Nuclear structure studies at VECC using INGA

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Plan of the Talk

Introduction

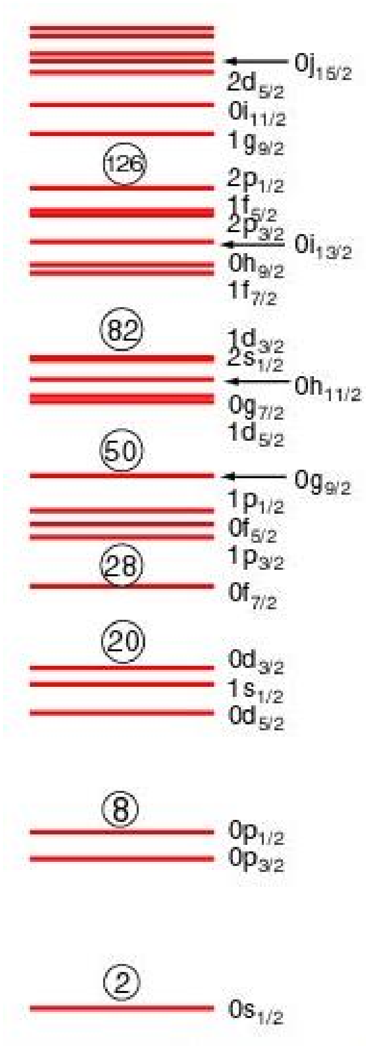
Beams and detection system for gamma ray spectroscopy at VECC: VENUS and INGA setup

Physics issues addressed in the recent INGA campaign

Transition from chiral to MR band in nuclei

Summary

Introduction



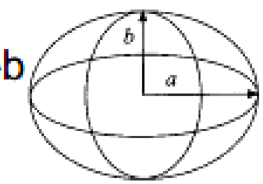
Shells and Shapes in Nuclei

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

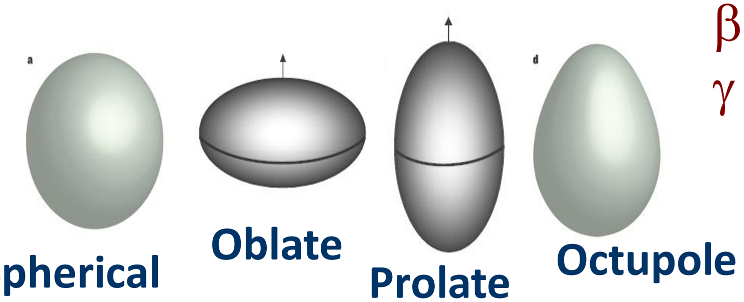
β is " **deformation parameter** " given by

$$= \frac{4}{3}\sqrt{\frac{\pi}{5}}\ \frac{\Delta R}{Rave}$$

ΔR = a-b



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



β_2: amount of deformation

γ : Nature of deformation

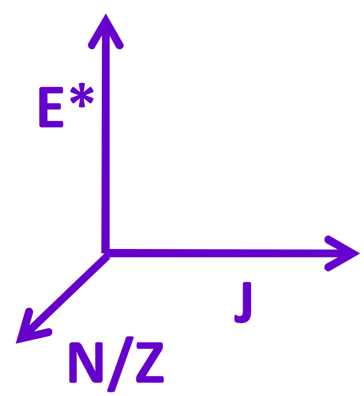
$\gamma = 0^o$ ➔ Prolate

$\gamma = -60^o$ ➔ Oblate

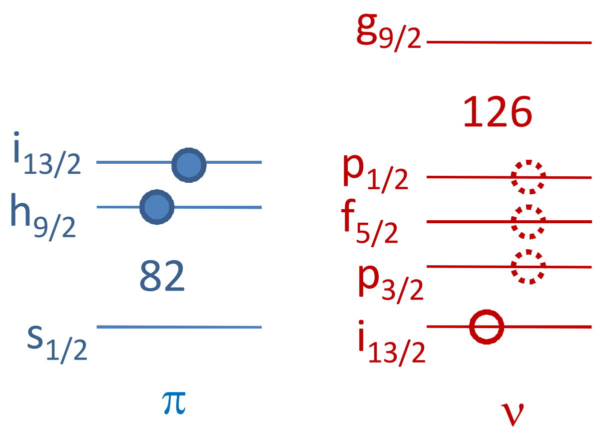
❖ Evolution of shape and shell structure as a function of E*, J and N/Z

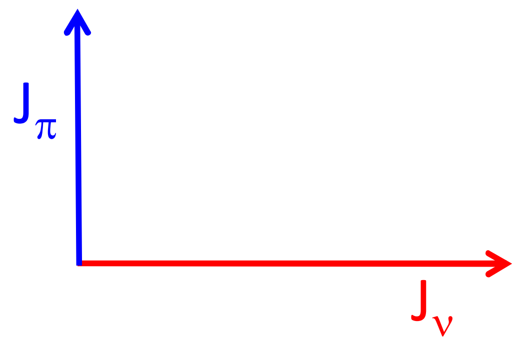
❖ Coupling of odd-particle with the collective excitations of the core

❖ Exotic excitations

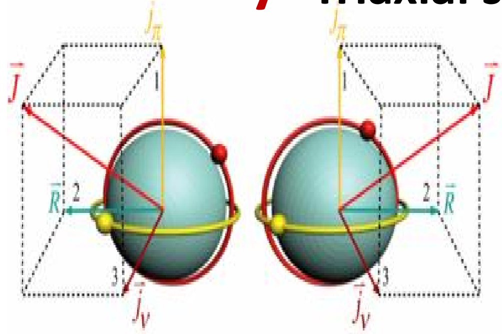


Particle-hole excitations in high-j orbitals near the closed shells



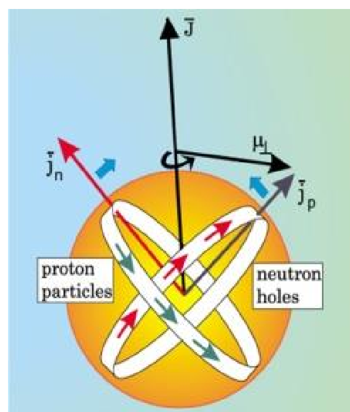


Chirality: Triaxial shape



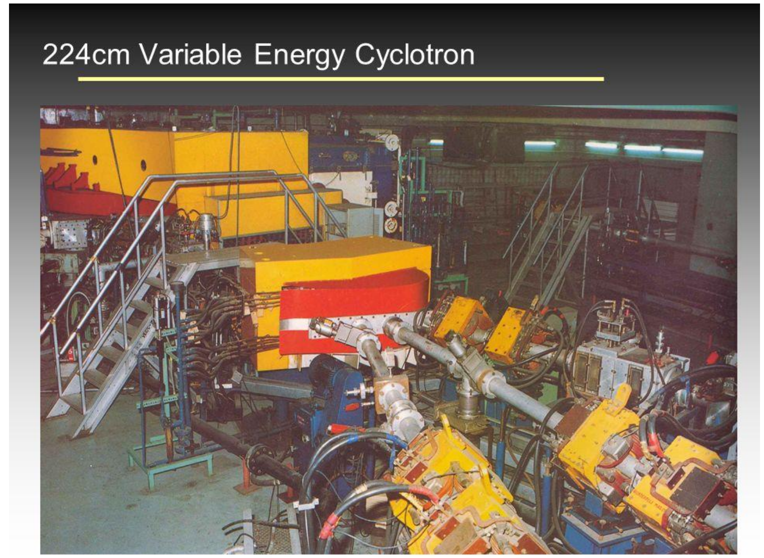
- Pair of nearly degenerate band structure
- Same configuration
- Same or very similar moment of inertia

Magnetic Rotation Near Spherical shape



- Band-like structure with strong M1 transitions
- No or very week 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 accelertors in the country.

Recent campaigns with alpha beams to study nuclear structure physics using γ-ray spectroscopy

Advantages of light ion beams for gamma ray spectroscopy

- ❑ Selective channels are only populated at a particular energy
- ❑ Cross section ~ 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

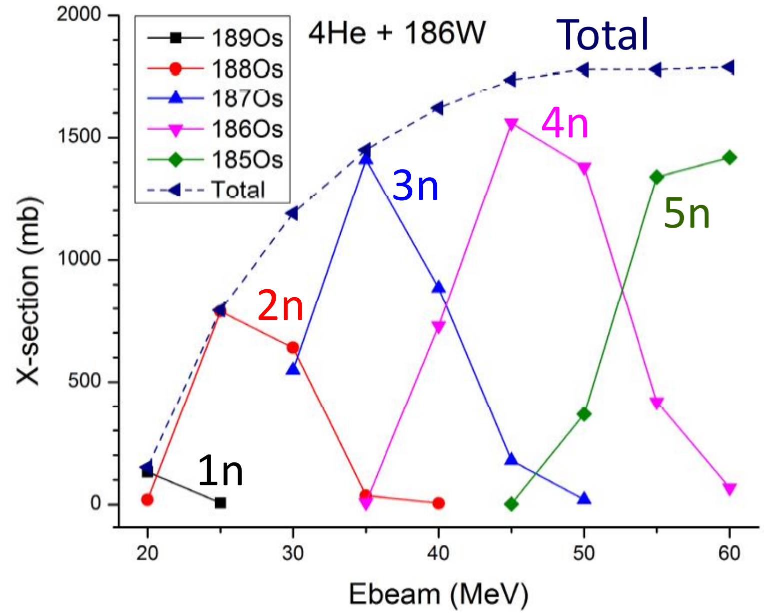
- ❑ Minimum overlap with the neighbouring channels

