Nuclear Instruments and Methods in Physics Research A 622 (2010) 281–287

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Technical Note

Indian National Gamma Array at Inter University Accelerator Centre, New Delhi

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ARTICLE INFO

Article history:
Received 26 June 2009
Received in revised form
11 June 2010
Accepted 11 June 2010
Available online 22 June 2010

Keywords:
Multi-detector array
Clover germanium detector array
Compton suppression
In-beam $\gamma-$ray spectroscopy
High voltage power supply
Front-end electronics for signal processing

ABSTRACT

A 4π multi-detector gamma-ray spectrometer named the Indian National Gamma Array (INGA) has been set up at the Inter University Accelerator Centre, New Delhi, for nuclear structure studies. The array is designed to incorporate twenty four Compton-suppressed Clover germanium detectors with a total photopeak efficiency $\sim 5\%$. The spectrometer along with sub-systems developed in-house like, mechanical support structure, high voltage power supplies, automatic liquid nitrogen filling system, front-end electronics and data acquisition system are described. The mechanical support structure facilitates the use of the Clover Germanium array with a recoil mass separator. The array has been used in a number of nuclear spectroscopic investigations. The in-beam and off-beam performance of the array are reported.

1. Introduction

Quest to excite nuclei to very high angular momenta, high excitation energies and different N/Z ratios, has led to discovery of many exotic excitation modes. Super-deformation, wobbling motion, magnetic rotation, chirality and reflection-asymmetric modes of excitation are some of the phenomena discovered in the last two decades. Simultaneous developments in heavy ion accelerators, theoretical computational methods and technology for fabricating large volume germanium (Ge) detectors made detailed study of the above phenomena possible. Availability of large efficiency Ge multi $\gamma-$detector arrays has played a prime role in these investigations.

Most of the large arrays, i.e., Gammasphere [1], Clarion [2], Clara [3], Yrast ball [4], GASP [5], Exogam [6], Rising [7], Afrodite [8], Tigress [9], Greta [10], Grape [11] and Jurogam [12] with photopeak efficiencies ranging 3–9%, are located in U.S.A. and Europe. In India, high-spin investigations were carried out utilizing a 12 Compton suppressed HPGe detector array [13] at the Inter University Accelerator Centre (IUAC formerly known as Nuclear Science Centre), New Delhi. A collaborative research facility called the Indian National Gamma Array (INGA) was initiated by Tata Institute of Fundamental Research, IUAC, Bhabha Atomic Research Centre, Saha Institute of Nuclear Physics, Variable Energy Cyclotron Centre, UGC-DAE-Consortium for Scientific Research, and many Universities in India. The array was upgraded to the present form with major funding from the Department of Science and Technology in India.

The present paper describes this INGA facility [14] developed at IUAC, New Delhi. It is presently operated in stand-alone mode without any auxiliary detectors for studying high-spin $\gamma-$spectroscopic investigations. The array is planned to be used in the future in coincidence with the recoil separator, HYbrid Recoil mass Analyzer (HYRA) [15] at IUAC for reaction channel selection. Some interesting physics problems that can be addressed with the

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doi:10.1016/j.nima.2010.06.200

combined setup are (i) spectroscopy of sd shell nuclei, (ii) isospin effects in N–Z nuclei, (iii) high-spin structure near proton and neutron shell closure and (iv) structure of trans-Uranium nuclei. The system details of the stand-alone INGA facility, along with its in-beam and off-beam performance, are presented in this paper. A preliminary account of this facility was reported earlier [16].

2. System details

The array has been designed to incorporate twenty four standard Compton-suppressed Clover HPGe detectors [17] in 4π geometry with detector to target distance ~ 24 cm. The total solid angle coverage by Ge crystals is 25% of 4π resulting in a total photo-peak efficiency $\sim 5\%$. The primary advantage of using Clover detectors in the array over conventional Ge detectors is the increased photo-peak sensitivity in add-back mode [17] for γ energies above 1 MeV. In addition, they can be used as a four-fold Compton polarimeter to measure linear polarization of $\gamma-$rays. This feature is of extreme importance for unambiguous assignment of spin-parity to the energy levels of the nucleus under study. The Anti-Compton Shields (ACS) are of Eurogam-II design each subtending an angle $\sim 30^\circ$ at the target. The total system is optimized for collecting data at triple or higher fold $\gamma-$ray coincidence events for unique assignment of γ transitions in a level scheme.

