Experimental work on degenerate dipole bands with INGA

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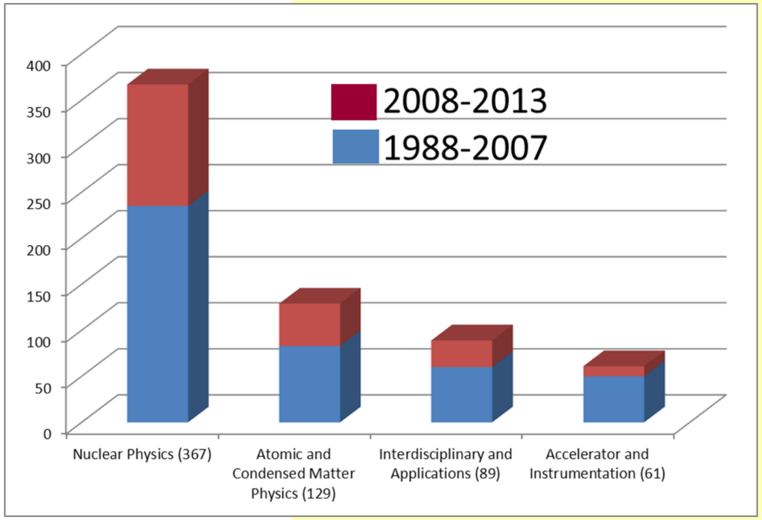
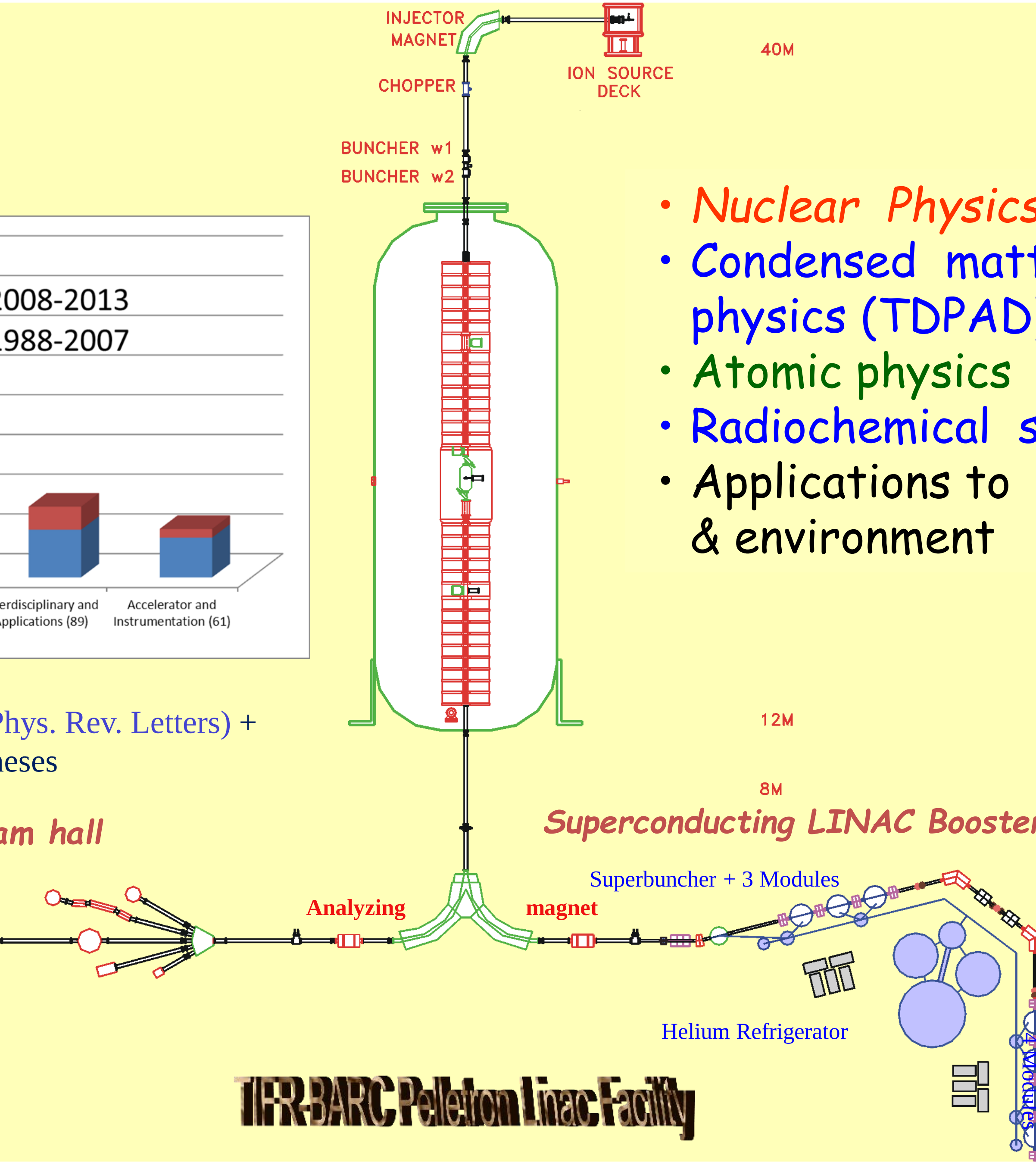
Chiral Bands in Nuclei, Nordita, Stockholm 20th – 22th April 2015



600 publications (19 Phys. Rev. Letters) + 100 Theses

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



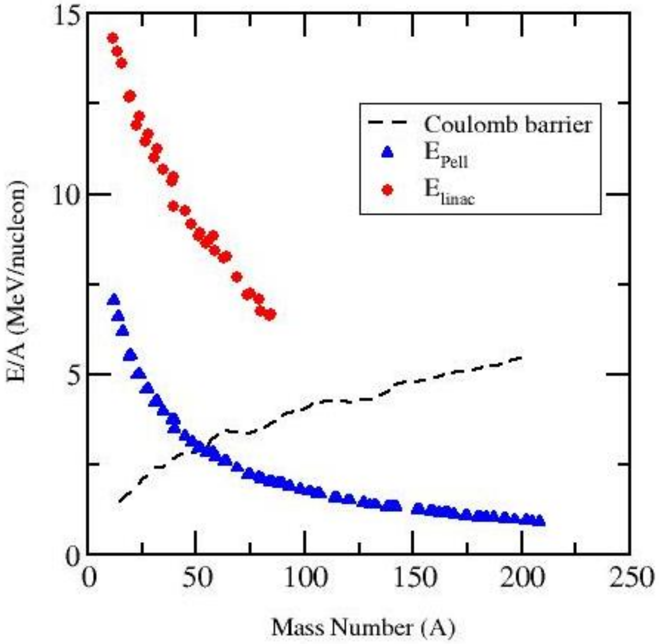
to new beam hall

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

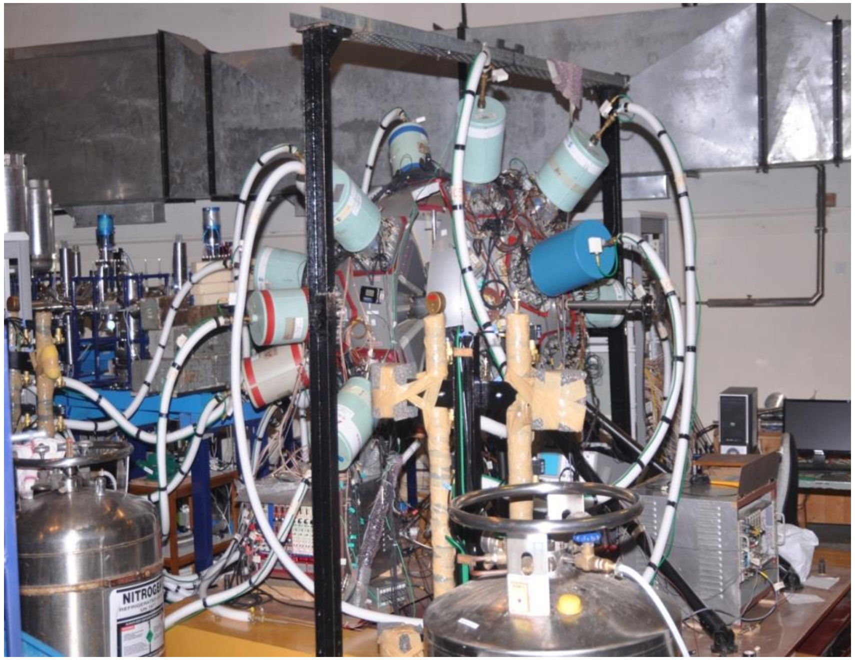
^{7}Li, ^{10,11}B, ^{12}C, ^{16,18}O, ^{19}F, ^{28,30}Si, ^{32}S, ^{35}Cl

Phase I commissioned on September 22nd, 2002
Phase II commissioned on July 9th, 2007
LINAC dedicated to users on Nov. 28th, 2007

Critical components of LINAC booster have been designed, developed and fabricated indigenously.

The superconducting LINAC has been a major milestone in the development of accelerator technology in India.

INGA campaign



Physics Highlights

Search and characterization of novel excitation

Magnetic and Anti-Magnetic Rotation

Degenerate dipole bands and chirality

Wobbling Excitation

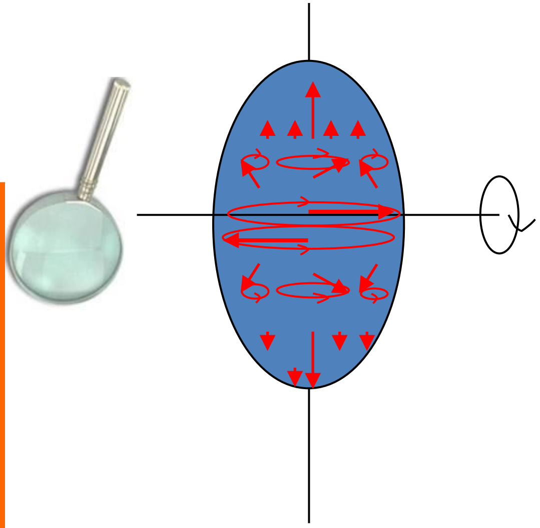
Shell model excitation and emergence of collectivity

Isomers and its application

Fission fragment spectroscopy

Reaction dynamics study

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.

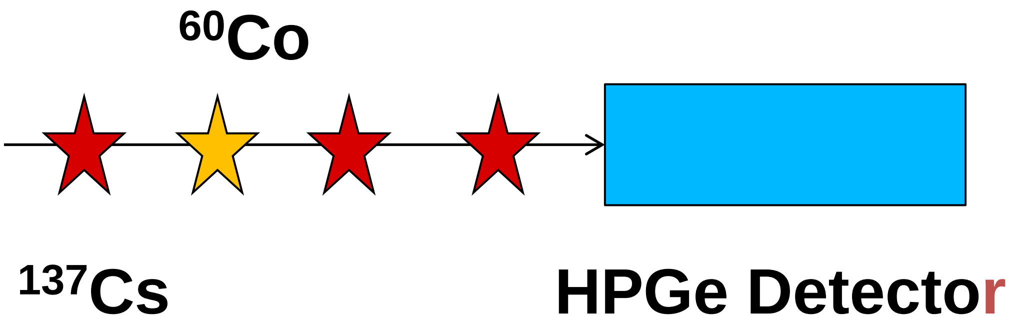
Experiments: ~50 (Current experimental campaign 180 days)

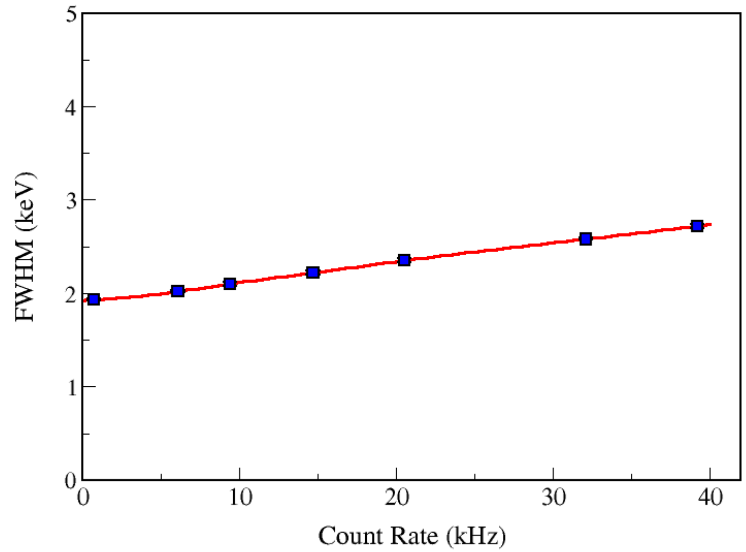
60 researchers including 25 PhD students; 30 publications (2012-2015)

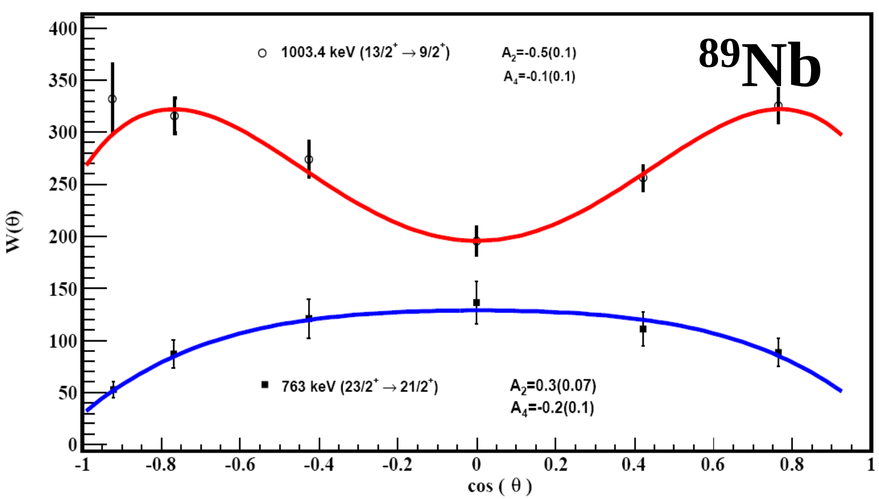
Moves between 3 accelerators (2001-2015) 120 publications; 50 PhDs

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

High Count Rate Measurements with DDAQ







- **Singles measurement with 40 kHz**
- **Data rate: 15 MB/sec**
- **Trigger less mode**
- **Cross section measurement**

<u>DSP Implementation for INGA</u>

- **Up to 96 channels**
- **Operation since 2011 (180 days)**
- **Ancillary detectors (Si and $LaBr_3$(Ce))**

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

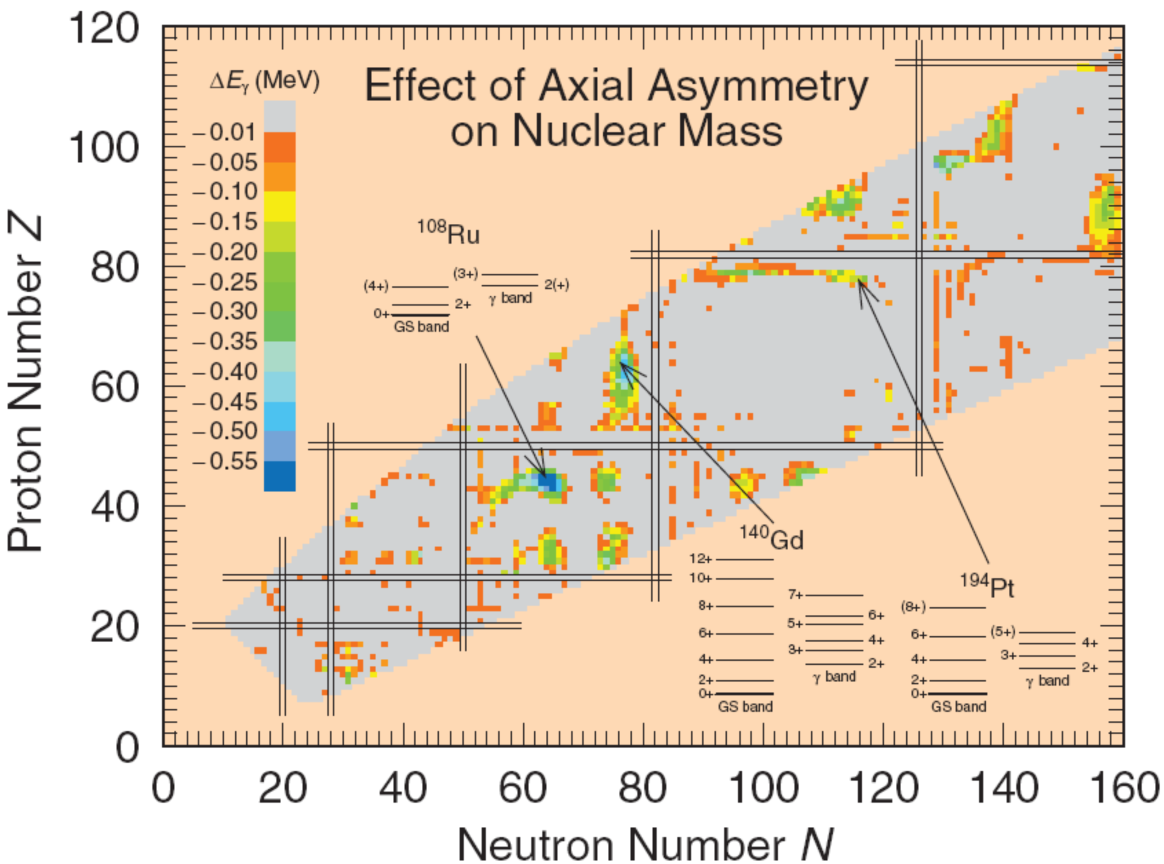
Outline

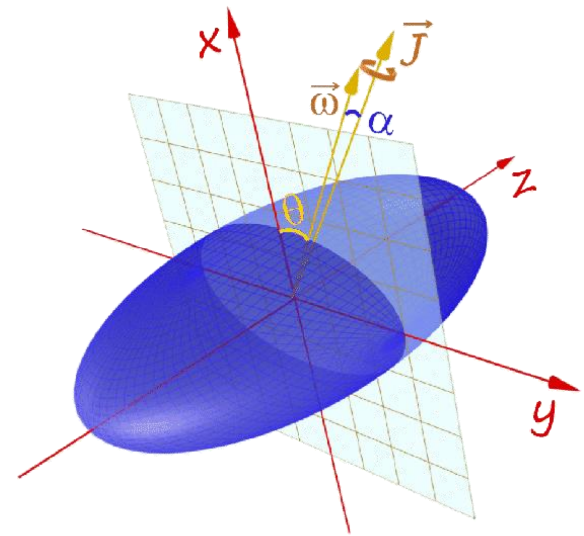
- Motivation
- Results from INGA on exotic rotations
    - Degenerate dipole bands & Chiral rotation
    - Wobbling rotation
    - Magnetic and Antimagnetic rotation
- Future plans with INGA

