Nuclear structure studies at VECC using INGA

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Plan of the Talk

Introduction

Beams and detection system for gamma ray spectroscopy at VECC: VENUS and INGA setup

Physics issues addressed in the recent INGA campaign

Transition from chiral to MR band in nuclei

Summary
Introduction

Shells and Shapes in Nuclei

$R(\theta,\phi) = R_{ave} \left[ 1 + \beta Y_{20}(\theta,\phi) \right]$

$\beta$ is “deformation parameter” given by

$$\beta = \frac{4}{3\sqrt{5}} \frac{\Delta R}{R_{ave}}$$

$\Delta R = a - b$

$\beta > 0$ prolate ; $\beta < 0$ oblate

$\beta_2$: amount of deformation
$\gamma$: Nature of deformation

$\gamma = 0^o \rightarrow$ Prolate
$\gamma = -60^o \rightarrow$ Oblate

- Evolution of shape and shell structure as a function of $E^*$, $J$ and $N/Z$
- Coupling of odd-particle with the collective excitations of the core
- Exotic excitations
Particle-hole excitations in high-j orbitals near the closed shells

Chirality: Triaxial shape

- Pair of nearly degenerate band structure
- Same configuration
- Same or very similar moment of inertia

Magnetic Rotation: Near Spherical shape

- Band-like structure with strong M1 transitions
- No or very weak E2 transitions
- B(M1) rate decreases with J
Specification of the VECC ion beams

Light-ion beams
- Proton: 7 – 13 MeV
- Deuteron: 15 – 20 MeV
- Alpha: 28 – 60 MeV

Heavy-ion beams
- Beam species: $^{14}$N, $^{16}$O, $^{20}$Ne,..., $^{40}$Ar, etc
- Energy: 7 – 10 MeV/A

The high-energy alpha beams, higher energy of heavy-ion beams, the beams of inert gases are unique and complementary to the other accelerators in the country.

Recent campaigns with alpha beams to study nuclear structure physics using $\gamma$-ray spectroscopy
Advantages of light ion beams for gamma ray spectroscopy

- Selective channels are only populated at a particular energy
- Cross section $\sim 1000 - 1500$ mb
  Good production yield, statistics within reasonable beam time
- Minimum energy loss of beam within target
  Thick target can be used for production of a single channel
- Minimum overlap with the neighbouring channels
  Selectivity and Clean spectroscopy
- Feeding to non-yrast states, not populated by heavy ion reaction
  Horizontal spectroscopy
  Complimentary to heavy ion induced reactions
Facilities for Nuclear Structure Studies at VECC

VENUS: VECC array for Nuclear Spectroscopy

INGA: Indian National Gamma Array
VENUS: VECC array for Nuclear Spectroscopy

- 6 CS Clover HPGe (now 8)
- Horizontal plane configuration
- Flexible angles
- Can be used for both online and offline experiments
- VME based DAQ
- A few experiments have been performed using $\alpha$ and p beams.
Geant 4 simulation of the VENUS Array

VENUS: VECC array for NUclear Spectroscopy: 6 CS clover HPGe detectors

Single crystal HPGe

Single Clover HPGe detector

Efficiency

Addback factor

Yrast and non-yrast spectroscopy of $^{199}$Tl using $\alpha$-induced reactions

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The excited states of the $^{199}$Tl nucleus have been studied by using the light ion induced fusion evaporation reaction $^{197}$Au($\alpha$, 2$n$)$^{199}$Tl at 30 MeV of beam energy by $\gamma$-ray spectroscopic methods. VECC Array for Nuclear Spectroscopy (VENUS) has been used to detect the prompt $\gamma$ rays. Level scheme of $^{199}$Tl has been significantly

[Diagram of the level scheme of $^{199}$Tl]
Gated Spectra and Angular distribution in $^{199}$Tl from VENUS data

Soumik Bhattacharya et al. PRC 96, 044311 (2018)
VENUS appears in the cover page of Association of Asia Pacific Physical Society Bulletin.