2.1. Mechanical support structure, target chamber and automatic liquid nitrogen filling system

The detector support structure consists of two sections—a backward hemispherical segment that can hold up to 16 Clover detectors and a forward hemispherical segment for 8 detectors. The structures are mounted on two platforms movable on a pair of precision guide rails (Fig. 1). The front section of the array is removable to facilitate the use of the array in coincidence with the recoil separator.

The detectors are arranged in the structure in five rings as indicated in Table 1. The surface of the mechanical structure of diameter ~ 1 m is machined to have 34 polygon faces of roughly equal area and with holes for mounting detectors and the inlet–outlet beam lines. The ACS can be mounted on the structure within an accuracy of $\pm 0.5^\circ$ with respect to the beam axis and their positions are reproducible to an accuracy of ± 0.5 mm with respect to the target [18]. In addition to 24 Clover Ge detectors, 6 Low Energy Photon Spectrometer (LEPS) can also be mounted in the support structure at two angles (see Table 1). A side view of the INGA setup is shown in Fig. 2.

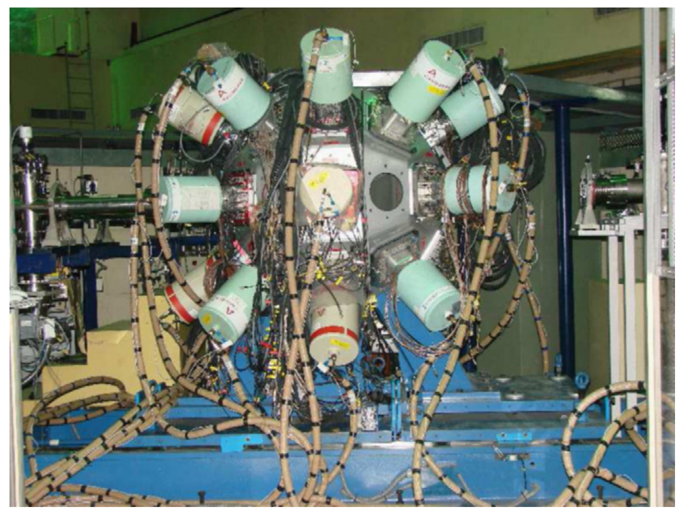

Fig. 2. Side view of the facility at IUAC.

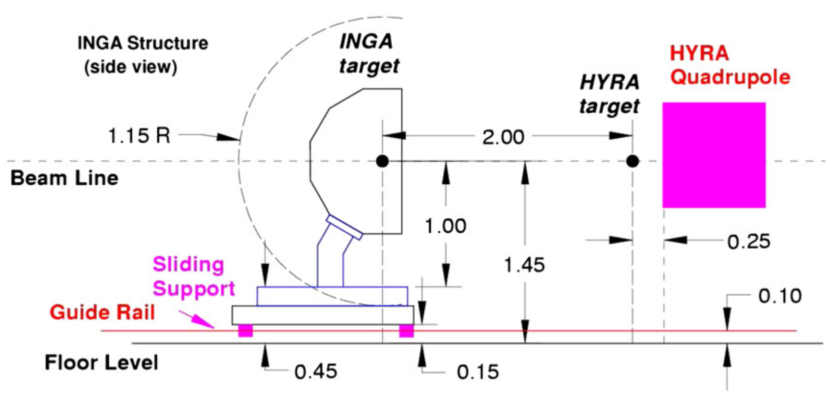

Fig. 1. Schematic diagram of the beamline with two target positions: (a) 'INGA target' for in-beam measurements using INGA and (b) 'HYRA target' for using INGA in conjunction with recoil mass separator HYRA. (All dimensions are given in m.)