PRL 97, 162502 (2006) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2006

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 Ichikawa[3]

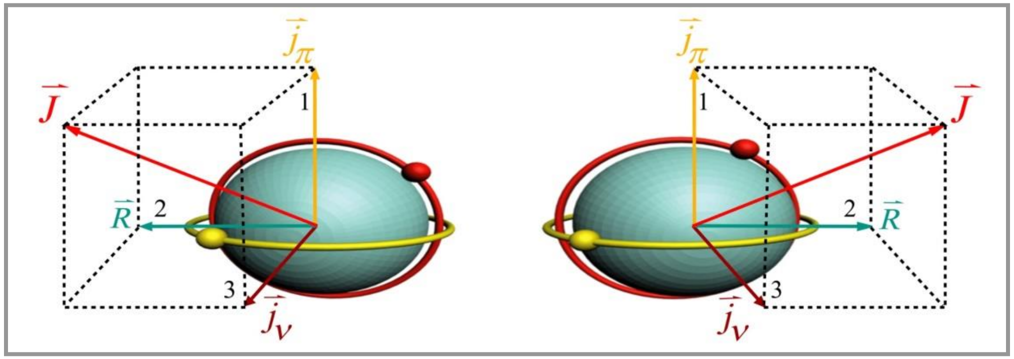




Rotation of Triaxial Nuclei

Rotation of Triaxial Nuclei

Chiral Rotation



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

Wobbling Mode

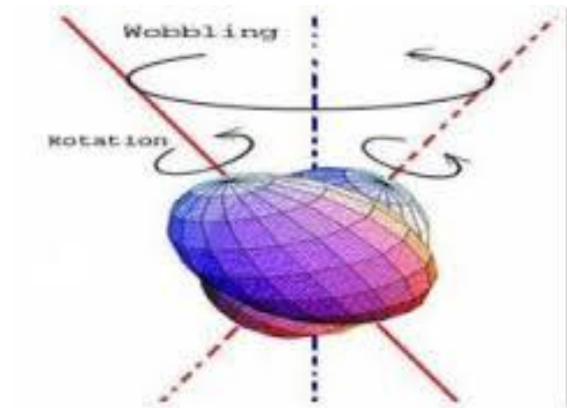
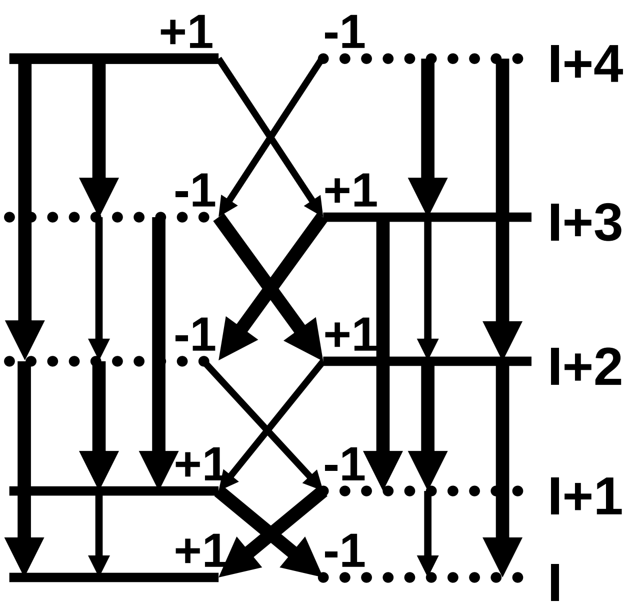


Figure 1.7. Nuclear wobbling motion

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



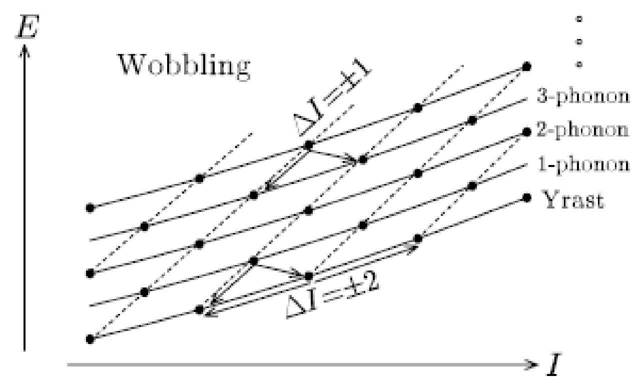
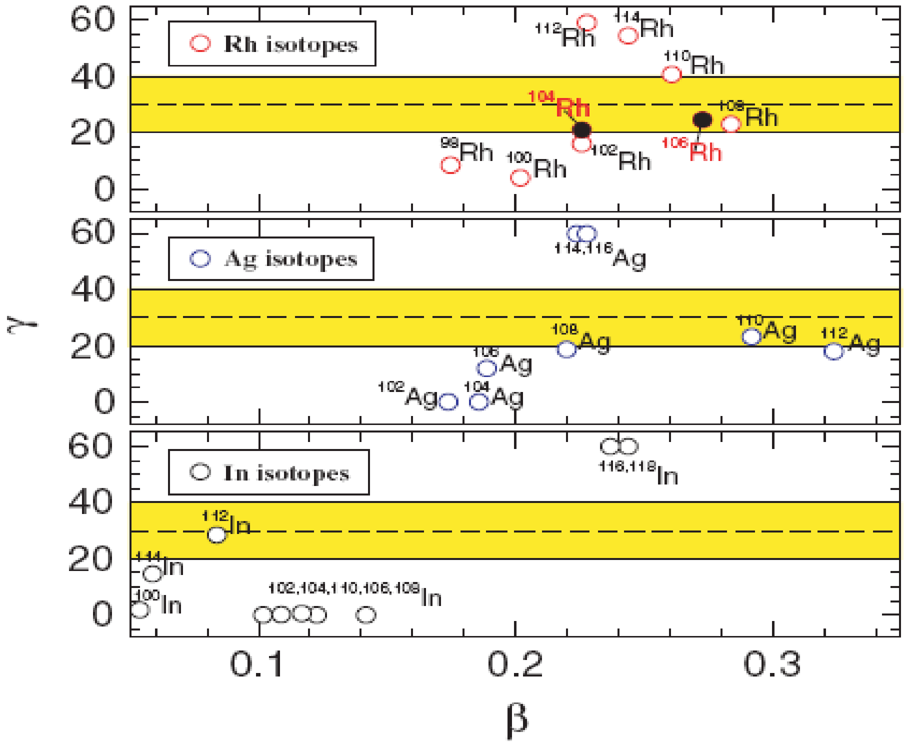
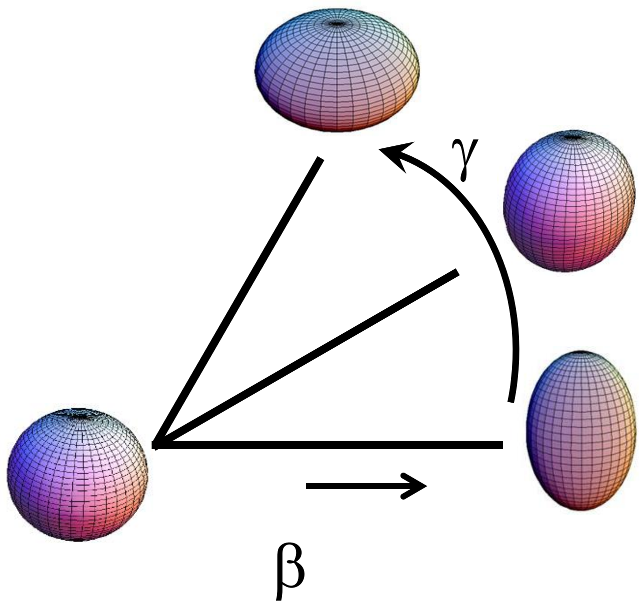


FIG. 1. Rotational spectra of a triaxial rotor Hamiltonian. Horizontal rotational bands are connected by solid lines; vertical phonon bands, by dotted lines.

Odd-odd Isotopes near A ~ 110

Meng et. al. PRC73 037303 (2006)



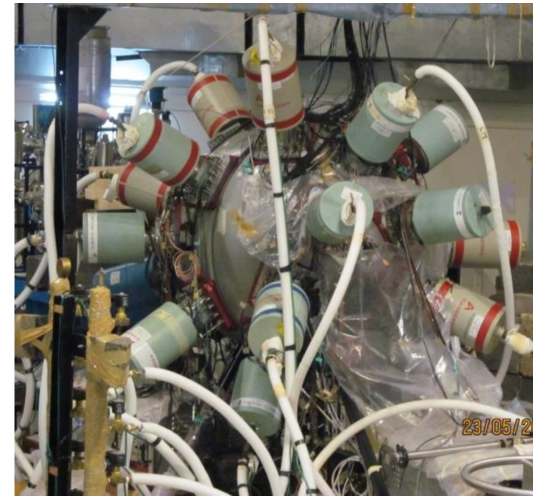


High spin Spectroscopy of ^{112}In, ^{108}Ag, ^{106}Ag isotopes have been carried out with Indian National Gamma Array (INGA).

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)

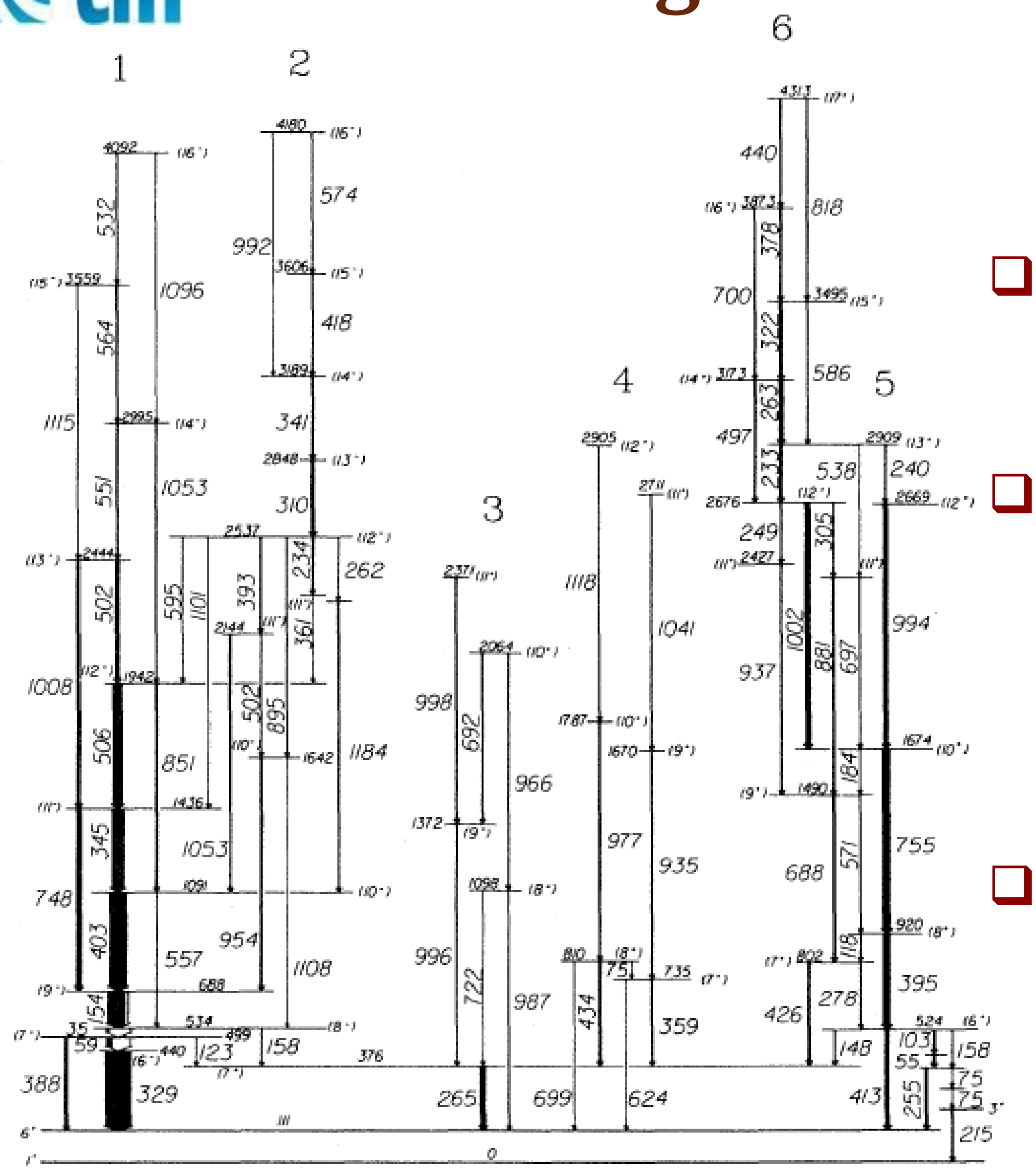
^{108}Ag : Experimental Details

- Reaction for level scheme:
  ^{100}Mo(^{11}B,3nγ) ^{108}Ag
- Set up : INGA @ TIFR
  18 Compton suppressed HPGe Clover detectors
- Pixie-16 DDAQ from XIA
- Target :
  ^{100}Mo (10 mg/cm^2) self supported.
- Beam : ^{11}B at 39 MeV.



- Reaction for lifetime : ^{94}Zr(^{18}O, p3nγ) ^{108}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/cm^2) backed with 10 mg/cm^2 ^{197}Au.
- Beam : ^{18}O at 72 MeV.

