Experimental work on degenerate dipole bands with INGA

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

Pelletron Beam hall

Helium Refrigerator

Superbuncher + 3 Modules

4 Modules to new beam hall

Analyzing magnet

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

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

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**

H, He, Li, Be, B, C, O, F, Si, S, Cl, ... Ag, I

**Beams accelerated through Linac**

Li, B, C, O, F, Si, S, Cl
Phase I commissioned on September 22\textsuperscript{nd}, 2002
Phase II commissioned on July 9\textsuperscript{th}, 2007
LINAC dedicated to users on Nov. 28\textsuperscript{th}, 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.
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**

**DSP Implementation for INGA**
- **Up to 96 channels**
- **Operation since 2011 (180 days)**
- **Ancillary detectors (Si and LaBr$_3$(Ce))**

• Motivation
• Results from INGA on exotic rotations
  • Degenerate dipole bands & Chiral rotation
  • Wobbling rotation
  • Magnetic and Antimagnetic rotation
• Future plans with INGA
Global Calculations of Ground-State Axial Shape Asymmetry of Nuclei

Peter Möller, Ragnar Bengtsson, B. Gillis Carlsson, Peter Olivius, and Takatoshi Ichikawa

Effect of Axial Asymmetry on Nuclear Mass

Rotation of Triaxial Nuclei
Rotation of Triaxial Nuclei

Chiral Rotation

Wobbling Mode

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

Frauendorf, Doenau, PRC 89, 014322 (201)

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 $A \sim 110$

High spin Spectroscopy of $^{112}\text{In}$, $^{108}\text{Ag}$, $^{106}\text{Ag}$ isotopes have been carried out with Indian National Gamma 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)
108Ag : Experimental Details

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

- Reaction for lifetime : \[ ^{94}\text{Zr}(_{18}\text{O},p3\gamma)^{108}\text{Ag} \]
- Detector set-up : INGA at TIFR with 21 Compton suppressed HPGe Clover detectors
- Pixie-16 DDAQ from XIA
- Target : \[ ^{94}\text{Zr} \text{ (0.9 mg/cm}^2 \text{)} \text{ backed with 10 mg/cm}^2 ^{197}\text{Au.} \]
- Beam : \( ^{18}\text{O} \text{ at 72 MeV.} \)
$^{108}$Ag : Level Scheme

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

Twin Bands of $^{108}$Ag

Partial Level Scheme and double gated spectra

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

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

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

Within ~500 keV
Two $10^+$ isomers with $-ve$ g-factor
The $\gamma$-bands built on the qp configurations modify the band crossing features.

Two-qp $\gamma$-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.

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

J. Sethi $^a$, R. Palit $^{a,b}$, 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 $^i$, D. Mehta $^j$, B.S. Naidu $^a$, Z. Naik $^j$, S. Sihotra $^l$, P.M. Walker $^k$

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

\[
\pi g_{9/2}^{-1} x \nu h_{11/2}
\]
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.

P. Joshi et al., PRL 98 102501(2007)
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$^4$

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(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 $A \sim 100$ nuclei

W.A. Dar$^1$, J.A. Sheikh$^{1,2}$, G.H. Bhat$^1$, R. Palit$^3$ and S. Frauendorf$^4$
Experimental Details

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

Lifetime measurements for bands A, C and D were performed.
Lifetime measurement in $^{112}$In

Positive parity band A

Comparison of $B(M1)$ values with TAC

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

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

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Physics Highlights of INGA Collaboration

- Isomer depletion
- Test of shell model interaction at extreme anti-magnetic rotation
- Fission dynamics
- Gamma softness of Cs isotopes
- Weakly bound nuclei
- Physics Highlights of INGA Collaboration
- Chiral rotation
- Nuclear wobbling
Wobbling mode in odd-A triaxial nuclei

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

Frauendorf, Doenau, PRC 89, 014322 (2014)
Polarization measurement @ INGA to Establish Wobbling mode in A~130

$^{135}$Pr level scheme

Spectroscopy was performed at Gammasphere.

James, Garg et al., PRL (2015)
The polarization measurements confirm $\Delta l=1$ E2 nature of the connecting transitions.

$T_{1/2} = 10 \text{ nsec}$

R. Palit et al.,
Magnetic & Antimagnetic Rotation

Ferromagnet

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

Anti-Ferromagnet

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

Magnetic rotor

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

$^{104}$Pd, $^{112}$In

A ~110 and 130

S. Frauendorf  Rev. Mod Phys 73, 463(2001)

Unlike MR, AMR: a rare phenomenon.

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

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

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

MR Band

\[ B(M1) \propto |\mu_\perp|^2 \]

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

Counts

\( 2 \)

\( h g d g \nu p \)

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

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

\[ (49/2^-) \]

\[ (47/2^-) \]

\[ (45/2^-) \]

\[ 43/^- \]

\[ 41/^- \]

\[ 39/^- \]

\[ 37/^- \]

\[ 35/2^- \]

\[ 33/2^- \]

\[ 31/2^- \]

\[ 29/2^- \]

\[ 774 \]

\[ 732 \]

\[ 698 \]

\[ 702 \]

\[ 723 \]

\[ 688 \]

\[ 491 \]

\[ 384 \]

\[ 285 \]

\[ 186 \]

\[ 385 \text{ keV} \]

\[ 491 \text{ keV} \]

Energy (keV)
Coexistence of MR and AMR

Magnetic Rotation (MR)

\[ B(M1) \propto |\mu_\perp|^2 \]

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

\[ B(E2) \propto (\sin \theta)^4 \]

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

107Cd

D. Choudhury, R. Palit et al., PRC 91, 014318 (2015)
A full INGA simulation has been performed for studying various properties of the array:
- Photo-peak efficiency
- Add-back factor
- RSAM analysis for $T_{1/2}$
80 element CsI(Tl) detector array and LaBr3(Ce) detector array to be coupled to INGA
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 $A\sim130$ 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