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Recent results from digital INGA at BARC–TIFR Pelletron Linac Facility and future plans

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Abstract. An experimental campaign aimed at studying various high spin phenomena using the Indian National Gamma Array (INGA) at the BARC–TIFR Pelletron Linac Facility has been successfully completed. The array consisting of a large number of Compton-suppressed clover detectors was coupled to a digital data acquisition system with 96 channels. The present system provides higher throughput, better energy resolution and better stability of gain for the multidetector Compton-suppressed clover array compared to its previous conventional system with analog shaping. Selected results from this array are discussed which highlight the exotic shapes, novel excitation modes and interesting isomers of the nuclei. The preliminary results from the experimental efforts to improve the sensitivity and capability of the array by adding ancillary detectors are also described briefly.

Keywords. Triaxial nuclear shapes; nuclear isomer; Indian National Gamma Array.

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1. Introduction

High-resolution γ-ray multidetector array at heavy-ion accelerator continues to provide new insights on the emergent properties of atomic nuclei with increasing angular momentum [1–6]. A collaborative research facility called the Indian National Gamma Array (INGA) was initiated by Tata Institute of Fundamental Research, Inter University Accelerator Centre, Bhabha Atomic Research Centre, Saha Institute of Nuclear Physics, Variable Energy Cyclotron Centre, UGC-DAE-Consortium for Scientific Research and many Universities in India [7]. In the current campaign at Mumbai, a PCI-PXI-based digital data acquisition (DDAQ) system with 96 channels has been implemented for the Compton-suppressed clover array and some ancillary detectors. Here, we present the performance of the clover array during the in-beam experiments. The physics covered with this device in the current campaign is the study of excitation related uniquely to triaxial nuclear shapes, antimagnetic rotation, tetrahedral nuclear shapes, shell model excitations, search for depletion pathways for long-lived isomers and reaction mechanism involving weakly bound nuclei.

We have organized the paper into the following sections. In §2, the new features of the set-up are highlighted along with the plans for the ancillary detectors to be coupled with INGA. Section 3 describes the recent results and §4 presents the summary.

2. Experimental set-up and its new features

Indian National Gamma Array (INGA) has the provision for 24 Compton-suppressed clover detectors arranged in a spherical geometry with six detectors at 90° and three detectors each at 23°, 40°, 65°, 115°, 140° and 157° with respect to the beam direction. The geometry of the complete array has been included in a program based on GEANT4 framework (see figure 1) to simulate various characteristics of the array such as the total photopeak efficiency and peak-to-total ratio [8]. The simulated quantities are compared with the measured values. For each of the clovers, the absolute photopeak efficiency has been found to be around 0.2% at 1 MeV from the simulation which is close to the measured efficiency. Similarly, the measured peak-to-total ratio of 40% for ^{60}Co is close to the simulation results (see figure 2 for simulated add-back spectra for ^{60}Co with and without Compton suppression). Each of the clovers has 4 *n*-type crystals kept in a single cryostat. The Compton-suppressed clover detectors used in the array facilitate polarization and lifetime measurements for the excited states due to the segmented structure of clovers and its higher efficiency [9,10]. These features of the INGA have found to be extremely

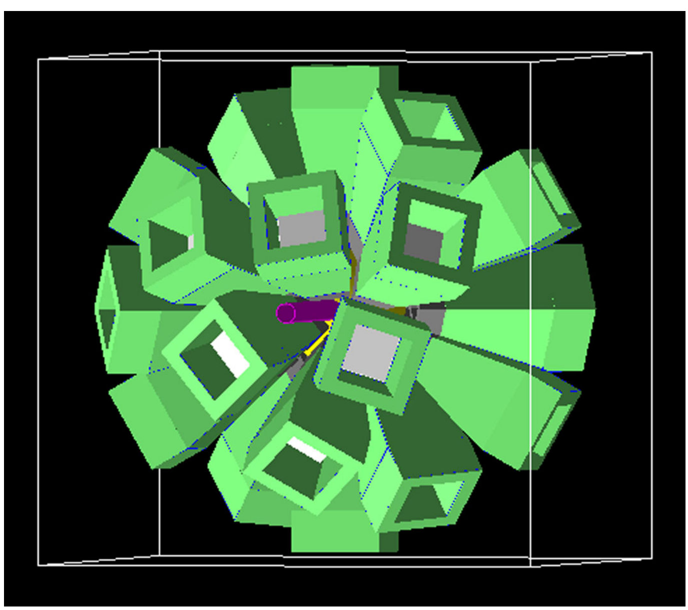

Figure 1. Geometry of the 24 Compton-suppressed clovers of the INGA at TIFR–BARC Pelletron Linac Facility used in the GEANT4 simulation.

