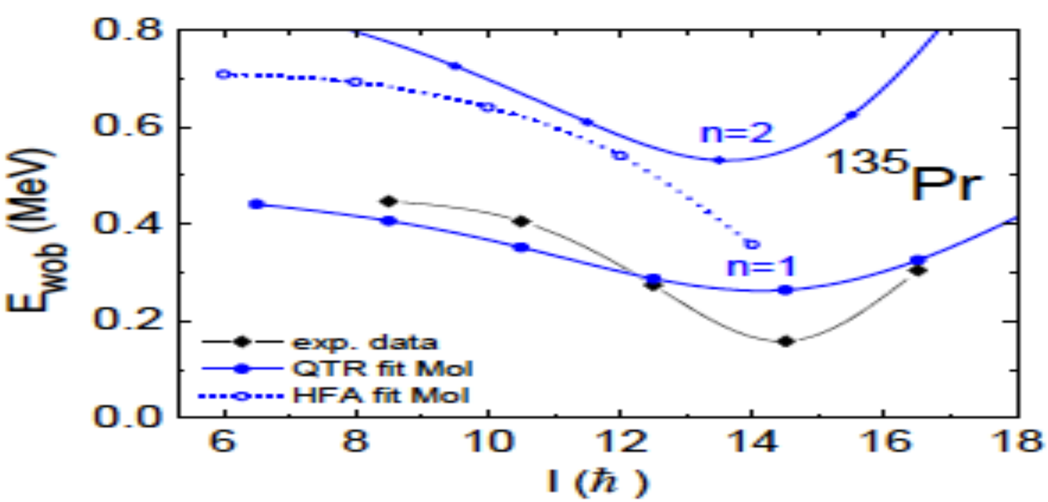


^{135}Pr

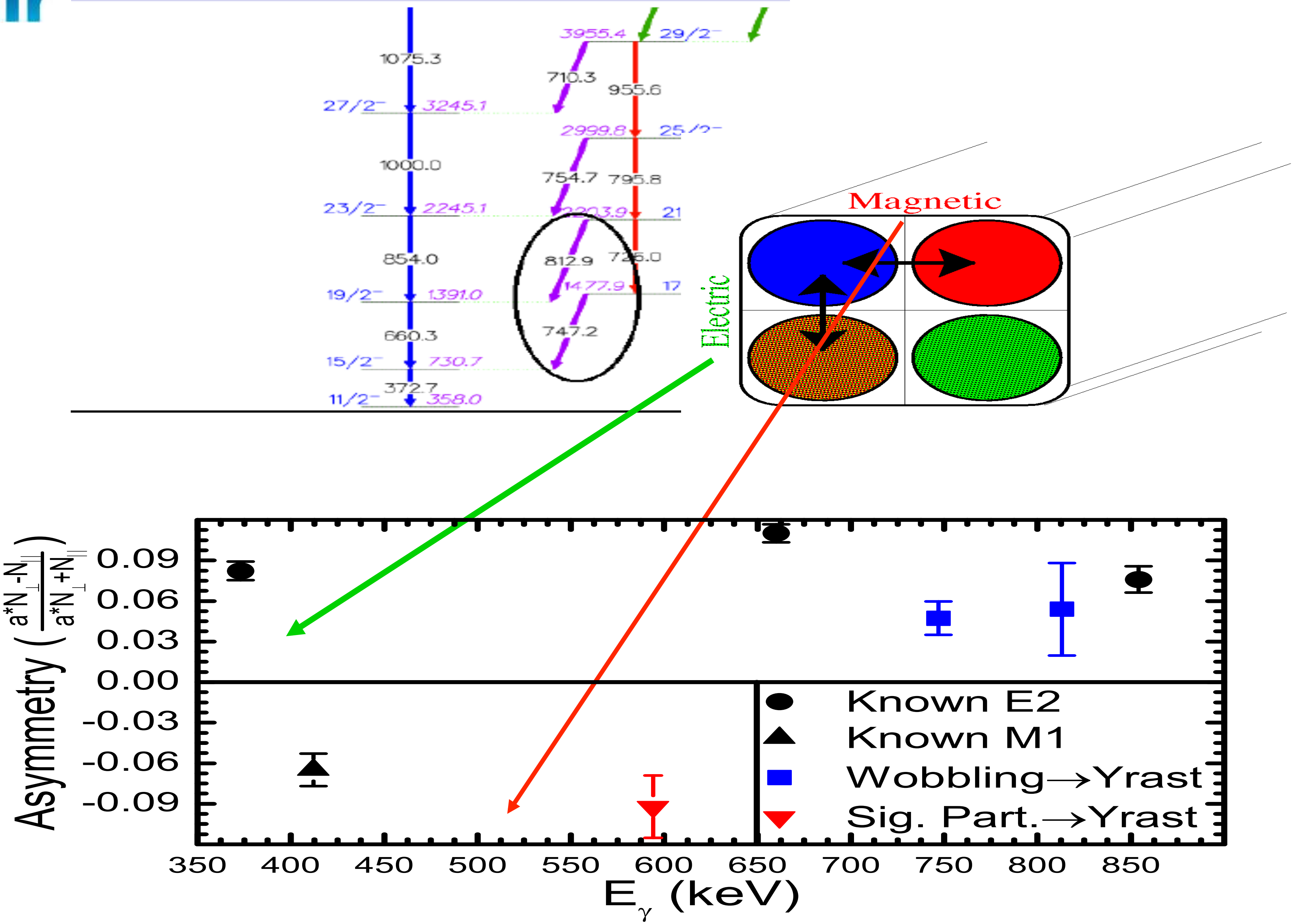
J. T. Matta *et al.*, Phys. Rev. Lett. 114, 082501 (2015)


35/2−
Yrast Band
844.0
31/2−
1075.5
27/2−
1000.1
23/2−
854.2
19/2−
660.2
15/2−
372.8
11/2−
358.0
Wobbling Band
33/2−
1112.0
29/2−
955.6
25/2−
796.0
21/2−
726.0
17/2−
525.9
86.8
747.0
812.8
754.6
710.2
Signature Partner Band
25/2−
845.4
21/2−
725.0
17/2−
481.6
13/2−
593.9
841.3
767.5
702.7
221.1


21/2−→19/2−
Fit
Pure ΔI=1, M1
Pure ΔI=1, E2
Iγ (x10³)
θ (°)


n=2
n=1
135Pr
exp. data
QTR fit MoI
HFA fit MoI
Ewob (MeV)
I (ℏ)

Polarization Asymmetries



Experiments undertaken:

Fusion-evaporation reaction at TIFR using INGA:

Beam: ^{11}B (55 MeV)
Target: ^{124}Sn (10.4 mg/cm^2) (self-supporting)
No. of detectors: 19 HPGe clover detectors
Two- and higher-fold events: 2×10^8

$\boxed{^{131}Cs}$

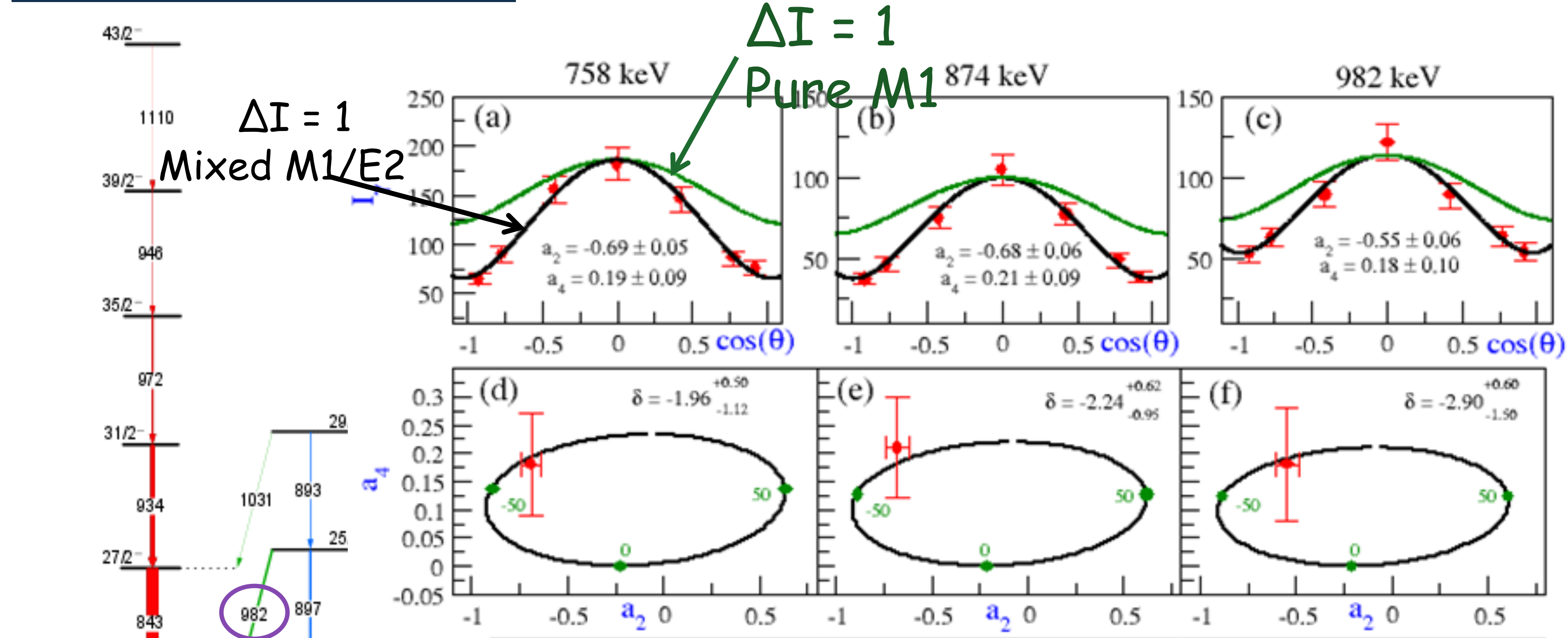
Beam: ^{11}B (52 MeV)
Target: ^{126}Te (1.1 mg/cm^2) (Au : 9.9 mg/cm^2)
No. of detectors: 21 HPGe clover detectors
Two- and higher-fold events: 3×10^8