Table 1
Orientation of the Compton-suppressed Clover germanium detectors in INGA facility.

Detector number	Orientation of the detectors ($\theta;\phi$) *w.r.t.* beam in degrees	Number of detectors	Shape of plate
	Backward hemisphere		
1–4	148 ; 0, 90, 180, 270	4 Clover/ACS	Hexagon
5–8	123 ; 45, 135, 225, 315	4 Clover/ACS	Pentagon
25–27	119 ; 0, 90, 180	3 LEPS	Trapezium
9–16	90 ; 0, 45, 90, 135, 180, 225, 270, 315	8 Clover/ACS	Rectangle
	Forward hemisphere		
28–30	61 ; 0, 90, 180	3 LEPS	Trapezium
17–20	57 ; 45, 135, 225, 315	4 Clover/ACS	Pentagon
21–24	32 ; 0, 90, 180, 270	4 Clover/ACS	Hexagon

The target chamber is made of glass tube (2 in. diameter) to minimize attenuation of γ−rays in the chamber walls. The target is mounted at the middle of the chamber on a 1 mm thick aluminum frame held by two 4.5 mm diameter stainless steel rods. A removable collimator of 5 mm diameter with current readout is placed at a distance $\sim$1.5 m upstream from the target and a Faraday cup is placed 1 m downstream after the target. The beam current intercepted by the collimator is minimized while that of the Faraday cup is maximized for centering beam on the target.

A PC-based '*Autofill*' controller system [19] has been developed to periodically fill the detector dewars with liquid nitrogen. The temperatures of the exhaust gas in the dewar outlets are monitored using PT100 sensors. Solenoid operated cryogenic valves are used for controlling flow of liquid nitrogen to detector dewars. These valves are operated through software working on Linux platform. To prevent warm-up during experiments, the detectors are normally filled every 12 h under software control.

2.2. Detector power supplies

Power supplies for the Clover detectors and anti-Compton shields have been developed in-house [20]. The Clover detectors are biased using high voltage ($\pm$5 kV/100 μA) DC power supply based on the Cockroft–Walton multipliers. The power supply has an automatic ramping facility that ramps up the output voltage to a preset value at chosen ramping rate, e.g. 5 kV in 30 minutes. The ramp-down option allows biasing down of all the detectors in parallel. The ACS detector photomultiplier tubes are biased by stable ($\leq$0.03%), low noise ($\pm$10 mV$_{pp}$ at 25 kHz) high voltage power supplies ($\pm$3 kV, 10 mA). These units are regulated switched mode supplies based on double ended push-pull switching scheme and protected against overload and output short-circuit. Linear regulated power supplies ($\pm$12 V, 1A and $\pm$24 V, 1A), are used to power the preamplifiers of Clover detectors. These supplies provide stable (0.005%) and low ripple (3 mV$_{pp}$ at full load) output voltages and are protected against excessive current and over temperature.

2.3. Front end electronics

The signal processing electronics is located in a radiation shielded area adjacent to the beamline. All signals from the detectors are brought to this area using $\sim$30 m long coaxial cables (RG-58). To minimize noise pickup, the signal from ACS is first fed to a preamplifier [21] containing a wide-band gain stage followed by a buffer amplifier.

An in-house developed Clover detector electronics module [22] is used to process energy and timing signals from Compton-suppressed Clover Ge detectors. This double width NIM unit includes four baseline corrected spectroscopy amplifiers with 3 μs shaping time and gain range selectable using jumper settings. The amplifiers have excellent stability (1 part in 10^4 in 24 h) and linearity (1 part in 10^4), as well as low electronic noise (0.5 keV for 2 MeV range). To extract the timing information from individual crystals and the corresponding anti-Compton shield, the Clover module also contains five timing filter amplifiers of fixed shaping time and fixed gain along with respective constant fraction discriminators (fraction 0.3, delay 25 ns). The time difference between individual crystals of a Clover detector can be adjusted in steps of 2.5 ns using internal jumpers.