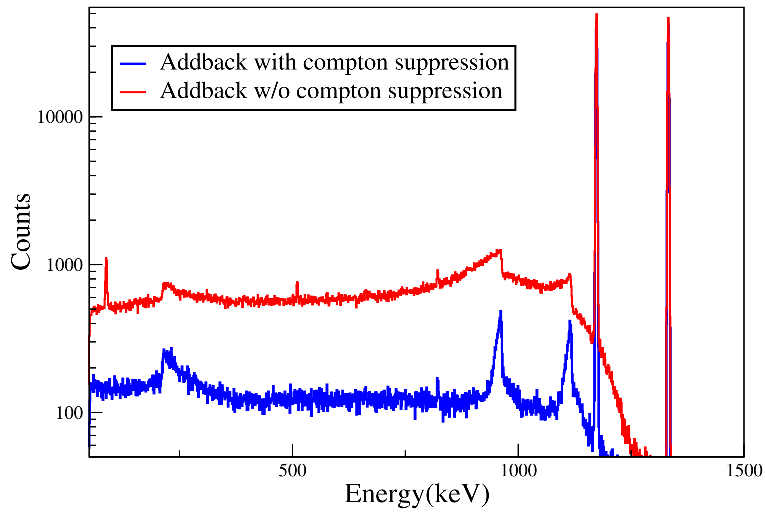

Figure 2. Simulated add-back spectra of ^{60}Co in clover with and without Compton suppression.

important for the investigation of a variety of nuclear structure phenomena, e.g., shape coexistence, magnetic/antimagnetic rotation, chiral rotations, coupling of gamma vibration with other modes, high spin states of neutron-rich nuclei in sd-shell and isomers near shell closure [11–16].

The present digital data acquisition (DAQ) system has been tested to provide good energy resolution over the full dynamic range from 50 keV to 4 MeV of the clovers, even upto the high count rate for each of the 96 crystals of the clover detectors of the INGA. Two-source method has been used to study the variation of energy resolution of γ-rays with changing count rate. In this method, a ^{60}Co source was kept at a fixed distance from the detector and ^{137}Cs source was moved towards the detector to change the total count rate in one of the crystals of a clover detector. The full-width at half-maximum (FWHM) for the 1173 keV transition is found to change from 1.9 keV at 700 Hz to 2.7 keV at 40 kHz (see figure 3). In addition, based on the time-stamping capability of the DAQ, the prompt-delayed coincidence data have been accumulated for developing a new level structure above the known isomeric states. The system has the capability to provide low-fold as well as high-fold coincidence data for in-beam experiments with minimum dead time. The present DDAQ has six Pixie-16 modules, two LVDS level translator modules and one controller arranged in a single Compact PCI/PXI crate [17]. More technical information about the digitizer Pixie-16 modules can be found in [18].

New experiments to incorporate a fast scintillator array consisting of $LaBr_3$(Ce) cylindrical crystals with the clover array has been carried out. The crystals coupled to photomultiplier tube (PMT), were cylindrical in shape with a diameter of 1.5″ and a thickness of 1.5″. During an in-beam experiment, two $LaBr_3$(Ce) detectors were coupled to the INGA to measure the lifetimes of the short-lived states in ^{89}Zr. The signals from the PMT were directly coupled to one of the channels of the DDAQ with a sampling rate of 100 MHz. The partial level scheme of ^{89}Zr relevant to this work is shown in figure 4. The

