Performance of Indian National Gamma Array (INGA) Coupled with a Fast Digital Data Acquisition System for Nuclear Structure Studies

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Abstract. The Indian National Gamma Array (INGA) is set up at TIFR-BARC accelerator facility, as a part of a national collaboration between different research Institutes and Universities. The array is designed for 24 Compton suppressed clover detectors providing around 5% photo-peak efficiency. Recently, a digital data acquisition system with 96 channels (based on Pixie-16 modules developed by XIA LLC) has been implemented for this Compton suppressed clover array. The digital system provides higher throughput, better energy resolution and better stability for the multi-detector Compton suppressed clover array compared to its previous conventional system with analog shaping. A number of nuclear spectroscopic experiments have been carried out using the array. The results from the initial in-beam experiments of the complete set-up will be discussed in this paper.

1. Introduction
The investigation of the discrete excited states of atomic nucleus through high resolution gamma ray spectroscopy continues to unravel its new excitation modes and improve the understanding of the nucleon-nucleon correlations [1, 2, 3, 4, 5]. A collaborative research facility called the Indian National Gamma Array (INGA) was initiated by Tata Institute of Fundamental Research, Inter University Accelerator Center, Bhabha Atomic Research Centre, Saha Institute of Nuclear Physics, Variable Energy Cyclotron Centre, UGC-DAE-Consortium for Scientific Research, and many Universities in India [6]. This array (INGA) consisting of Compton suppressed clover detectors facilitates polarization and lifetime measurements for the excited states due to the segmented structure of clovers and its higher efficiency [7, 8]. The goal of the INGA is to perform high resolution discrete gamma ray spectroscopy of excited nuclei produced in different reactions for the investigation of variety of nuclear structure phenomena, e.g., shape coexistence, magnetic/anti-magnetic 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 [9, 10, 11, 12, 13, 14]. Recently, a PCI-PXI based digital data acquisition (DDAQ) system with 96 channels has been implemented for the Compton suppressed clover array. Here, we present the performance of the clover array coupled to the new digital data acquisition system during the in-beam experiments.
2. Feature of INGA and the configuration of its associated DDAQ

The detector array is designed for 24 Compton suppressed clover detectors arranged in a spherical geometry with 6 detectors at 90° and 3 detectors each at 23°, 40°, 65°, 115°, 140° and 157° with respect to the beam direction [15]. The picture of the array is shown in Fig. 1. The distance from the target to crystal is 25 cm and the overall photo-peak efficiency is around 5% at $E_\gamma \sim$ 1 MeV. Each of the clovers has 4 n-type crystals kept in a single cryostat. The preamplifier of each of 4 crystals has a gain of 200 mV/MeV and the decay time constant of the output is 50 µsec. The sum of the 16 photo-multipliers of the Compton suppressed BGO shield is given to a timing filtering amplifier and then to the analog constant fraction module which generates a NIM logic signal. This goes as an input to the digital data acquisition system for the veto of the clover signals.

The basic requirement of the digital DAQ of INGA is to provide the energy and timing information for all the 96 channels of 24 clovers vetoed with the respective Compton suppressed BGO shields. The system should provide good energy resolution over the full dynamic range from 50 keV to 4 MeV of the clovers up to high count rate (~20 kHz for each of the 96 crystals of the clover detectors). The timing properties of each of the crystals should be optimized with the digital system so that lifetime measurements for the isomers should also be possible with pulsed beam experiments. The system should have the capability to provide low-fold as well as high-fold coincidence data for in-beam experiments with minimum dead time. The DDAQ has six Pixie-16 modules, two LVDS level translator modules, and one controller arranged in a single Compact PCI/PXI crate as depicted in Fig 2. Elaborate technical information about digitizer Pixie-16 modules can be found in Ref. [16]. Each Pixie-16 card has sixteen channels and serves to four clover detectors. The preamplifier signal is digitized with a 12-bit 100 MHz Flash Analog to Digital Converter (FADC). Each of the input signal is treated in the analog circuitry for compensating the dc offset, removing the high frequency component of the signal and amplification before passing it to the 100 MSPS digitizer. The digitized data stream of the incoming analog pulse enters the signal processing circuitry. This data stream is fed into two branches. The first branch generates a trigger through a fast filter for total multiplicity
computation in the on-board FPGA. The fast trigger is generated when the fast trapezoid filter output crosses the defined threshold. The fast triggers generated from any of the 16 channels of a Pixie-16 module can be distributed to its adjacent modules through the PXI back-plane for generation of global trigger. This fast filter, generated for forming multiplicity groups, was stretched to pulse width of 100 nsec. In the second branch, the data is passed through a Delay FIFO and further branched into energy filter for sampling the energy and trigger filter for fast trigger detection for local signal processing (e.g., pile up detector). In the present configuration, of the six cards in a single crate one card named as Director receives and distributes the triggers among all the channels. The Director computes the multiplicity and opens the coincidence window with a defined length. The veto signal of the BGO shield is given via the front panel LVDS 1/O port. A valid fast trigger is generated in absence of the veto pulse in a specific time window. A sample timing diagram showing an event vetoed by the BGO veto signal followed by another event validated by the external trigger is shown in Fig 3. The first event was vetoed since the stretched veto window was open when delayed fast trigger arrived. For a given channel the fast trigger validated by the external trigger and not vetoed by channel veto signal, the time-stamp will be latched and the event header information will be written. All the modules are required to synchronize clocks for the coincidence measurement. In the current setup, the first Pixie-16 module is configured to be the PXI clock master and all the modules receive the clock through the back plane.