The schematic diagram of IUAC Clover detector electronics module is shown in Fig. 3. The timing signals from individual crystals of each Clover detector are 'OR'ed, followed by 'VETO' from the ACS signal, to get 'A_{coinc}' signal. The global event trigger for data acquisition system is generated from 'A_{coinc}' signals from individual detectors satisfying the desired γ−multiplicity of the Compton-suppressed event (typically $M_\gamma \geq 3$).

2.4. Data acquisition system

The Data Acquisition System (DAS) at IUAC is CAMAC based, with the digital hardware distributed over three 24-slot CAMAC crates. Custom made 14-bit, 8-channel AD814 ADCs [23] are used to digitize the energy signals from Compton-suppressed detectors as shown in Fig. 4. The timing signals from the individual Clover detectors are digitized using Phillips 7186 TDCs. The signals from all detectors are divided into three event fragments and read in parallel from three different crates along with the event identification tag for each event. Data readout and buffering are accomplished by a home-made List Processing Crate Controller (LPCC) [24]. The data acquisition system is operated in a common dead time mode with the trigger generators [25] used for synchronization of individual crates. The multi-crate data acquisition program *Candle* [26] is used to assemble the event

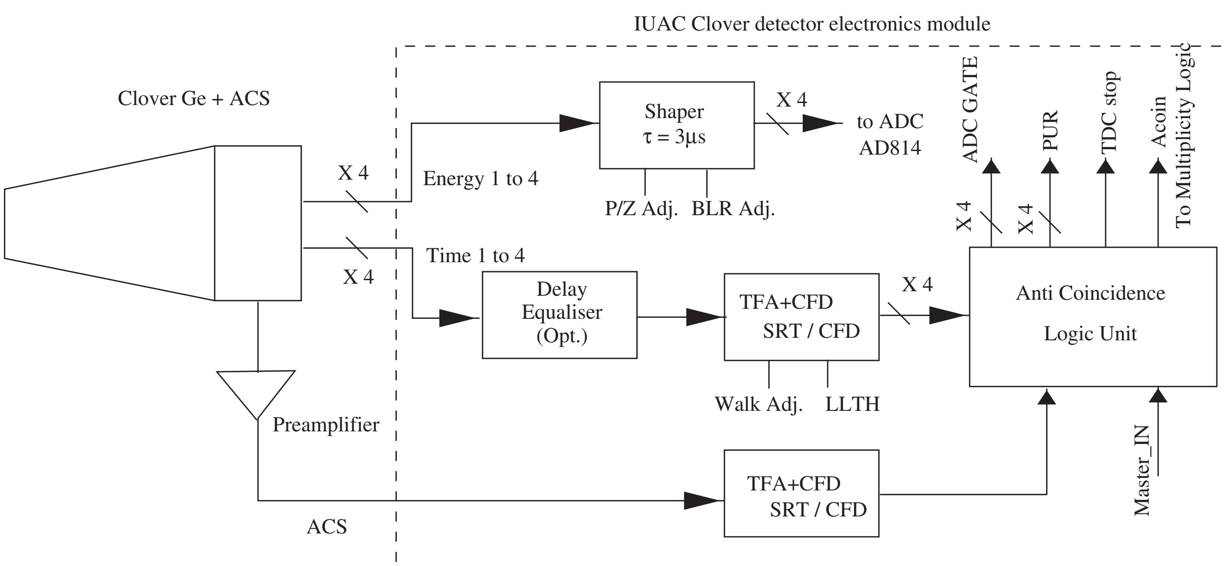

Fig. 3. Block diagram showing the signal processing in Clover detector electronics module.