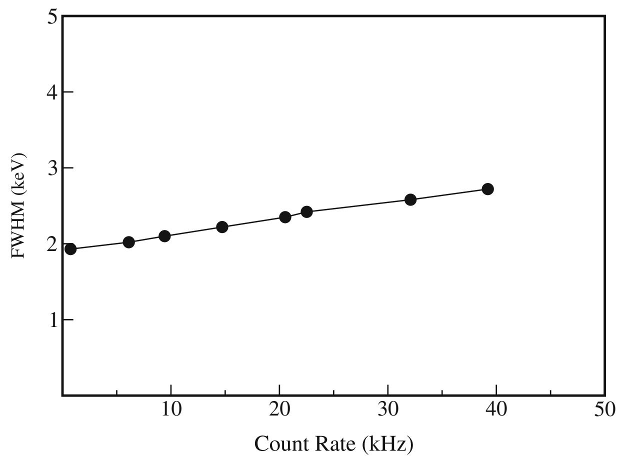

Figure 3. Variation of FWHM of 1173 keV transition emitted in the decay of ^{60}Co at different count rates using the present DDAQ. A two-source method has been used to study the effect of high count rate on the energy resolution of γ-rays.

excited states of ^{89}Zr were produced in the ^{13}C+^{80}Se reaction [19]. Data were sorted to build clover: E_{γ_1}– LaBr$_3$(Ce): $E_{\gamma_2} - \Delta T$ cube. Here, ΔT represents the time difference between the clover and the LaBr$_3$(Ce) detectors. The 1944 keV gated energy spectrum observed in LaBr$_3$(Ce) is shown in figure 5. The time difference spectrum between 271

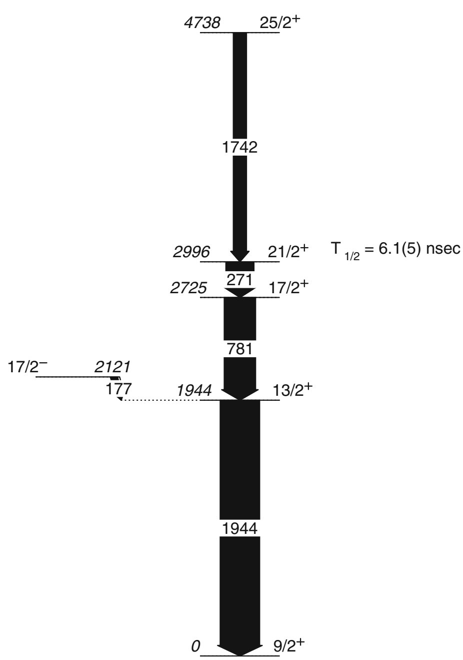

Figure 4. Partial level scheme of ^{89}Zr showing the decay of $21/2^+$ isomer.

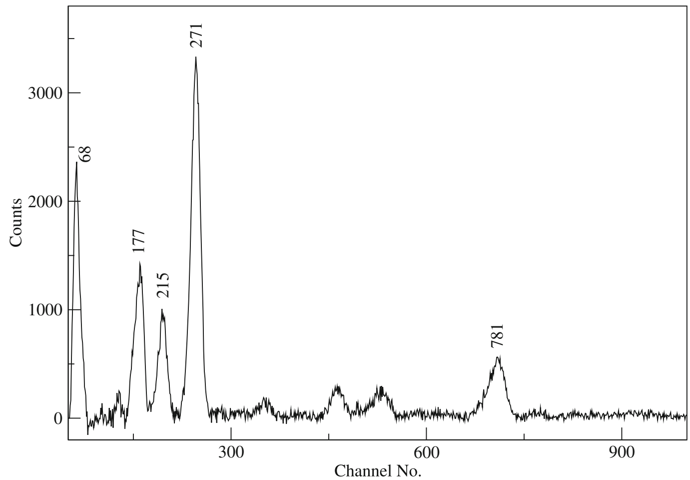

Figure 5. LaBr$_3$(Ce) spectrum obtained with gate on 1944 keV transition of ^{89}Zr is depicted. The strong lines of ^{89}Zr are marked in the spectrum.

and 1742 keV transitions in ^{89}Zr plotted in figure 6 gives a lifetime of $T_{1/2} = 6.1(5)$ ns for the $I^{\pi} = 21/2^{+}$ state of ^{89}Zr which is in agreement with the value given in [20].