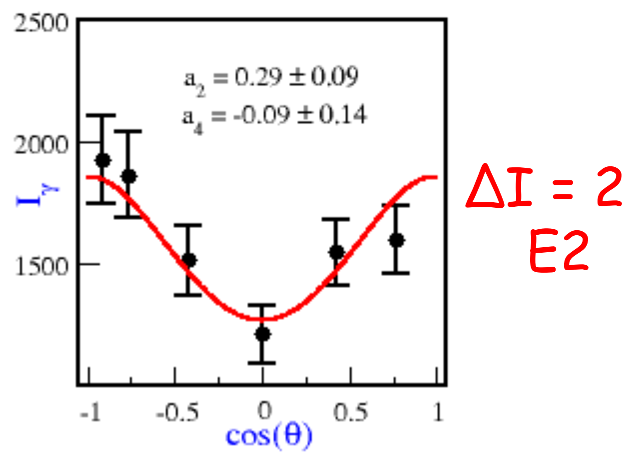
$\boxed{^{133}La}$

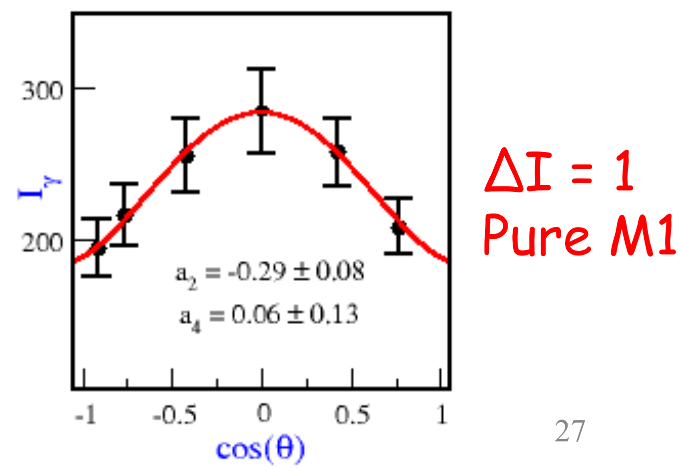
Techniques used: (i) Level scheme -> Coincidence analysis
(ii) Spin of state -> DCO-Ratio
(iii) Parity of state -> Polarization of γ-rays
(iv) Spin and parity -> Angular Distribution

Spin & Parity ^{133}La:

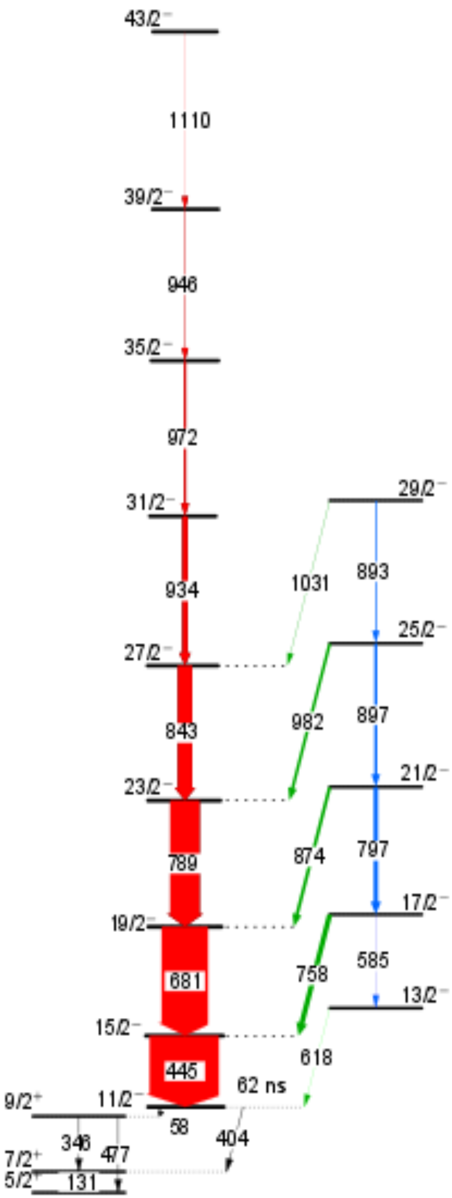
2) Angular Distribution

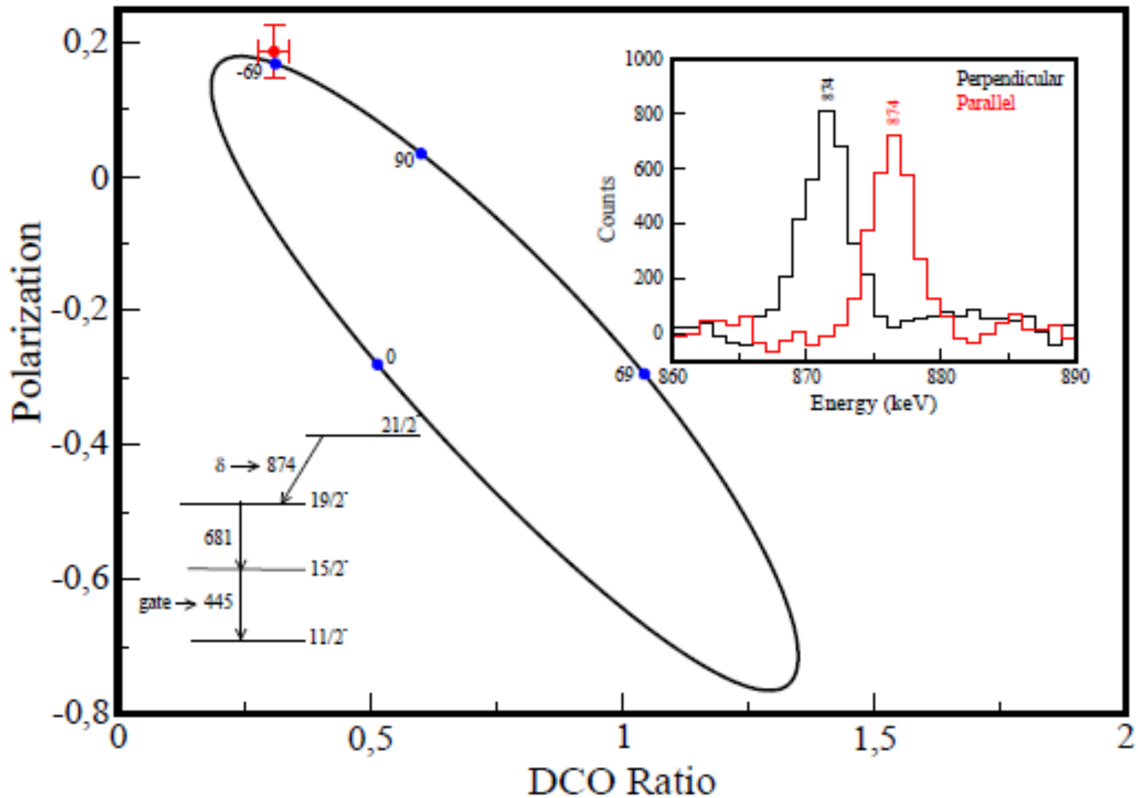






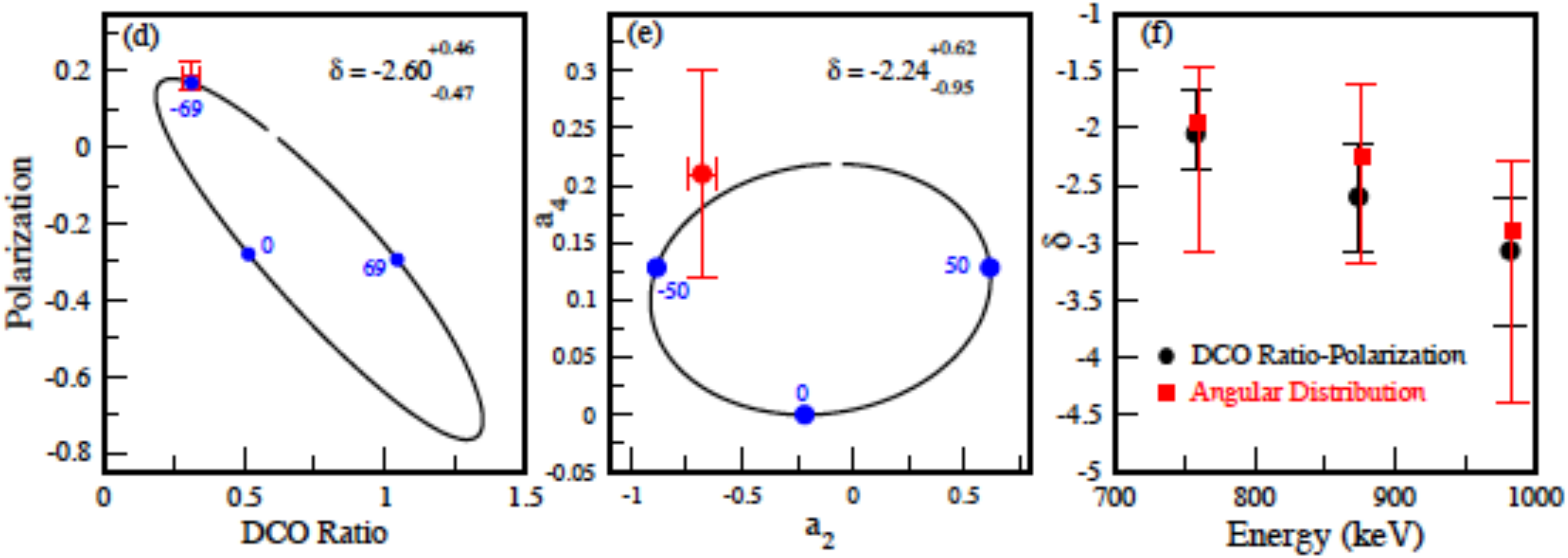
Search for wobbling mode in ^{133}La at low spin