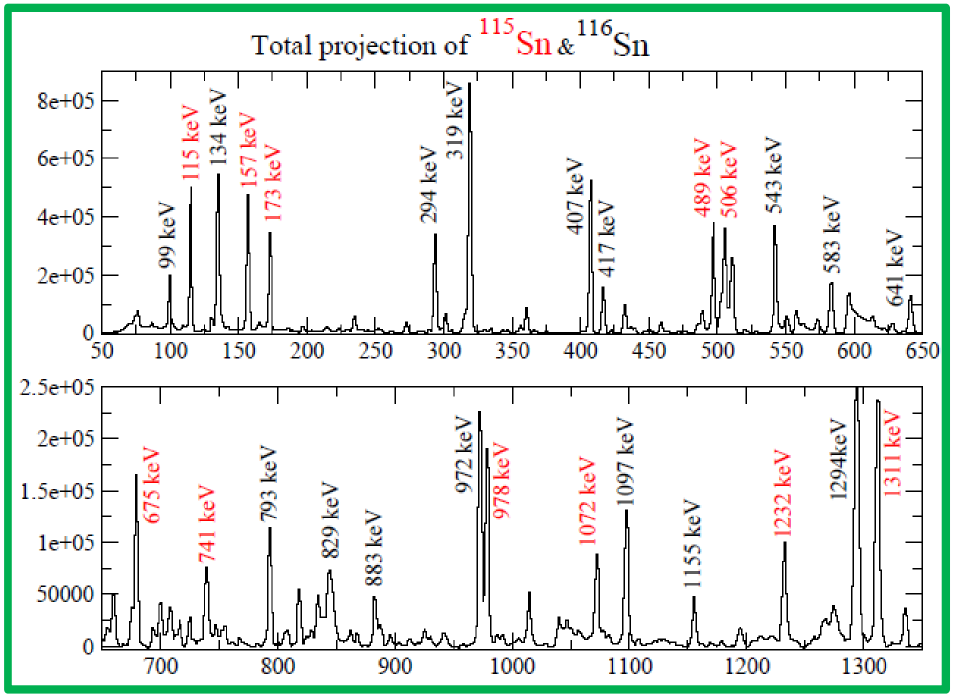
  Selectivity and Clean spectroscopy

- ❑ Feeding to non-yrast states, not populated by heavy ion reaction

  Horizontal spectroscopy

Complimentary to heavy ion induced reactions

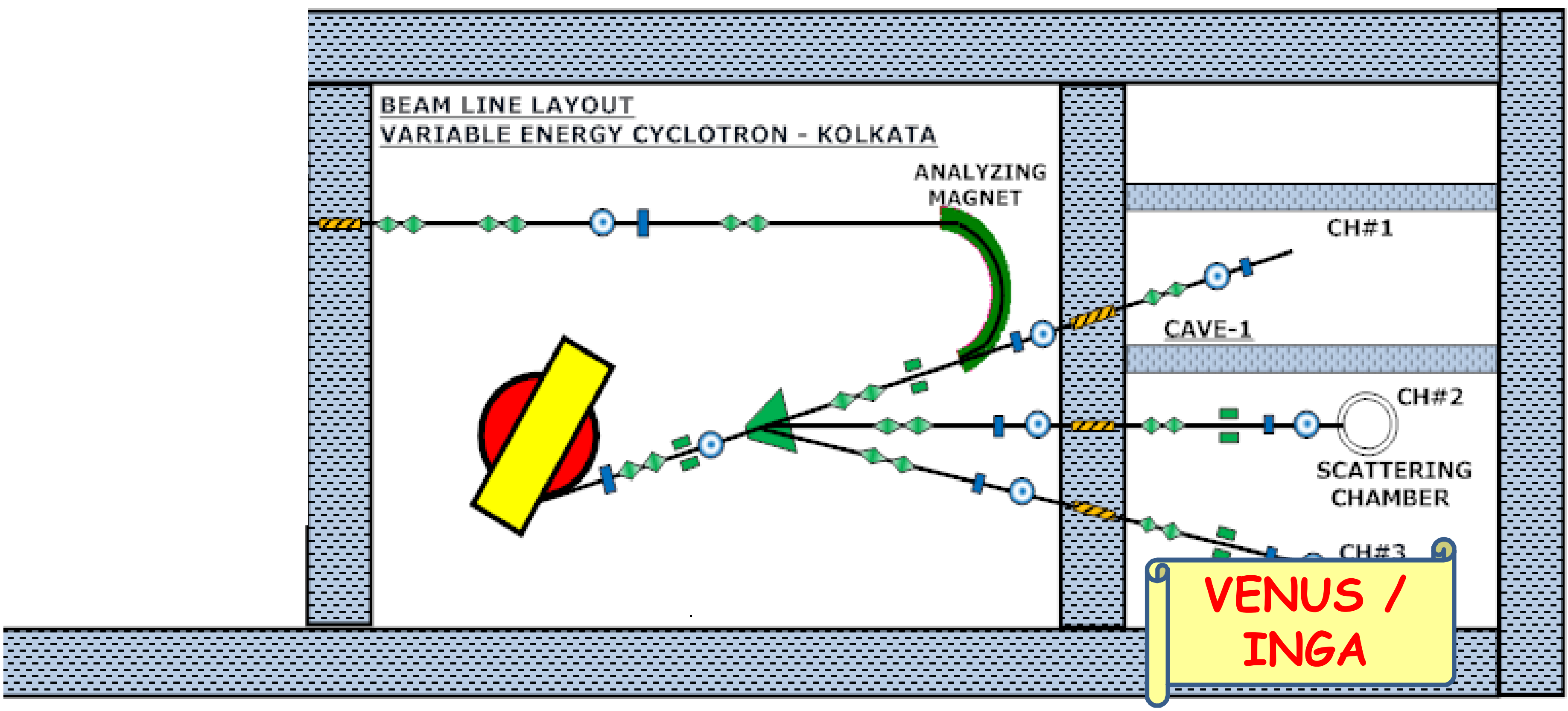




Facilities for Nuclear Structure Studies at VECC

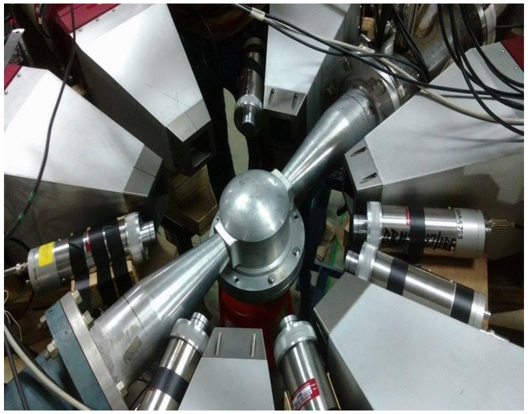
VENUS: **VE**CC array for **NU**clear **S**pectroscopy

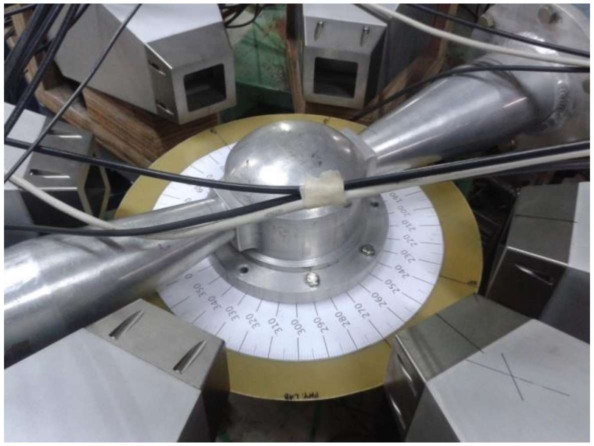
INGA: **I**ndian **N**ational **G**amma **A**rray



VENUS: VECC array for NUclear Spectroscopy

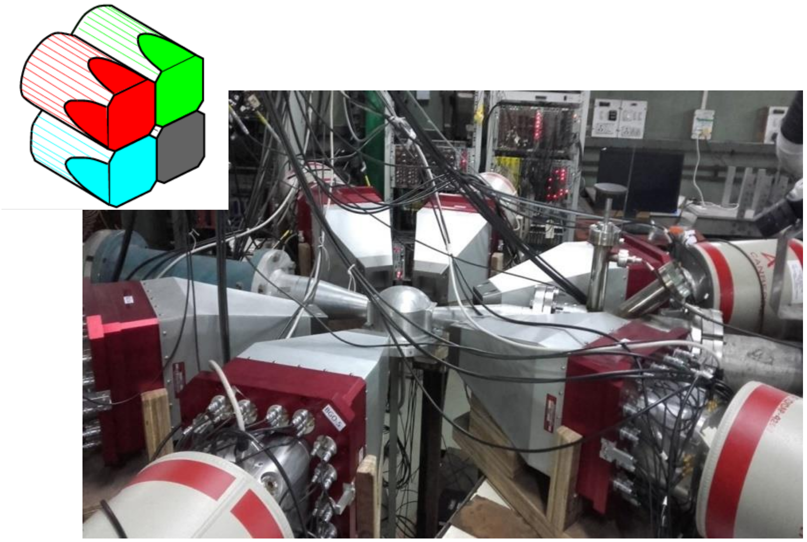
- 6 CS Clover HPGe (now 8)
- Horizontal plane configuration
- Flexible angles
- Can be used for both online and offline experiments
- VME based DAQ
- A few experiments have been performed using α and p beams.



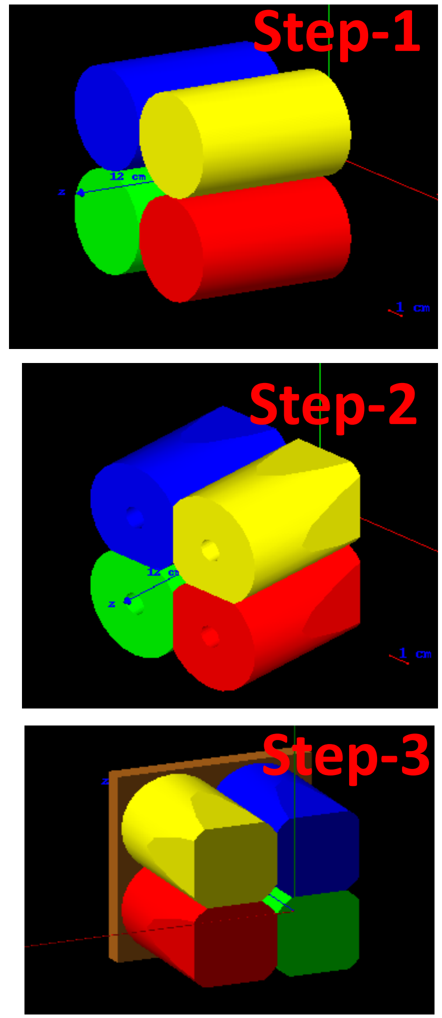


Geant 4 simulation of the VENUS Array

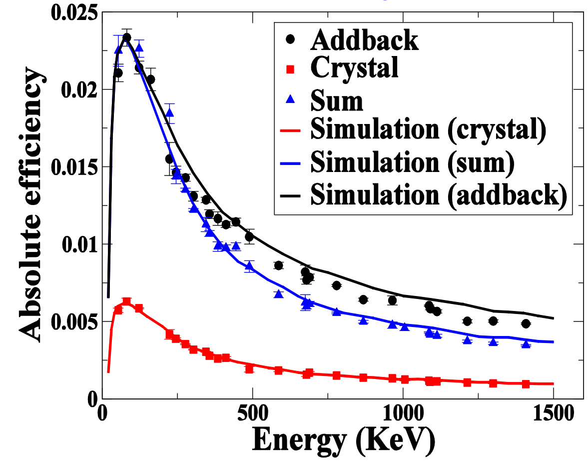
VENUS: VECC array for NUclear Spectroscopy: 6 CS clover HPGe detectors

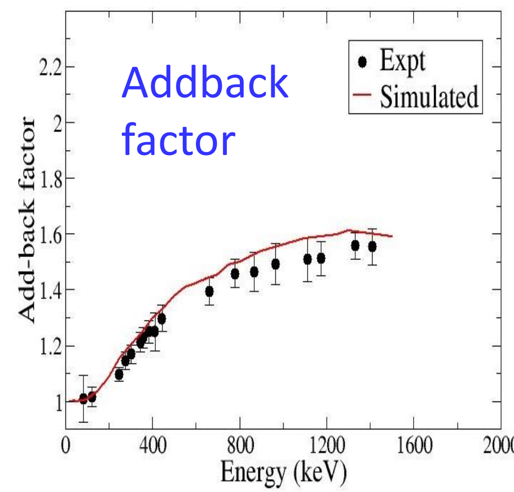


Single Clover HPGe detector

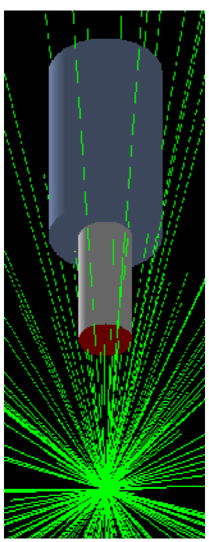


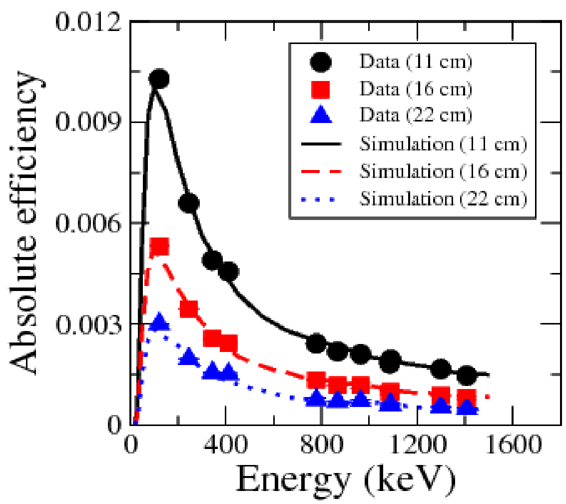
Efficiency





Single crystal HPGe





Md. A. Asgar et al., DAE Symp Nucl Phys. (2016)

PHYSICAL REVIEW C 98, 044311 (2018)

Yrast and non-yrast spectroscopy of ^{199}Tl using α-induced reactions

Soumik Bhattacharya,[1,2] S. Bhattacharyya,[1,2,*] R. Banik,[1,2] S. Das Gupta,[3] G. Mukherjee,[1,2] A. Dhal,[1] S. S. Alam,[1,2] Md. A. Asgar,[1,2,†] T. Roy,[1,2] A. Saha,[1,2] S. Nandi,[1,2] T. Bhattacharjee,[1,2] A. Choudhury,[1] Debasish Mondal,[1,2] S. Mukhopadhyay,[1] P. Mukhopadhyay,[1] S. Pal,[1] Deepak Pandit,[1] I. Shaik,[1] and S. R. Banerjee[1]