^{108}Ag : Level Scheme

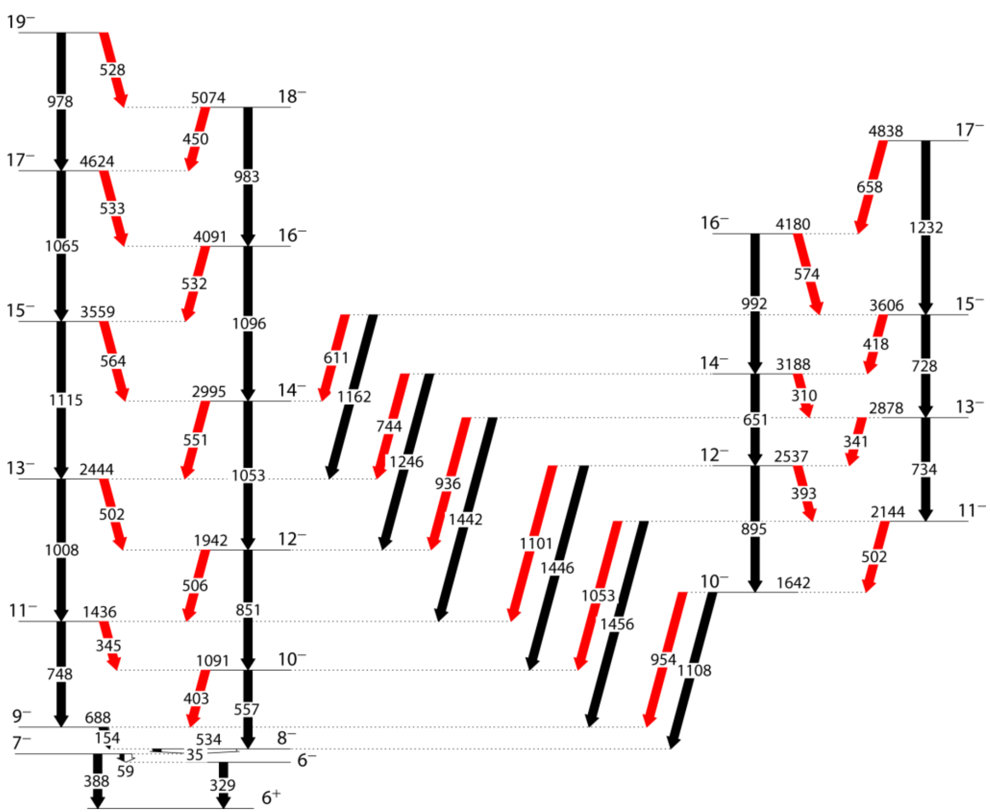


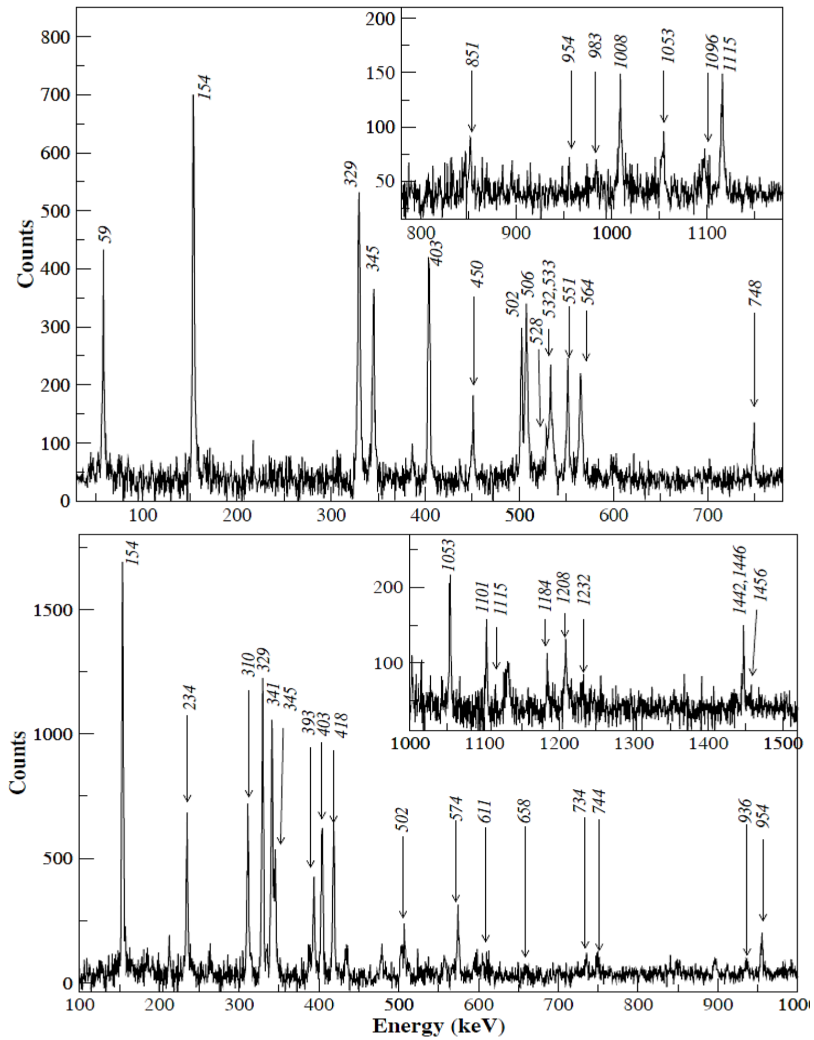
- ^{100}Mo(^{11}B,3nγ) ^{108}Ag @ 39 MeV
- With 5 HPGe single crystal detectors and 8 NaI detectors as multiplicity filters
- 7 X 10^7 events: 2-fold

Espinoza-Quinones *et al.*, Phys. Rev. C **52,** 104(1995

Twin Bands of ^{108}Ag

Partial Level Scheme and double gated spectra





J. Sethi *et al.*, Phys. Lett. *B* **725,** 85 (2013

Triaxial Projected Shell Model

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

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

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).

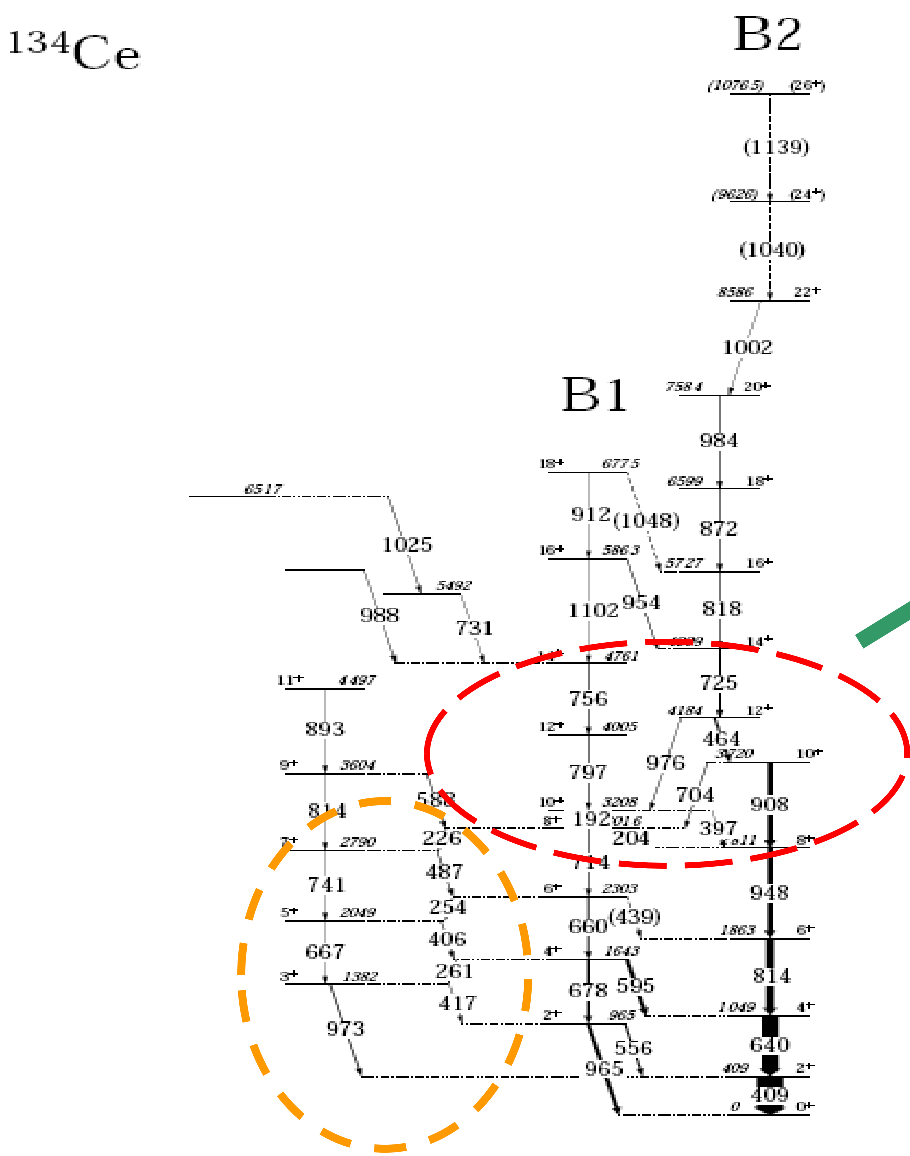
G.H. Bhat, J.A. Sheikh, R. Palit, Phys. Lett, B **707**, 237 (2012).

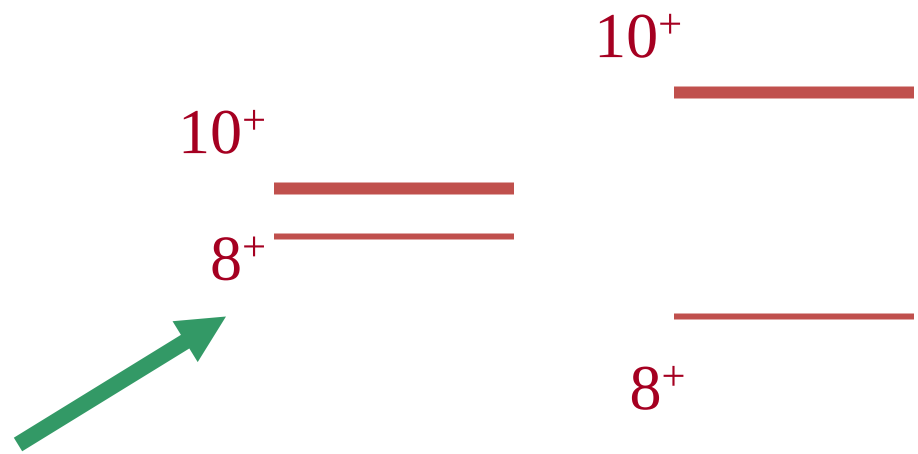
G.H. Bhat, J.A. Sheikh, W.A. Dar, S. Jehangir, R. Palit, P. Ganai, Phys. Lett, B **738**, 218 (2014).

Structure of 10^+ states in gamma-soft ^{134}Ce

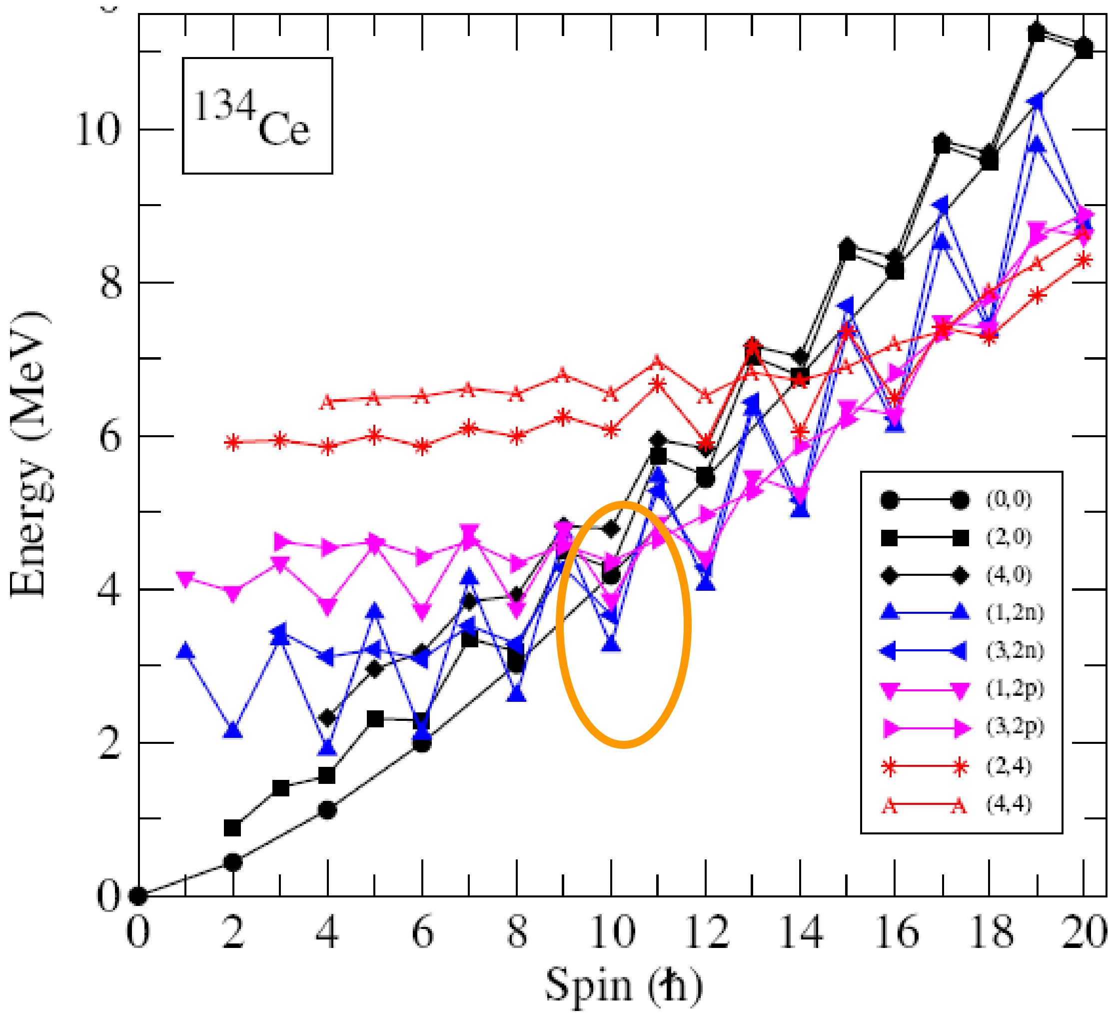
Within ~500 keV

Two 10^+ isomers with –ve g-factor





Band crossing in ^{134}Ce



- The γ- bands built on the qp configurations modify the band crossing features.
- Two-qp γ-band with K=3 is shown to be energetically favored for some spin states and form 1st excited state.
- Two $I^{\pi} = 10^{+}$ states in ^{134}Ce originate from the same two quasi-neutron configurations and both these states should have negative g-factors.

Nucl Phys A 824, 58(2009) & Phys. Rev C 77, 034313 (2008).

Physics Letters B 725 (2013) 85–91

Contents lists available at SciVerse ScienceDirect

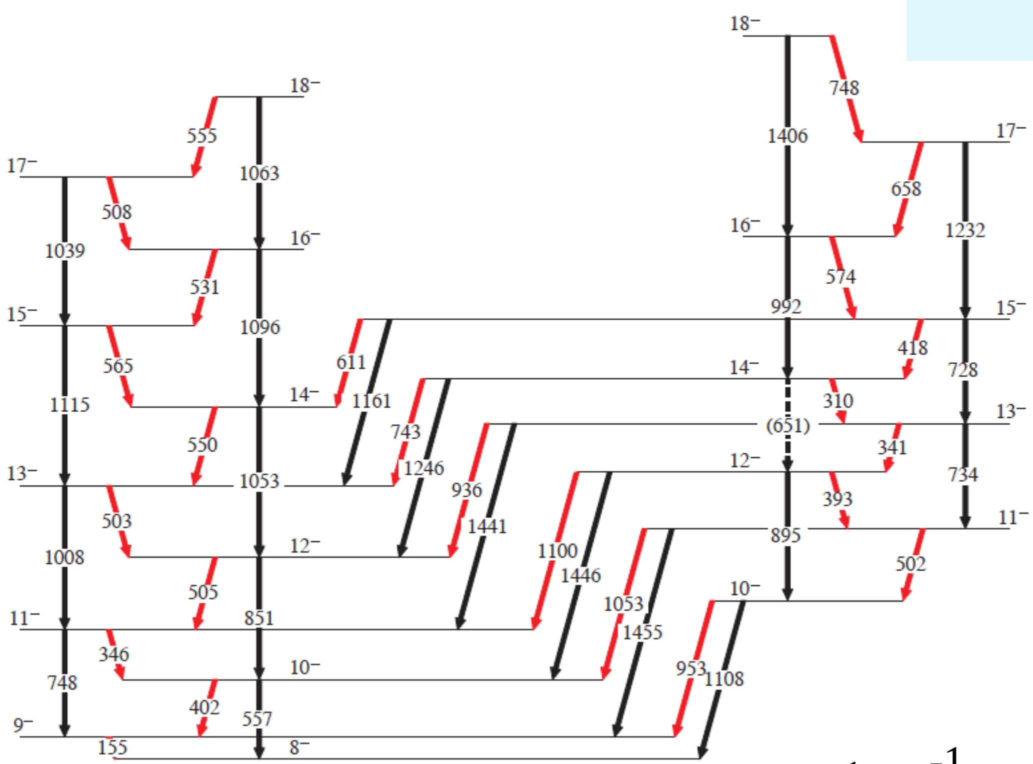
Physics Letters B

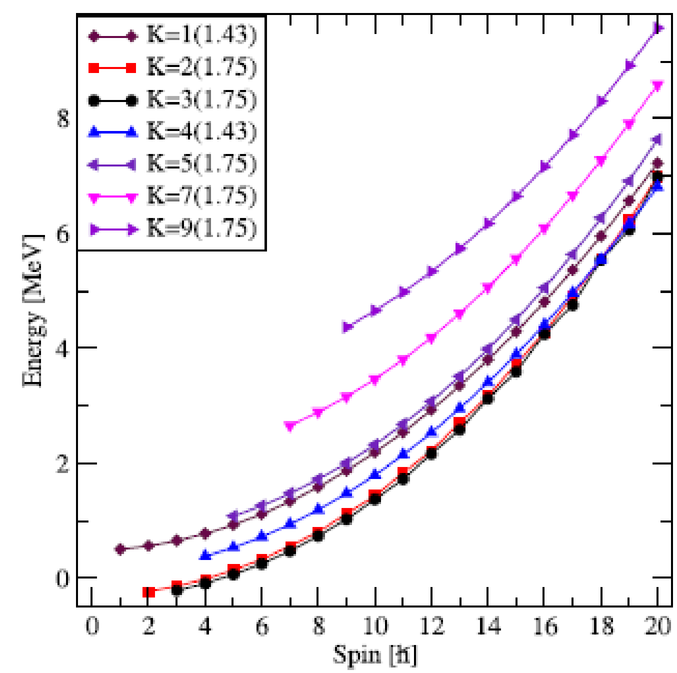
www.elsevier.com/locate/physletb

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. Donthi [a], U. Garg [f], S. Jadhav [a], H.C. Jain [a], S. Karamian [g], S. Kumar [h], M.S. Litz [d], D. Mehta [i], B.S. Naidu [a], Z. Naik [j], S. Sihotra [i], P.M. Walker [k]