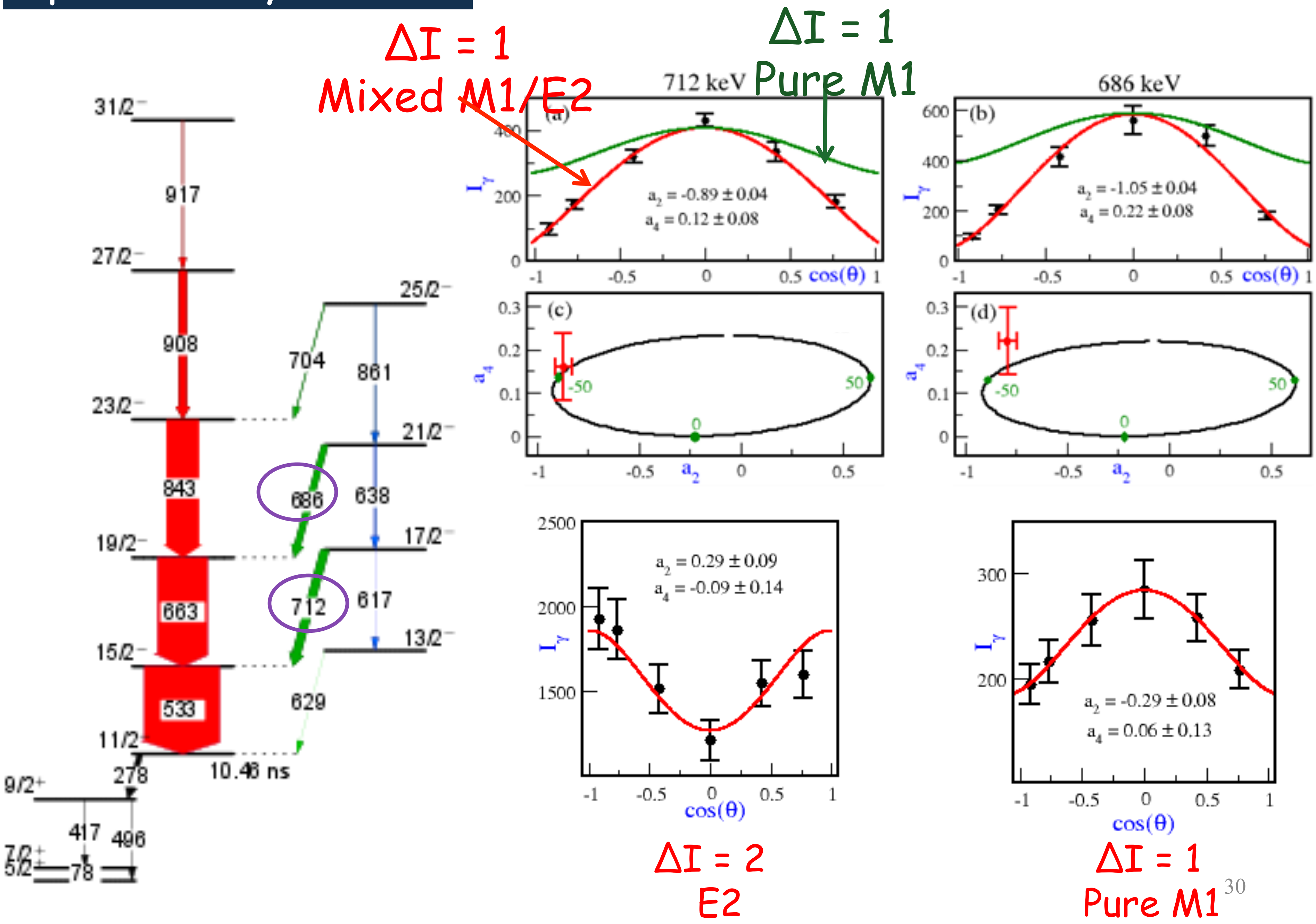
S. Biswas, et al.,

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



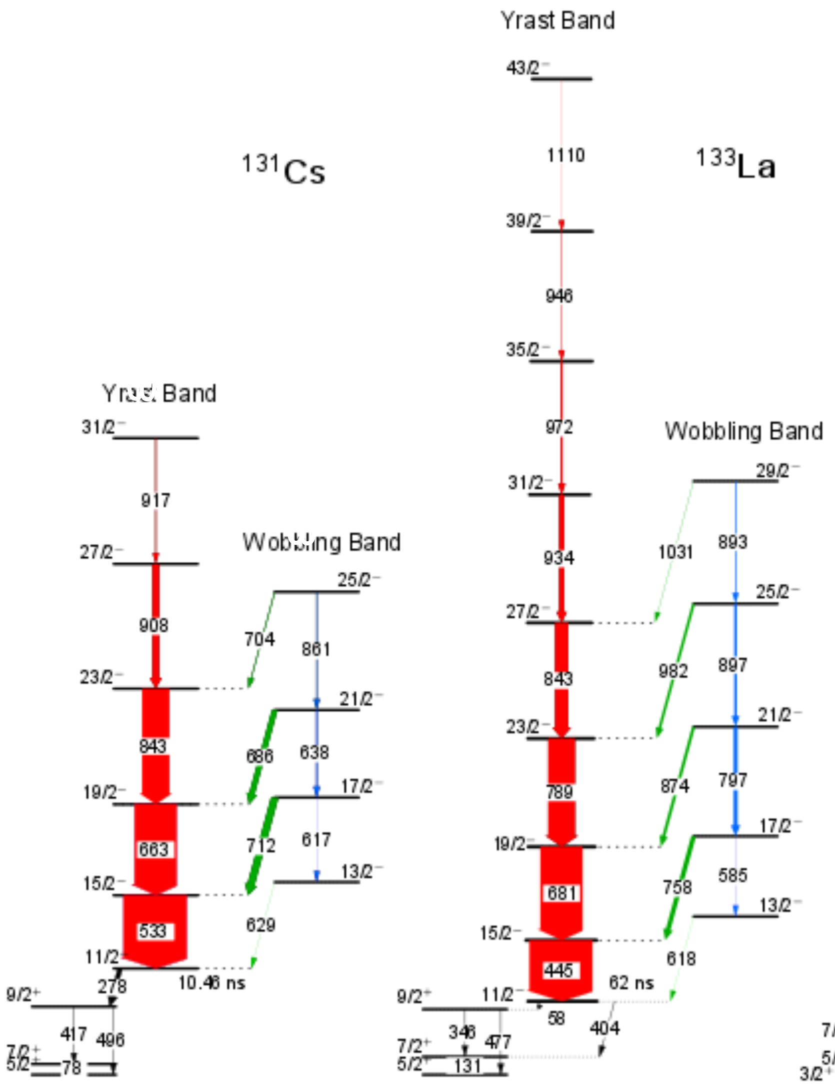
Spin & Parity in ^{131}Cs:

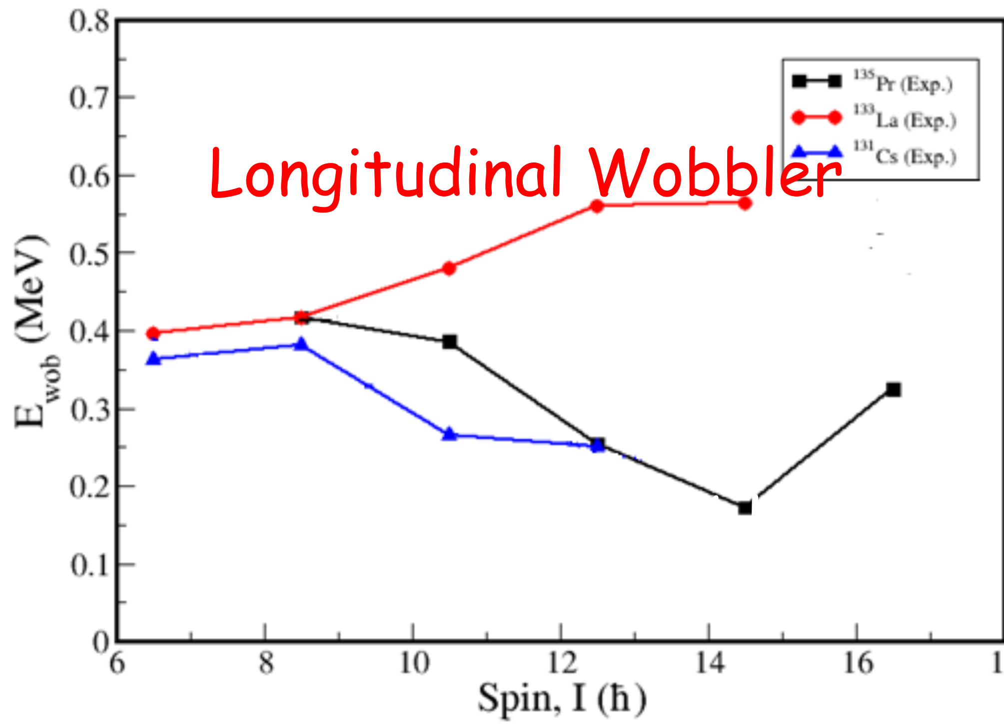
Angular Distribution

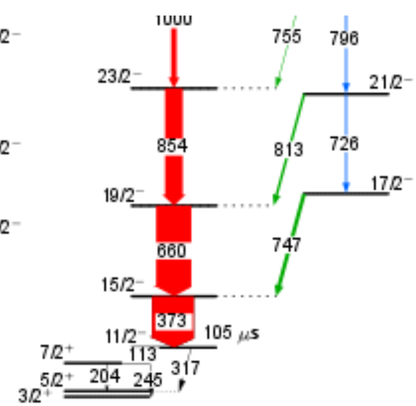


Wobbling Energy for N = 76 isotones:

$$E_{wob} = E(I, n_\omega = 1) - \frac{E(I-1, n_\omega = 0) + E(I+1, n_\omega = 0)}{2}$$