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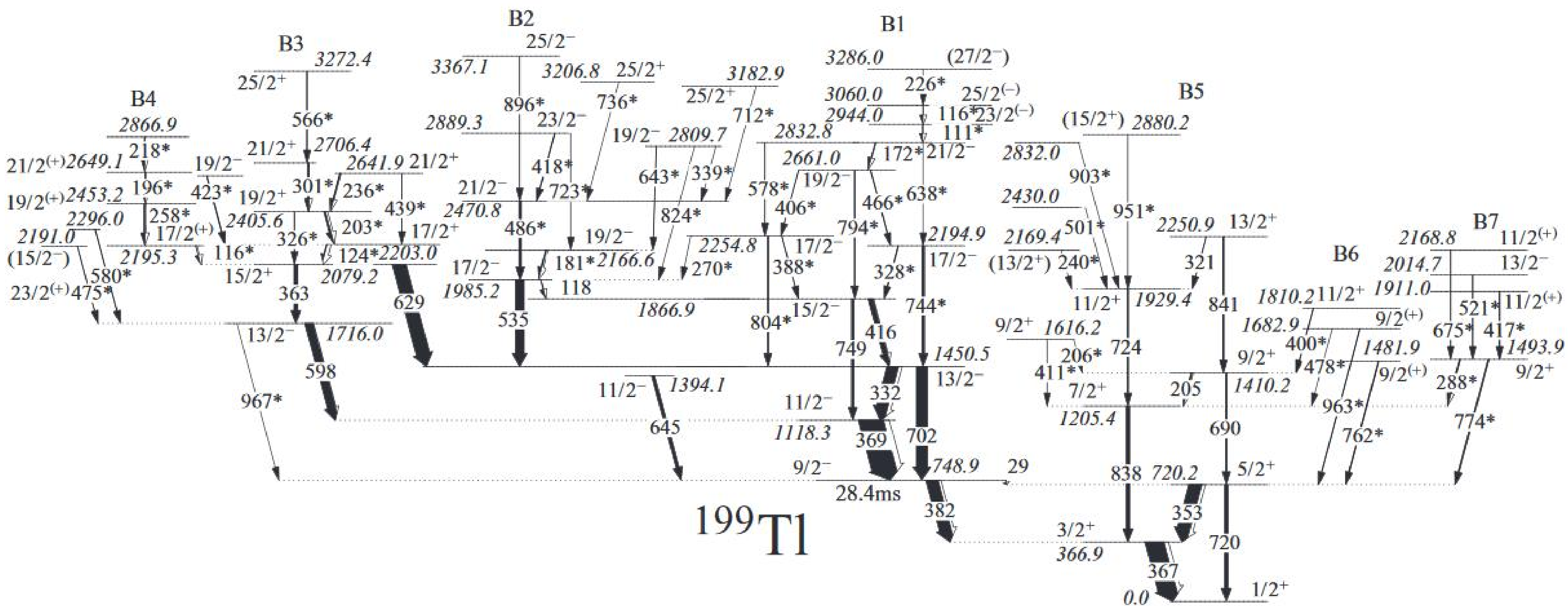
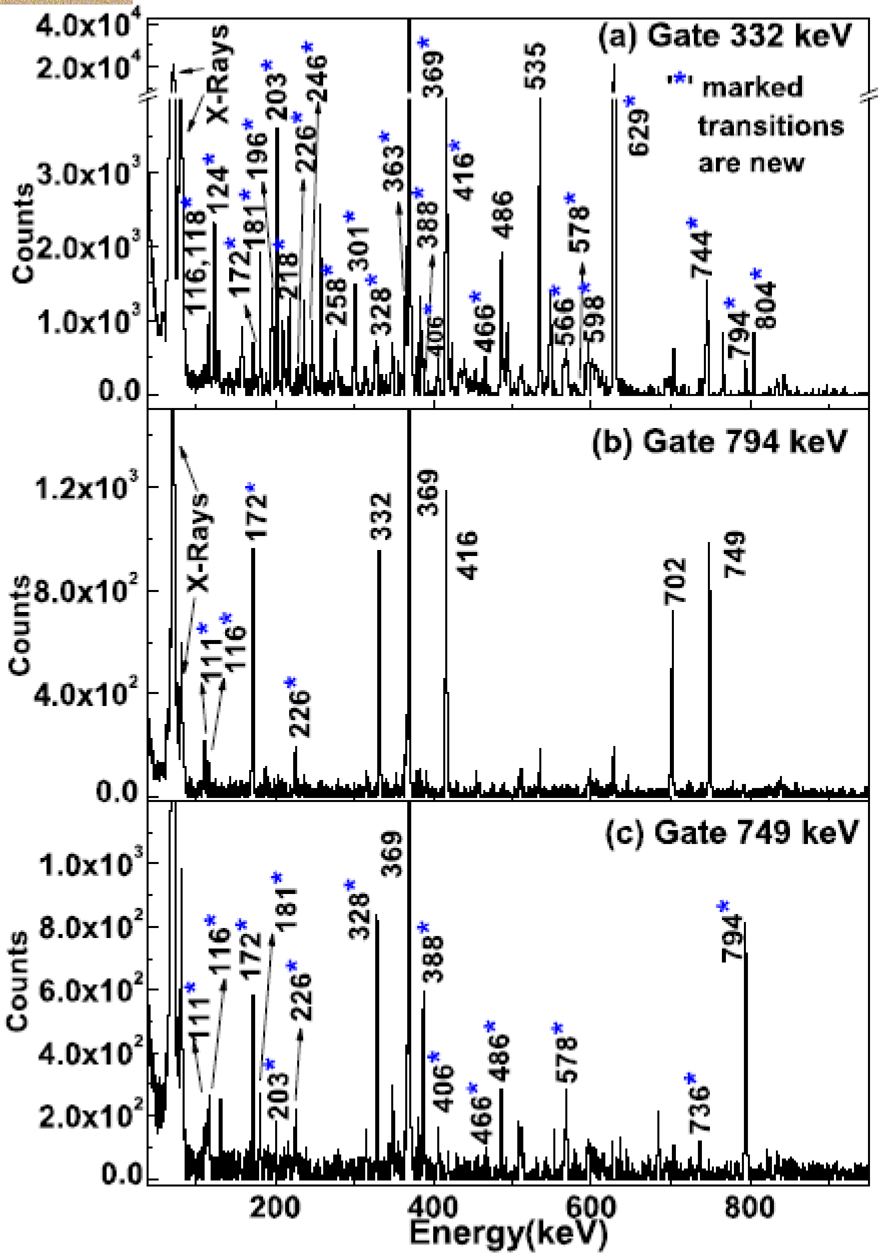
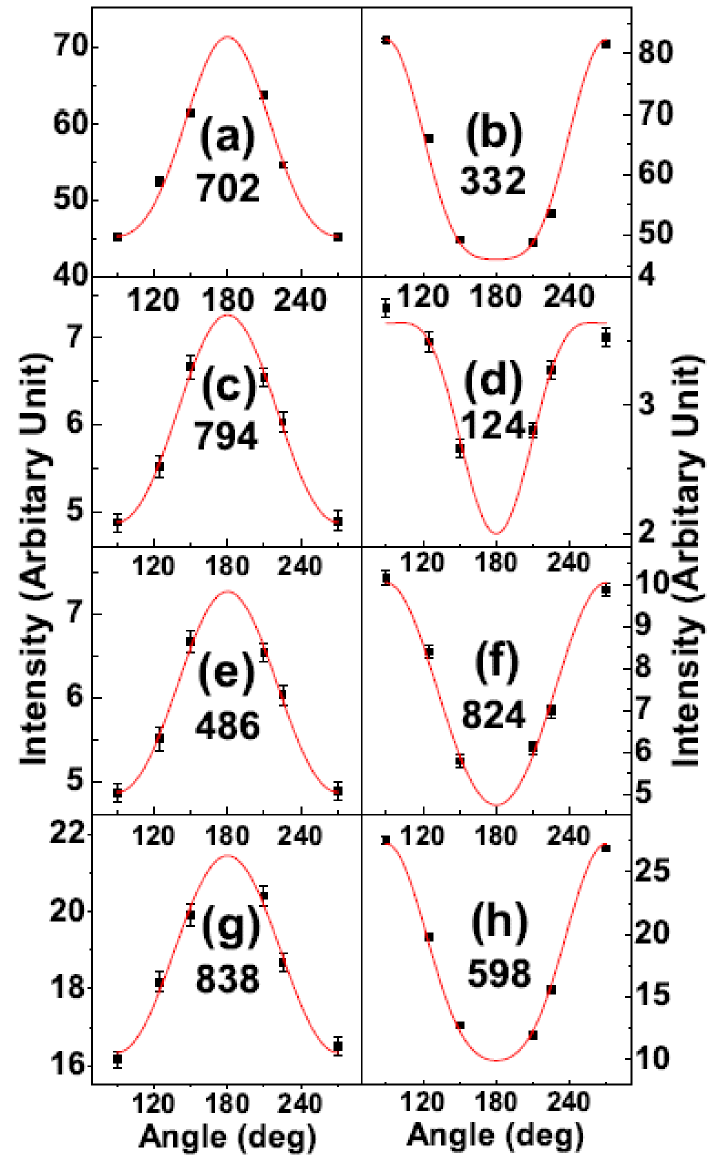
The excited states of the ^{199}Tl nucleus have been studied by using the light ion induced fusion evaporation reaction ^{197}Au(α, 2n)^{199}Tl at 30 MeV of beam energy by γ-ray spectroscopic methods. VECC Array for NUclear Spectroscopy (VENUS) has been used to detect the prompt γ rays. Level scheme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

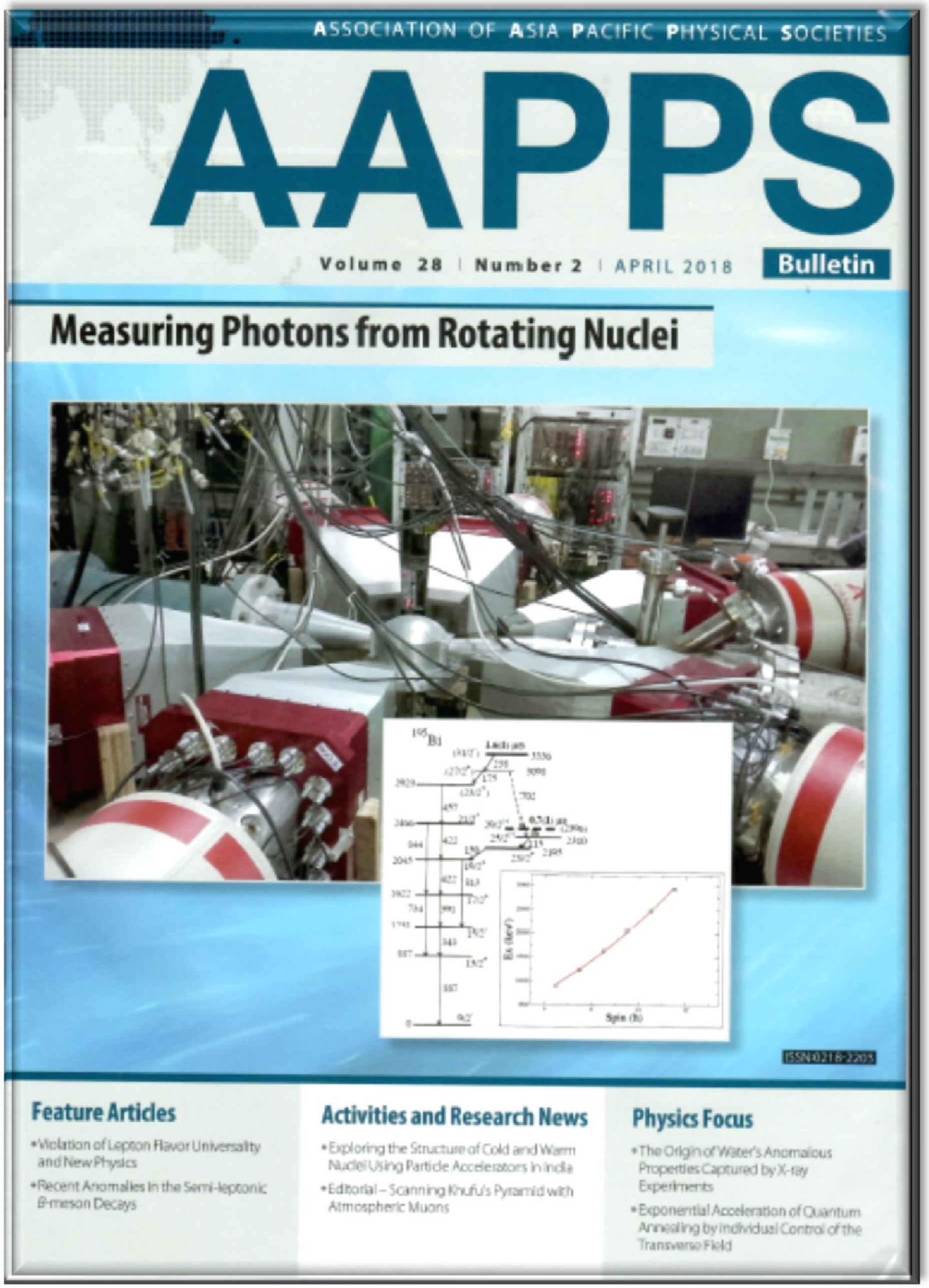


Gated Spectra and Angular distribution in ^{199}Tl from VENUS data





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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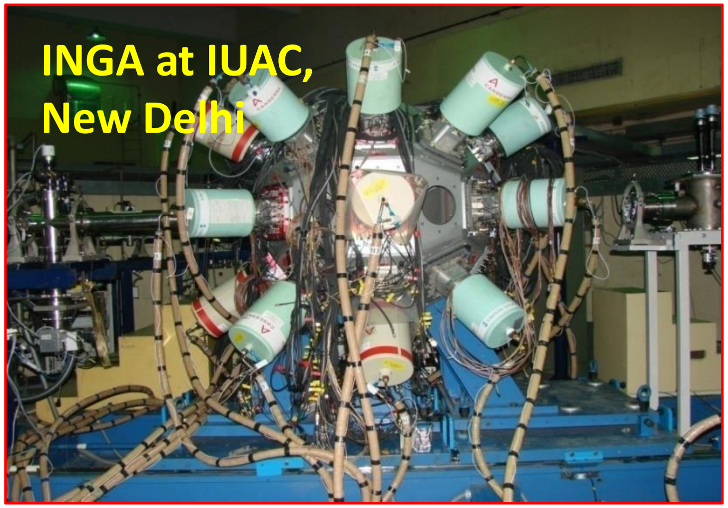
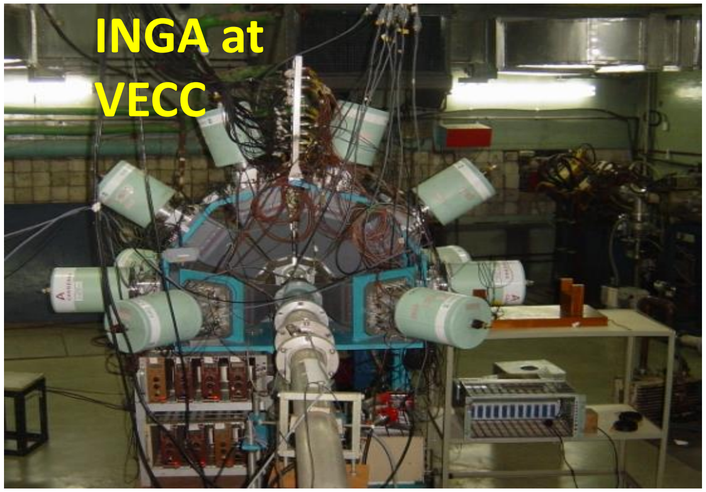
Indian National Gamma Array (INGA) @ VECC