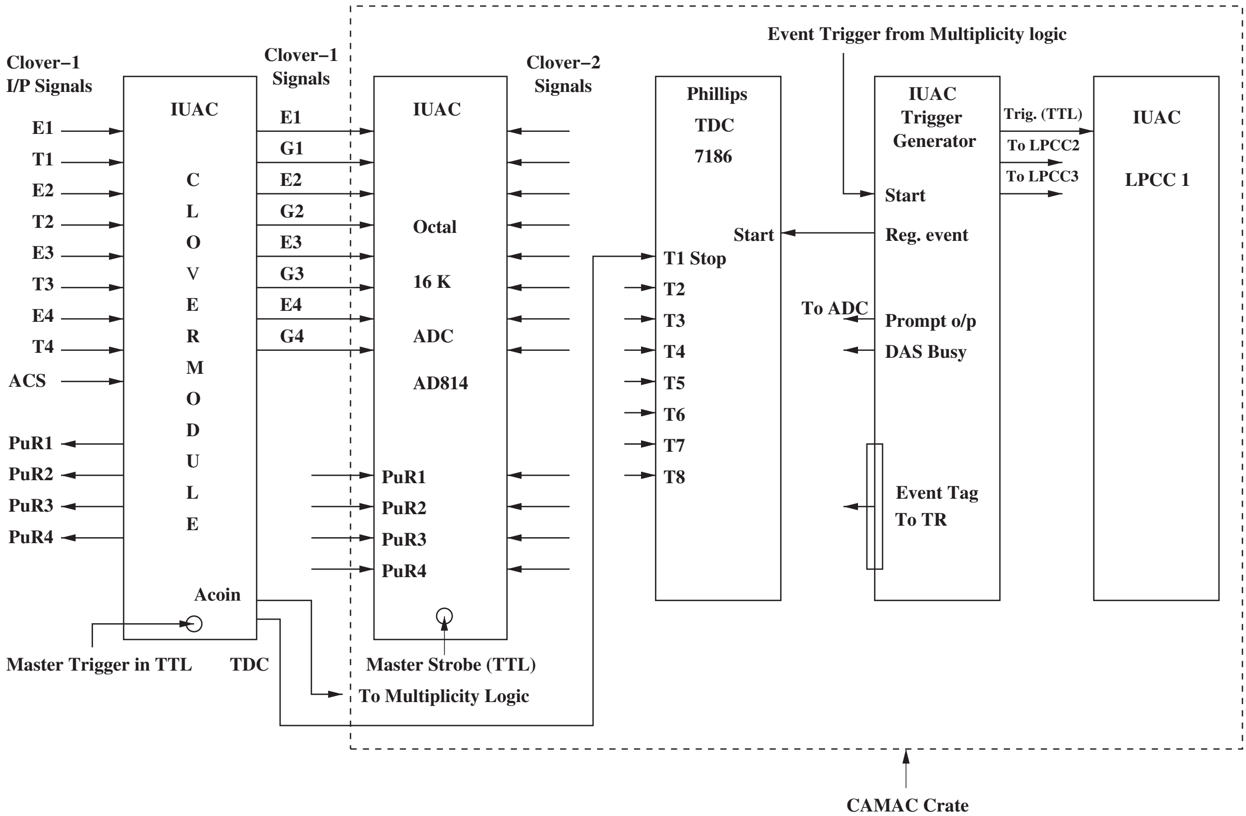

Fig. 4. Block diagram showing processing of signals from the suppressed Clover Ge detector and the data acquisition system.

fragments from the individual crates to reconstruct the entire event. To minimize readout time, energy information from only those detectors having valid timing information is read by the crate controllers.

For multi-crate data collection of 113 parameters, the total dead time per event, including signal processing and readout time, is measured to be $\sim 75\,\mu s$. For singles γ count rates of ~ 50 K per second, typical coincidence count rates are ~ 12 K per second for $\gamma-\gamma$ events and ~ 4 K per second for $\gamma-\gamma-\gamma$ events. The maximum data collection rate in DAS for random trigger is ~ 10 K events/s with bit pattern based zero-suppression readout, and ~ 6.5 K events/s without zero-suppression. An FPGA based global event-identifier module [27] for generating the multiplicity logic, time stamping and event synchronization is under development.

