Recent Results from INGA

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Outline:
- New features of the array at TIFR
- Recent results
- Future possibilities
INGA campaigns at different accelerator facilities

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Mounting position for 24 Clovers ($\varepsilon_p \sim 5\%$)

- 3 at $23^\circ, 40^\circ, 65^\circ, 115^\circ, 140^\circ, 157^\circ$ and 6 at $90^\circ$

- Detectors -> DSP cards -> PCI Bridge -> PC -> Gigabit -> PC
Technical specifications

- 100 MHz & 12-bit ADC's
- Data rate: 80 MB/sec
- Particle ID in CsI detectors using digital pulse shaping
- Trigger less system
- XIA based system

H. Tan et al., NSS 08, IEEE (2008) p 3196

Implementation for INGA

- Modular so easily expandable
- Versatile with complex trigger
- High count rate
- High stability
- Zero dead-time
- Long lived isomer measurements

R. Palit, AIP Conf Proc. 1336 (2011) 573
Angular Distribution & Polarization

- Singles measurement with 60 crystals each counting at 4-5 kHz
- Total throughput is 260 kHz
- Data rate: 15 MB/sec
- Trigger less mode
- Cross section measurement

DDAQ has increased the data throughput by 10 times for INGA
Long Lived Isomers near $N=50$

A. Chakrabarti, et al. PRC 72, 054309 (2005)

Reconfirmed the previous reported $T_{1/2} = 460 (10)$ nsec

$^{28}\text{Si} + ^{65}\text{Cu} @ 105 \text{MeV}$

T-stamped data

A. Chakrabarti, et al. PRC 72, 054309 (2005)
Indian National Gamma detector Array for high resolution spectroscopy of atomic nuclei

How does simple pattern emerge in excitation of complex nuclei?
What are the different patterns possible?
How are they related with symmetry and correlations present in nuclei?
What are the limits when the ordered pattern will disappear?
Physics Focus of INGA

Structure of heavy nuclei
- Octupole correlations
- Effect of shape driving orbitals

Isomers near shell closure
High-K isomers
Isomers for application

Fusion of weakly bound nuclei
Fission dynamics

High spin states near shell-inversion
- \( ^{18}\text{O} + ^{18}\text{O} \)
- Super-deformation

- Exotic rotations
- Symmetry

A\( \sim 110, 130 \)

A\( \sim 200-240 \)

sd-shell
Recent results from INGA

Search for multiple chiral bands

Axial asymmetry in Cs isotopes

Anti-magnetic rotation in $^{105}$Cd
A high speed digital data acquisition system for the Indian National Gamma Array at Tata Institute of Fundamental Research


Tata Institute of Fundamental Research, Colaba, Mumbai 400 005, India
XIA LLC, Hayward, CA 94544, USA

PHYSICAL REVIEW C 82, 061308(R) (2010)

Evidence of antimagnetic rotation in odd-A $^{105}$Cd


PHYSICAL REVIEW C 86, 034315 (2012)

Experimental investigation of shell-model excitations of $^{89}$Zr up to high spin


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Electric and Magnetic Rotations

$\Delta I = 2$
E2 Transitions

$\Delta I = 1$
M1 Transitions

Twin PRL1986

Hübel PPNP2005
Magnetic Rotation

Observed in 78 nuclei: Role of deformation and beyond MR

Proton Number Z vs. Neutron Number N

Stable Nuclei

A~60
A~80
A~110
A~130
A~190

r-process path
High spin structure of $^{112}$In
Lifetime measurement for dipole band in $^{112}$In

Doppler Shift Attenuation study for sub-pico sec $T_{1/2}$ levels decaying by 272, 393, 554, and 708 keV transitions.
Comparison of $B(M1)$ values with TAC calculations