A new charged particle detector array consisting of 80 CsI(Tl) crystals coupled to Si-PIN diodes has been fabricated. The size of the crystals are 1.5 cm $\times$ 1.5 cm with a thickness of 3 mm. The preamplifier signal of the CsI(Tl) detector has been digitized with the 100 MHz digitizers and pulse shape analysis has been completed to identify the type of radiations detected in the CsI(Tl) detector. Figure 7 shows the differences in the rise time of the preamplifier pulses registered in the digitizer due to the α-particles and γ-rays emitted from the radioactive sources during offline tests. Different algorithms are

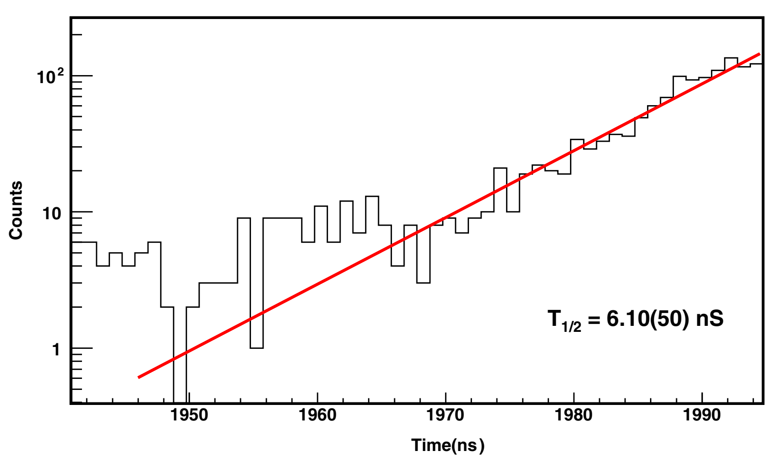

Figure 6. Time difference spectrum between 271 and 1742 keV transitions in ^{89}Zr.

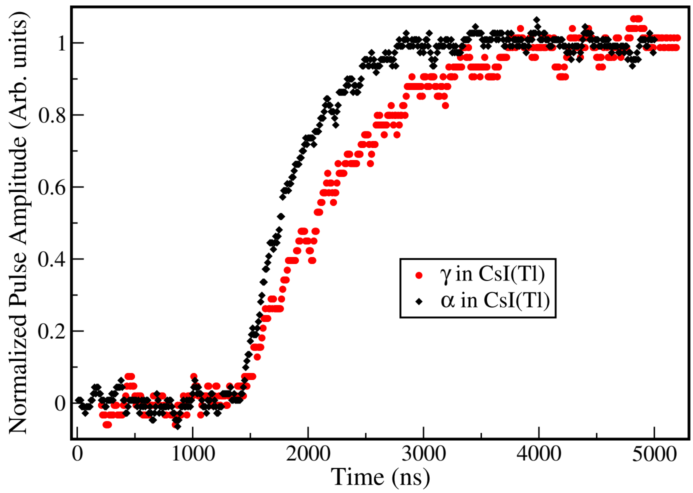

Figure 7. Preamplifier pulses from the CsI(Tl) detector stored in the DDAQ originating from the interaction of the α-particles (black) and γ-rays (red) in the detector.

tested in the offline mode on the stored traces to optimize the efficiency of the particle identification process during the online data processing.

Since the commissioning of the array at the TIFR–BARC Pelletron Linac Facility, Mumbai, a number of nuclear spectroscopic investigations have been carried out using the array. The implementation of the coupling of the DDAQ to the INGA has been reported in [17]. Recently, a pair of degenerate dipole bands with negative parity along with the linking transitions have been established in ^{108}Ag. Comparison of the measured energy levels and ratio of the transition strengths of these bands with the calculations of the triaxial projected shell model (TPSM) suggest that the partner band has a different quasiparticle structure as compared to the yrast band [21]. Another highlight of the present campaign, is the observation of two antimagnetic rotational bands in the single nucleus ^{107}Cd [22]. The high-spin states of ^{122}I have been studied upto spin $I = 30$ and the maximally aligned states involving all eight particles outside the ^{114}Sn core have been identified [23]. Two new band structures, with six-quasiparticle configuration, have been observed in ^{194}Tl [24]. Near-yrast states of ^{89}Zr were investigated upto high spin and the levels were compared with the results of the shell model calculations based on the recently developed shell model calculations [19].

