# Nuclear Physics with Indian National Gamma Array ( INGA)

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Internationally front ranking research into the exotic nuclear states at extremes of spin and isospin formed in reactions using the heavy ion beams from the national accelerator centres has been a truly rewarding research and developmental activity undertaken by a large number of the universities and research and teaching institutes by using the INGA Facility (Indian National Gamma-Detector Array). Currently a major campaign of experiments using BARC/TIFR Pelletron at TIFR, Mumbai is nearly accomplished. Substantial scientific and technical developments have been achieved under the ambit of INGA project pertaining to the hardware and software requirements for experiments using INGA. The research by the INGA community has led to a large number of publications in high impact journals. With nuclear near yrast spectroscopy being the most pursued field, impressive amount of work has also been carried out in the nuclear reaction and dynamics. A glimpse of the vast canvass of research in nuclear physics pursued using INGA over the years will be covered in the talk. Some ideas on the future of INGA will also be presented.

## 1. Introduction

INGA is an exemplary national collaboration of various universities and research/teaching institutions and DST, India in the field of advanced nuclear research using gamma ray spectroscopy. The facility with a few detectors in the beginning of the 21$^{st}$ century is presently expanded to 24 BGO suppressed HPGe Clover gamma ray detectors and is powered by digital high speed data acquisition and analysis systems.

The nuclear states studied thru the INGA are formed thru nuclear collisions facilitated by the three accelerator centres, viz., IUAC, New Delhi, TIFR-BARC, Mumbai and VECC, Kolkata. The research carried out using INGA in our country has resulted in a large number of publication (over 80) in reputed journals and more than 25 Ph D theses.

INGA has led to substantial technological developments in various laboratories and universities in the field of nuclear detectors, numerical simulation of the detector performance, analogue and digital pulse processing electronics, data acquisition and analysis etc.

The physics program pursued has focused on the high spin behavior of the nuclei with a small but significant number of nuclear reaction studies.

A very significant part of the INGA project relates to development of expertise in theoretical simulation of nuclear dynamics thru participation of nuclear theory groups in the country.

Presently INGA comprises of ~24 clover detectors and uses digital processing at the pre-amplifier level (Fig 1). More than 35 experiments are in the process of being completed in this campaign at TIFR which began in 2011.

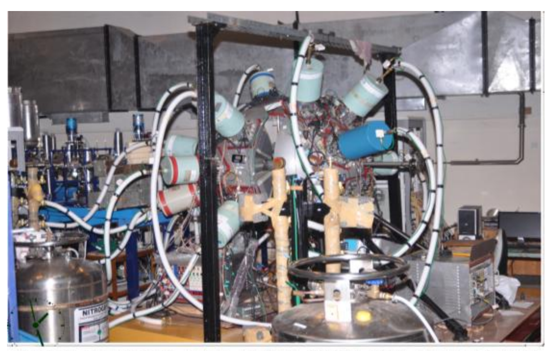

Figure 01: Picture of the INDIAN NATIONAL GAMMA ARRAY with the Comptron Suppressed Clover Detectors at TIFR-BARC Pelletron LINAC Facility at Mumbai installed during the 2011-12 Campaign (www.tifr.res.in/~nsg/INGA_nuc.html)

The next INGA Campaigns propose to exploit spectroscopy of high fissility heavy systems using the residue-decay tagging using the Hybrid Heavy Ion Recoil Analyser at IUAC and using the light ion beams at VECC permitting to form transitional nuclei near the stability line which show highly fluctuating shape variations in the relatively low spin region.

We have had users meeting for these INGA campaigns planned to begin in 2013 and the presently highly vibrant nuclear physics community across the country has considered more than 50 exciting nuclear experiments for these campaigns.

## 2. INGA: Experimental Aspects

There are numerous indigenous developmental efforts over the decade in order to have successful INGA campaigns at the three accelerator centres. These include developments of specific ion beams from Pelletrons, Cyclotron and LINACs (with appropriate energy, intensities and timings characteristics) including those of rare isotopes, development of isotopically pure nuclear targets (which may be often chemically reactive) for various experiments.

There has been extraordinary indigenous developments in the electronics and computer based measurements and data collection methods besides advancements in the data analysis. The Clover Module developed at IUAC with 4 high resolution amplifiers and CFDs built in a single NIM module has found high acceptance even in laboratories abroad. The use of digital electronics processing from the pre-amplifier level has been another critical development at TIFR leading to substantial reduction of the extant of cabling etc in the ongoing INGA campaign at BARC-TIFR Accelerator laboratory.