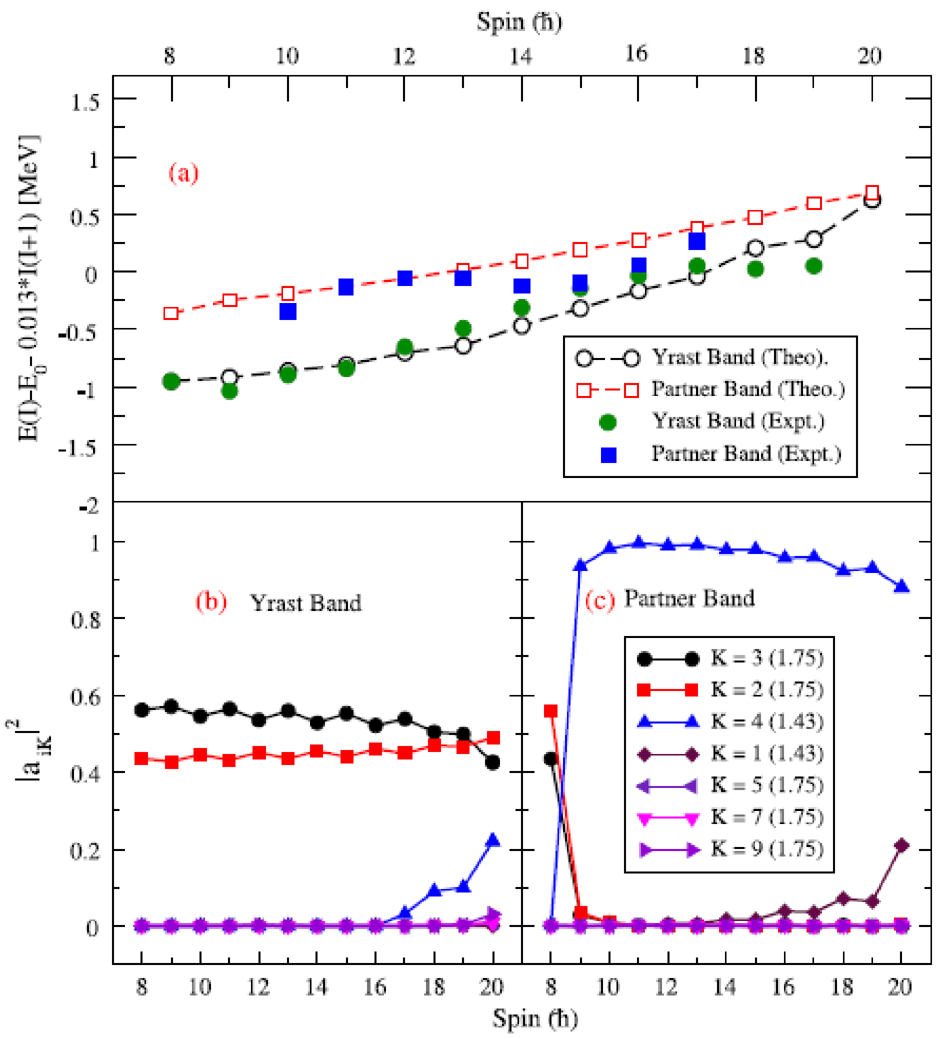
$$\hat{H} = \hat{H}_0 - \frac{1}{2}\chi \sum_{\mu} \hat{Q}^{\dagger}_{\mu}\hat{Q}_{\mu} - G_M \hat{P}^{\dagger}\hat{P} - G_Q \sum_{\mu} \hat{P}^{\dagger}_{\mu}\hat{P}_{\mu}$$





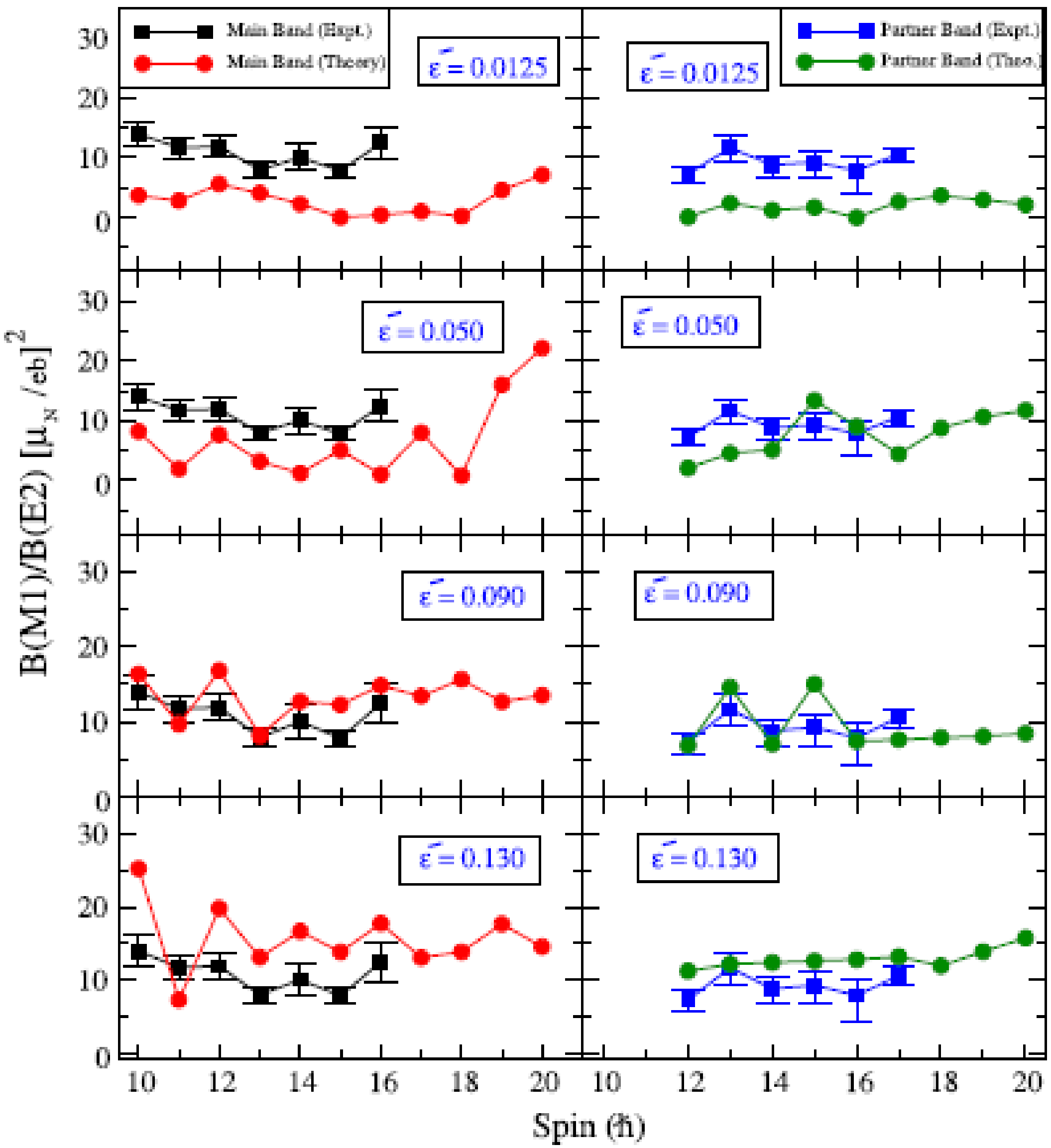
$\pi g_{9/2}{}^{-1} \times \nu h_{11/2}$

Comparison of energy of measured levels with calculation



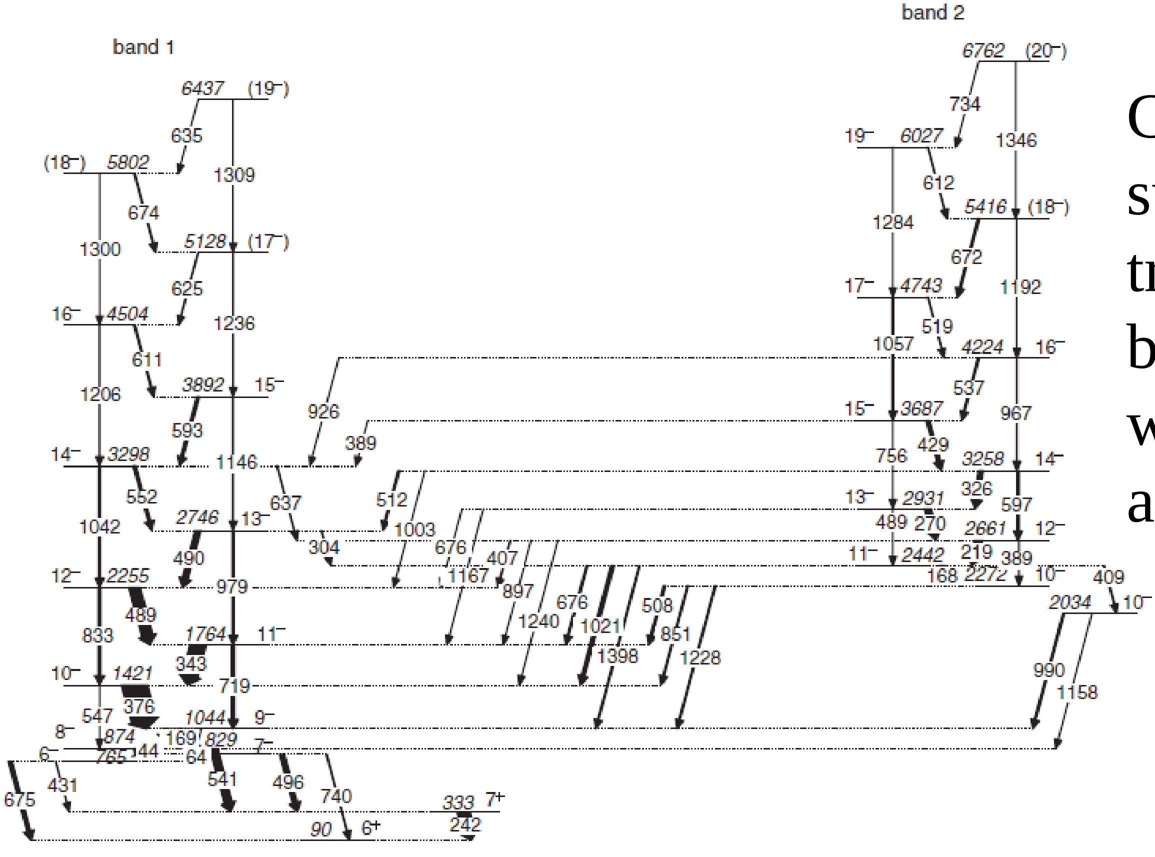
Degenerate bands reproduced with triaxial deformations
ε_2=0.265 and ε'= 0.09

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.

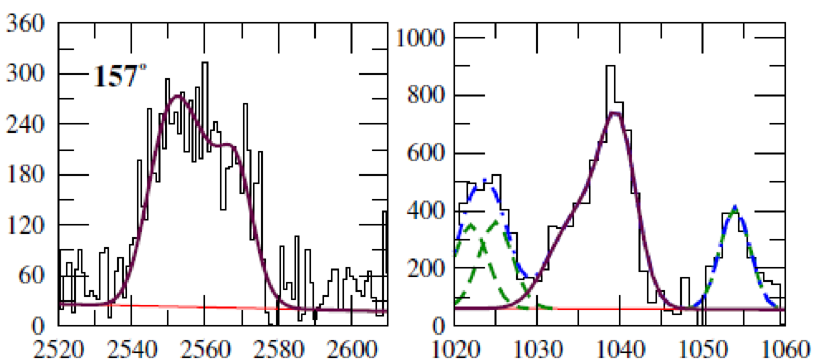
P. Joshi et al., PRL 98 102501(2007)

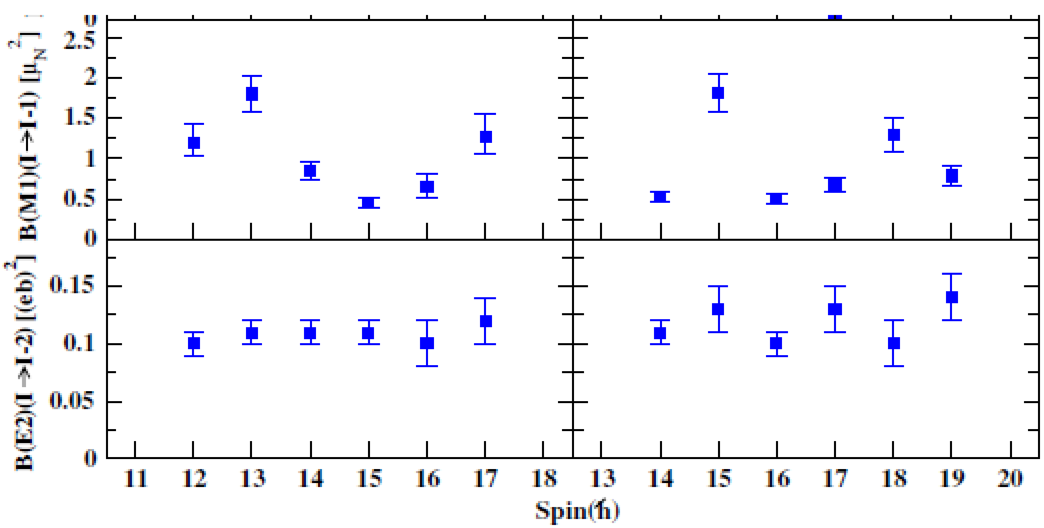
112, 202503 (2014) PHYSICAL REVIEW LETTERS week ending 23 MAY 2014

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

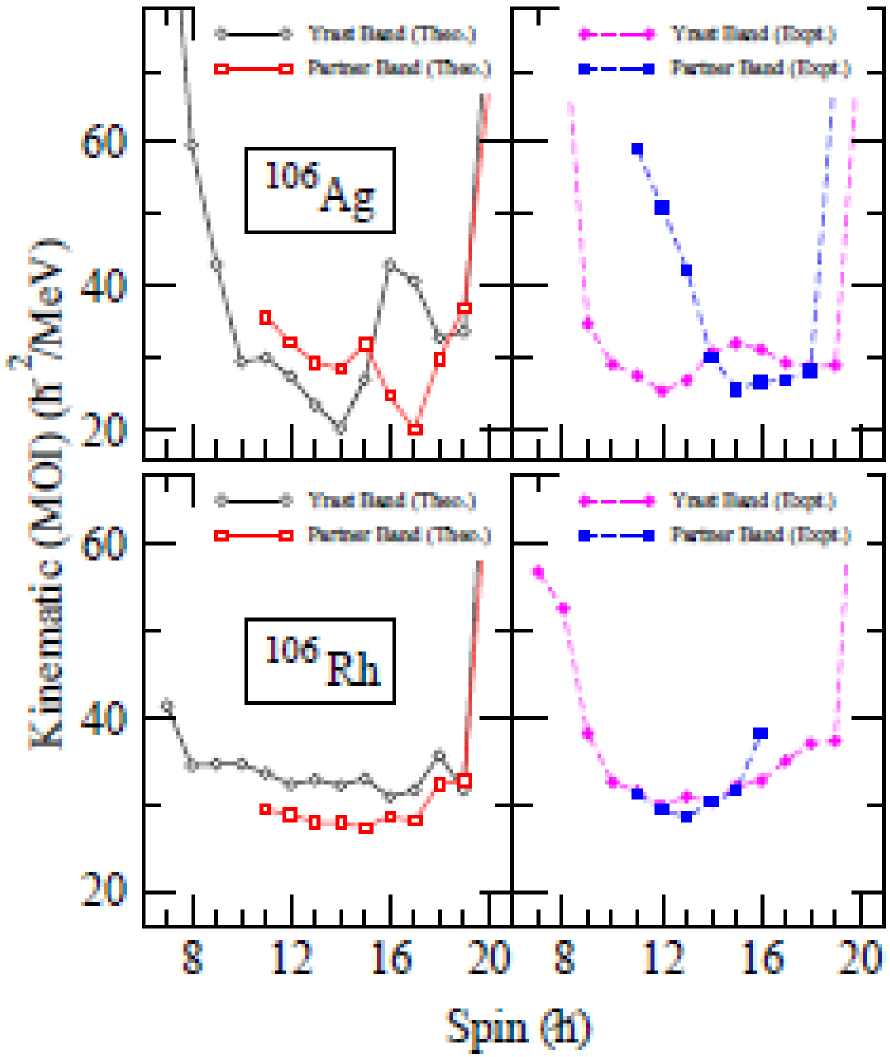
N. Rather,[1] P. Datta,[2,*] S. Chattopadhyay,[1] S. Rajbanshi,[1] A. Goswami,[1] G. H. Bhat,[3] J. A. Sheikh,[3] S. Roy,[4]
R. Palit,[4] S. Pal,[4] S. Saha,[4] J. Sethi,[4] S. Biswas,[4] P. Singh,[4] and H. C. Jain[4]
[1]*Saha Institute of Nuclear Physics, Kolkata 700064, India*
[2]*Ananda Mohan College, 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.