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 (α, p) induced reactions

INGA setup @ VECC (2017-18)

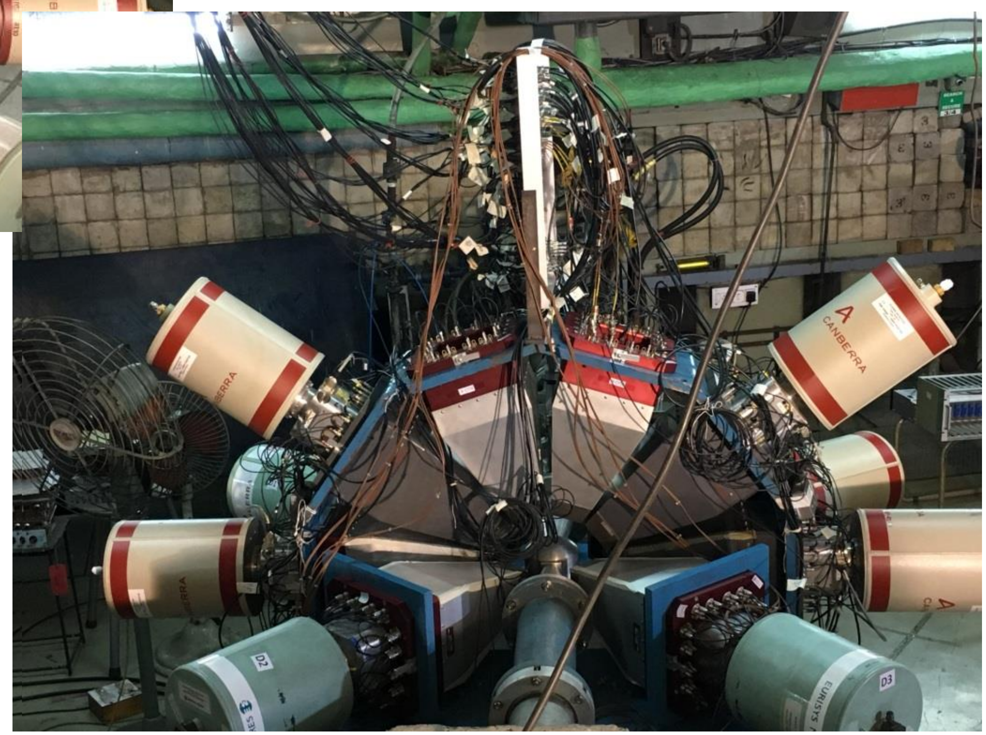
In two phases:

1st Phase

Å7 Clovers + 1 LEPS

ÅDigital Data Acquisition

Å15 user experiments



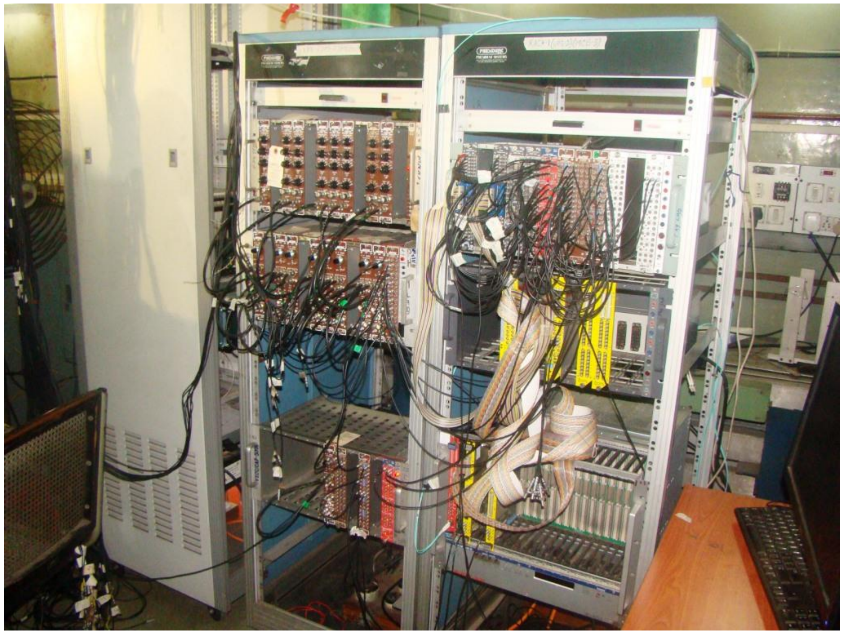
2nd Phase

Å8 Clovers + 2 LEPS

ÅDigital Data Acquisition

Å7 user experiments

Electronics and Data Acquisition



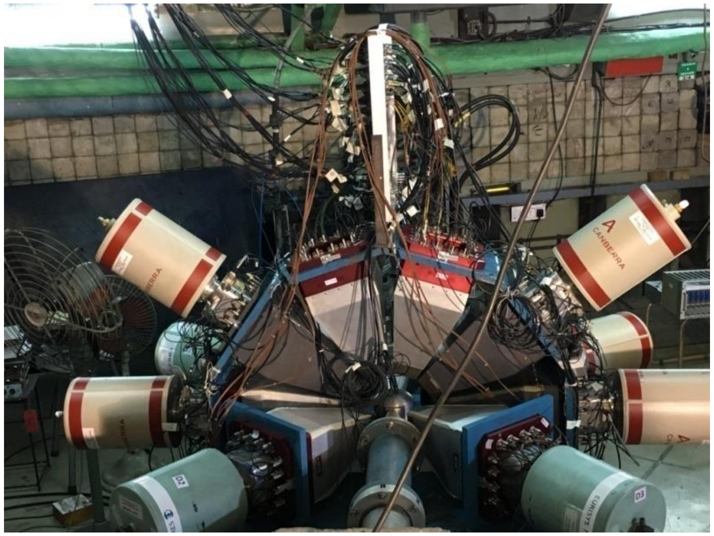
- ❖ Digital DAQ from XIA
- ❖ Setup by UGC-DAE-CSR, Kolkata
- ❖ Preamplifier signal are directly plugged in
- ❖ No analog processing for BGO

- ❖ 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

No.	PI of the experiment	Institute	Beam
1.	Ajay Kumar Singh	IIT Kharagpur	Alpha
2.	Asimananda Goswami	SINP	Alpha
3.	S.S. Ghugre	UGC-DAE-CSR	Alpha
4.	Soumik Bhattacharya	VECC	Alpha
5.	Sarmishtha Bhattacharyya	VECC	Alpha
6.	Gopal Mukherjee	VECC	Alpha
7.	Haridas Pai	SINP	Alpha
8.	Sukhendu Sekhar Sarkar	IIEST, Shibpur	Alpha
9.	Anagha Chakraborty	Visva Bharati	Alpha
10.	D.C. Biswas	BARC	Alpha
11.	Suresh Kumar	Delhi University	Alpha
12.	T. Bhattacharjee / D. Banerjee /	VECC / RCD, BARC	Alpha
13.	Krishichayan	TUNL, Duke University	Alpha
14.	Maitreyee Saha Sarkar	SINP	Proton
15.	T. Bhattacharjee/ D. Banerjee	VECC / RCD, BARC	Proton



Experiments performed in phase-II using INGA at VECC

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

No.	PI of the experiment	Institute	Beam
1.	Abhijit Bisoi	IIEST, Shibpur, West Bengal	Alpha
2.	Pradip Datta & Biswarup Das	Ananda Mohan College, Kolkata	Alpha
3.	Rudrajyoti Palit	TIFR, Mumbai	Alpha
4.	Riitwika Chakrabarti	Mumbai University, Mumbai	Alpha
5.	Somsundar Mukhopadhyay	BARC, Mumbai	Alpha
6.	Sujit Tandel	CEBS, Mumbai	Alpha
7.	Shinjinee Das Gupta	Victoria College, Kolkata	Alpha

Total 22 user experiments performed

2 runs with proton beam

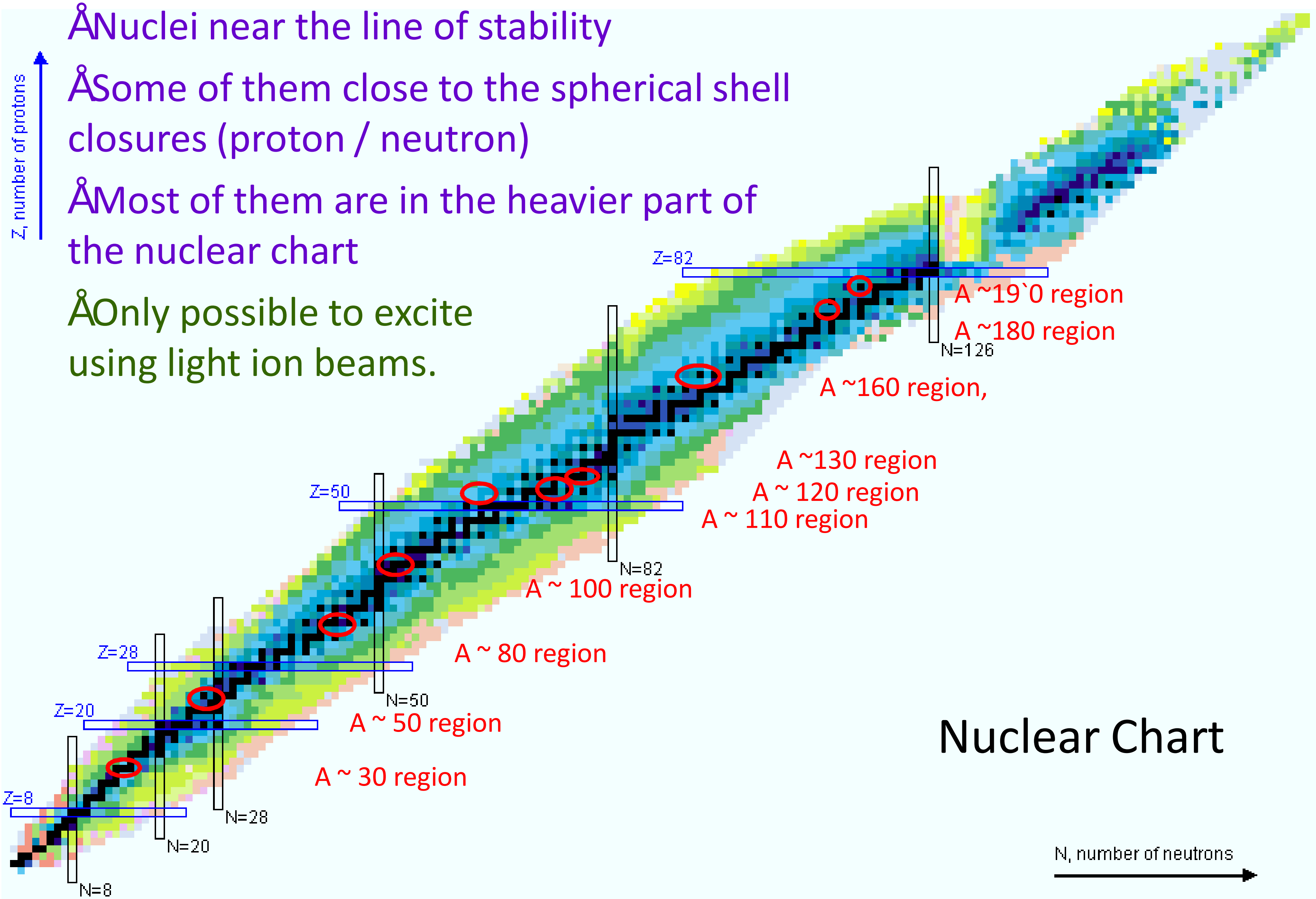
20 runs are with alpha beam


CANBERRA
Local INGA Group
(VECC, SINP, UGC-DAE-CSR)

Support of a strong team of students who worked together !