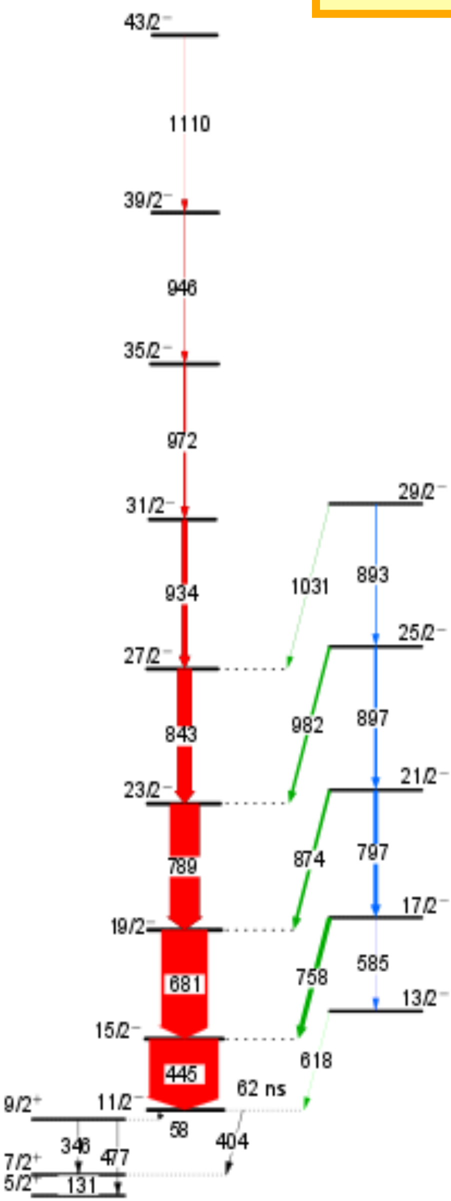


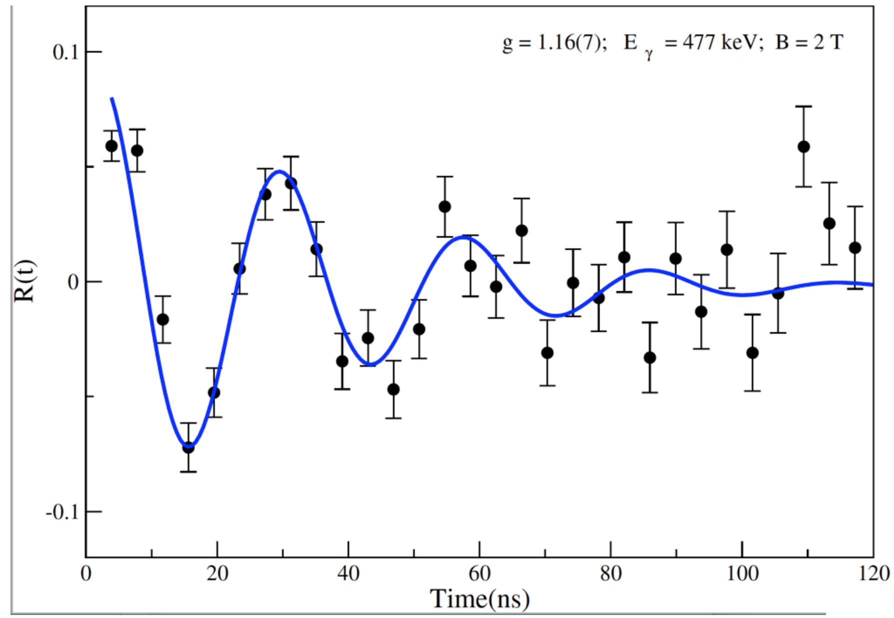


J. T. Matta et al., Phys. Rev. Lett., 114, 082501 (2015)

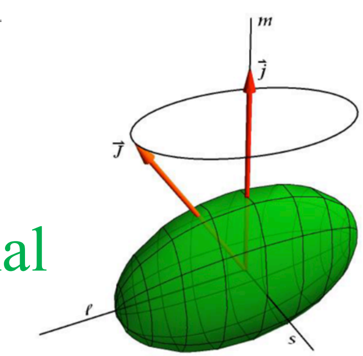
S. Biswas et al. arXiv:1608.07840 [nucl-ex]