Comparison of energy of levels for odd-odd isotopes



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

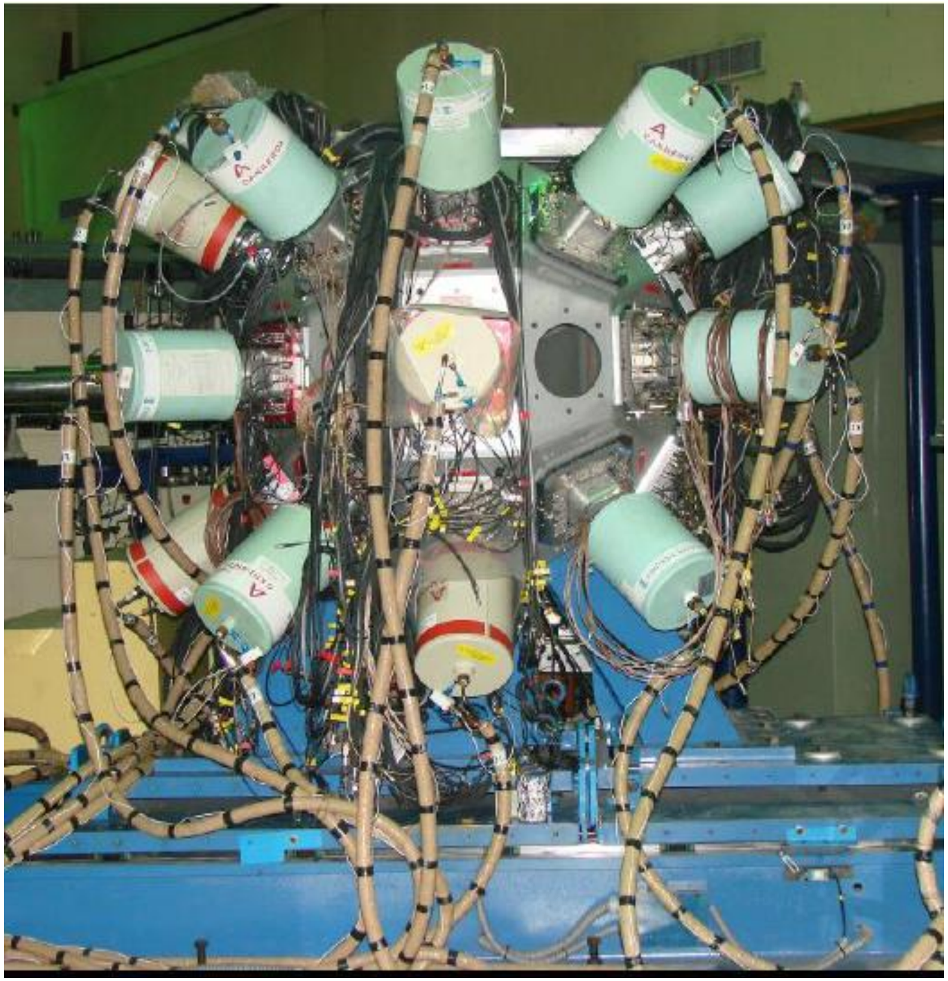
NPA 933, 123 (2015).

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

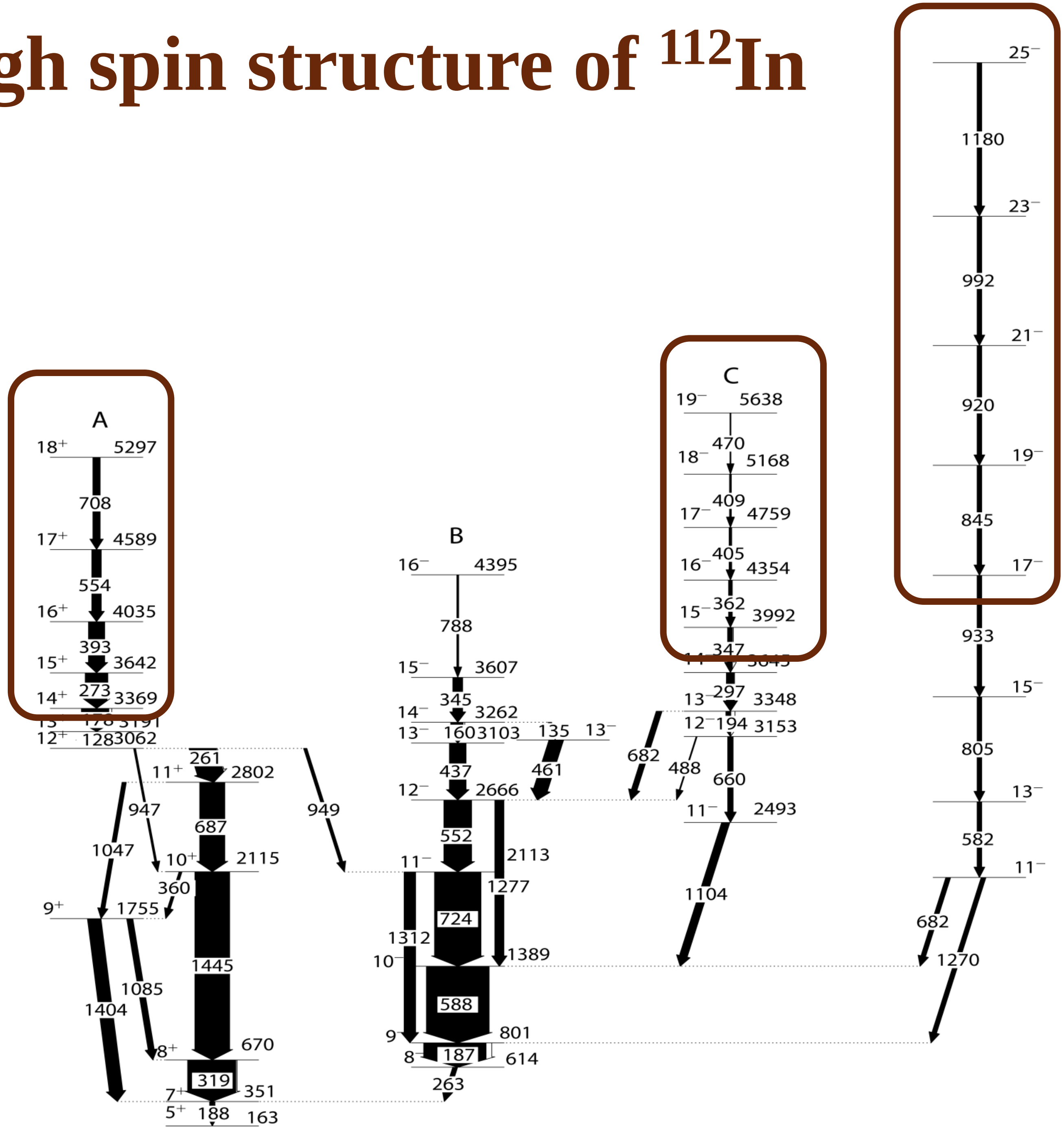
W.A. Dar[1], J.A. Sheikh[1,2], G.H. Bhat[1], R. Palit[3] and S. Frauendorf[4]

Experimental Details

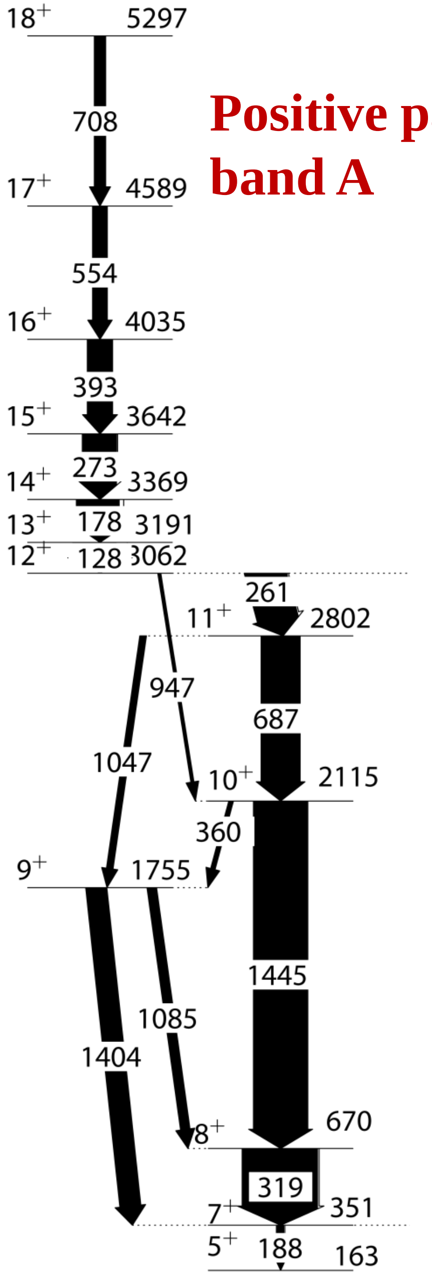
- Reaction : $^{100}Mo(^{18}O, p3n\gamma)$ ^{112}In
- Detector set-up : INGA at IUAC with 18 Compton suppressed HPGe Clover detectors
- Target : ^{100}Mo (2.7 mg/cm^2) with Pb backing (12 mg/cm^2) thick.
- Beam : ^{18}O at 80 MeV.