The fig. 02 shows a typical example of the data gathered in a run from an INGA setup showing the often all important gamma emissions with Doppler shift contributed line shapes which permit lifetime measurement of the nuclear states allowing for a more complete spectroscopic information about the nuclear states. Figures 03 and 04 show some detection characteristics of the clover detectors used

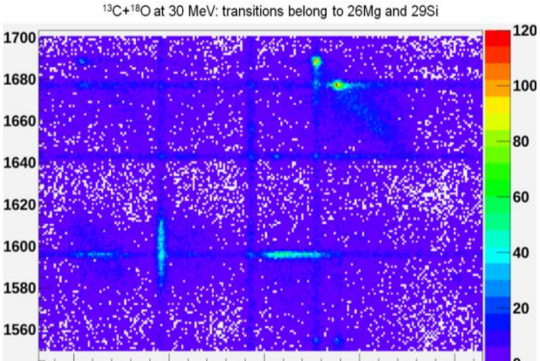


Figure 02: Color Coded Instensity Display of a part of a typical two dimensional spectral matrix of the energy measured in a pair of clover detectors showing Doppler shifted and Doppler unshifted gammas from fast and slow transitions

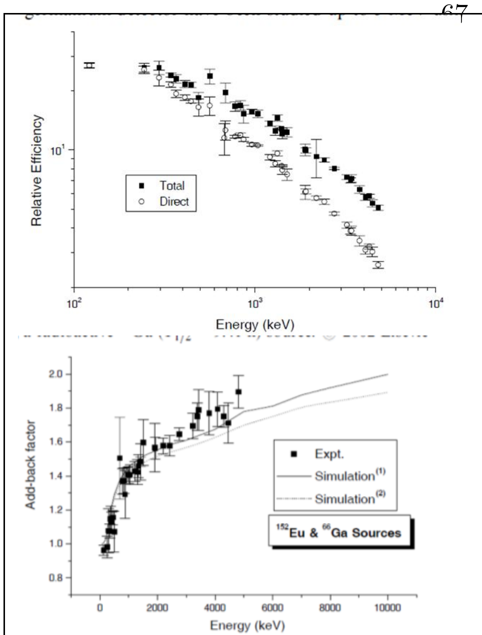


Fig. 03: Characteristics of a Compton suppressed clover detector of INGA up to 5 MeV as measured by M Saha Sarkar et al, NIM A491(2002)1113

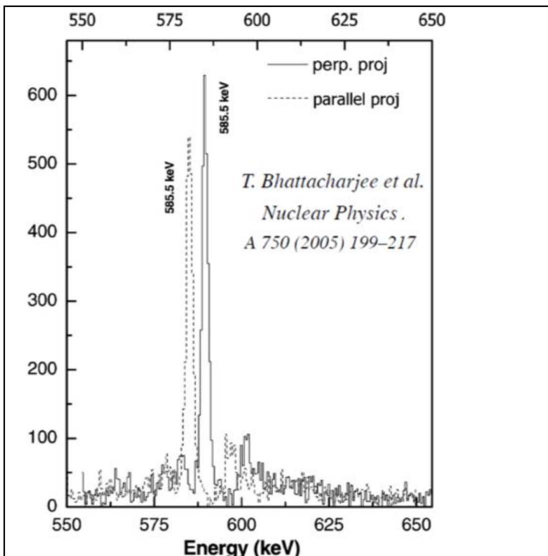


Fig. 04: Use of Clovers in INGA permit measurement of the polarization of the gamma rays emitted in a nuclear cascade. The figure from Nucl Phys A750(2005) 199 illustrates the possibility of using crystal to crystal scattering within a clover detector to use the clover as a polarimeter for ~ 600 keV gamma rays emitted from the odd odd $^{136}$La.

in the INGA array. A consideration of these characteristics of the clover INGA array actually leads to an enhanced efficiency and defines an unique capability of the array (in comparison to arrays in various other laboratories worldwide) in terms of the polarization measurements and associated identifiability of the electric or magnetic nature of an unmixed gamma transition.

The INGA community has strived for critical requirements concerning channel selection and enhancement of high spin selectivity of INGA. There have been campaigns taken with add-on detection systems with INGA for the purpose which include NaI(Tl) multiplicity ball, neutron detectors, charged particle detectors and a major campaign where INGA was coupled with the recoil mass separator HIRA at IUAC. Efforts are on to have a dedicated approach to provide a high gamma-fold cut for an enhanced high spin selectivity.

## 2. Understanding the Nuclear Behaviour with INGA

The research engine that is provided by the INGA with the accelerators in the country is continually gaining momentum with multifaceted nuclear studies for understanding the behaviour of nuclear excited states and the reaction dynamics.