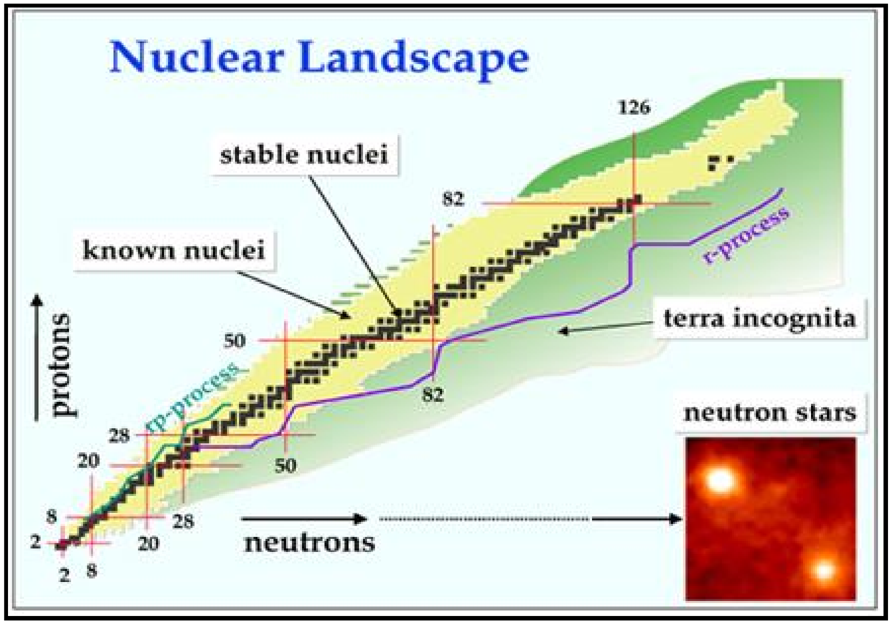
Regions of nuclear chart covered with INGA@VECC

- 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

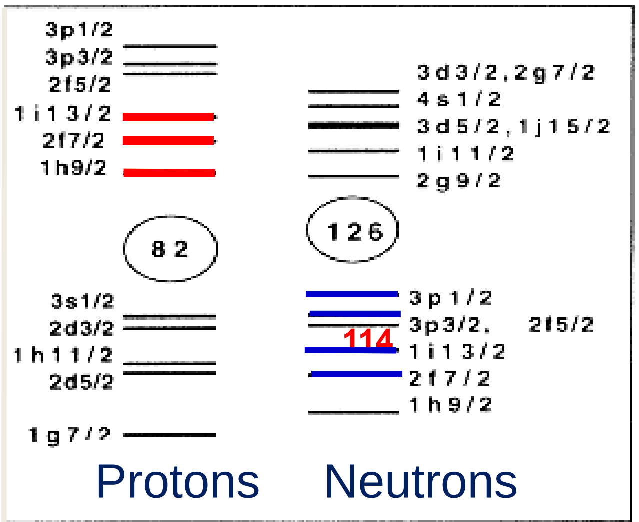
- Spectroscopy of heavy nuclei in A~ 200 region near Z=82 shell closure
- Search for octupole deformation in different mass regions
- Spectroscopy of neutron-rich nuclei through fission
- Yrast and non-yrast states near Z=50 shell closure
- Mixed symmetry states
- Transition moment measurement
- Vibrational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



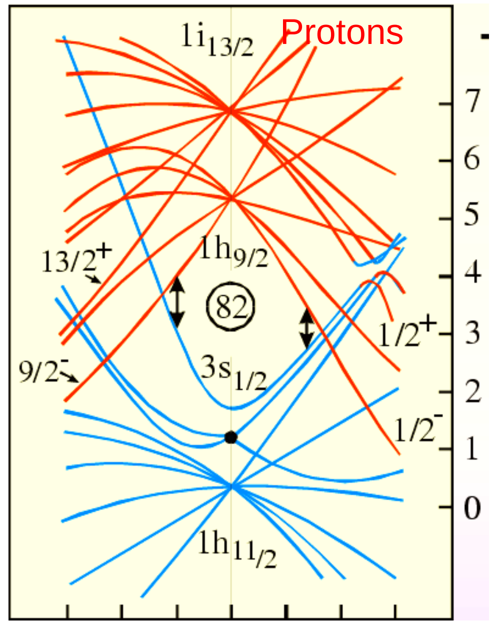
Some important recent Results in nuclei around Z = 82

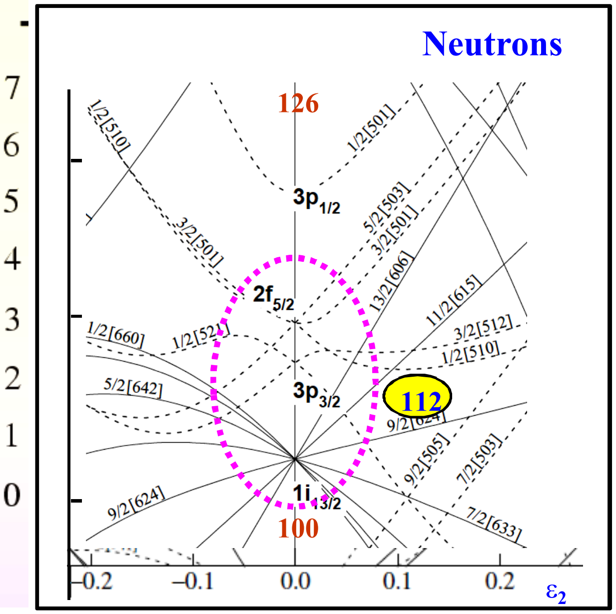
Proton and neutron orbitals in A ~ 190 - 200 region

(Z ~ 82 and 104< N <126)



Spherical





Deformed

- **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

- **Onset of deformation at N = 112 for Bi (Z = 83) isotopes. Identification of high spin isomer in ^{195}Bi.** [PRC**85**, 064317 (2012)**,** Eur. Phys. J. A (2015) **51: 153]**

- **Several MR bands with large multi-qp configuration at high excitation in ^{198}Bi [** PRC90, 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**88**, 044328 (2013); ibid. 064302; PRC**98**, 044311 (2018)**]**

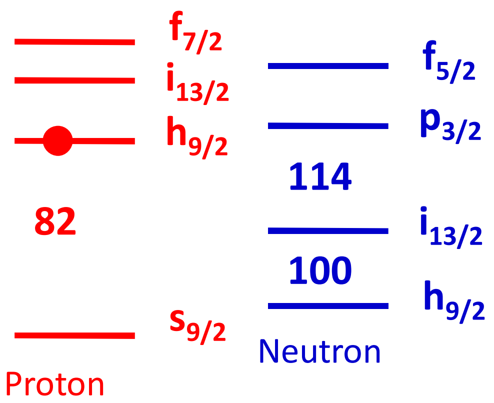
- **Identification of band crossing in odd-odd ^{194,196,200}Tl [**PRC**85**, 064313 (2012), PRC**95**, 014301 (2017)**]**

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

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

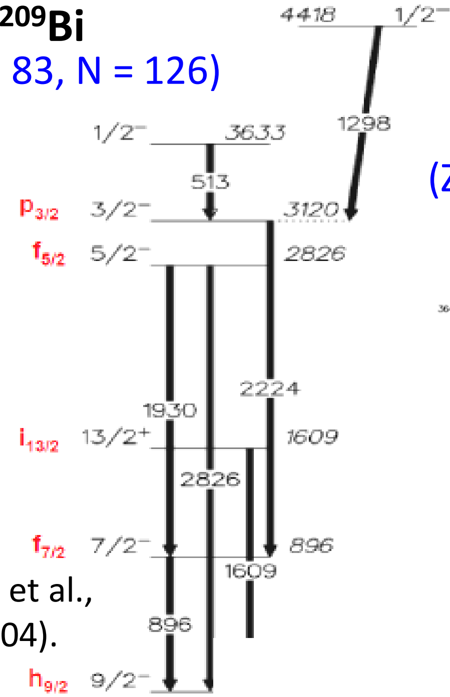
- **Evidence for Multiple Chiral Doublet (MχD) bands in odd-A ^{195}Tl [**PLB**782** (2018) 768**]**

Structural evolution in odd-Z Bi (Z = 83) nuclei



^{209}Bi

(Z = 83, N = 126)

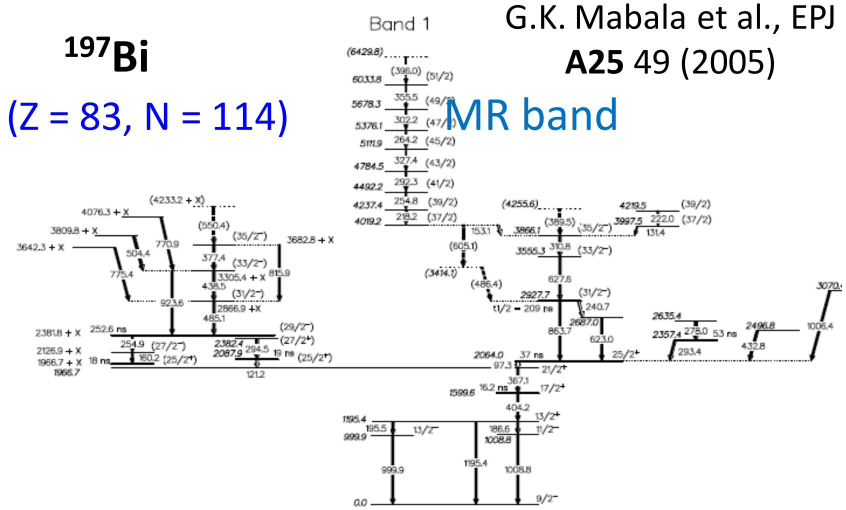


M. Lipoglavsek, et al., PLB 593, 61 (2004).

^{197}Bi

(Z = 83, N = 114)

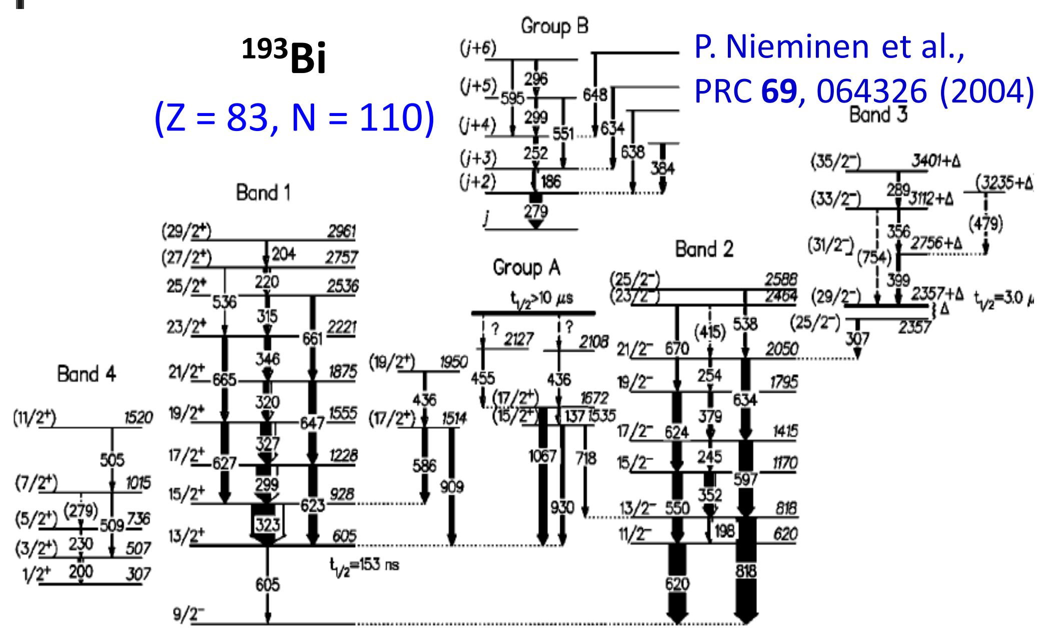
G.K. Mabala et al., EPJ **A25** 49 (2005)



^{193}Bi

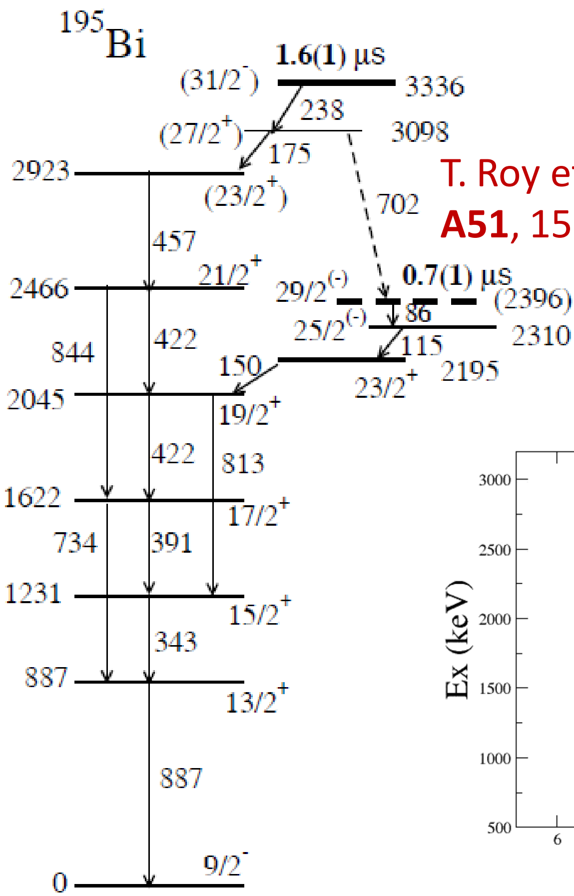
(Z = 83, N = 110)

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



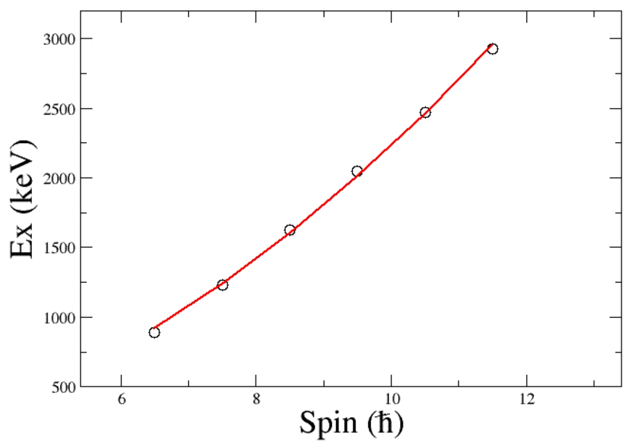
- **Spherical s.p excited states to deformed rotor through small deformation at high excitation**
- **The MR band in ^{197}Bi is the only MR band reported in Bi isotopes.**