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





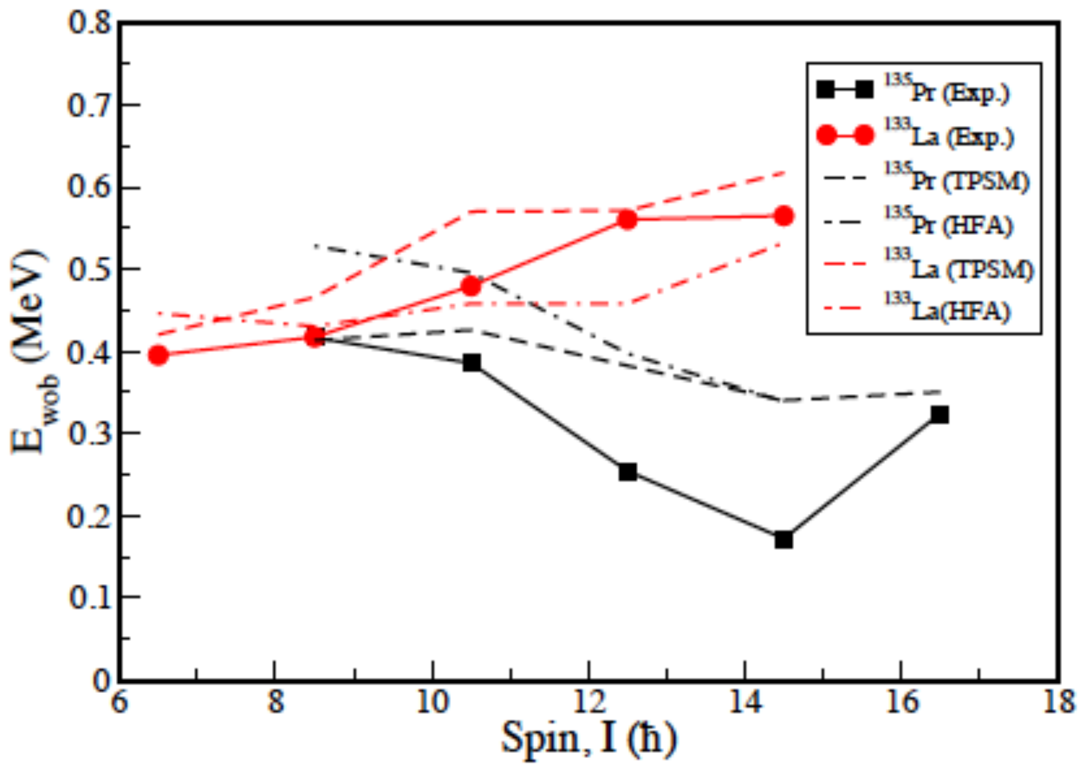
j || m-axis



Longitudinal

Md. S.R. Laskar, R. Palit, S.N. Mishra, et al

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



TPSM: 133La, 135Pr

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

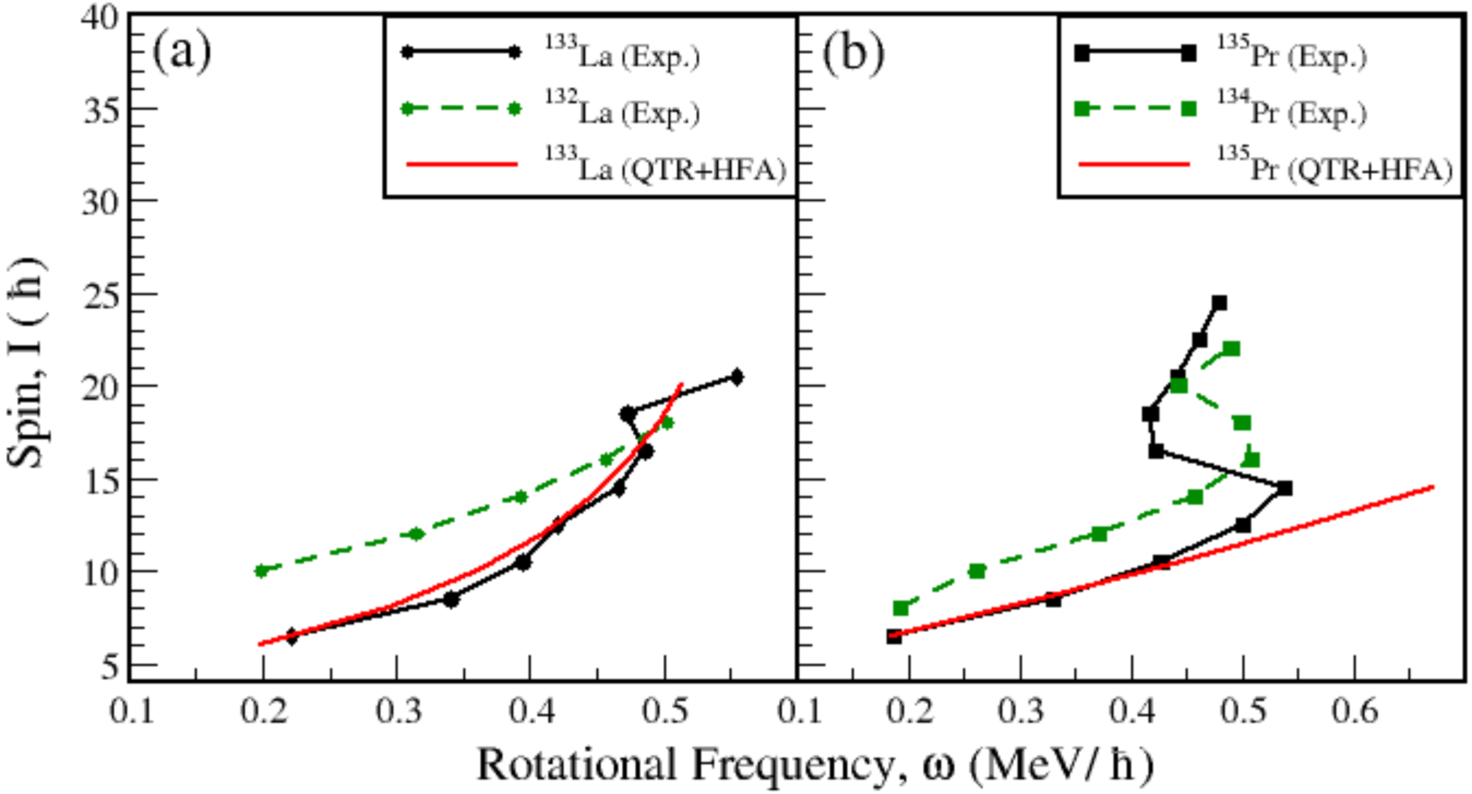
QTR+HFA

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

135Pr: 21/15.4/4

133La: 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

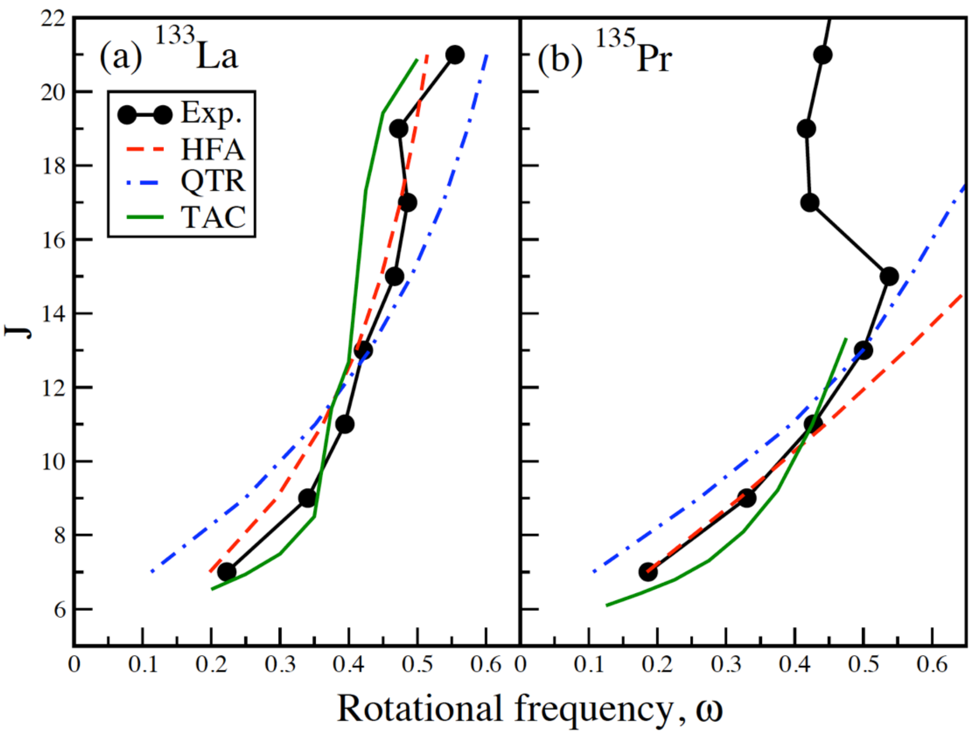
Spin dependent M.I. for short axis in QTR+HFA

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

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

Difference in neutron/proton alignment causing the transition

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



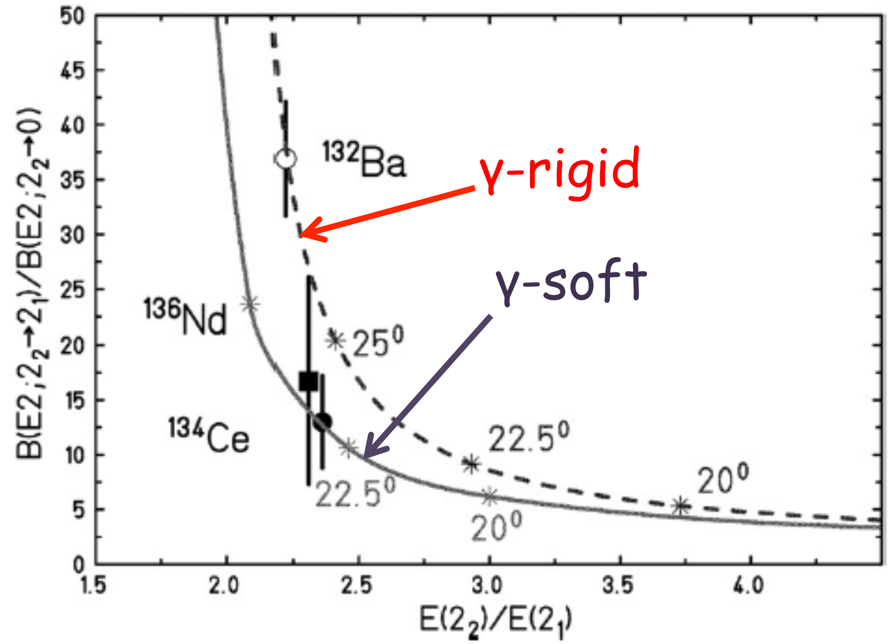
S. Frauendorf

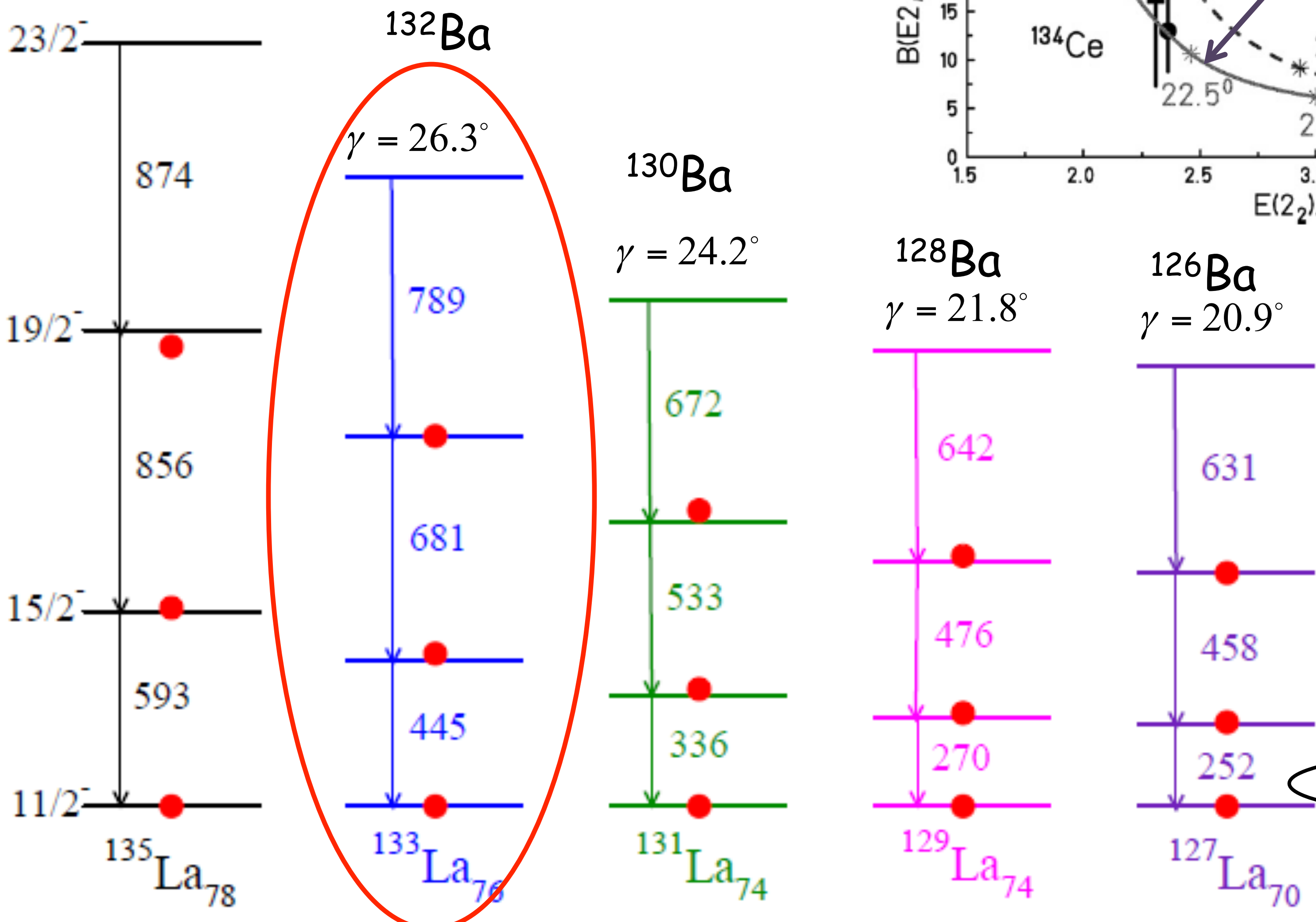
^{135}Pr:
$h_{11/2}$ proton along short axis
Core rotation along m-axis causing TW; neutron alignment causes LW
^{133}La:
Early alignment of additional pair of $h_{11/2}$ protons along the short axis which increases the Effective MoI along the short axis; Causing LW

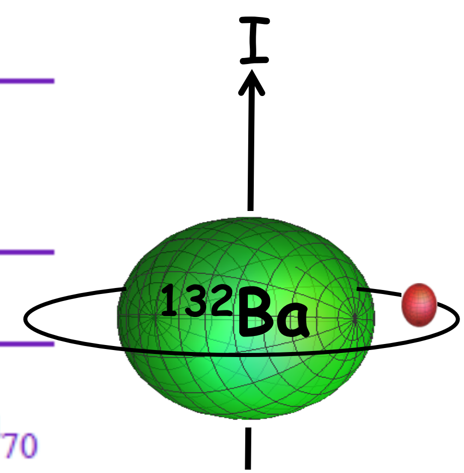
Spin dependent M.I. for short axis in QTR+HFA
^{135}Pr: MoI of shorter axis is smaller than medium axis
^{133}La: MoI of shorter axis is similar to medium axis

Angular momentum coupling in ^{133}La (from systematic):

T. R. Saito et al., Phys. Lett. B, 669, 19 (2008)







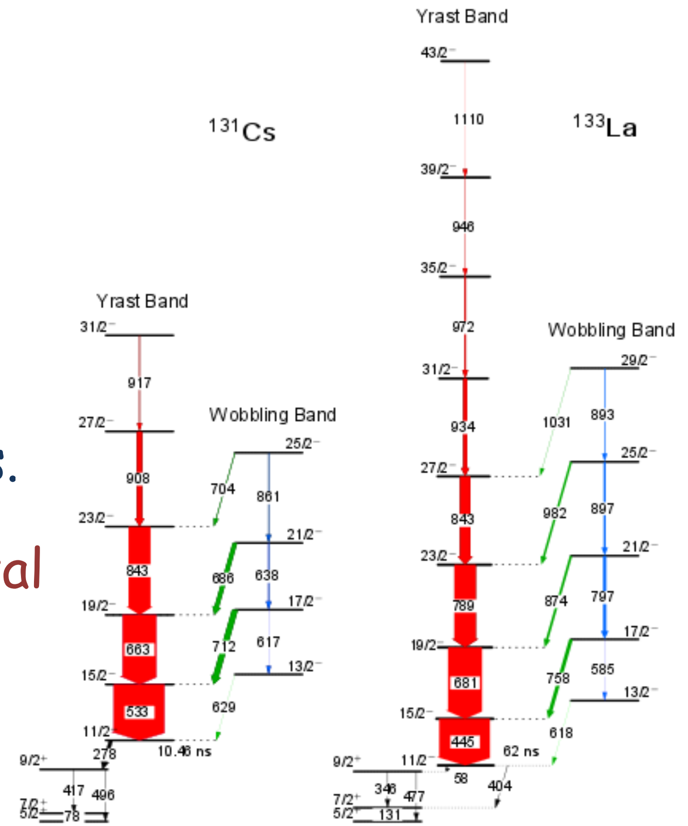
Summary :