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

TAC configuration
\[ \pi g_{9/2} - \nu((h_{11/2})^2d_{5/2}/g_{7/2}) \]
\[ \varepsilon_2 = 0.12 \text{ and } \gamma = 6^0 \]
\[ \varepsilon_2 = 0.08 \text{ and } \gamma = 5^0 \]

T. Trivedi, et al., PRC85 (2012)
Magnetic & Antimagnetic Rotation

- Rotational bands with $\Delta I = 1$
- Near spherical nuclei
- Weak E2
- Strong M1
- $B(M1)$ decreasing with freq
- Shears mechanism

- Rotational bands with $\Delta I = 2$
- Near spherical nuclei
- Weak E2
- No M1
- $B(E2)$ decreasing with spin
- Two-shears mechanism

S. Frauendorf  Rev. Mod Phys 73, 463(2001)
Anti Magnetic Rotation in $^{105}$Cd

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

$B(E2) = \frac{15}{32\pi} (eQ)_{\text{eff}}^2 \sin^4 \theta$

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

D. Choudhury, et al. PRC82, 061308 (R)(2010)
Microscopic Description of Anti Magnetic Rotation in $^{105}$Cd

D. Choudhury, et al. PRC82, 061308 (R)(2010)
Zhao, et al., PRL 107, 122501 (2011)
First evidence of 2 AMR bands in one nucleus.
Present work

$E_{\text{exc}} = 11.4$ MeV

Spin $= 30 \hbar$

Core excitations beyond maximally aligned configurations in $^{122}$I

Core-excitations

Level scheme of $^{122}$I

Aligned and anti-aligned states

Proton (Z=53)
\[ \pi(d_{5/2}g_{7/2})^2(h_{11/2})^1_{11/2}; \quad I^\pi_{\text{max}} = 23/2^- , \]

Neutrons (N=69)
Neutrons (maximally-aligned configuration)
\[ \nu(h_{11/2})_{35/2}(s_{1/2}d_{3/2})^0_0; \quad I^\pi_{\text{max}} = 35/2^- \]
\[ \nu(h_{11/2})_{16}^4(s_{1/2}d_{3/2})^1_{3/2}; \quad I^\pi_{\text{max}} = 35/2^+ \]
I_{\text{max}}=29+,29-

Neutrons (anti-aligned configuration)
\[ \nu(h_{11/2})_{21/2}(s_{1/2}d_{3/2})^0_0; \quad I^\pi_{\text{max}} = 21/2^- \]
\[ \nu(h_{11/2})_{8}^4(s_{1/2}d_{3/2})^1_{3/2}; \quad I^\pi_{\text{max}} = 19/2^+ \]
I_{\text{max}}=22+,21-

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

ΔEγ (MeV)

Proton Number Z

Neutron Number N
Odd-odd Isotopes near $A \sim 110$

Detailed Spectroscopy of $^{112}$In & $^{108}$Ag isotopes using INGA

Meng et. al. PRC73 037303 (2006)
Exotic 3-dim Rotation of Nuclei

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

Chiral Rotation

FIG. 1. Rotational spectra of a triaxial rotor Hamiltonian. Horizontal rotational bands are connected by solid lines; vertical phonon bands, by dotted lines.
Degenerate dipole bands of $^{108}\text{Ag}$

Two degenerate dipole bands have been identified with linking M1 and E2 transitions.

$^{11}\text{B} + ^{100}\text{Mo} @ 39 \text{ MeV}$

$\pi g_{9/2} \otimes \nu h_{11/2}$ Two degenerate dipole bands have been identified with linking M1 and E2 transitions.
Triaxial projected shell model study of chiral rotation in odd–odd nuclei

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\(^b\) Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA
\(^c\) Department of Nuclear and Atomic Physics, Tata Institute of Fundamental Research, Colaba, Mumbai, 400 005, India
Projected Shell Model Calculation

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


Degenerate bands reproduced with triaxial deformations 
\( \varepsilon_2 = 0.19 \quad \varepsilon' = 0.135 \)