Onset of deformation in ^{195}Bi (Z = 83, N = 112)

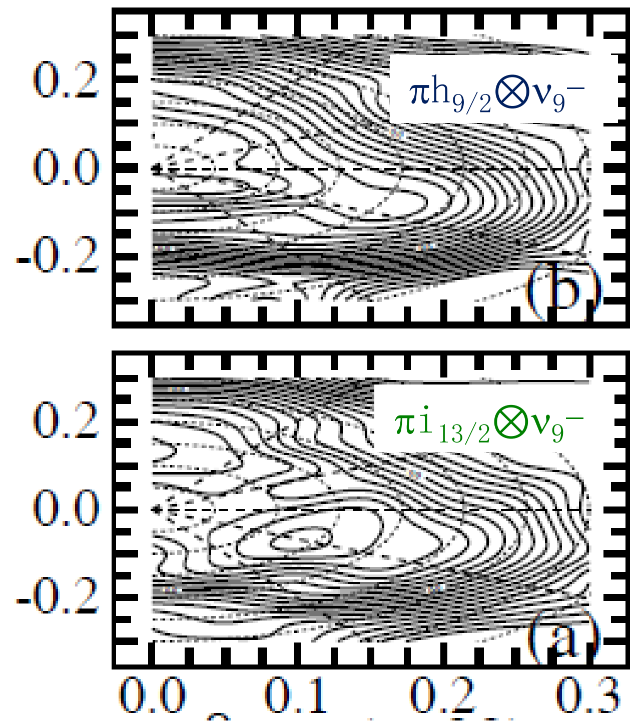


T. Roy et al., EPJ **A51**, 153 (2015)

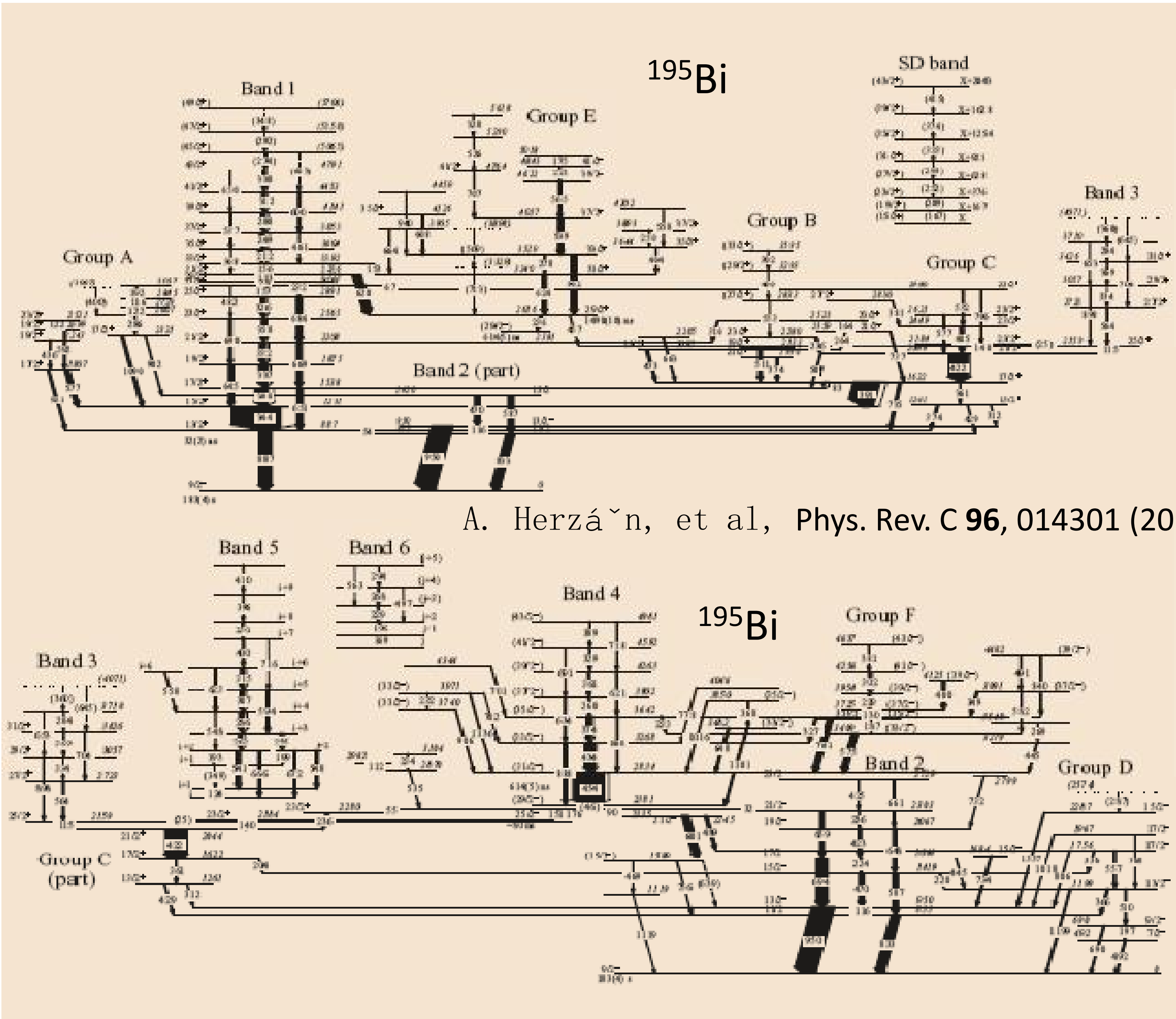
H. Pai et al., PRC **85**, 064317(2012)



TRS Calculations with WS potential



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

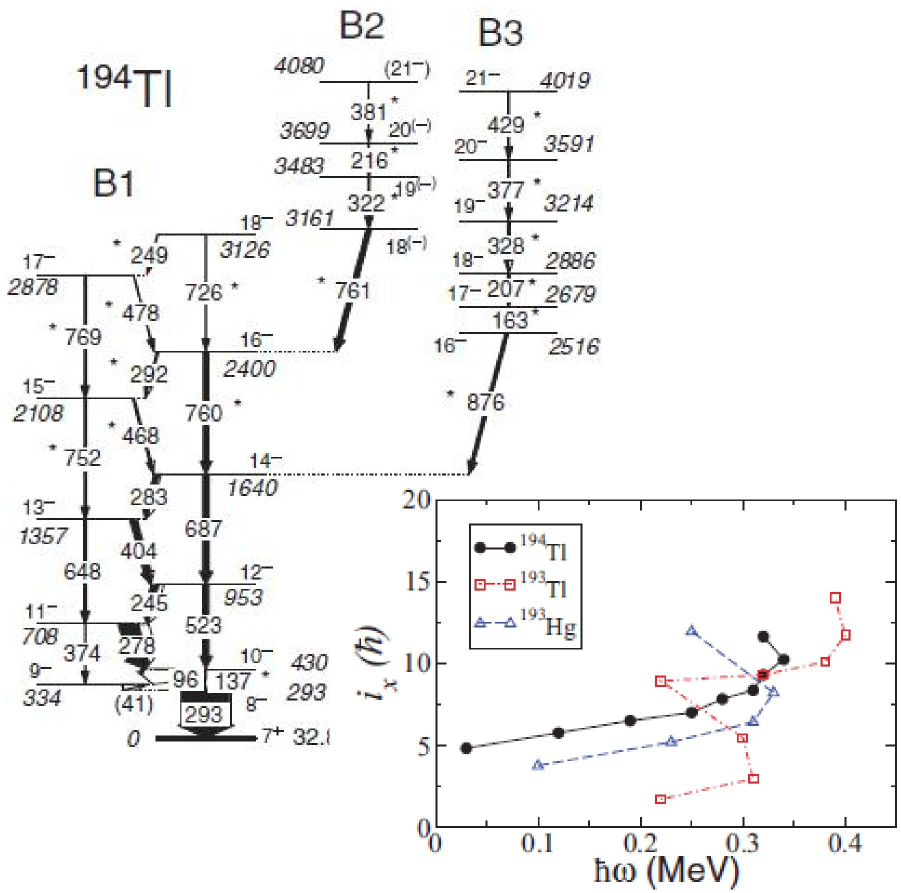


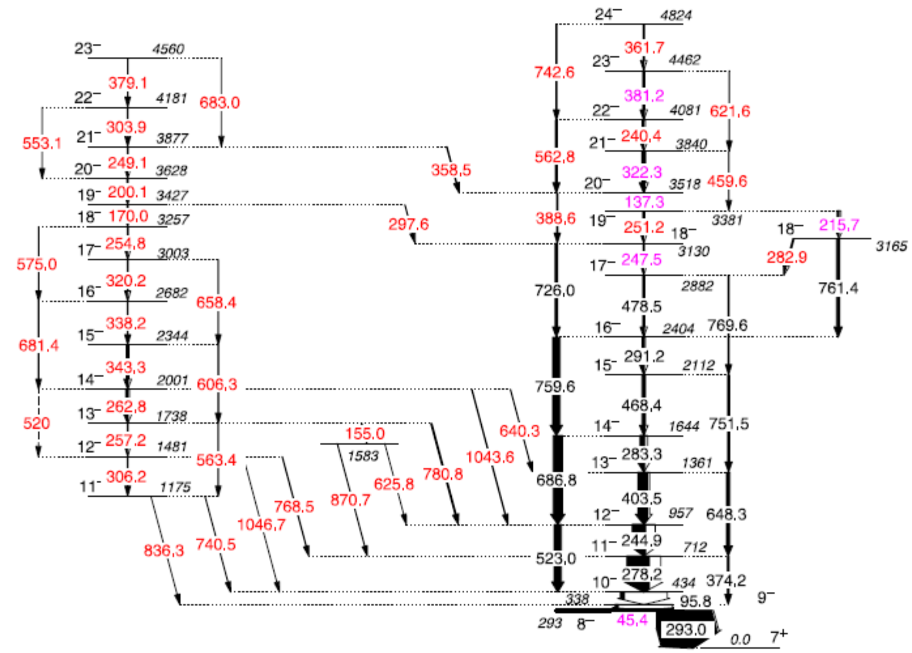
A. Herzáˇn, et al, Phys. Rev. C **96**, 014301 (2017)

Results on Tl nuclei

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

P.L. Masiteng et al., PLB 719, 83 (2013)





Å Deformed rotational band structure based on $\pi h_{9/2} \otimes \nu i_{13/2}$ configuration

Å Band crossing and MR band identified.

Å Chiral doublet band identified by Masiteng et al.

Results on ^{196}Tl

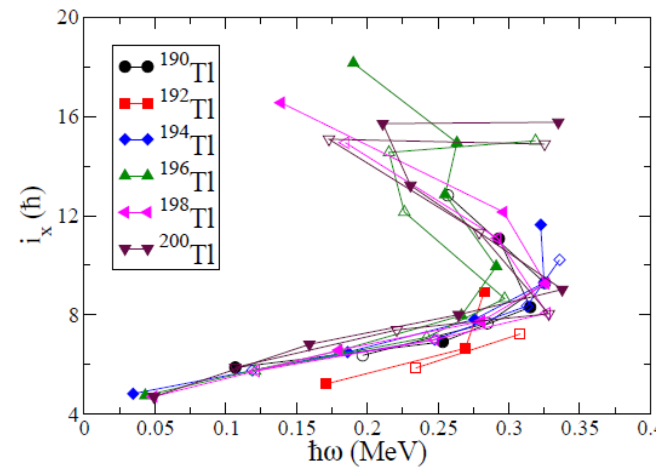
Å A large level scheme with band crossing identified

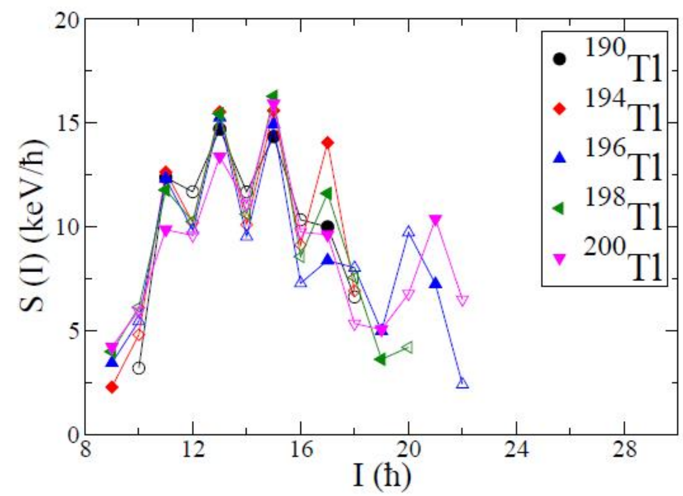
Å Similar behaviour of all the $\pi h_{9/2} \otimes \nu i_{13/2}$ bands in all odd-odd Tl isotopes.