3. Results on the structure of ^{108}Ag

Investigation of the dipole bands in odd–odd nuclei is a subject of current interest. Even though many nuclei in $A \sim 105$ region are triaxial, the occurrence of chiral rotation in this region is not a regular phenomenon. Meng *et al* predicted multiple chiral bands in some of the odd–odd isotopes of Rh, Ag and In using the relativistic mean field (RMF) calculations [25]. In addition, these nuclei have proton holes and neutron particles in the high *j*-orbitals. The low-lying two-quasiparticle states involving high-*j* orbitals can lead to low-energy isomers [26]. ^{108}Ag nucleus has a very long-lived isomer with half-life $T_{1/2} = 438$ years at 110 keV excitation energy and can be produced in neutron capture reactions. Such long-lived isomers are of particular relevance in exploiting their applications in the field of high-energy density storage devices [27]. A spectroscopic measurement of states around the isomer is of great importance due to its crucial role in estimating the depletion pathway of the isomer and the concerned rate. To search for these various interesting phenomena, a detailed spectroscopic study of ^{108}Ag was carried out using INGA at BARC–TIFR Pelletron Linac Facility.

The excited states of ^{108}Ag at high spin were populated in a heavy-ion fusion evaporation reaction ^{100}Mo(^{11}B, 3n)^{108}Ag at 39 MeV beam energy. The ^{11}B beam was provided by the Pelletron–Linac Facility at Mumbai. The ^{100}Mo target used was 10 mg/cm^2 thick. The γ-rays from the de-excitation of the nuclei populated in the experiment were detected using the INGA. Two- and higher-fold clover coincidence events were recorded in a fast digital data acquisition system based on Pixie-16 modules of XIA LLC [17]. The data sorting routine 'Multi pARameter time-stamped based COincidence Search program (MARCOS)' developed at TIFR, sorts the time-stamped data to generate $E_\gamma - E_\gamma$ matrices and $E_\gamma - E_\gamma - E_\gamma$ cubes compatible with the Radware format [28]. The three-fold coincidence data were used to develop the level scheme.

The level scheme of ^{108}Ag was developed upto 8 MeV excitation energy with the addition of around 60 new γ-rays compared to the previously known level scheme [29]. A typical γ-spectrum obtained with the sum of the double gates from 310, 329, 341 and 345 keV transitions of ^{108}Ag is shown in figure 8. A total of 3.7×10^8 triple coincidence events were obtained. A few changes in the placement of energy levels were made, which

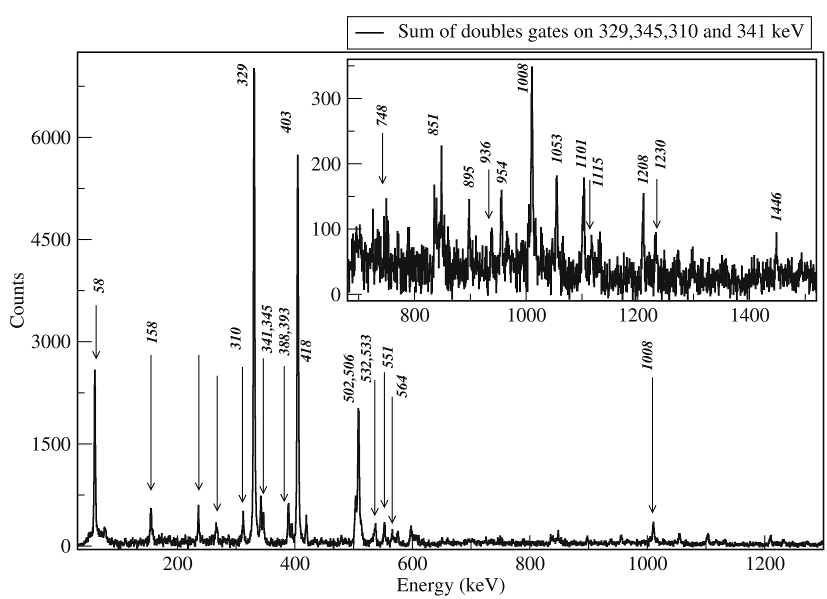

Figure 8. Spectrum obtained with double gates on 310, 329, 341 and 345 keV transitions of ^{108}Ag.

were confirmed by the newly placed crossover transitions and the connecting transitions from the $E_\gamma - E_\gamma - E_\gamma$ analysis. The directional correlation of oriented (DCO) states and the integrated polarization direction correlation (IPDCO) analysis of different transitions were carried out to determine the spin and parity of the excited states. In the low-spin region, substantial changes have been made along with the addition of new γ-rays near the isomer. The branching ratios of a few low-lying transitions in the depleting path were obtained.