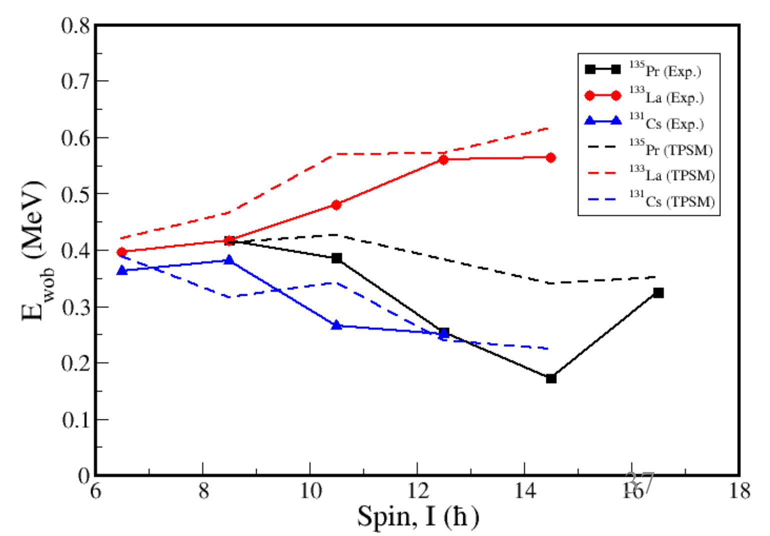
1) Electromagnetic properties of the interband transitions
   -> ΔI = 1, E2 (angular distribution and DCO-polarization measurements)
   -> confirming the presence of wobbling bands.

2) ^{133}La: Longitudinal Wobbling (first experimental observation)
   ^{131}Cs and ^{135}Pr: Transverse Wobbling

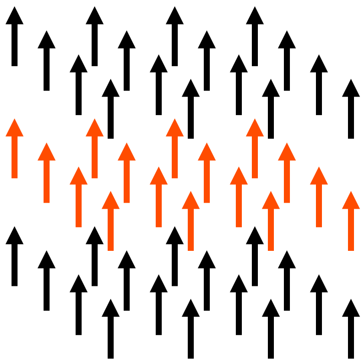
3) Evolution of the wobbling behavior
   -> explained from systematics
   -> explained using TPSM calculation

4) Coulex of the isomeric beams at RIBs



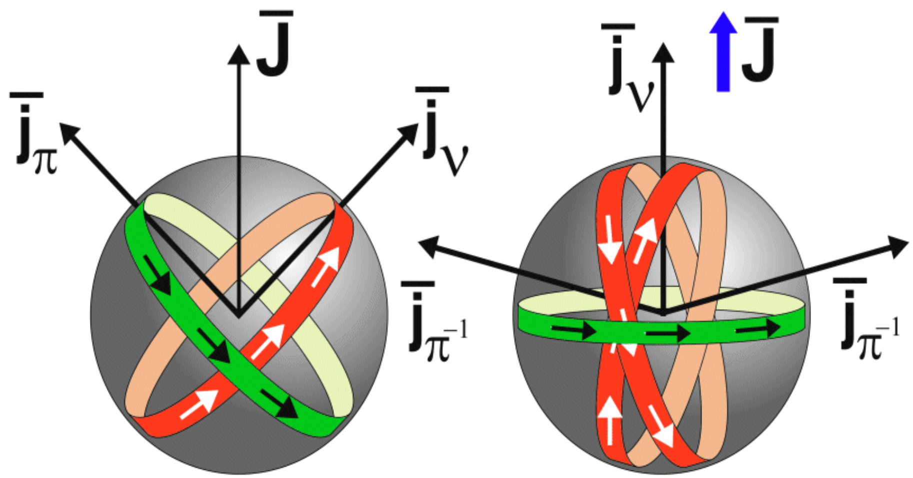


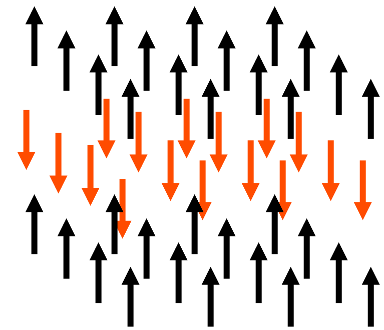
Magnetic & Antimagnetic Rotation



Ferromagnet

Magnetic rotor





Anti-Ferromagnet

Antimagnetic rotor

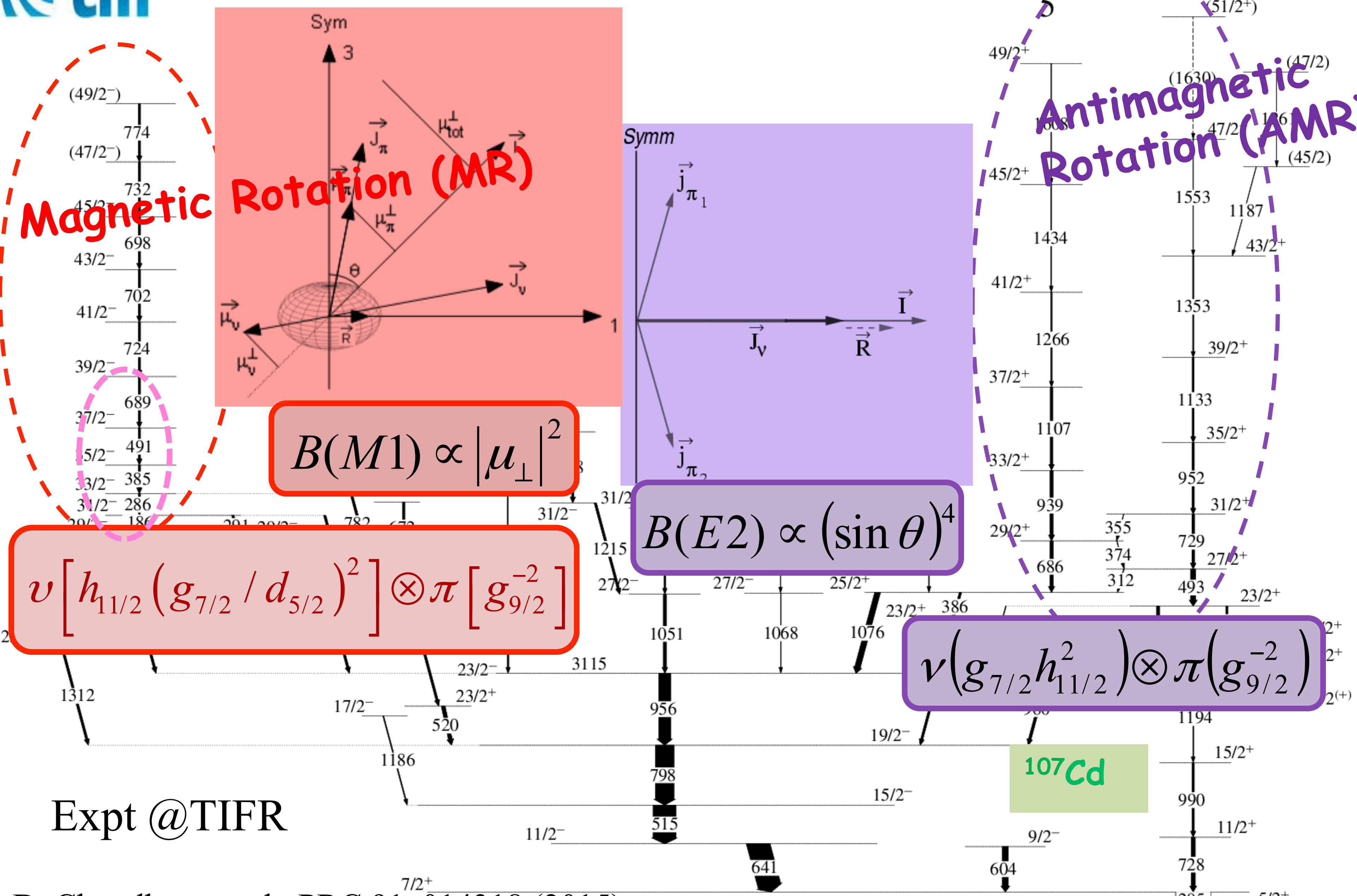
- ➢Rotational bands with $\Delta I = 1$
- ➢Strong M1
- ➢B(M1) decreasing with freq

- ➢Rotational bands with $\Delta I=2$
- ➢No M1
- ➢B(E2) decreasing with spin

S. Frauendorf Rev. Mod Phys 73, 463(2001)
R. M. Clark and A. O. Macchiavelli, Annu. Rev. NP Sci., 2000, 50(1)

Unlike MR, AMR: a rare phenomenon.

Coexistence of MR and AMR



$$B(M1) \propto \left|\mu_{\perp}\right|^2$$

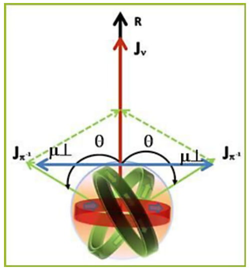
$$B(E2) \propto (\sin\theta)^4$$

$$\upsilon\left[h_{11/2}\left(g_{7/2}/d_{5/2}\right)^2\right] \otimes \pi\left[g_{9/2}^{-2}\right]$$

$$\nu\left(g_{7/2}h_{11/2}^2\right) \otimes \pi\left(g_{9/2}^{-2}\right)$$

Expt @TIFR

D. Choudhury et al., PRC 91, 014318 (2015)



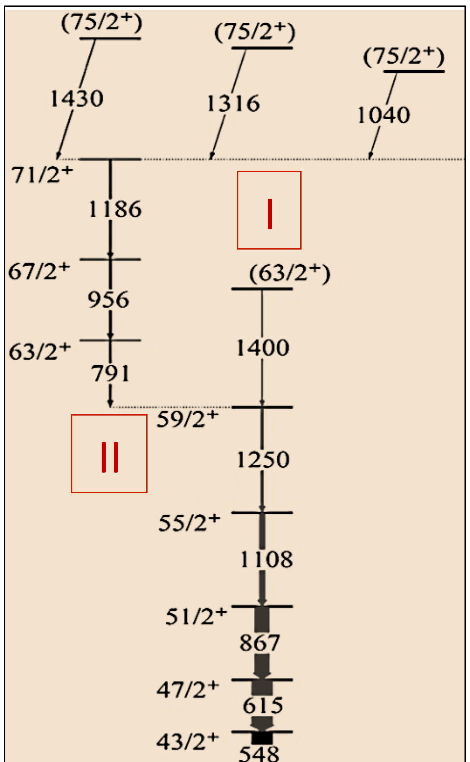
Antimagnetic rotation
and sudden change of electric quadrupole transition strength in ^{143}Eu