Å Changes observed after the band crossing

Å No chiral doublet band observed

Thesis of Md. A. Asgar: VECC-HBNI (2018)





Md. A. Asgar, et al., DAE Symp. on Nucl. Phys. Vol. 60, 172 (2015).

Results on ^{195}Tl

Physics Letters B 782 (2018) 768–772

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

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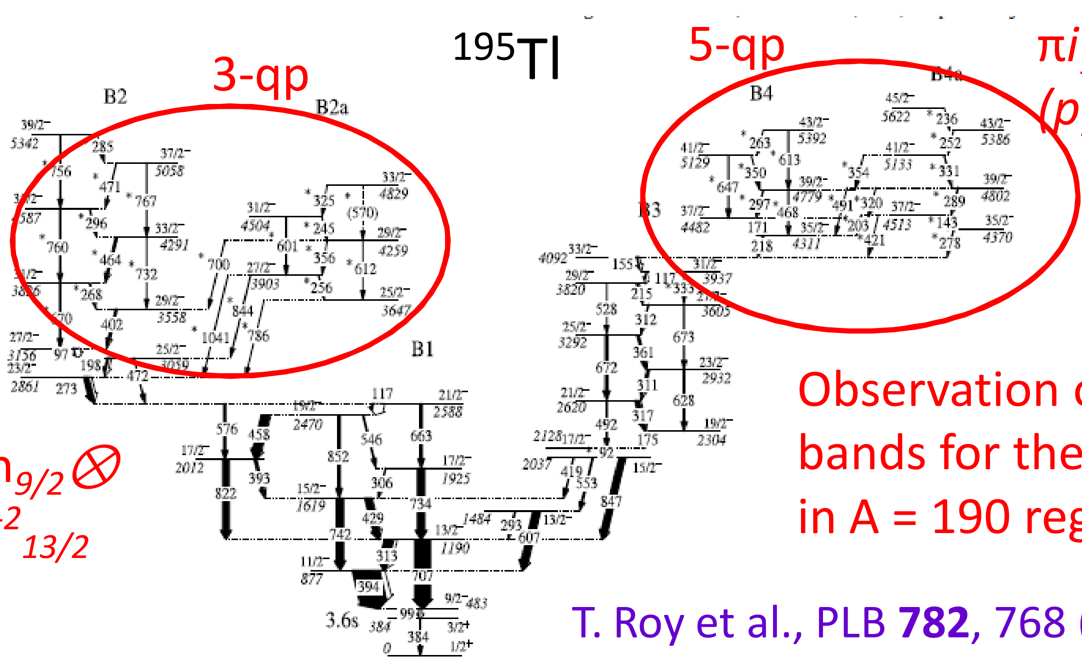
PLB **782**, 768 (2018)

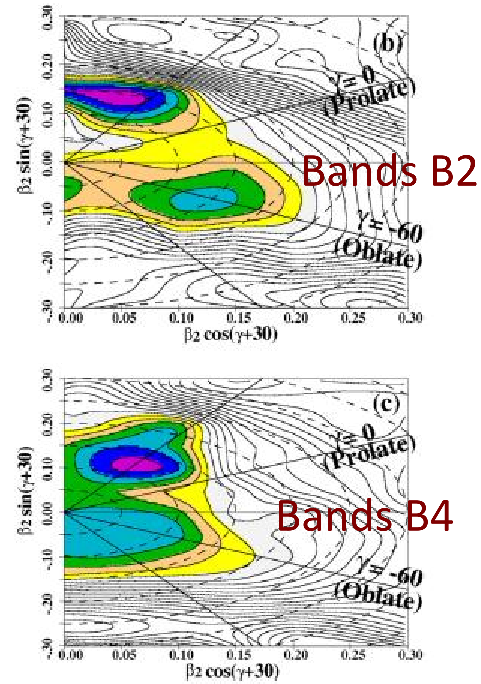
$\pi h_{9/2} \otimes \nu i^{-2}_{13/2}$



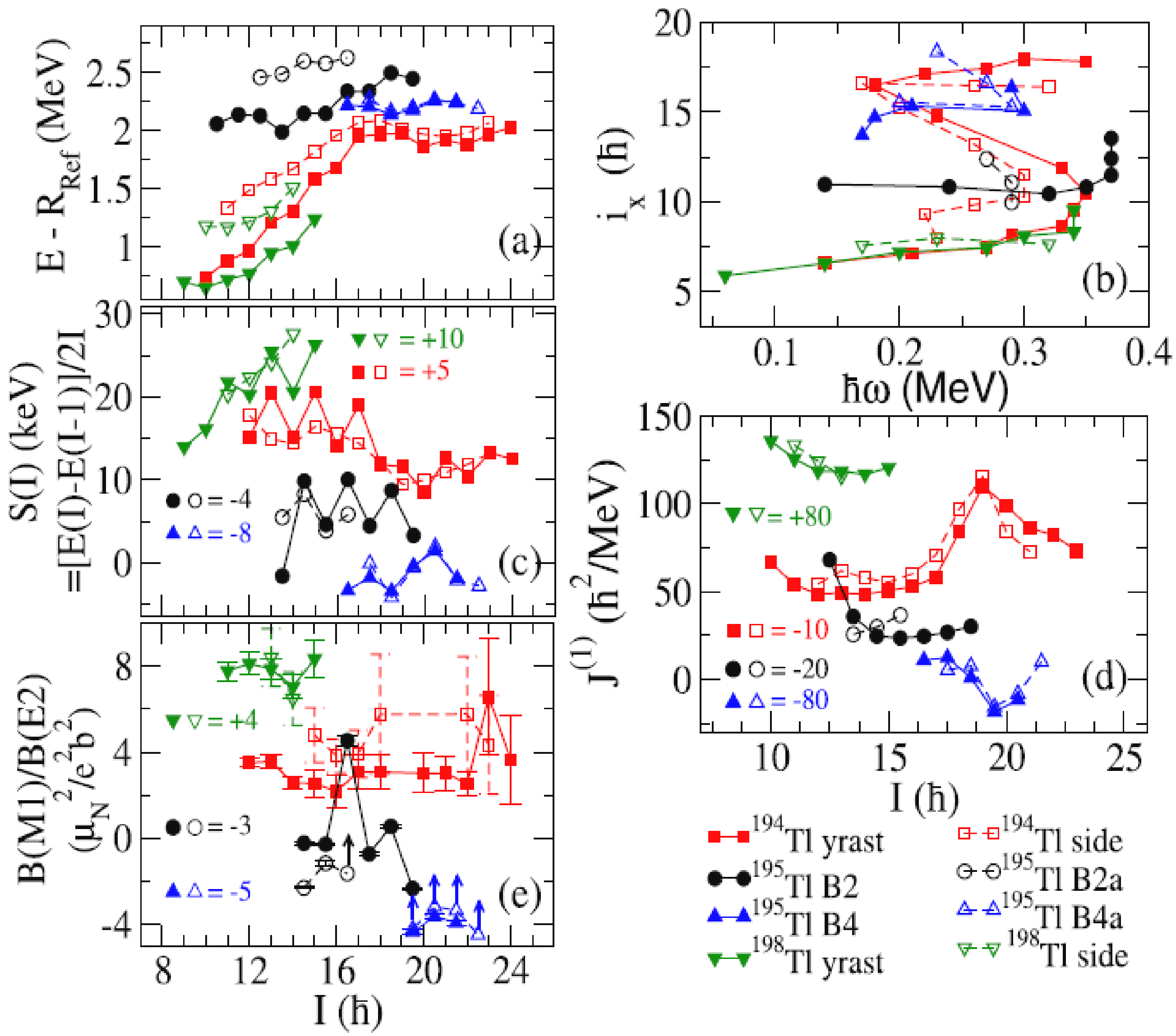
$\pi i_{13/2} \otimes \nu i^{-3}_{13/2}$
$(p_{3/2}f_{5/2})^{-1}$

Observation of MχD 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



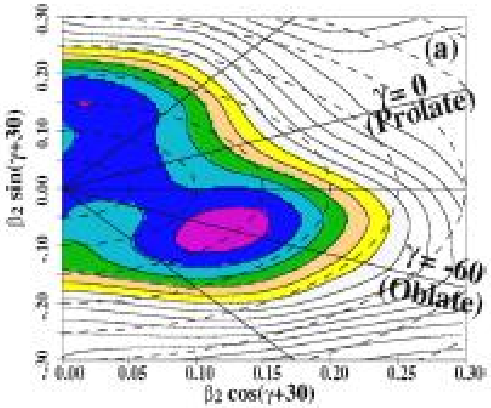
Å First observation of Multiple Chiral Doublet (MχD) in A = 190 region.

Å First observation of doublet bands with configuration involving as large as 5 quasi-particles.

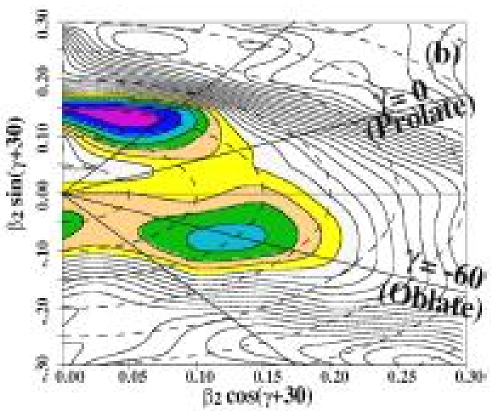
Å ΔE_{av} ~25 keV (Δe_{max} = 59 keV) for B4-B4a represents one of the best degenerate bands.

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

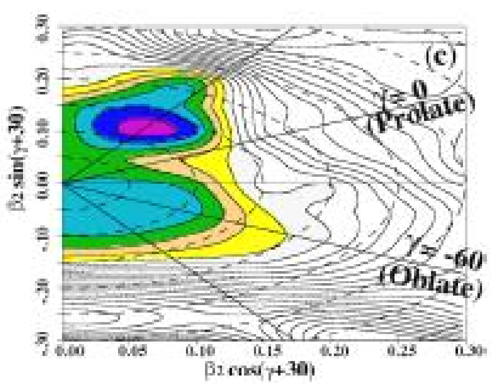
1-qp



3-qp



5-qp



The Oblate shape for 1-qp configuration changes to a triaxial shape with γ ~ + 39^{o} for 3-qp configuration.

For 5-qp configuration, a stable triaxial minimum with γ ~ + 31^{o} 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}Tl.

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

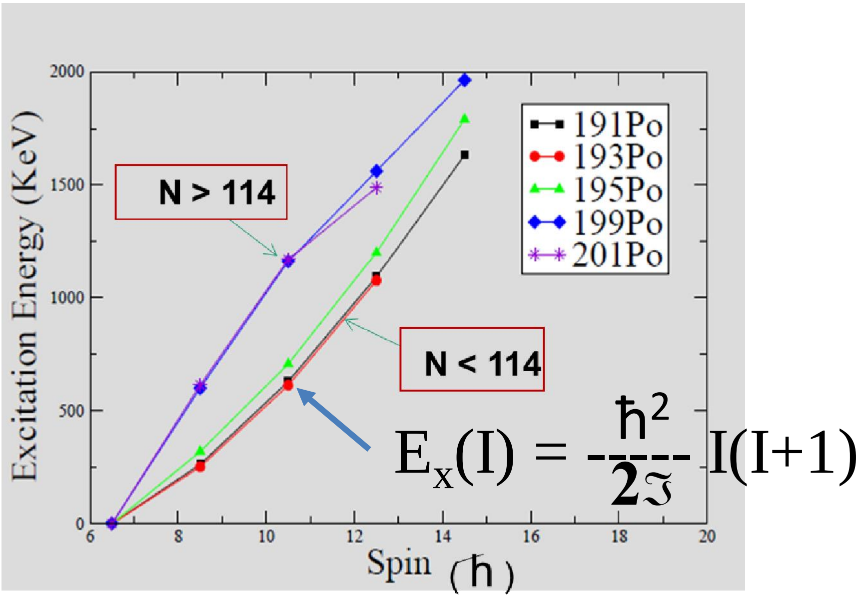
Recent results on ^{197}Tl

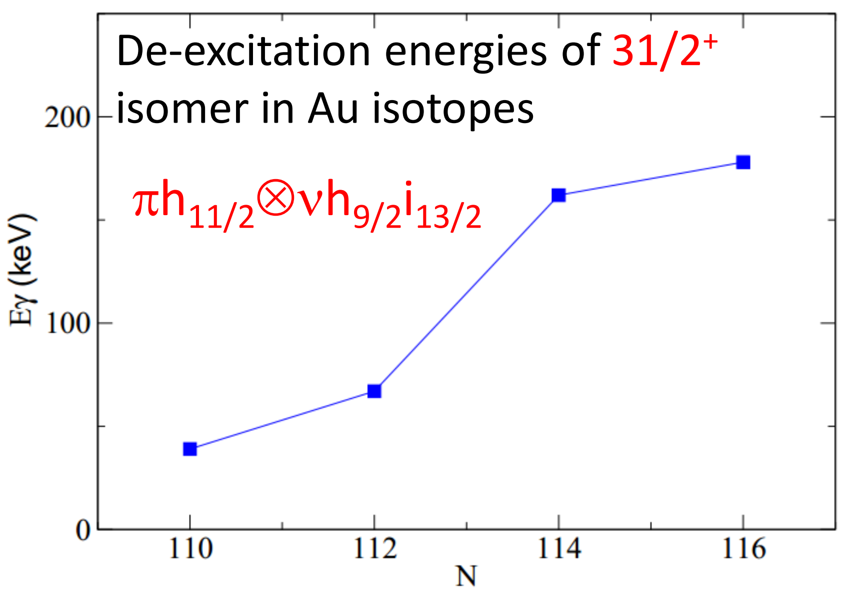
Multiple MR bands in ^{197}Tl (N = 116) at same no. of qp as in chiral bands in ^{195}Tl (N = 114)