Once the FIFO of each of the modules is ready the data is transferred to the PC in block mode and written to the respective file of the module. Firstly, the time-stamped data from different modules are merged to a single data stream as per the 48 bit 100 MHz time-stamp and event number. The event building software “Multi pARameter time-stamped based

Figure 2. Picture of the PXI crate with the modules for the 24 Compton suppressed clover detectors.
Figure 3. Different triggers showing for a vetoed event and the second one is for a valid event. $D_0$ is the delayed fast trigger. $D_1$ is the validated, delayed local fast trigger and $D_2$ is the stretched external trigger. $D_4$ is the coincidence trigger. $D_5$ and $D_3$ are veto signal from the Compton BGO shield and the stretched veto window, respectively. For the first case, the event was vetoed as delayed fast trigger $D_0$ appears within the stretched veto window $D_3$. In case of a valid event, the valid trigger $D_1$ will appear by the existence of triggers $D_2$ and $D_4$ and absence of veto trigger $D_3$ during the arrival of $D_0$. [16]

COincidence Search program (MARCOS) developed at TIFR sorts the combined data stream to usual coincident events based on the mapping of DDAQ channels to different crystals of the detectors. The gains of the different crystals have been matched by the event building program by energy calibration coefficients. The event building program has the capability of making prompt gamma-prompt gamma correlations as well as the prompt gamma - delayed gamma correlation study by choosing the proper time windows as the external parameters. Conditional time spectra are also generated to look for the prompt and delayed components between different transitions.

3. Performance from the in-beam experiments
The array in its present configuration was commissioned in the TIFR-BARC Pelletron Linac Facility at Mumbai in the middle of 2010. Since then 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 Ref. [17]. The high spin states of $^{122}$I have been studied up to spin $I = 30$ and the maximally aligned states involving all eight particles outside the $^{114}$Sn core have been identified [18]. Two new band structures, with six-quasiparticle configuration, have been observed in $^{194}$Tl [19]. Near yrast states of $^{89}$Zr were investigated up to high spin and the levels were compared with the results of the calculations based on recently developed shell model [20]. In the following the description of the performance of the present DDAQ system during the in-beam experiments will be presented.
In one of the experiments, the excited states of $^{89,90}$Zr were populated using the $^{13}$C + $^{80}$Se reaction at 50 MeV of beam energy. Prompt $\gamma\gamma$-coincidence analysis was performed to construct the level scheme of $^{89,90}$Zr. Two fold coincidence between any of the available clovers was set for the current set-up. In the software the firing pattern of a clover was generated from the “OR” of its four crystals and this further decides the clover multiplicity in a given event. The addback energies of the different clovers were sorted through the 48-bit time-stamp into two dimensional matrix and three dimensional cube for further analysis. The gated spectra were obtained by symmetrization of the gamma-gamma matrix and gamma-gamma-gamma cube followed by Compton background subtraction using the procedure mentioned in Ref [21]. The gate width of the prompt timing was set to 150 nsec. Two gated spectra relevant for identifying transitions of the level schemes of $^{89,90}$Zr [20, 22] are shown in Fig. 4. The double gated spectrum of 1944 and 781 keV transitions identifies a number of new $\gamma$-rays belonging to $^{89}$Zr (see Fig. 4(a)). In this way, the excited levels of $^{89}$Zr have been observed up to $\sim$10 MeV excitation energy and spin $\sim 37/2$ $\hbar$. Similarly, the different transitions of $^{90}$Zr were observed in the 2055 - 1310 keV double gated spectrum in Fig. 4(b).