An interesting feature in this nucleus is a pair of negative-parity nearly degenerate dipole bands. The yrast band has been established up to spin 19^- along with a partner band up to spin 18^-. The linking transitions from the partner band to the yrast band have also been identified. DCO and polarization measurements of the linking transitions established the spin and parity of some of the states of the partner band. These degenerate bands have been studied using TPSM which is discussed in detail in [21].

The newly developed microscopic TPSM approach was used to understand the nature of the observed twin bands [30]. In the TPSM, first a triaxial Nilsson Hamiltonian along with monopole and quadrupole pairing terms was solved in the BCS approach to generate the quasiparticle states. Then the three-dimensional angular momentum projection operator was used to project out the angular momentum basis states from the intrinsic Nilsson states. In the final step, these angular momentum projected basis states were used to diagonalize the shell model Hamiltonian consisting of the pairing and the quadrupole–quadrupole interactions.

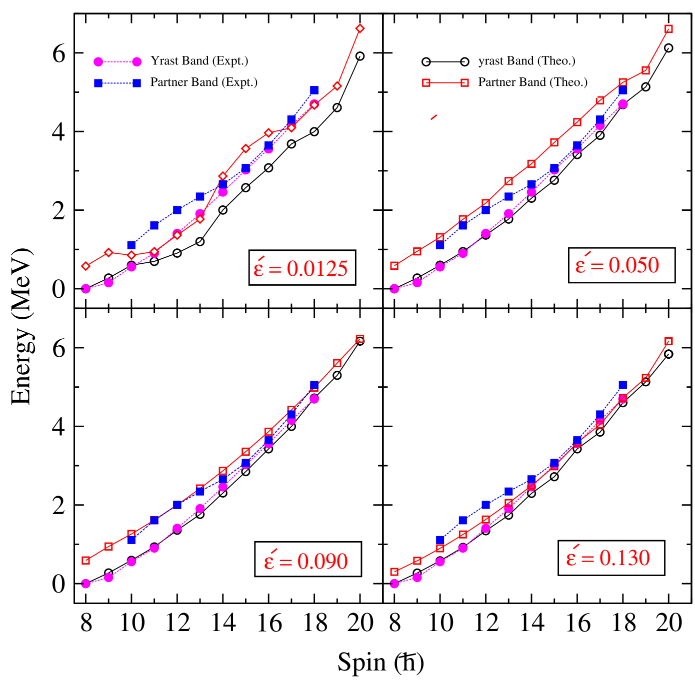

Figure 9. Comparison of the measured energy levels of the yrast and the partner bands of ^{108}Ag with the results of the TPSM calculations for different triaxiality parameters.

A detailed calculation to see how much the theoretical results depend on the choice of the triaxiality parameter was carried out. The measured energy as well as the $B(M1)/B(E2)$ ratios of the yrast and the partner bands were compared with the results of the TPSM calculations for different triaxiality parameters. The comparison of the energy levels can be seen in figure 9. The triaxiality parameter having a value of 0.09 clearly gives a better agreement between the experiment and the calculations.

An important fact about this work is the analysis of the wave functions which reveals that the two bands have different quasiparticle structures. This work gives an interesting and important insight to the structure of the degenerate dipole bands in ^{108}Ag which is clearly a significant advancement in the field.

4. Summary

A number of inbeam experiments have been completed in the INGA campaign at Pelletron Linac Facility at TIFR for investigating exotic modes of spinning nuclei and different high-spin phenomena. Some of the results obtained from the current INGA campaign have been published recently. In particular, the experimental results from the detailed study of the high-spin states of ^{108}Ag carried out in the INGA Facility were published. The negative-parity degenerate bands were studied using the triaxial projected shell model (TPSM) and were found to be based on different intrinsic quasiparticle structures. Preliminary results of the lifetime measurements using $LaBr_3$(Ce) scintillator detector coupled to the DDAQ were discussed. The basic results from the pulse shape analysis of the CsI(Tl) detectors of the 80 element array based on digital signal processing demonstrate the versatile capability of the present DDAQ. We plan to augment the Compton-suppressed clover array at Mumbai with fast scintillators and 80 element charged particle array to carry out a variety of spectroscopic studies of nuclei mainly, near the line of stability.

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