Out of more than 70 nuclei studied so far using INGA (shown in the nuclear chart in Fig. 05), a large no of them are chosen (within limits set by the beam energies} to be slowly distancing away towards n-deficient sides from the shell closure lines (shown as black double lines in Fig05). These are transient regions where nucleus sensitively evolves from spherical shapes towards highly deformed ones going thru various instabilities. The region is of great current interest providing a fertile testing ground with increasing core-valence_nucleons interactions and evolution of the shape/deformation of the nuclear mean field. This has been the focus of the INGA campaigns so far as opposed to the studies of the stably-deformed rapidly rotating nuclear structures as was done in the earlier decades of gamma spectroscopy.

The research community of the country has carried out numerous investigations leading to over 70 publications in the field of nuclear yrast and near yrast state spectroscopy for such transient nuclei. There has been also international participation in the some of the experiments. Mostly the fusion evaporation reaction (with stable beams and targets) has been used for forming the high spin nuclear states of interest on the neutron deficient side of the valley of stability. Several publications in Rapid Communication (PRC) and Physics Letters have been possible (some of them are listed in the attached list of publications out of INGA collaboration). Studies leading to new M1 Bands, detailed confirmation of magnetic rotation (shear mechanism) thru lifetime studies (& anti magnetic rotation), potential chiral partner bands, etc have been published and results have been compared and understood in terms of the semi-classical tilted axis cranking. The studies have been quite thorough and each study has led to wider understanding of the multi quasiparticle-core coupling contributing to identified bands structure. These works are profound and an outline of these studies will be attempted to be described in the talk.

There have been few experiments where rather heavy nuclei are studied and interesting results have been obtained and published [6,15,29]. This direction of research will benefit in the upcoming INGA campaign by use of appropriate tagging device (HYRA) to reduce the fission related background and also nuclear identification from recoil alpha-decay tagging.

One of the challaenging experiment has been concerned with the low backgroud decay study of micro-second range isomers transporting the recoiling residue to the focal plane of the recoil separator HIRA and delayed (from the decay of mass identified transported isomer) and prompt gamma ray consicidences have been studied [57,61].

The use of fusion-fission reaction has been attempted in few studies where fragment spectroscopy has been done for understanding nuclear structure of n-rich medium mass nuclei (the only way of synthesising them using low energy beams) or using gamma identification method to characterize fission in terms of fission fragment mass yield distributions. The gamma rays permit N and Z identification of the large number of fission fragments and interestingly, it has been possible to provide an Isospin based interpretation of the observed yield distribution [25].

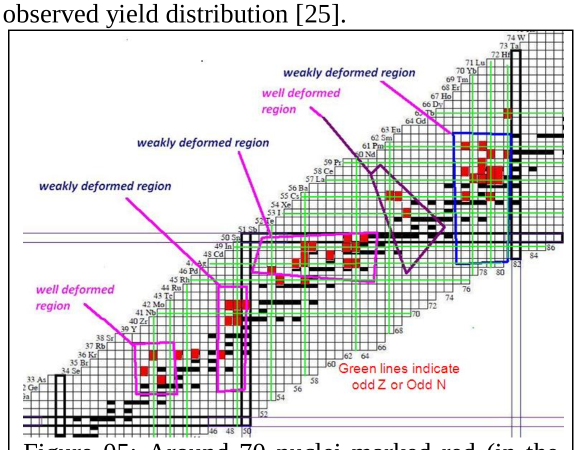


Figure 05: Around 70 nuclei marked red (in the electronic version- will appear gray otherwise) in the nuclear chart above have been studied over the last decade using INGA at different accelerator centres (black boxes represent stable nuclei).

Gamma ray based complete identification of the residues provides perhaps the only way for fusion reactions near barrier with light ion beam. Reactions with light ions with low breakup threshold has been carried out using INGA. These studies with loosely bound projectiles have been performed by a good number of reaction groups with exciting observations related to breakup coupling effects etc relevant from the nuclear astrophysics point of view.

There have been few studies for gamma ray spectroscopy of lighter systems where nuclei on the stability line or on the n-rich side of it are covered with fusion of suitable light targets and beams aiming to carry out a detailed large basis shell model investigation as neutron excess is increased from N~Z region. Interesting results have been obtained in terms of the evolution of the nuclear mean field with n-excess where the tensor interaction seems to modify the shell gap in the sd & fp shells (which eventually leads to the "island of inversion").

## Acknowledgments

Details of some of the INGA work will be shown in the talk but it has not been possible to include them in this report prepared before the delivery of the talk. The author has taken help from a large number of members of the INGA research community and acknowledges thankfully their help and guidance.

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