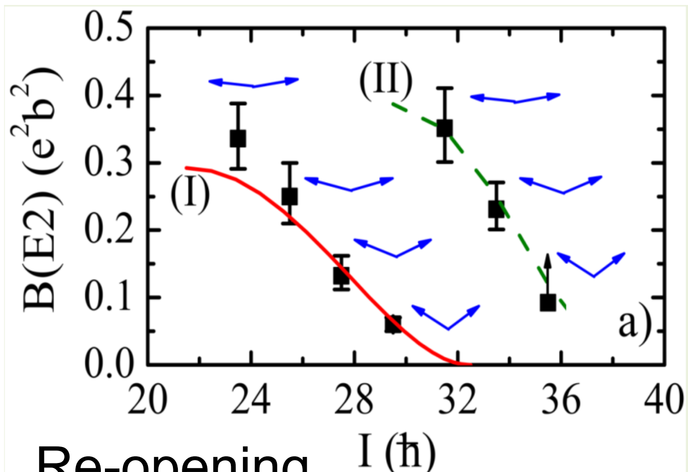
SR et al., PLB 748, 387 (2015); SR et al., PRC 96, 021304R (2017)

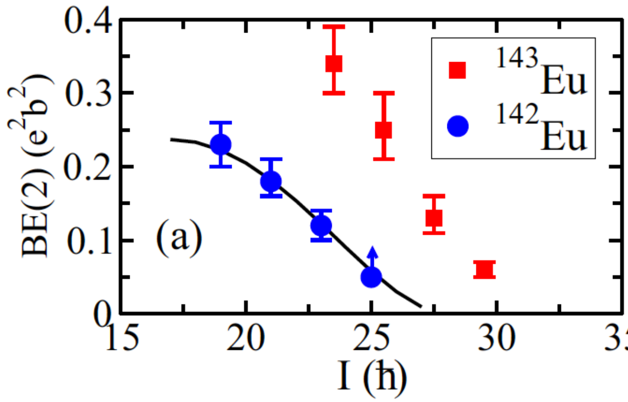
The lifetimes of the excited states in ^{143}Eu, ^{142}Eu: DSAM.

^{143}Eu: ^{116}Cd (^{31}P, 4n)
E_{lab}= 148 MeV @
BARC-TIFR PLF

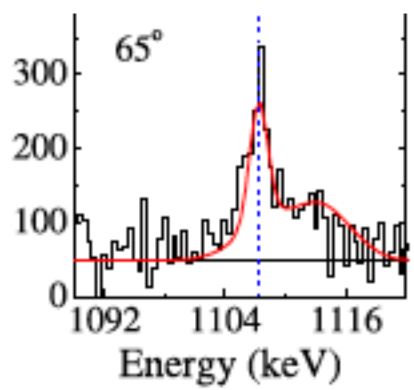
First evidence of Antimagnetic rotational band in mass other than 100 region



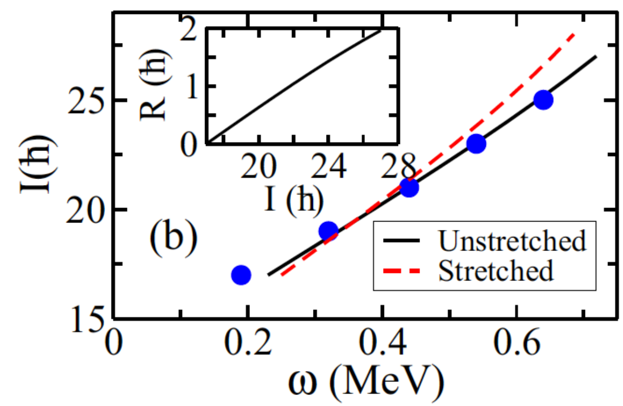




Re-opening of shears structure



0.37(8) ps

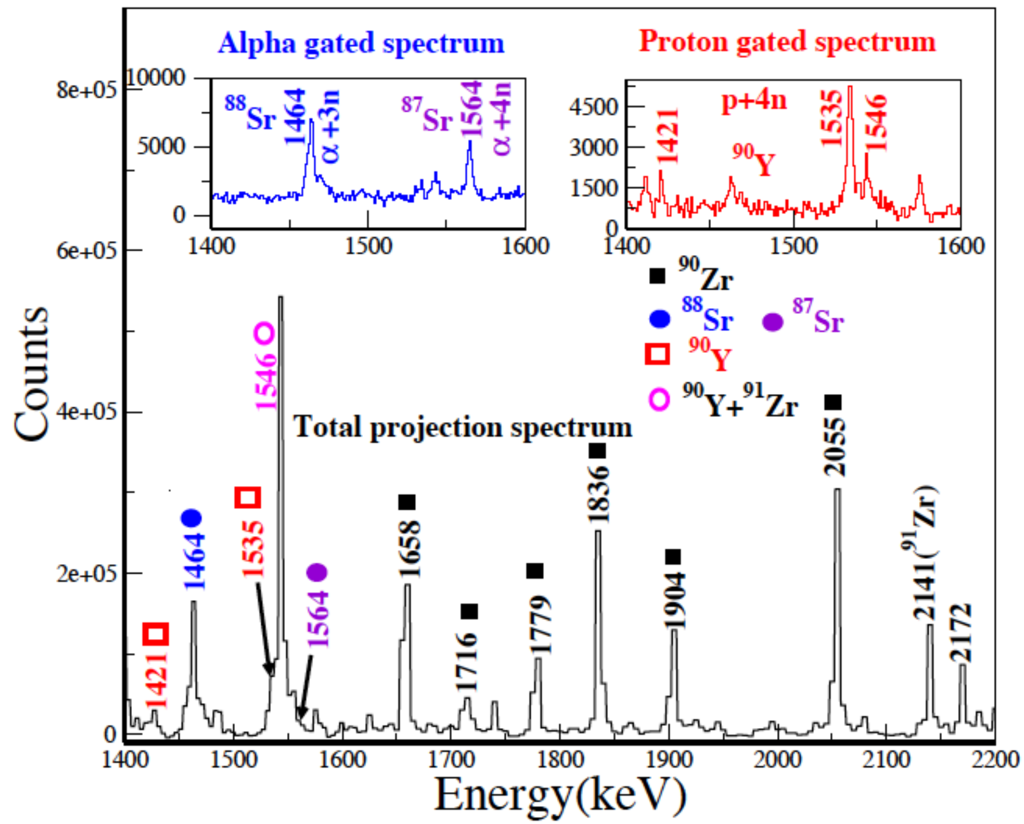


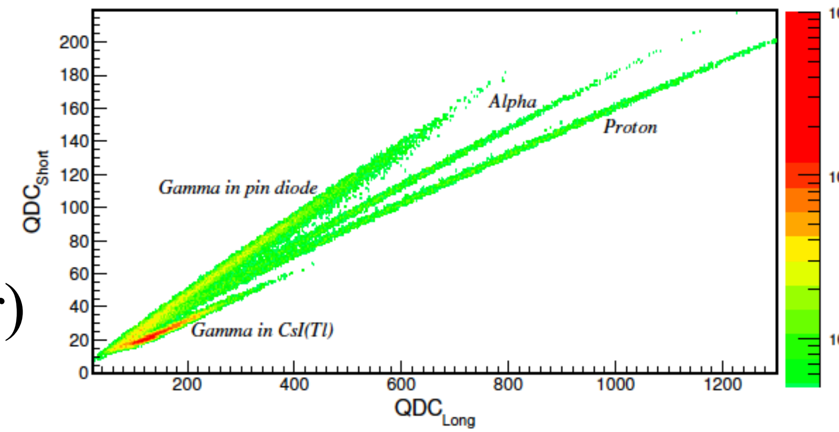
A. Goswami (SINP)

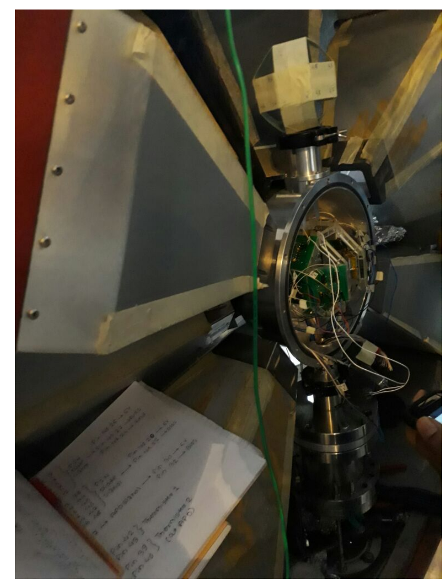
4pi CsI(Tl) array

$^{13}C+^{82}Se$ @60 MeV at TIFR (2017)
Au backed target
11 CS-Clover + 24 CsI(Tl)

Analysis in progress (Md. S. R. Laskar)