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Indian National Gamma Array (INGA) @ VECC

Two Campaigns at VECC with INGA:

2004-06:
- up to 10 detectors (clover and LEPS)
- heavy-ion induced reactions

2017-18:
- up to 10 detectors (clover and LEPS)
- light-ion \((\alpha, p)\) induced reactions
INGA setup @ VECC (2017-18)

In two phases:

1\textsuperscript{st} Phase
- 7 Clovers + 1 LEPS
- Digital Data Acquisition
- 15 user experiments

2\textsuperscript{nd} Phase
- 8 Clovers + 2 LEPS
- Digital Data Acquisition
- 7 user experiments
Electronics and Data Acquisition

- Digital DAQ from XIA
- Setup by UGC-DAE-CSR, Kolkata
- Preamplifier signal are directly plugged in
- No analog processing for BGO

- Analog NIM Electronics and VME DAQ
- Backup system from VECC
- 16-ch amplifiers for Clovers
- 13 bit high resolution VME ADC
Experiments performed in phase-I using INGA at VECC

**Alpha : 30-40 MeV, Proton: 7-10 MeV**

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<th>No.</th>
<th>PI of the experiment</th>
<th>Institute</th>
<th>Beam</th>
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<tr>
<td>1.</td>
<td>Ajay Kumar Singh</td>
<td>IIT Kharagpur</td>
<td>Alpha</td>
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<td>Asimananda Goswami</td>
<td>SINP</td>
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<td>S.S. Ghugre</td>
<td>UGC–DAE–CSR</td>
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<td>Gopal Mukherjee</td>
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<td>Haridas Pai</td>
<td>SINP</td>
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<td>8.</td>
<td>Sukhendu Sekhar Sarkar</td>
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<td>9.</td>
<td>Anagha Chakraborty</td>
<td>Visva Bharati</td>
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<td>10.</td>
<td>D.C. Biswas</td>
<td>BARC</td>
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<td>11.</td>
<td>Suresh Kumar</td>
<td>Delhi University</td>
<td>Alpha</td>
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<td>12.</td>
<td>T. Bhattacharjee / D. Banerjee</td>
<td>VECC / RCD, BARC</td>
<td>Alpha</td>
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<td>13.</td>
<td>Krishichayan</td>
<td>TUNL, Duke University</td>
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<td>14.</td>
<td>Maitreyee Saha Sarkar</td>
<td>SINP</td>
<td>Proton</td>
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## Experiments performed in phase-II using INGA at VECC

**Alpha :** 40-53 MeV + Heavy ion (\(^{20}\text{Ne}\)) (test)

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<td>6.</td>
<td>Sujit Tandel</td>
<td>CEBS, Mumbai</td>
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<td>7.</td>
<td>Shinjinee Das Gupta</td>
<td>Victoria College, Kolkata</td>
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**Total 22 user experiments performed**

**2 runs with proton beam**

**20 runs are with alpha beam**
Local INGA Group (VECC, SINP, UGC-DAE-CSIR)
Support of a strong team of students who worked together!
Regions of nuclear chart covered with INGA@VECC

- Nuclei near the line of stability
- Some of them close to the spherical shell closures (proton / neutron)
- Most of them are in the heavier part of the nuclear chart
- Only possible to excite using light ion beams.
Main physics issues addressed in various experiments

- Spectroscopy of heavy nuclei in A~ 200 region near Z=82 shell closure
- Search for octupole deformation in different mass regions
- Spectroscopy of neutron-rich nuclei through fission
- Yrast and non-yrast states near Z=50 shell closure
- Mixed symmetry states
- Transition moment measurement
- Vibrational states
- Shape coexistence
- Multi-quasiparticle structures
Some important recent Results in nuclei around $Z = 82$
Proton and neutron orbitals in A ~ 190 - 200 region

\((Z \sim 82 \text{ and } 104 < N < 126)\)

- **Proton particle and neutron hole**
- This favours the occurrence of different exotic modes of nuclear excitation
- Different shape driving orbitals and onset of collectivity

- For neutron number \(N < 114\), \(i_{13/2}\) orbital opens up for neutron hole
- **High-j** proton and neutron orbitals give rise to high-spin isomers
Our Major findings in nuclei around Z = 82


- Several MR bands with large multi-q\-p configuration at high excitation in $^{198}\text{Bi}$ [PRC\textbf{90}, 064314 (2014)]

- Systematic study of the $\pi h_{9/2}$ bands in odd-A Tl (Z = 81) isotopes reveals the persistence of rotational band (deformation) of $\pi h_{9/2}$ configuration up to N = 120. [PRC\textbf{88}, 044328 (2013); ibid. 064302; PRC\textbf{98}, 044311 (2018)]

- Identification of band crossing in odd-odd $^{194,196,200}\text{Tl}$ [PRC\textbf{85}, 064313 (2012), PRC\textbf{95}, 014301 (2017)]

- Evidence of MR band in $^{194}\text{Tl}$ [PRC\textbf{85}, 064313 (2012)]

- No evidence for Chiral bands in odd-odd $^{196}\text{Tl}$ [to be published]

- Evidence for Multiple Chiral Doublet (M$\chi$D) bands in odd-A $^{195}\text{Tl}$ [PLB\textbf{782} (2018) 768]
Structural evolution in odd-Z Bi (Z = 83) nuclei

- Spherical s.p excited states to deformed rotor through small deformation at high excitation
- The MR band in $^{197}$Bi is the only MR band reported in Bi isotopes.