3. Performance of INGA

The array consisting of ~ 18 Clover detectors has been in operation at IUAC for the last two years. An extensive in-beam and offline test of the INGA data acquisition system has been carried out to validate the data obtained from the array. The performance of the array has been measured by taking data both in pre-scaled singles and doubles mode using ^{152}Eu and ^{60}Co sources. The energy resolution of individual crystals of Clover detector is ~ 2.2 keV FWHM at 1332 keV and peak-to-total ratio of suppressed detectors are measured to be $\sim 45\%$ for ^{60}Co source. The variation of add-back factor of a detector with energy agreed with that reported in Ref. [17]. Careful analysis of singles data showed that although different detectors are expected to have similar photo-peak efficiency at various energies, actual measurements indicated variations, as shown in Fig. 5. It is to be noted that in INGA, all detectors are mounted at the same distance of 24 cm from the source and energies from four crystals of Clover detectors are used in the add-back mode. The counting rate in various Clover detectors varies by as much as $\pm 12\%$, which is mainly attributed to absorbers like the target frame and holding rods, coming in front of certain detectors.

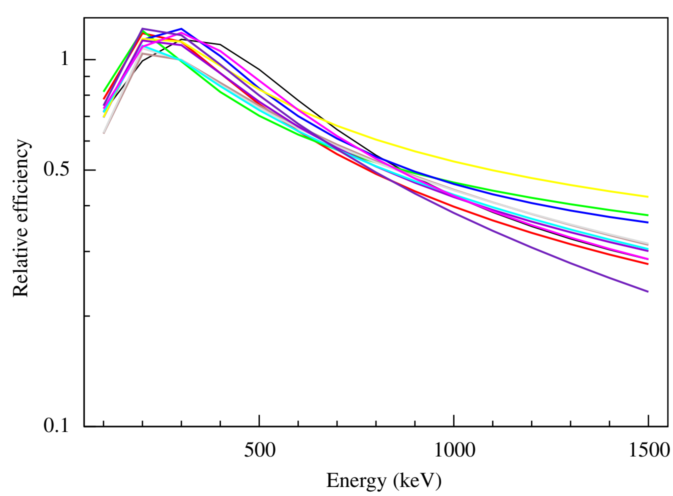

Fig. 5. The relative efficiency curves for various Clover detectors.

In order to calibrate the array for angular coincidence sensitivity, the angular correlation for the 1173–1332 keV $(4^+ \rightarrow 2^+ \rightarrow 0^+)$ $\gamma-$ray cascade from ^{60}Co decay was measured. Eleven Clover detectors were placed at five angles (see Table 1), which gave data at a number of angle pairs. The angle between any pair of coincident detectors was calculated using orientation of the detectors. The area under the 1173 keV $\gamma-$ray peak in

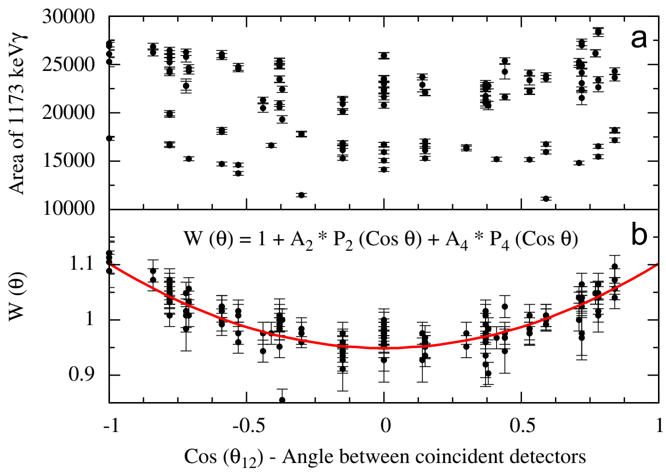

Fig. 6. (a) The peak area of the 1173 keV γ–ray in the coincidence spectrum obtained by gating the 1332 keV γ–ray from the ^{60}Co decay, (b) efficiency corrected angular correlation function $W(\theta)$ for 1173–1332 keV ($4^+\rightarrow2^+\rightarrow0^+$) γ–ray cascade as a function of *cosine* of angle between the coincident detectors (gated time window $\sim$100 ns). The solid curve represents the theoretical $W(\theta)$ function expected from the E2 cascade.

coincidence with the 1332 keV γ–ray, for all possible detector combinations, i.e. 110 pairs, are plotted in Fig. 6(a) as a function of *cosine* of the relative angle (θ_{12}) between the coincident detectors. Normalized coincidence data, with individual detector efficiency corrections, follow the trend as expected from angular correlation theory [28] (solid curve in Fig. 6(b)). This study confirms that the data fragments of each event, coming from three crates of DAS, are treated on equal footing by the trigger generator hardware [25], DAS software *Candle* [26] and offline analysis code *Ingasort* [29].