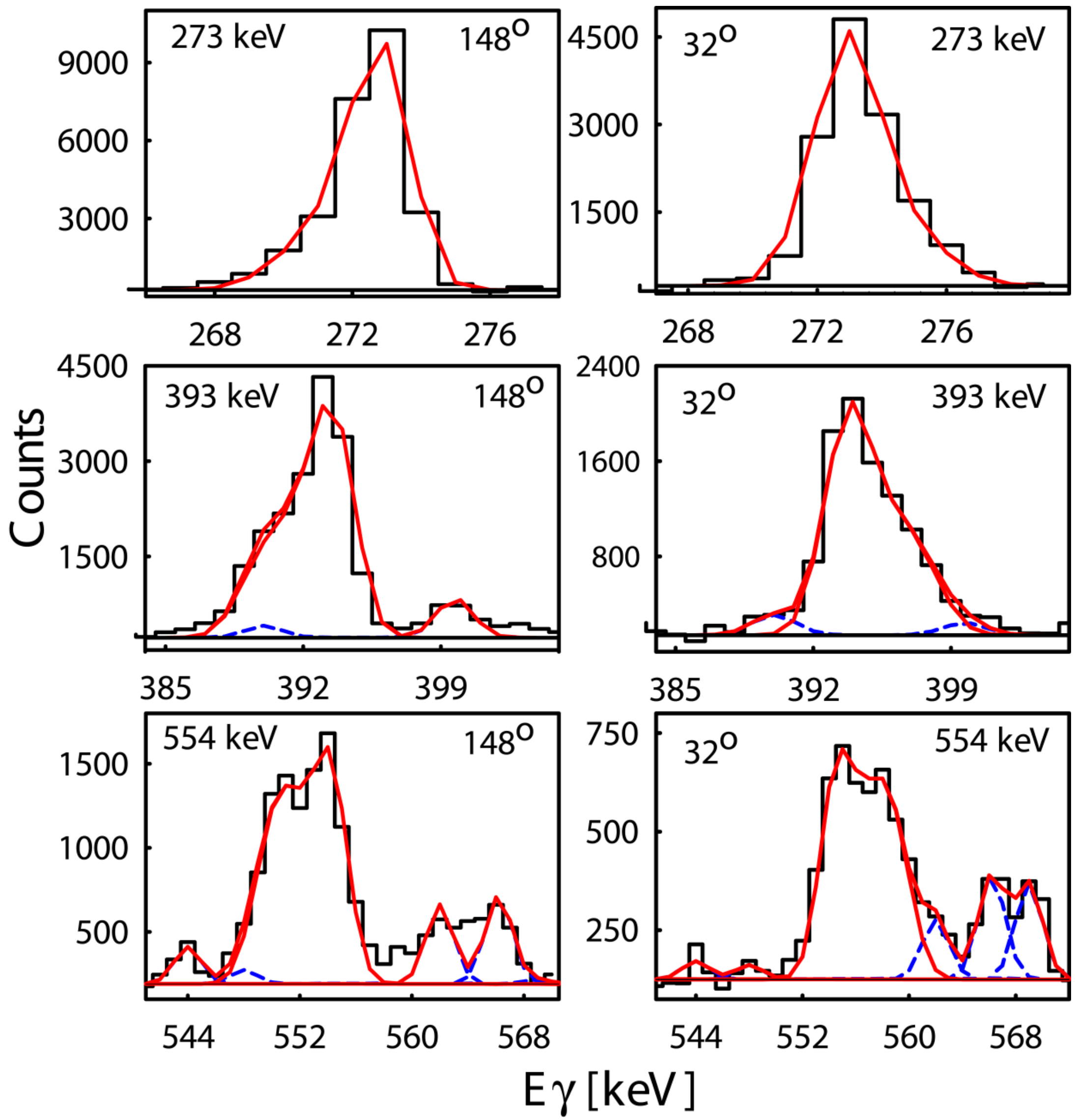
High spin structure of ^{112}In



Lifetime measurement in ^{112}In

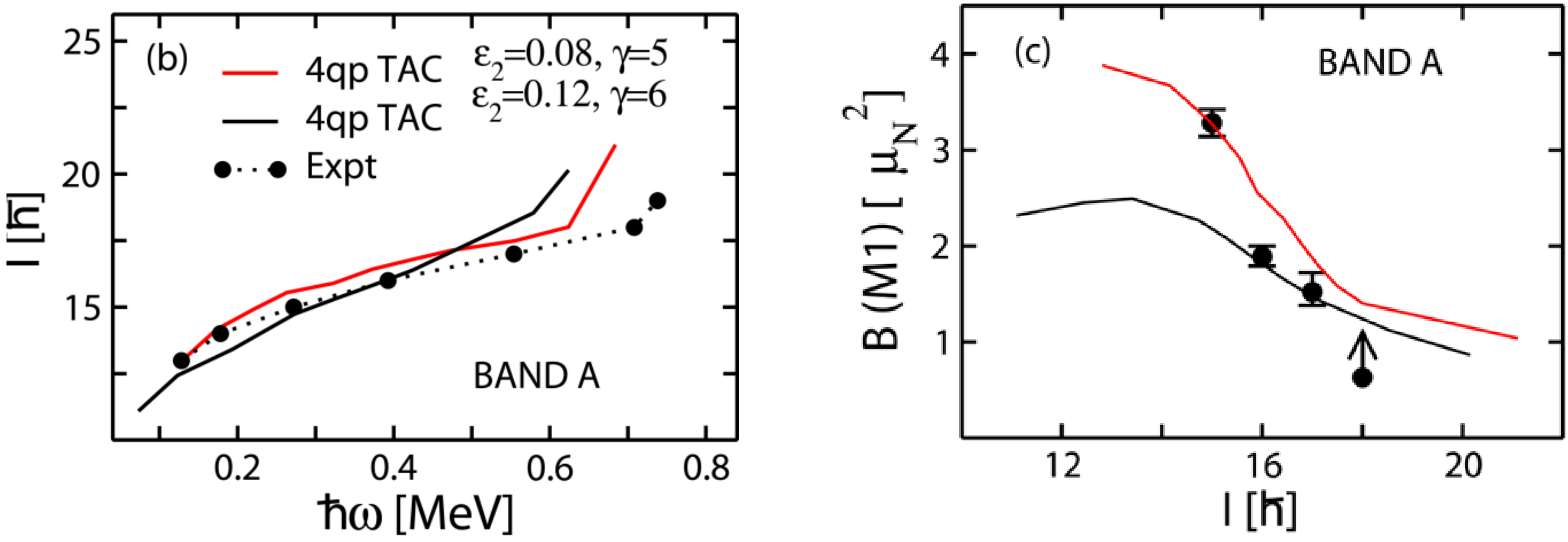


Positive parity band A



T. Trivedi, *et al.*, Phys. Rev. C **85** (2012)

Comparison of B(M1) values with TAC

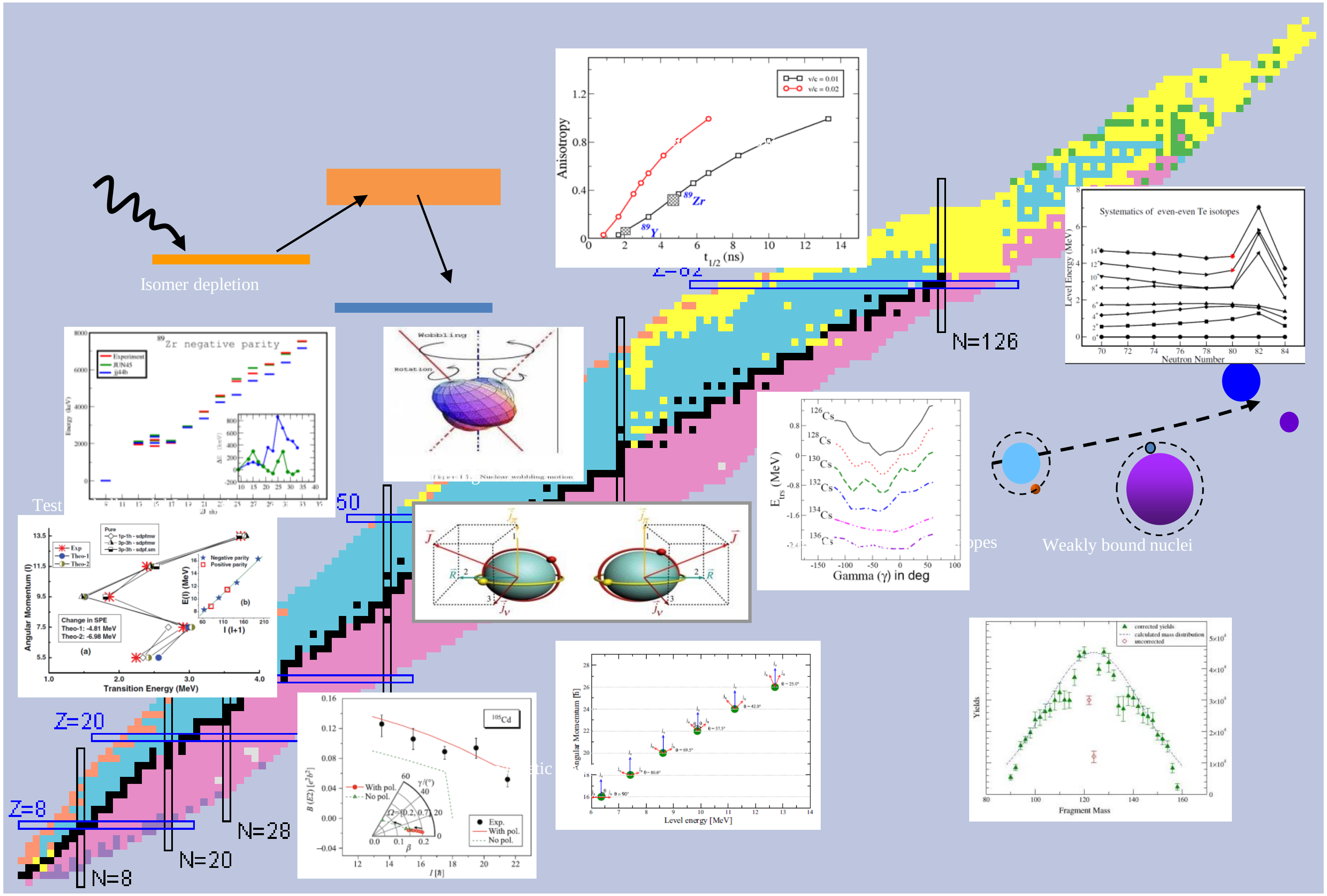


TAC configuration: $\pi g_{9/2} \otimes \nu((h_{11/2})^2 d_{5/2}/g_{7/2})$

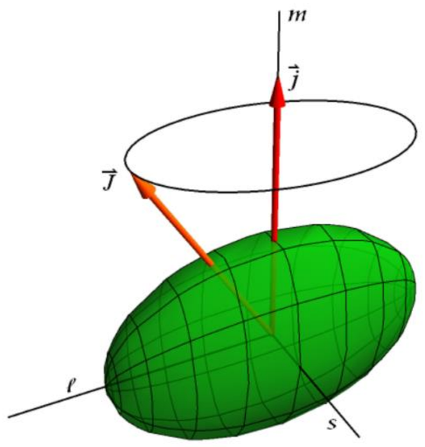
1. Regular sequences of M1 transitions
2. Weak or absent E2 transitions
3. B(M1) decreases with angular momentum

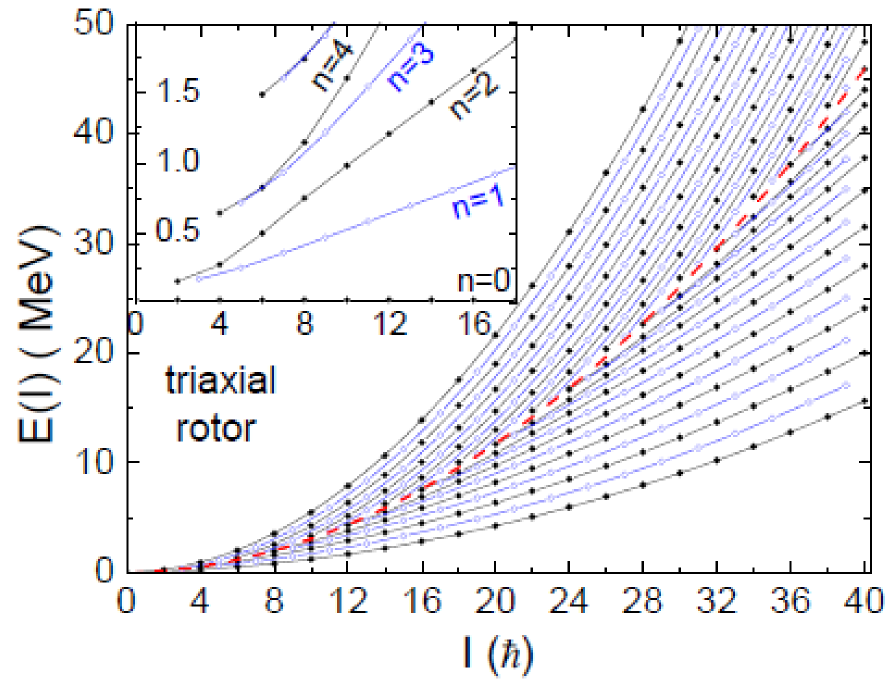
T. Trivedi, *et al.*, Phys. Rev. C **85** (2012)

Physics Highlights of INGA Collaboration



Wobbling mode in odd-A triaxial nuclei





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

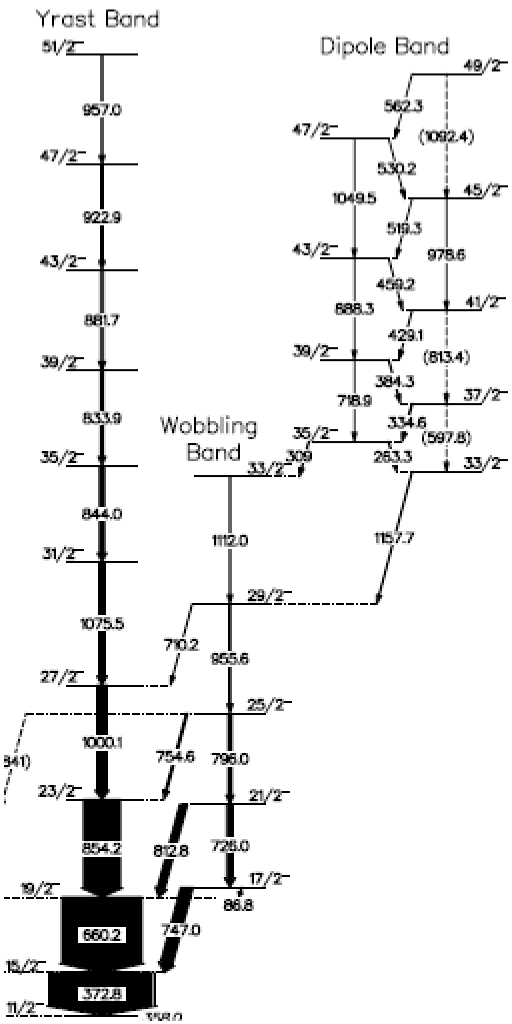
$$\hbar\omega_w = \frac{j}{\mathcal{J}_3}\left[\left(1 + \frac{J}{j}\left(\frac{\mathcal{J}_3}{\mathcal{J}_1} - 1\right)\right)\left(1 + \frac{J}{j}\left(\frac{\mathcal{J}_3}{\mathcal{J}_2} - 1\right)\right)\right]^{1/2}$$

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

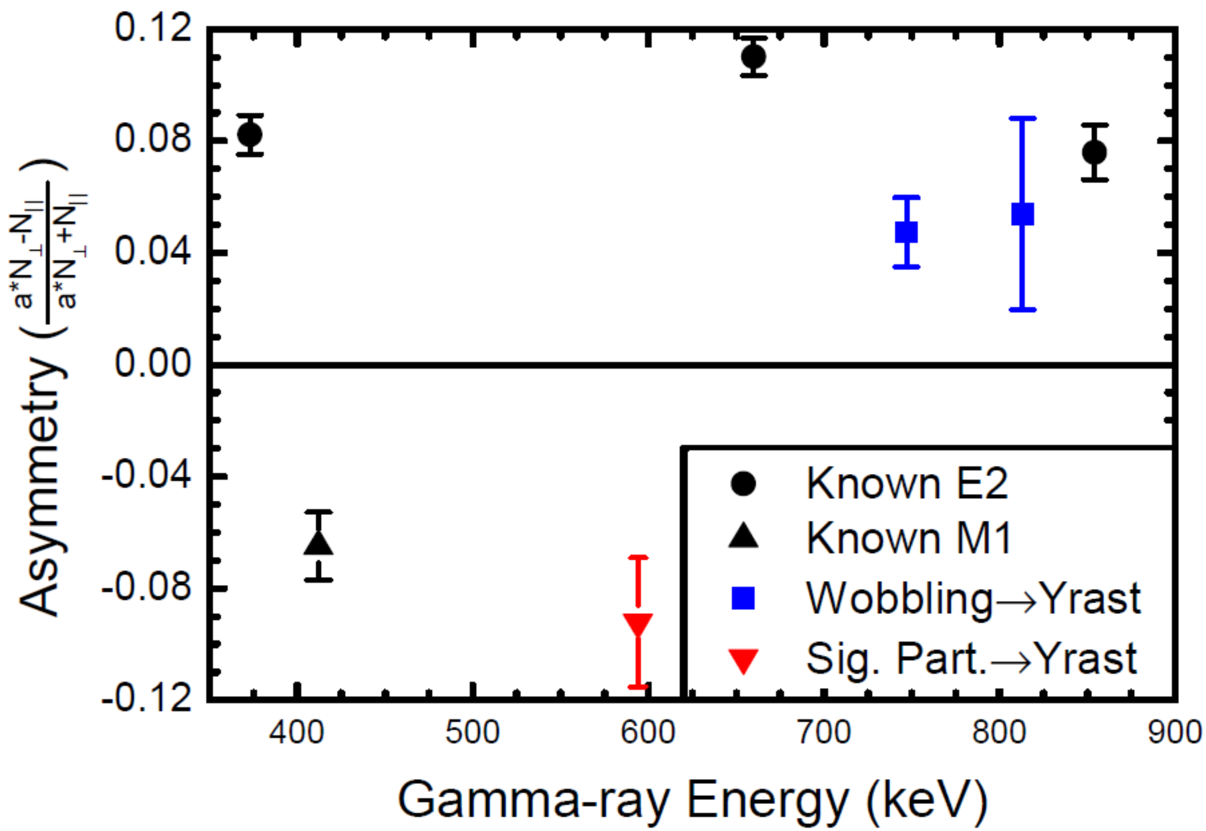
Frauendorf, Doenau, PRC 89, 014322 (2014)

Polarization measurement @ INGA to Establish Wobbling mode in A~130

^{135}Pr level scheme



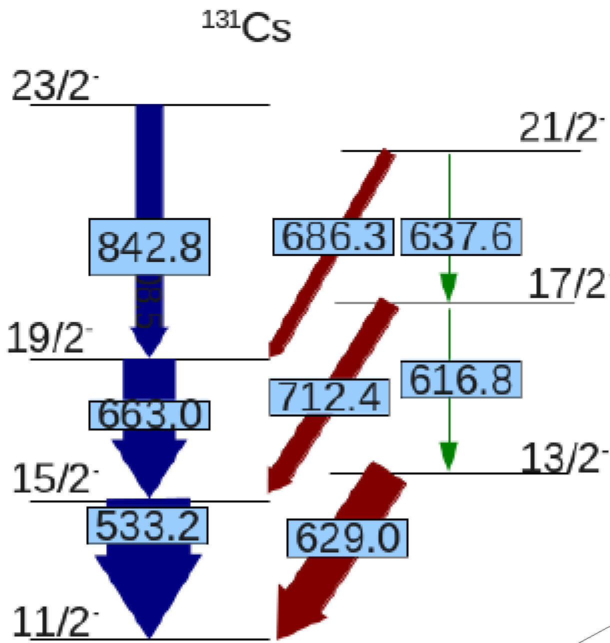
James, Garg et al., PRL (2015)

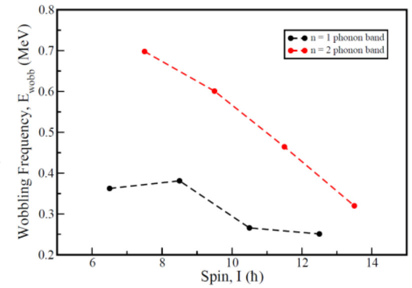


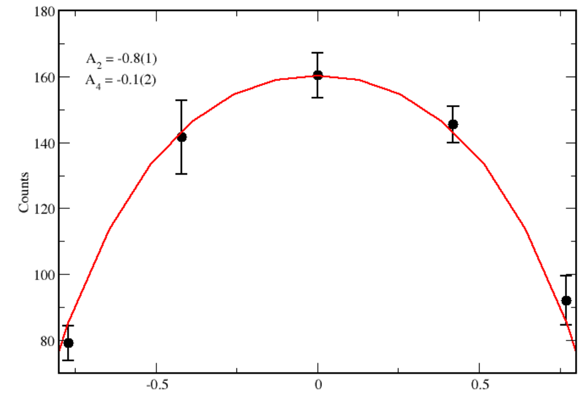
Spectroscopy was performed at Gammasphere.

Search for wobbling mode in A~130 region at low spin

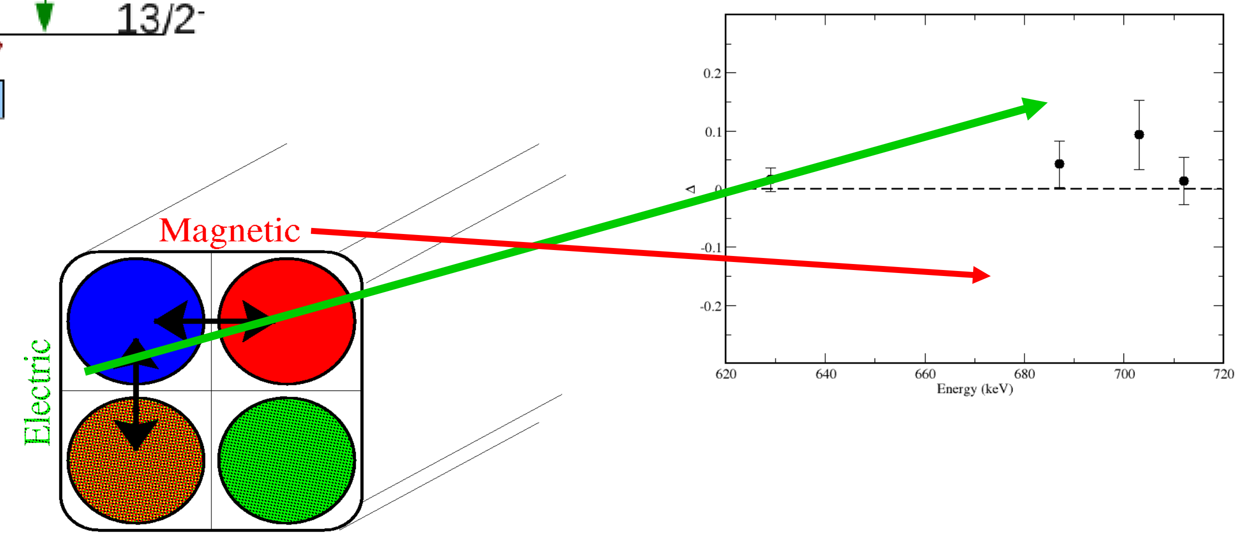
- The polarization measurements confirm ΔI=1 E2 nature of the
- connecting transitions.





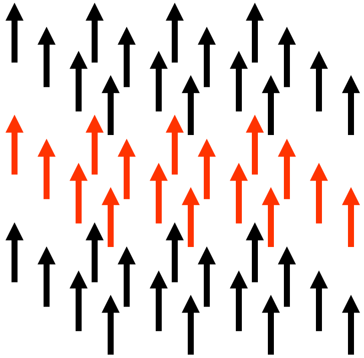


- $T_{1/2}$ = 10 nsec



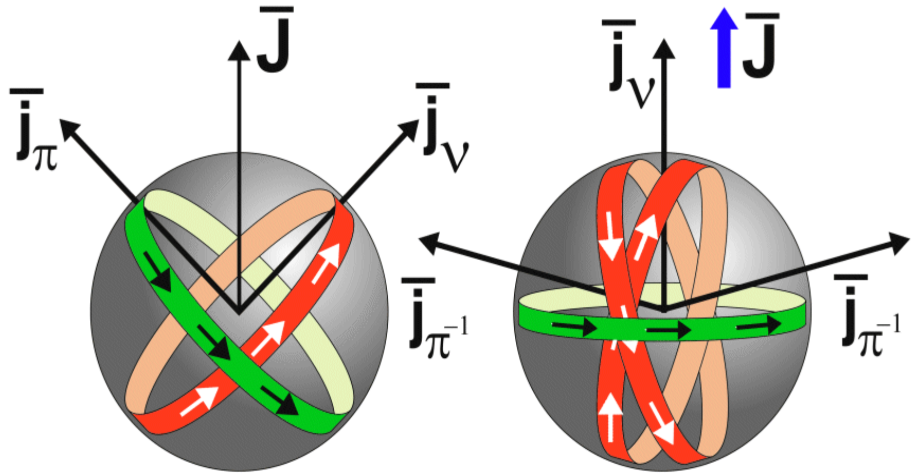
R. Palit et al.,

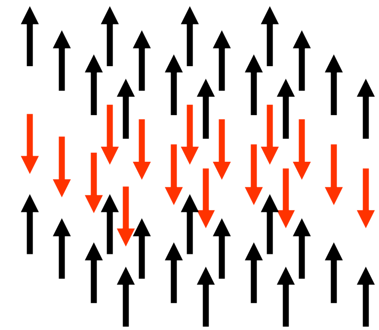
Magnetic & Antimagnetic Rotation



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)

A.J. Simons et al., PRL 162501 (2003)

Unlike MR, AMR: a rare phenomenon.