G.K. Mabala et al., EPJ A25 49 (2005)

$^{197}$Bi

(Z = 83, N = 114)

MR band


$^{193}$Bi

(Z = 83, N = 110)

P. Nieminen et al., PRC 69, 064326 (2004)

$^{209}$Bi

(Z = 83, N = 126)

Spherical s.p excited states to deformed rotor through small deformation at high excitation

The MR band in $^{197}$Bi is the only MR band reported in Bi isotopes.
Onset of deformation in $^{195}$Bi ($Z = 83, N = 112$)

H. Pai et al., PRC 85, 064317(2012)

T. Roy et al., EPJ A51, 153 (2015)

Larger shape driving effect of $i_{13/2}$ orbital than $h_{9/2}$ orbital

TRS Calculations with WS potential
Results on Tl nuclei

H. Pai et al., C 85, 064313 (2012)

- Deformed rotational band structure based on $\pi h_{9/2} \otimes v_{i13/2}$ configuration
- Band crossing and MR band identified.
- Chiral doublet band identified by Masiteng et al.

P.L. Masiteng et al., PLB 719, 83 (2013)
Results on $^{196}$Tl

- A large level scheme with band crossing identified
- Similar behaviour of all the $\pi h_{9/2} \otimes \nu i_{13/2}$ bands in all odd-odd Tl isotopes.
- Changes observed after the band crossing
- No chiral doublet band observed


Results on $^{195}\text{Tl}$

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


Observation of $\ell\chi\delta$ bands for the first time in $A = 190$ region.

T. Roy et al., PLB 782, 768 (2018)
**Comparison of the doublet bands (b2-B2a and B4-B4a) in $^{195}$Tl with the Chiral bands in $^{194,198}$Tl**

- First observation of Multiple Chiral Doublet (M$\chi$D) in A = 190 region.
- First observation of doublet bands with configuration involving as large as 5 quasi-particles.
- $\Delta\Delta E_{av} \sim 25$ keV ($\Delta e_{max} = 59$ keV) for B4-B4a represents one of the best degenerate bands.
Total Routhian Surface (TRS) Calculations: Shape of $^{195}\text{Tl}$

For different configuration

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

For 5-qp configuration, a stable triaxial minimum with $\gamma \sim +31^\circ$ appears.

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

The proton particle in $h_{9/2}$ and neutron holes in $i_{13/2}$ coupled with the triaxial core provides the chiral geometry in $^{195}\text{Tl}$.

Recent results on $^{197}$Tl

Multiple MR bands in $^{197}$Tl ($N = 116$) at same no. of qp as in chiral bands in $^{195}$Tl ($N = 114$)

→ A transition from aplanar (Chiral) to Planar (MR) configuration around $N \sim 114$

S. Nandi: Poster
Some other structural changes around $N \sim 114$

De-excitation energies of $31/2^+$ isomer in Au isotopes

$$E_x(I) = \frac{\hbar^2}{2I} I(I+1)$$
Similar transition for the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in Cs ($Z = 55$) isotopes

Chiral bands

( $N = 73$)

( $N = 75$)

( $N = 77$)

MR band

$^{134}$Cs ($Z = 55$, $N = 79$)

A different band structure in $^{134}$Cs.

TAC Calculations

TAC Calculations (S. Kumar) reproduces the data in $^{134}$Cs and confirms the MR nature of the band ➞ In sharp contrast to $^{132}$Cs.

Suggests an aplanar configuration for $N < 79$ to a planar one for $N \geq 79$

H. Pai et al. PRC 84, 041301(R) (2011)

TRS Calculations

Change in shape from triaxial to $\gamma$-soft and towards lower $\beta_2$ as neutron number increases.
Summary

- The light-ion induced reaction has certain advantages for gamma ray spectroscopic studies.

- VENUS and INGA are the two setups with Clover detectors at VECC for gamma ray spectroscopy studies.

- Several experiments have been performed by different users from all over the country using the INGA setup at VECC with Digital DAQ.

- A transition from Chiral to Magnetic Rotation behaviour has been observed in Tl isotopes from the recent experiments at VECC. This seems to be related with the closure of neutron $i_{13/2}$ orbital. The result is similar to that observed for the Cs isotopes in $A \sim 130$ region.

- More experimental and theoretical investigations are required.

Thank You