J. Sethi, R. Palit, et al.
High spin states of nuclei near \( N=50 \)

- Positive & negative parity bands up to high spin using polarization measurements.
- Negative parity high spin states using proton excitations \( p_{3/2} \) & \( f_{5/2} \) to \( g_{9/2} \)
- Thin target data to look for higher spin states

Emergence of collectivity at high spin in spherical nuclei.
Emergence of collectivity at high spin in spherical nuclei

CNS Calculations
Some of the key future experiments with particle gamma coincidence

• Identify candidates for prompt proton emission outside of $Z \sim 28$, $N \sim 28$
  – Possibly neutron-deficient Te isotopes?

• Study astrophysically important nuclei around $N=Z$ line

• Heavy nuclei spectroscopy with tagging on fast particle emission

• Investigation of proton rich nuclei in light mass region

• Investigation of lifetime of states in quasi-continuum
Summary

New features of INGA coupled to a DDAQ (increased data throughput (~10 times) compared to our previous analogue readout scheme)

Results of search for chiral bands in $^{108}\text{Ag}$ & $^{112}\text{In}$

Anti-magnetic rotation in $^{105,107}\text{Cd}$

Regular structure at high spin in spherical nucleus $^{89}\text{Zr}$

Core excitations in $^{122}\text{I}$

Addition of ancillary detectors, HYRA spectrometer at IUAC and overall efficiency will enhance its capability for the investigation of

Nuclear structure with varying $J$ & $T(N-Z)$ for probing

- Different phases, their coexistence & transitions
- Insight for shell structure and residual interactions
Collaboration & Acknowledgements

S. Saha, J. Sethi, T. Trivedi, S. Biswas,

B.S. Naidu, P.B. Chavan, S. Jadhav, R. Donthi

D. Choudhury, S. Sharma, Z. Naik, P. Singh, A.Y. Deo, H. Pai, S. Kumar, G. Mukherjee, S. Sihotra,

D. Mehta, A.K. Jain

P.K. Joshi, P. Verma, S. Sinha

And INGA Collaboration


S.K. Sarkar

Pelletron-Linac staff members, Central Workshop & LTF of TIFR
Thank You
Single particle levels near $Z \sim 114$ $N \sim 164$ shell gaps influence the structure of rotational bands for lighter nuclei.
Structure of $^{234}\text{U}$ with ICF

Experimental Condition:
- 52 MeV 9Be beam
- 1 mg/cm$^2$ self supporting 232Th target
- $4 \times 10^6$ a-g-g coincidence
- 6 CS-HPGe (25%)

Coincidence with CPD array
ICF ER: 10 mb
ER: $\sim$ 5 mb

G. J. Lane et al. page 304, NS98
Study of Octupole correlations in Np isotopes

- In U-Pu-Cm region, the pairs $j_{15/2} \otimes g_{9/2}$ neutrons and $i_{13/2} \otimes f_{7/2}$ protons are at the Fermi surface.

- Octupole Correlations are strongest when the pair of orbits with $\Delta j = \Delta \ell = 3$ are near the Fermi Surface.

- Strong octupole correlations are observed for the nuclei $^{238-244}\text{Pu}$.

- Would like to populate $^{235}\text{Np}$ using $^7\text{Li}(^{232}\text{Th},xn)$ reaction at 50 MeV.
Future experiments with INGA coupled to ancillary detectors and Spectrometer

- Structure of high spin isomers
- Structure of heavy nuclei with $A > 200$
- Heavy nuclei spectroscopy with tagging on fast particle emission
- Identify candidates for prompt proton emission outside of $Z \sim 28, N \sim 28$
  - Possibly neutron-deficient Te isotopes?
- Study of important nuclei around $N=Z$ line
- Investigation of proton rich nuclei in light mass region
- Investigation of quasi-continuum to look for nuclear shape evolution and dynamics
Dual mode of Operation of HYRA at IUAC