![Figure 4](image-url)

**Figure 4.** Spectra generated from the double gates of (a) 1944 - 781 keV transitions of $^{89}$Zr and (b) 2055 - 1310 keV transitions of $^{90}$Zr.

The angular distributions for some of the strong transitions were measured to determine their multipolarities. The $\gamma$-rays were detected in the singles mode by the clover detectors placed at angles of 157°, 140°, 115° and 90°, 65° and 40° with respect to the beam direction. The angular distribution data were fitted according to the following formula:

$$W(\theta) = a(1 + a_2P_2(\cos(\theta)) + a_4P_4(\cos(\theta)))$$

(1)

The angular distribution plot for the 781-keV transition is shown in Fig. 5. The $a_2$ and $a_4$ coefficients for the angular distribution of this transitions suggest the pure $\Delta I = 2$ nature.

Each of the four clover detectors present at 90° was used as a Compton-polarimeter to assign the electric or magnetic nature of $\gamma$-rays. For a Compton-polarimeter, polarization asymmetry $\Delta$ of the transition is defined as [23]

$$\Delta = \frac{a(E_\gamma)N_\perp - N_\parallel}{a(E_\gamma)N_\perp + N_\parallel}$$

(2)
Figure 5. Angular distribution of 781 keV transition of $^{89}$Zr with respect to the beam direction is plotted along with the fit.

Figure 6. (Colour online) Gated spectra of the parallel and perpendicular Compton scattering in the 90° clover detectors. Higher counts of 215 and 533 keV transitions of $^{89}$Zr in the perpendicular scattering spectra indicates their electric nature. The reverse condition for 589 and 2121-keV transitions of $^{89}$Zr suggest their magnetic nature.

where, $N_{\perp}(N_{\parallel})$ is the number of counts of $\gamma$ transitions scattered perpendicular (parallel) to the reaction plane. The correction factor $a(E_{\gamma})$ is a measure of the perpendicular to parallel scattering asymmetry within the crystals of the clover detector. For the 90° detectors this
Figure 7. The time spectrum obtained for the decay of $8^+$ state in $^{90}\text{Zr}$ at 3589 keV excitation energy. This spectrum is generated by measuring at the time difference between 2055 keV and 1129 keV transitions across the isomeric state.

The $8^+$ state of $^{90}\text{Zr}$ at 3589 keV excitation energy is an isomeric state and decays by 141 - 1129 - 2319 keV cascade of $\gamma$-rays [22]. Time difference spectrum between two transitions, ($E_1$) above the isomer and ($E_2$) below the isomer can be obtained from the time-stamped data using the following procedure. Four conditional time spectra ($T_{p1,p2}$, $T_{p1,bg2}$, $T_{bg1,p2}$ and $T_{bg1,bg2}$)
needs to be generated from the time-stamped data. Here, $T_{p_1,p_2}$ represents the time difference spectrum obtained with energy gate around the $E_1$ and $E_2$ peaks, while $T_{p_1,bg_2}$ represents the same for energy gate around the $E_1$ peak and background near $E_2$ peak. Similarly, the 3rd and 4th spectra are for background-peak and background-background spectra. Then the final time difference spectrum will be given by,

$$T(i) = T_{p_1,p_2}(i) - T_{p_1,bg_2}(i) - T_{bg_1,p_2}(i) + T_{bg_1,bg_2}(i)$$

(3)

The decay spectrum obtained from the time difference between the time-stamps of 2055 - 1129 keV transitions is shown in Fig. 7. The half-life was extracted to be $122 \pm 8 \text{ nsec}$ in the present experiment and is in agreement with the reported lifetime in Ref [22].

4. Summary
A fast digital data acquisition system has been coupled with the Indian National Gamma array consisting of Compton suppressed clover detectors. Several experiments were performed using the current set-up to investigate different high spin phenomena. Many interesting results have been obtained from experiments on INGA and part of the results have also been published recently. Using the time-stamped gamma-gamma coincidence data lifetime of isomeric state of $^{90}$Zr was found to be $122(8)$ nsec from the present set-up. Inclusion of a fast timing array consisting of LaBr$_3$(Ce) scintillators with the INGA is planned. This will facilitate the lifetime measurements of isomeric states from 1 nsec to few µsec during the usual gamma-gamma coincidence measurement. Testing of the DDAQ for the light charged particle identification using CsI(Tl) and Si detectors is also planned. The coupling of INGA and its different ancillary detectors to the digital DAQ has improved the overall efficiency and sensitivity of the gamma detector array for nuclear structure and reaction studies.

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