^{105}Cd, ^{106}Cd, ^{107}Cd, ^{108}Cd, ^{110}Cd

^{104}Pd, ^{112}In

A ~110 and 130

P. Datta et al., PRC 71 041305 (R) (2005)

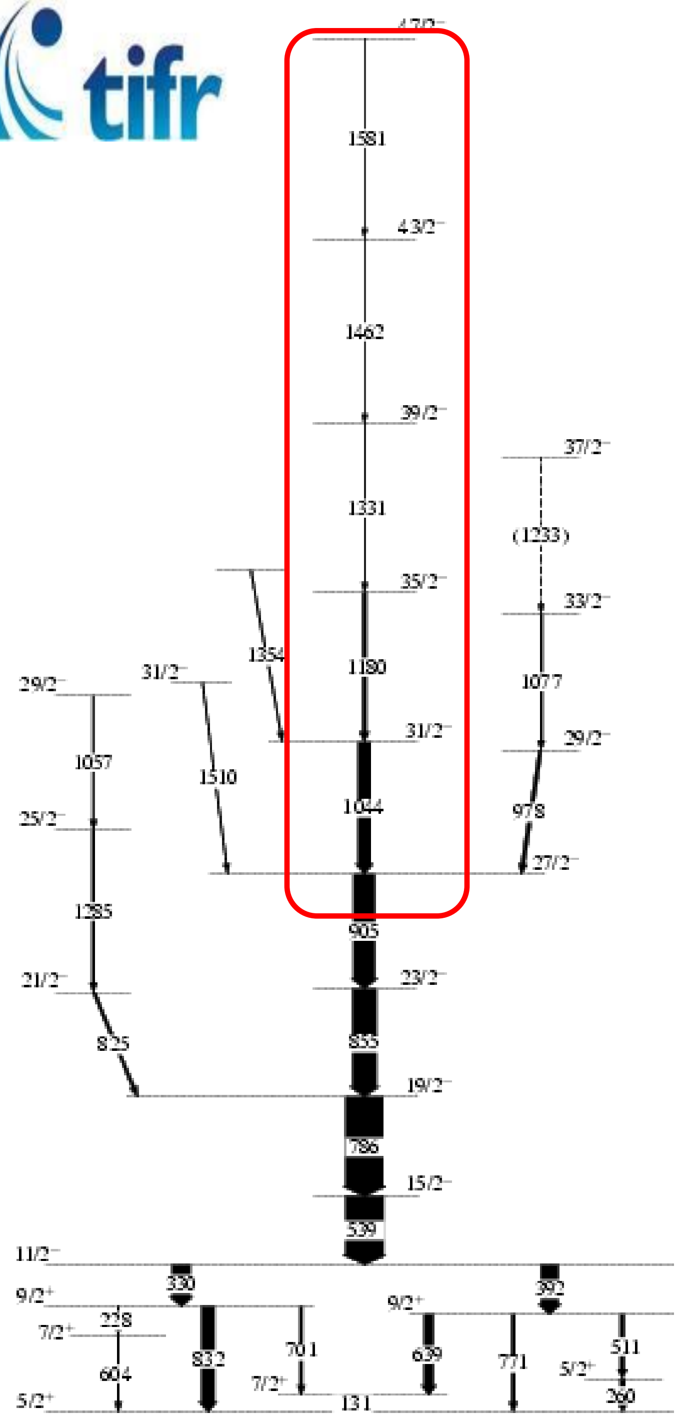
D. Choudhury et al., PRC82 061308(R) (2010)

S. Roy et al., PLB 694 324 (2011)

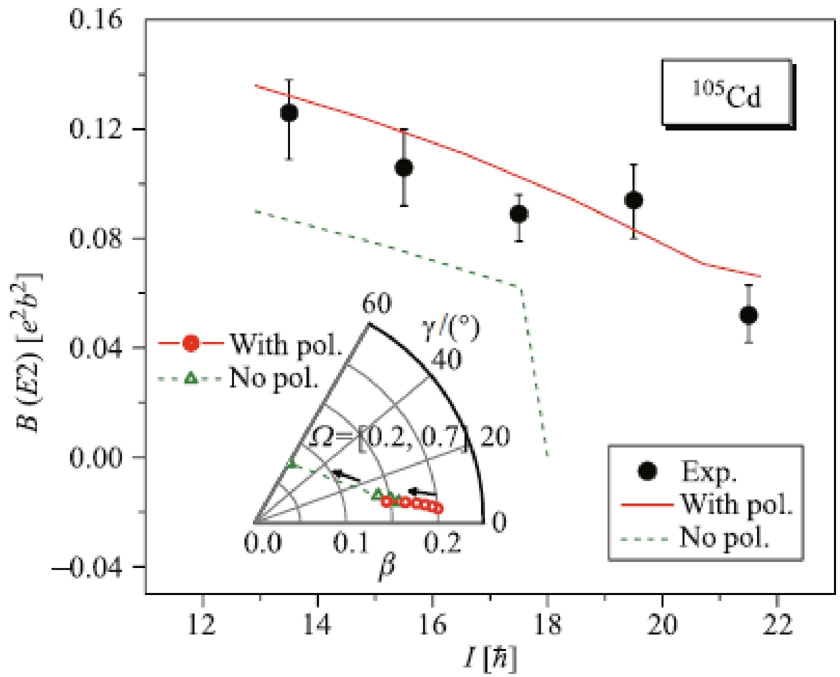
D. Choudhury et al., P.RC 87, 034304 (2013)

N. Rather et al., PRC 89, 061303 (R)(2014)

Microscopic Description of Anti Magnetic Rotation in ^{105}Cd



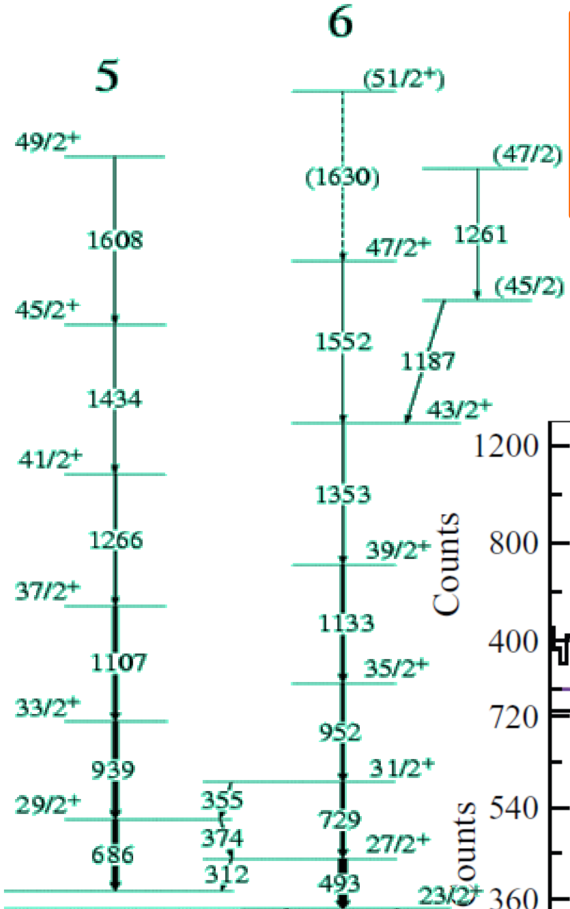
1st evidence of AMR to be operative in an odd-A nucleus

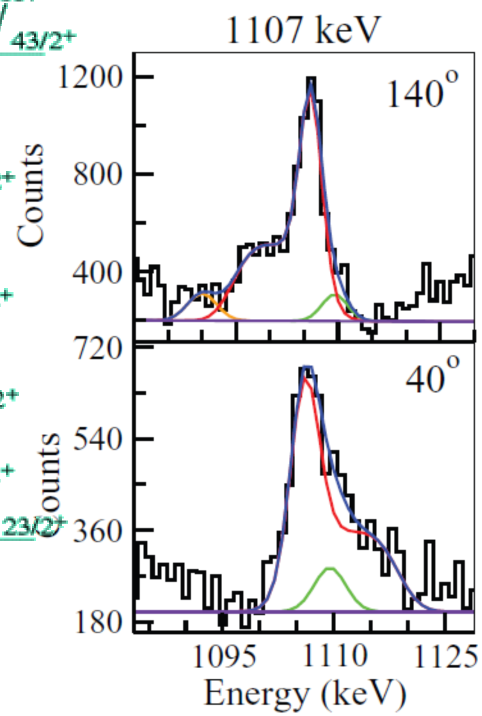


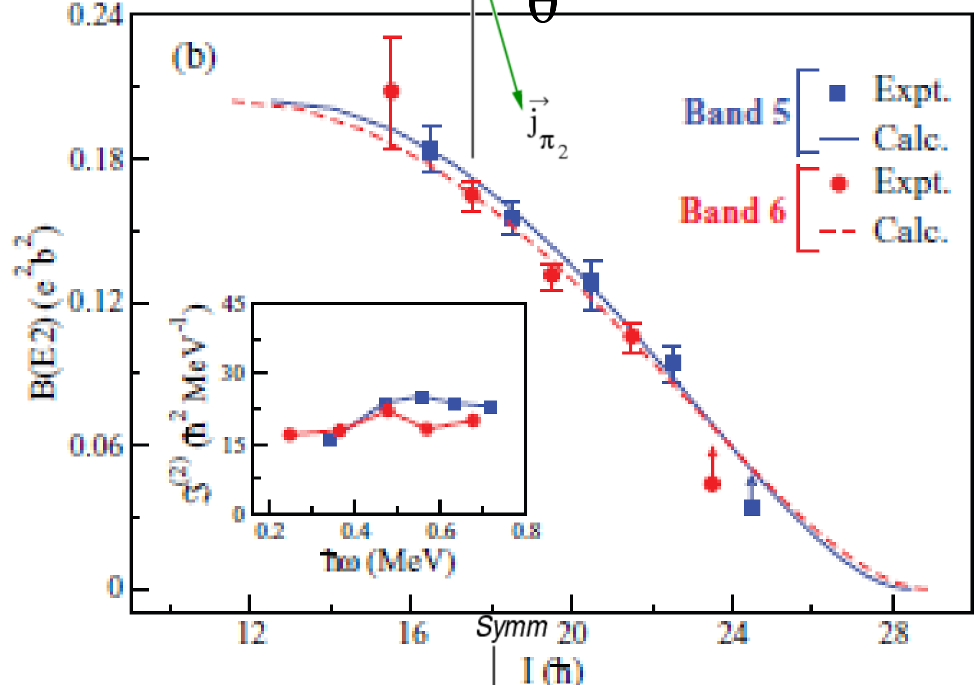
D. Choudhury, et al. PRC82, 061308 (R)(2010)

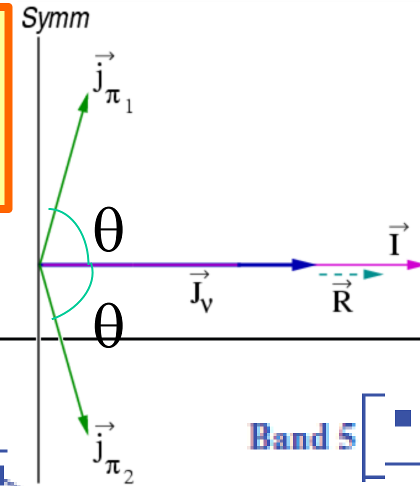
P.W. Zhao, et al., PRL 107, 122501 (2011)

Multiple AMR bands in ^{107}Cd



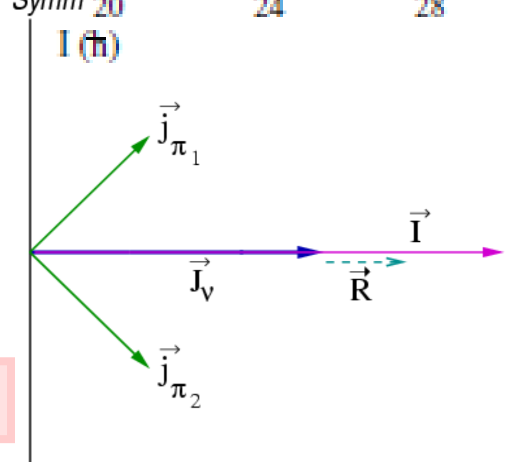






$$\nu\left(g_{7/2}h_{11/2}^{2}\right)\otimes\pi\left(g_{9/2}^{-2}\right)$$

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

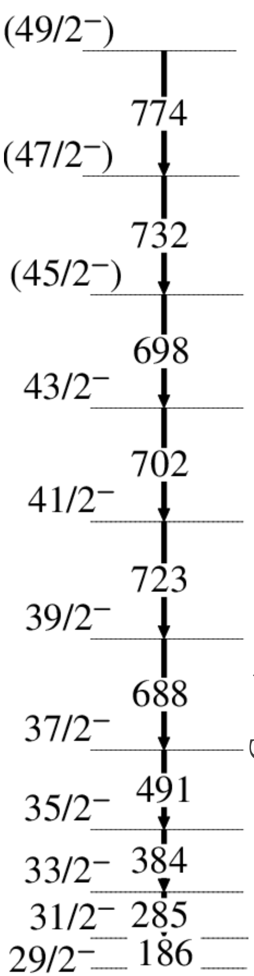


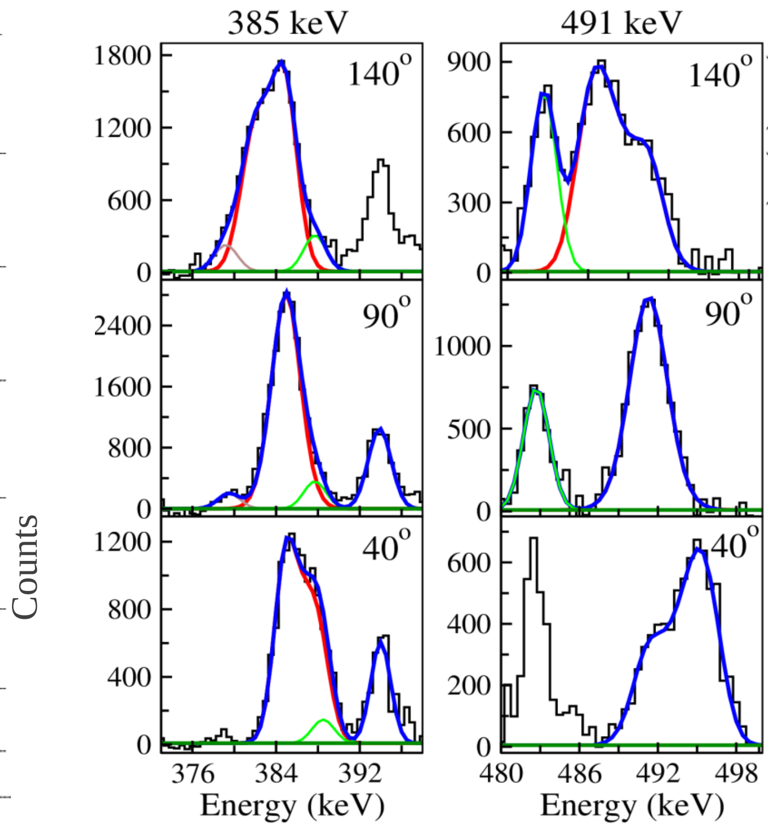
D. Choudhury et al. ***Phys. Rev C 87, 034304 (2013)***