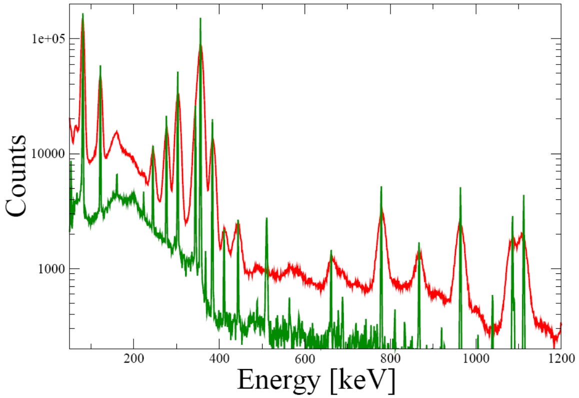


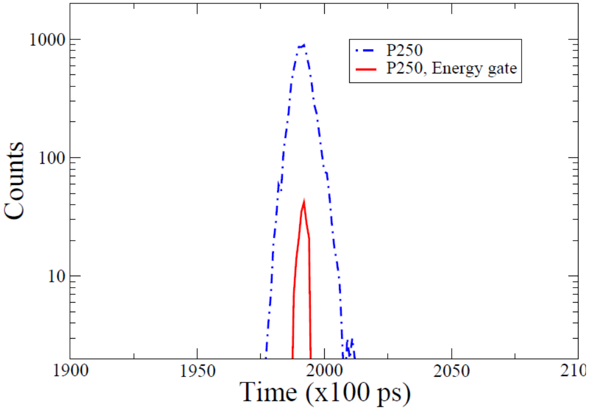


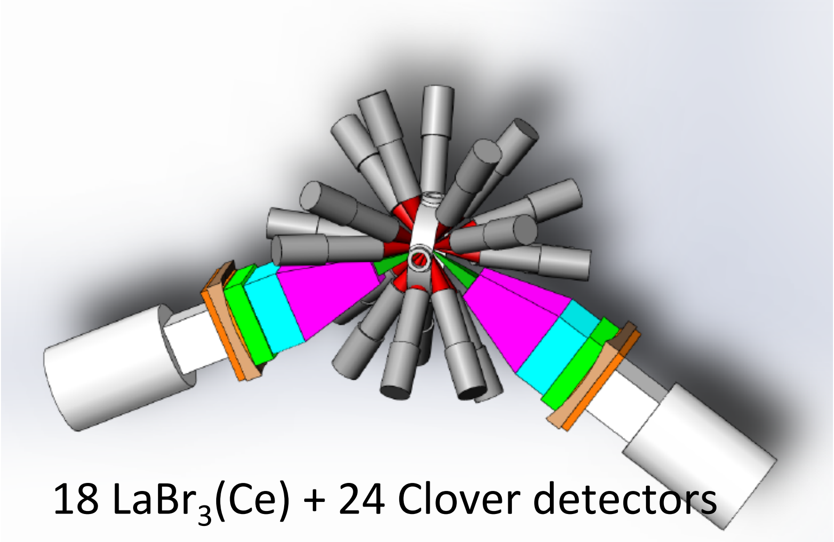


TIFR - IUAC Collaboration

$LaBr_3(Ce)$ array coupled to INGA







Excellent energy resolution observed 2.8% at 1.33 MeV

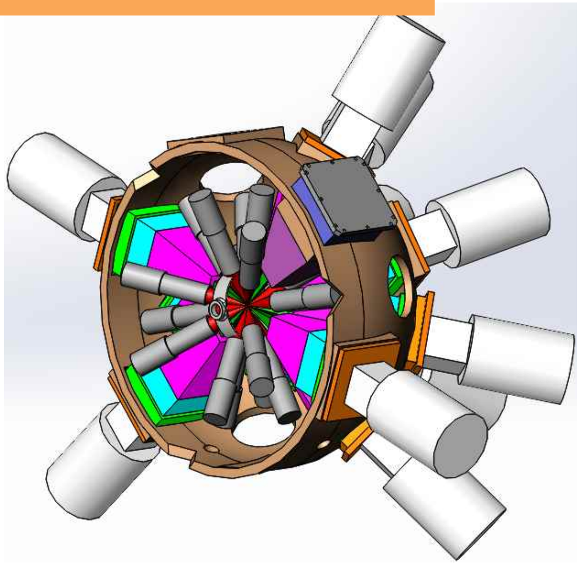
FWHM of peak-to-peak coincidence resolving time ~400 ps

P. Singh et al. Proc. of DAE NP symposium, Vol 59, 942 (2014)

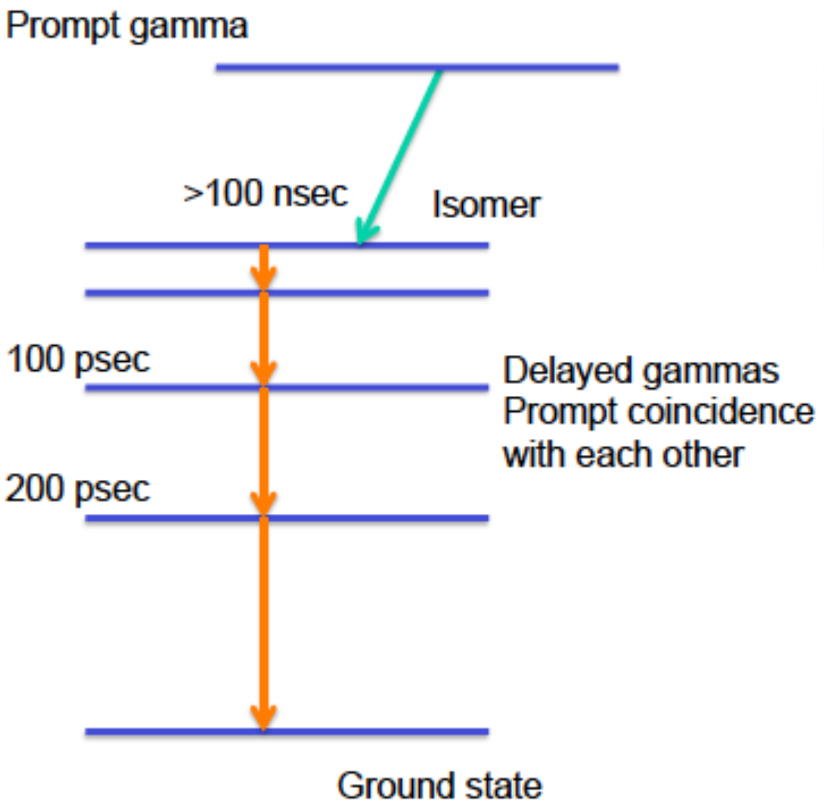
Energy Calibration using ^{60}Co, ^{152}Eu, ^{137}Cs
Timing properties using ^{60}Co and ^{152}Eu

DDAQ is being upgraded to include 500 MHz cards for $LaBr_3(Ce)$ coupled to INGA tifr

Hybrid Array 24 HPGe Clover – 18 LaBr3(Ce) at TIFR
Best of both worlds for nuclear structure



Use of HPGe for enhanced, highly selective decay path isolation
and
Use of LaBr3(Ce) for gated sub-nanosecond lifetime measurements
(With other ancillary detectors/set-up (CsI(Tl), Si detectors, plunger)



Physics cases:
Isomer depletion
Lifetime measurements for E1 decays, Octupole shapes,Gamma bands, Wobbling mode, Test of K-hindrance, Collectivity in heavy nuclei, Shell model states

Summary

- Chiral structure in A~110, 190
- Wobbling in A~130 at low spin.
- Anti-magnetic rotation in A~110,140

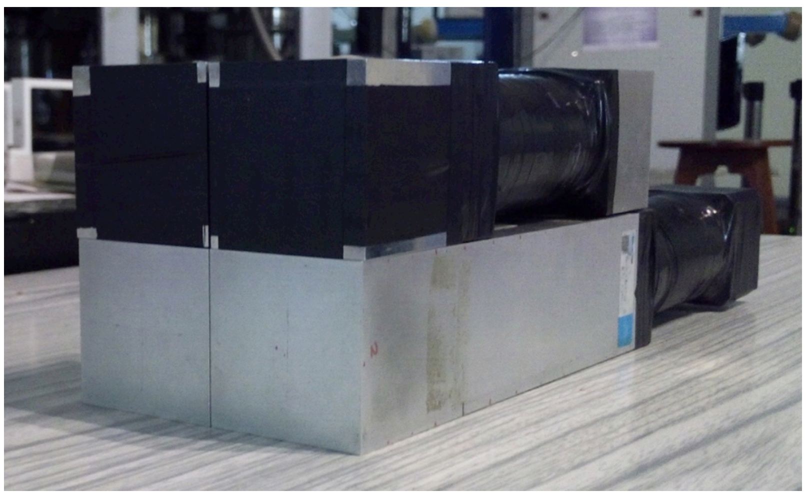
- INGA coupled to a DDAQ and other ancillary detectors will provide opportunities to probe various exotic modes of nuclear rotation and excitation.
- Use of different reactions for nuclear structure.

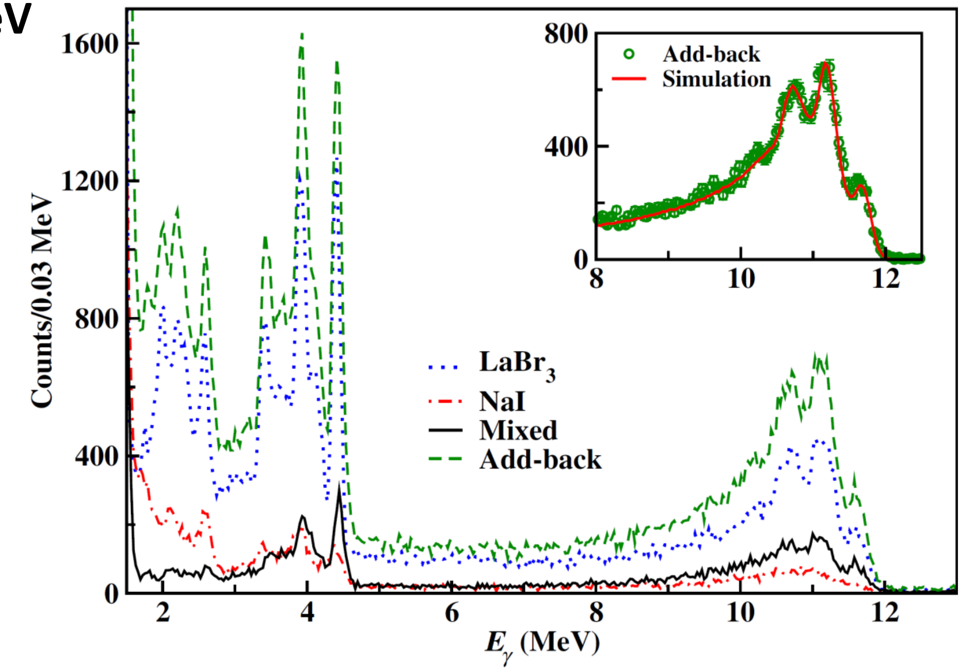
Investing in the polarization measurements of gamma rays and "wide-range timing spectroscopy" proved to be a successful approach for creating our specific "niche" and complement research at large scale facilities.

Thank You for Your Attention!!

demonstration of phoswich add back concept (4-12 MeV)

$^{11}B(p,\gamma)$ at 163 keV





$N(E_{add})/N(E_1)$ ~1.4 @4.4 MeV
~ 1.5 @ 12 MeV

C. Ghosh *et al* 2016 *JINST* **11** P05023

In-beam test of PARIS mini-cluster (2x2) @ Mumbai

V. Nanal