Vacuum Mode:
- For $A < 100$ amu
- Inverse Kinematics
- Good beam rejection (two stage filter)
- Good Collection Efficiency (kinematics)
- $Z, A$ identification using $X, \Delta E, E$ and $T$

Gas-Filled Mode:
- For $A > 200$ amu
- Normal Kinematics
- Good beam rejection (charge equilibrium)
- Good Collection Efficiency ($q, v$ focus)
- $Z, A$ identification using recoil decay tagging
High spin states of nuclei near $N=50$

$^{13}\text{C} + ^{80}\text{Se} @ 60$ MeV; Thin target

Sum of double gates

High spin states in $^{89}$Zr

- A regular sequence of $\Delta I = 1$ magnetic transitions
- Spin range: $(33/2^+ \text{ up to } 49/2^+)$
- $\hbar^2/2I \sim 14 \text{ keV}$
- M.I. Similar to $^{93}$Nb and $^{131}$La
- No cross-over E2 (high K)
- Need to wait for getting confirmation for precession mode as predicted near shell closure
What is expected for chiral scenario (general)

Chiral vibration near the band head \((I < I_c)\)

Near degeneracy at sufficient spin (chiral tunneling induces energy separation) \((I > I_c)\)

Small inter band E2 transitions \((I > I_c)\)

Identical band properties

Shape

Moment of inertia

Identical/similar intra band B(M1) & B(E2)

Spin independence of \(S(I) = [E(I)-E(I-1)]/2I\): small Coriolis and deformation aligned geometry with a triaxial core (all \(I\))
Most consistent with chiral interpretation: $^{135}$Nd

$\pi h_{11/2}^2 \nu h_{11/2}$

$^{110}$Pd ($^{30}$Si, 5n)

0.5mg/cm$^2$ X 2

Gam.Sph.(LBNL)

$\gamma \gamma \gamma \gamma \gamma \leq$ trigger

S. Zhu et al., PRL91 132501, 2003
Cryostat modules housing the resonators with liquid He distribution box

Critical components of LINAC are designed, developed and fabricated indigenously

Specifications

Heavy ions upto A~80
E/A~5-12 MeV

Energy gain 14MV/q
Module 7 nos
Resonators 28 nos

Bunch width ~200 ps
Beam Intensity 0.1-10 pnA

Quarter Wave Resonators

Material
Superconducting surface
Frequency
Cavity Length
Cavity Diameter
Optimum velocity
Design goal

OFHC Cu
2 µm thick. Pb
150 MHz
64 cm
20 cm
β=0.1
2.5 to 3 MV/m
@ 6 to 9 Watts

R.G. Pillay et al.
Basic Configuration at TIFR from 2010

- Set up in Beam hall II of TIFR-BARC (LINAC beam hall)
- Mounting position for 24 Clovers (~5% \( \varepsilon_p \))
- Movement on rails for precision alignment
- Space for mounting Charged Particle Array
- 3 at 23°, 40°, 65°, 115°, 140°, 157° and 6 at 90°
Basic characteristics of DDAQ

- Clover Add-back: ~22% (BGO off), ~40% (BGO on)
- Single crystal: ~10% (BGO off), ~15% (BGO on)

152Eu spectrum for calibration

Counts vs. Channel

Counts vs. Time Difference (msec)

Counts vs. Time Difference (10 nsec)
Fig 3. Comparison of neutron gated spectrum with singles spectrum

AMR in $^{105}$Cd

1st evidence of AMR to be operative in an odd-A nucleus
Timing with Fast Scintillators $\text{LaBr}_3(\text{Ce})$
**Particle-gamma Coincidence**