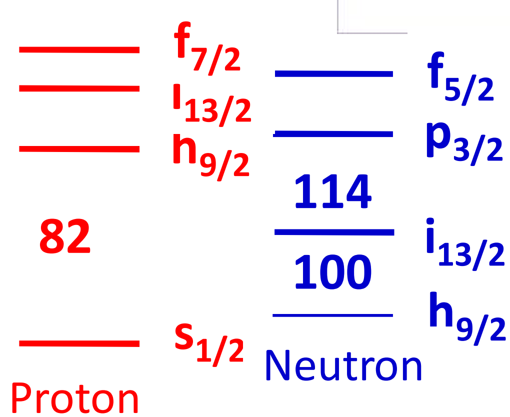
➔ A transition from aplanar (Chiral) to Planar (MR) configuration around N ~ 114

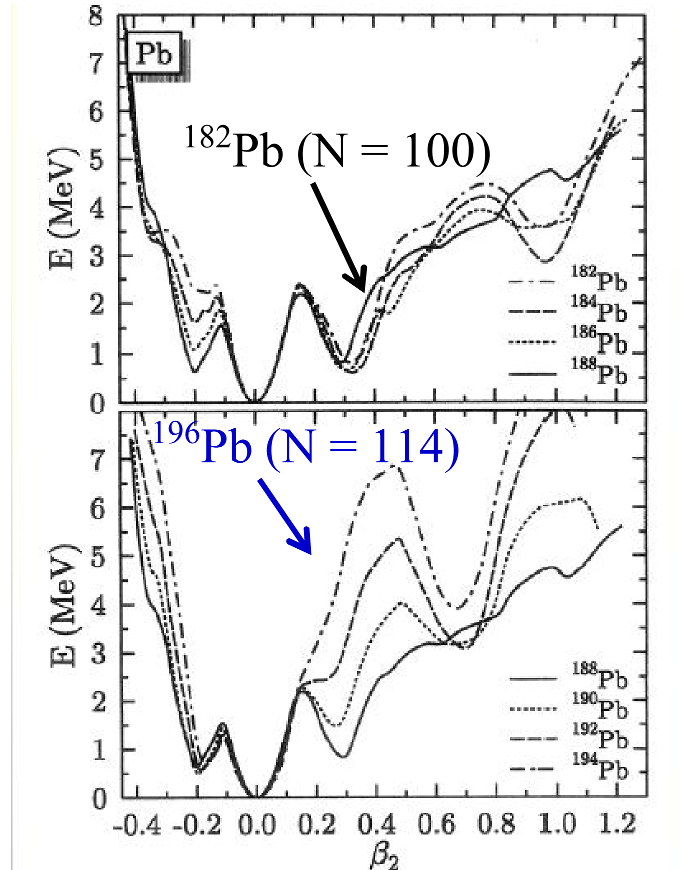
S. Nandi: Poster

Some other structural changes around N ~ 114









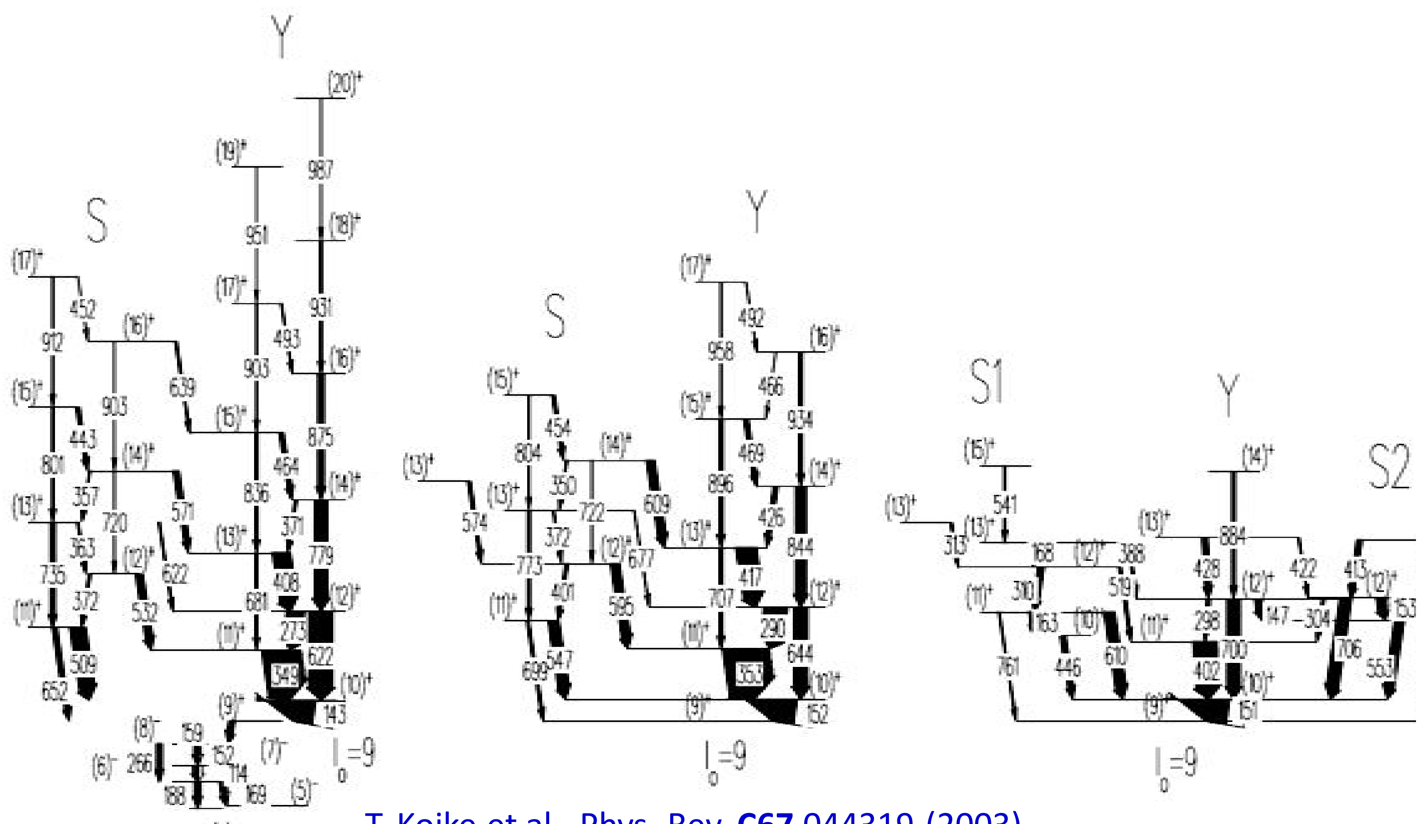
M. Bender et al., PRC **69**, 064303 (2004)

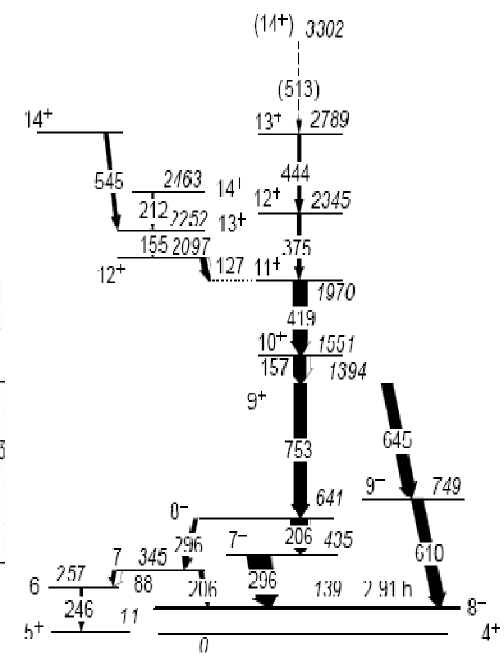
Similar transition for the $\pi h_{11/2} \otimes \nu h_{11/2}$ bands in Cs (Z = 55) isotopes

Chiral bands

MR band

^{128}Cs (N = 73) ^{130}Cs (N = 75) ^{132}Cs (N = 77) ^{134}Cs(Z = 55, N = 79)



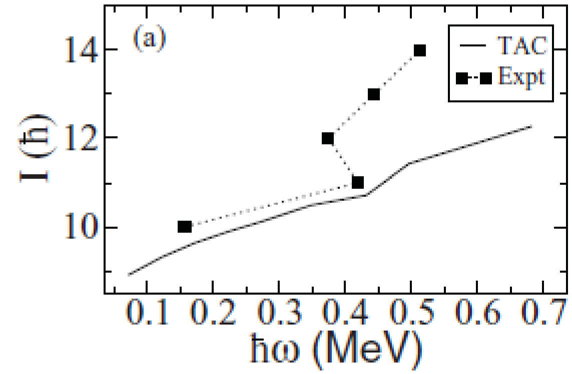


T. Koike et al., Phys. Rev. **C67** 044319 (2003)

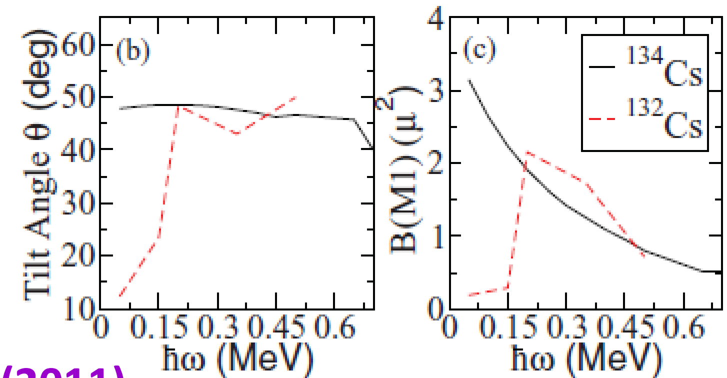
A different band structure in ^{134}Cs.

TAC Calculations

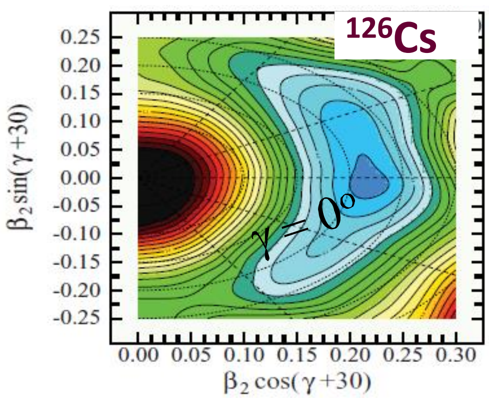
TAC Calculations (S. Kumar) reproduces the data in ^{134}Cs and confirms the MR nature of the band ➔ In sharp contrast to ^{132}Cs.

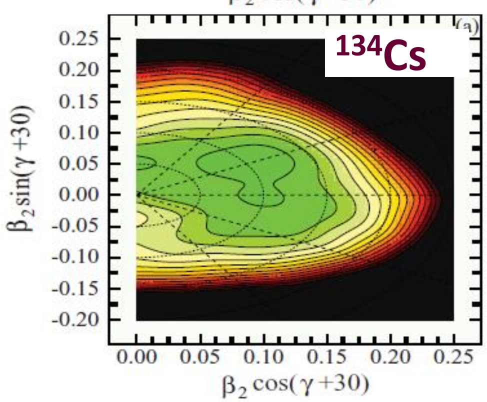


Suggests an aplanar configuration for N <79 to a planar one for N ≥ 79



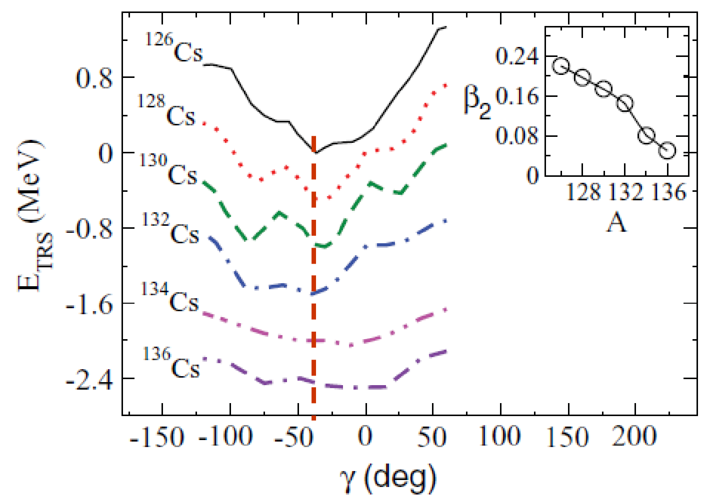
H. Pai et al. PRC 84, 041301(R) (2011)





TRS Calculations

Change in shape from triaxial to γ-soft and towards lower β_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 ~ 130 region.

- More experimental and theoretical investigations are required.

Thank You