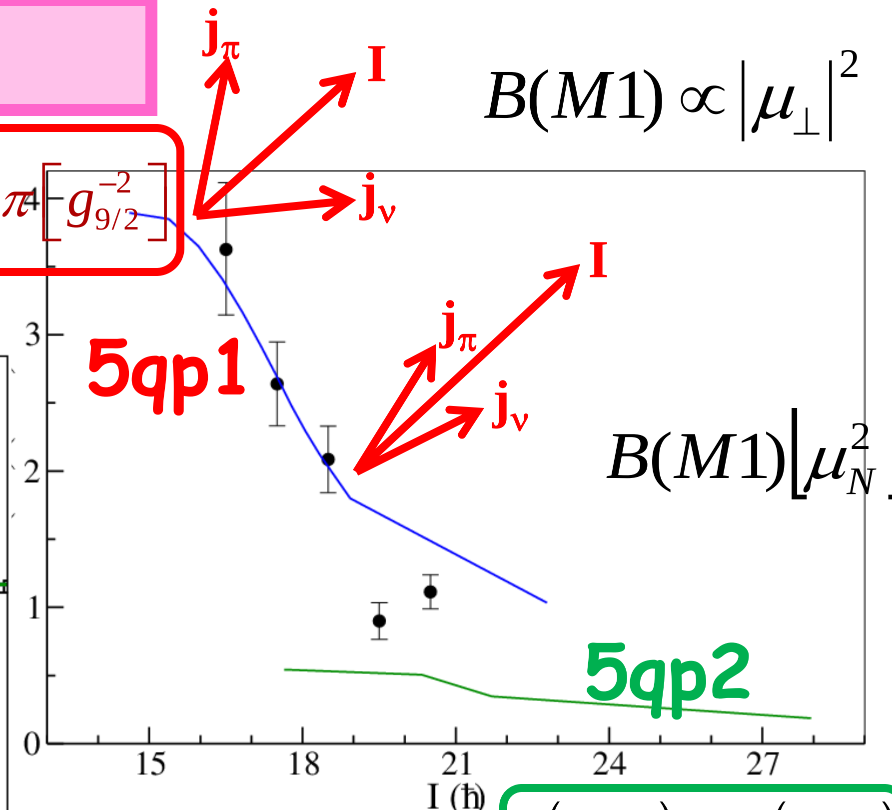
MR Band

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

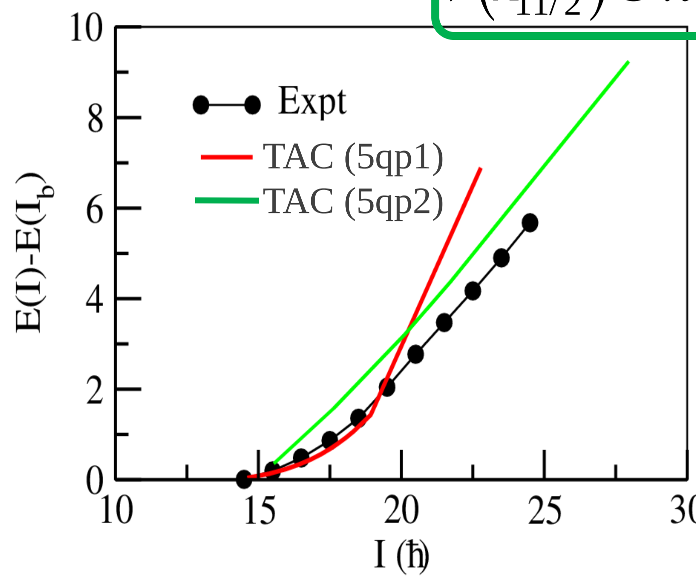
$B(M1)\propto|\mu_\perp|^2$



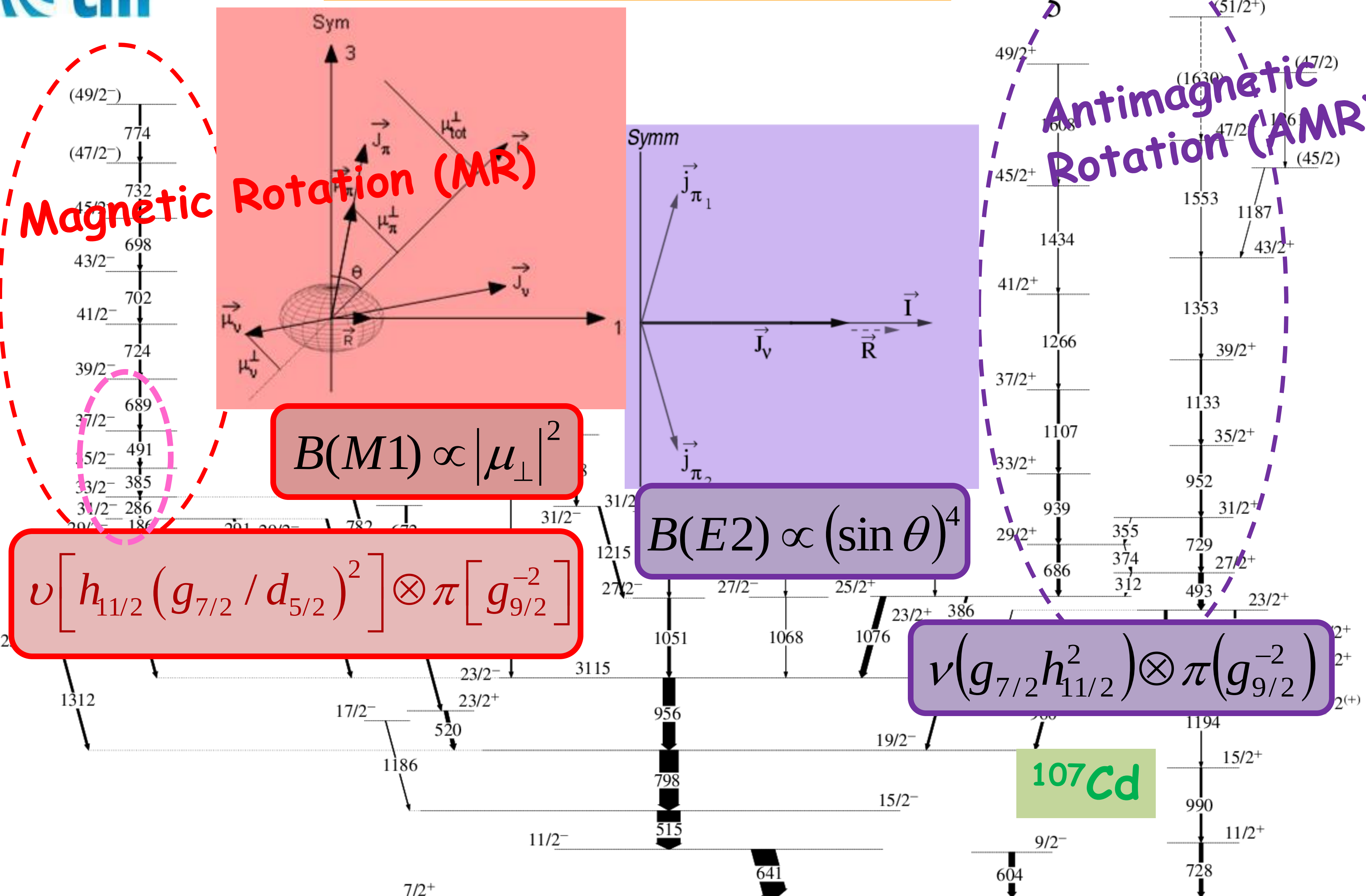




$\nu\left(h_{11/2}^3\right)\otimes\pi\left(g_{9/2}^{-2}\right)$



Coexistence of MR and AMR



$$B(M1) \propto |\mu_\perp|^2$$

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

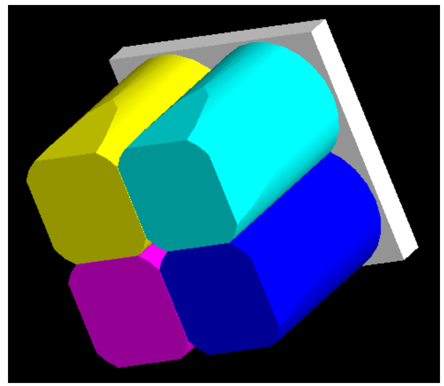
$$\upsilon\left[h_{11/2}\left(g_{7/2}/d_{5/2}\right)^2\right]\otimes\pi\left[g_{9/2}^{-2}\right]$$

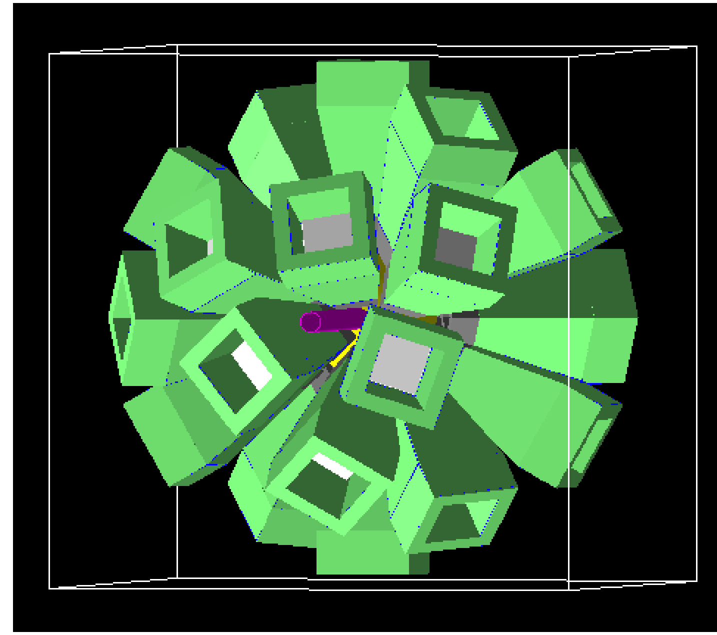
$$\nu\left(g_{7/2}h_{11/2}^2\right)\otimes\pi\left(g_{9/2}^{-2}\right)$$

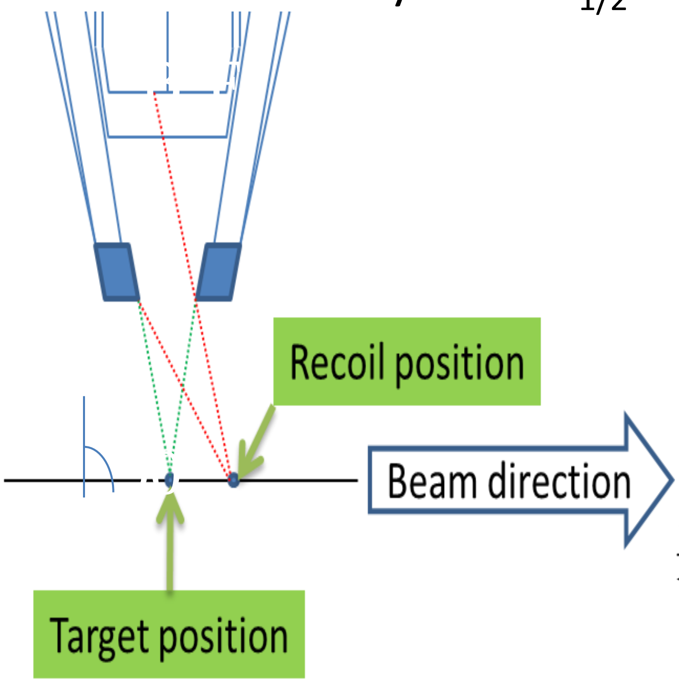
D. Choudhury, R. Palit et al., PRC 91, 014318 (2015)

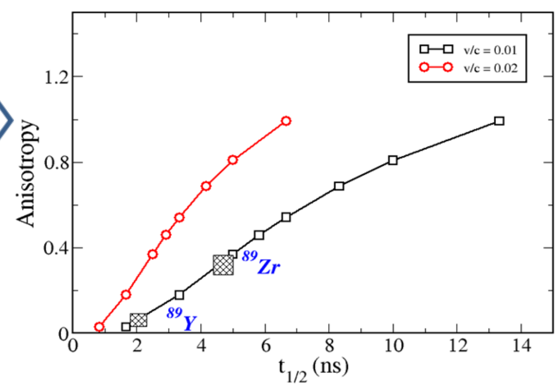
INGA Simulation

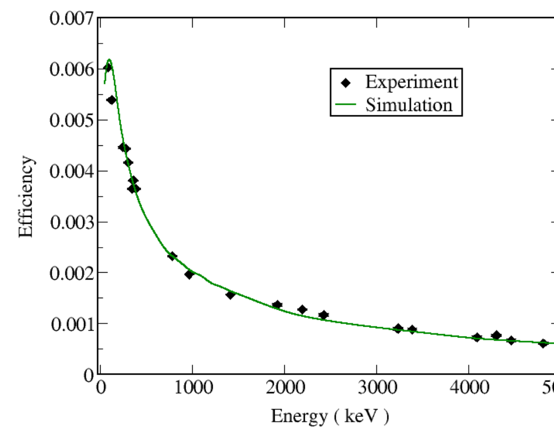
- A full INGA simulation has been performed for studying various properties of the array:
  - Photo-peak efficiency
  - Add-back factor
  - RSAM analysis for $T_{1/2}$





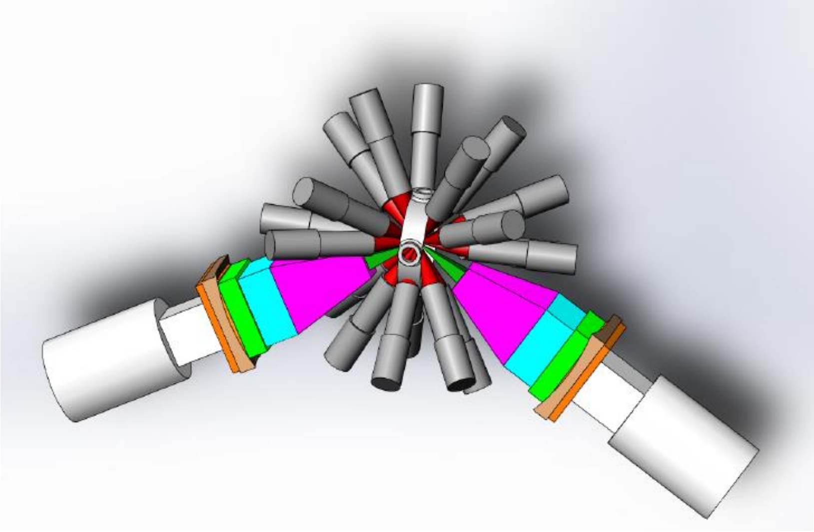


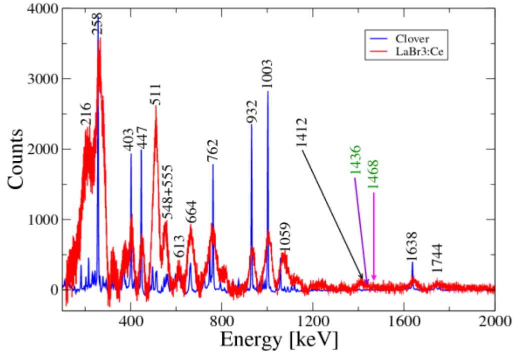


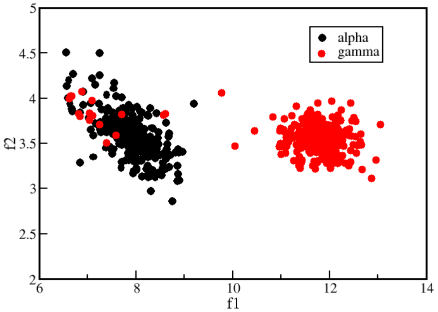


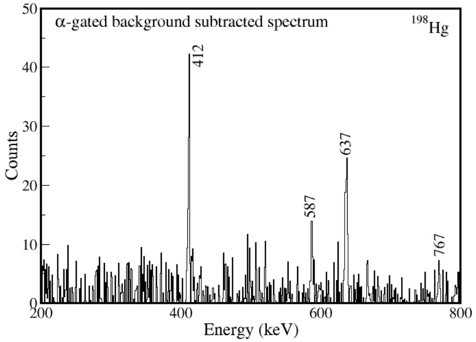
Sudipta *et al.*,

80 element CsI(Tl) detector array and LaBr3(Ce) detector array to be coupled to INGA

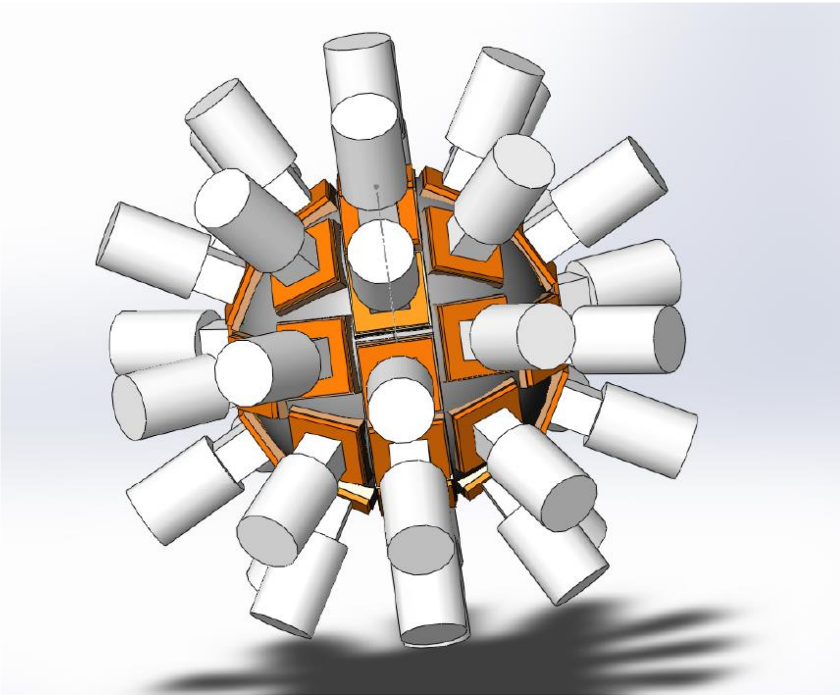








Conceptual Design of HPGe Clover array with ~8% Efficiency



Enhance the solid angle to 40%;
Gamma multiplicity filter;
Need innovative design for BGO shields, collimators; R&D effort;
Ancillary detector;

Need for upgrade of Clover detector resources.
Proposal for complete array in 3 accelerator facilities in near future.

Summary

- Structure of degenerate dipole bands in ^{108}Ag and nearby nuclei.
- MR in ^{112}In indicates axially symmetric shape contrary to predictions.
- Wobbling in A~130 at low spin.
- Coexistence of AMR and MR in ^{107}Cd.

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