**α gated γ spectra :** $t + {}^{198}\text{Pt} : {}^{201}\text{Au}^*$ (ERs $^{198}\text{Au}, {}^{199}\text{Au}$)

**t gated γ spectra :** $α + {}^{198}\text{Pt} : {}^{202}\text{Hg}^*$ (ERs $^{200}\text{Hg}, {}^{199}\text{Hg}$)

A. Srivastava, et al.
Reduced transition probability $B(M1)$ values decreases rapidly with increasing spin, showing the shears mechanism. Experimental values are in good agreement with TAC calculations. Weakly deformed axially symmetric structure contrary to the prediction of RMF calculations which indicates multiple chiral bands on triaxial deformation. A pair of degenerate dipole bands have been identified in $^{108}\text{Ag}$. TPSM calculations reproduce the degenerate bands. Need to do lifetime measurements to confirm the predictions of RMF calculations.
108Ag

**High spin states of nuclei near N=50**

**Motivation:**
- Shape isomers in high spin states near shell closure
- Precession mode predicted
  - Shimuzu et al. PRC72 (2005)

High spin Isomers with two LaBr$_3$(Ce) coupled to INGA

$^{89}$Zr: 1944 – 780 – 270 – 1740 cascade extending the level scheme to 25/2$^+$

Sudipta et al.
Evidence of antimagnetic rotation in odd-\(^{105}\text{Cd}\)

Deepika Choudhury,\(^1\), A. K. Jain,\(^1\) M. Patial,\(^1\) N. Gupta,\(^1\) P. Arumugam,\(^1\) A. Dhal,\(^2,6\) R. K. Sinha,\(^2\) L. Chaturvedi,\(^3\) P. K. Joshi,\(^4\) T. Trivedi,\(^4\) R. Palit,\(^4\) S. Kumar,\(^5\) R. Garg,\(^5\) S. Mandal,\(^5\) D. Negi,\(^6\) G. Mohanto,\(^6\) S. Muralithar,\(^6\) R. P. Singh,\(^6\) N. Madhavan,\(^6\) R. K. Bhowmik,\(^6\) and S. C. Pancholi\(^6\)

Structural change of the unique-parity \(\pi h_{11/2} \otimes \nu h_{11/2}\) configuration in \(^{134}\text{Cs}\)

H. Pai,\(^1\) G. Mukherjee,\(^1,6\) A. Raghav,\(^2\) R. Palit,\(^2\) C. Bhattacharya,\(^1\) S. Chanda,\(^3\) T. Bhattacharjee,\(^1\) S. Bhattacharyya,\(^1\) S. K. Basu,\(^1\) A. Goswami,\(^4\) P. K. Joshi,\(^2\) B. S. Naidu,\(^2\) Sushil K. Sharma,\(^2\) A. Y. Deo,\(^2,6\) Z. Naik,\(^2,6\) R. K. Bhowmik,\(^5\) S. Muralithar,\(^5\) R. P. Singh,\(^5\) S. Kumar,\(^6\) S. Sihotra,\(^7\) and D. Mehta\(^8\)

Small quadrupole deformation for the dipole bands in \(^{112}\text{In}\)

T. Trivedi,\(^1\) R. Palit,\(^1,6\) J. Sethi,\(^1\) S. Saha,\(^1\) S. Kumar,\(^2\) Z. Naik,\(^1\) V. V. Parkar,\(^1,6\) B. S. Naidu,\(^1\) A. Y. Deo,\(^1\) A. Raghav,\(^1\) P. K. Joshi,\(^1\) H. C. Jain,\(^1\) S. Sihotra,\(^3\) D. Mehta,\(^3\) A. K. Jain,\(^4\) D. Choudhury,\(^4\) D. Negi,\(^5\) S. Roy,\(^6\) S. Chattopadhyay,\(^6\) A. K. Singh,\(^7\) P. Singh,\(^7\) D. C. Biswas,\(^8\) R. K. Bhowmik,\(^5\) S. Muralithar,\(^5\) R. P. Singh,\(^5\) R. Kumar,\(^5\) and K. Rani\(^5\)