For extracting the Directional Angular Correlation (DCO) for selected transitions [30] in the fusion–evaporation reactions, it is necessary to add up the contributions from a large number of detector pairs in order to improve statistics. To simplify the analysis, efficiency curves for individual detectors are generally replaced by an 'average efficiency curve'. The reliability of the extracted DCO was checked in the reaction ^{109}Ag(^{32}S,2p2n)^{137}Pm reaction at 150 MeV [31]. This reaction populates a long chain of stretched E2 transitions in the ground-state band. The extracted DCO ratios of the transitions fed from levels ($15/2^-$ to $43/2^-$) were measured to be 1.0 ± 0.1.

For the INGA setup, timing information from all Compton-suppressed detectors is used to extract multiplicity of each event. In one of the experiments [32], the ^{96}Zr(^{19}F,*xnyp*) reaction was studied at a bombarding energy of 105 MeV. The beam was obtained from the 15UD Pelletron accelerator [33] at IUAC, New Delhi. Data were collected in list mode requiring at least three suppressed detectors to be in coincidence for the event. The fold distribution obtained from the raw data and that with gate on respective energy and time are shown in Fig. 7. The observed ratio of $\gamma-\gamma-\gamma-\gamma$ and $\gamma-\gamma-\gamma$ coincidences is consistent with the array having an average detection efficiency of $\sim$10% for Compton-suppressed photons.

The nuclear states populated in heavy-ion fusion-evaporation reactions are spin aligned and the gamma rays emitted from such aligned states are linearly polarized. In a typical Compton γ–ray polarimeter, one crystal (scatterer) is used to Compton-scatter the incident gamma radiation. Another crystal (absorber) detecting the scattered radiation defines the scattering plane. Such a polarimeter is used to determine the electric or magnetic character of a γ–transition. Perpendicular Compton scattering is favored for electric type transitions while parallel Compton scattering is favored for magnetic type transitions. As the Clover detector has four Ge crystals mounted together, it can be used as a four fold polarimeter where any of the crystals can act as scatterer with its neighboring crystal acting as absorber [17].

A large number of in-beam experiments, that utilized the polarization sensitivity of Clover detectors for the assignment of multipolarity to the observed transitions, have been performed.

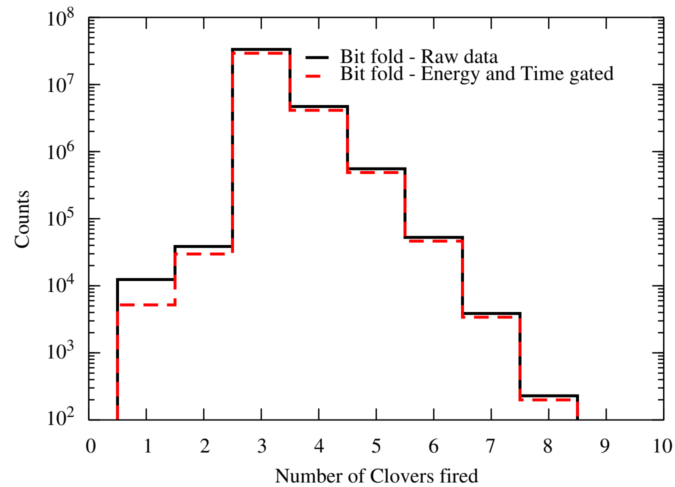

Fig. 7. The γ–ray multiplicity spectra from the reaction ^{96}Zr(^{19}F,*xnyp*) at a bombarding energy of 105 MeV. The spectra show the number of detectors fired in $\gamma-\gamma-\gamma$ coincidence and with gate on Clover detector energy and time.

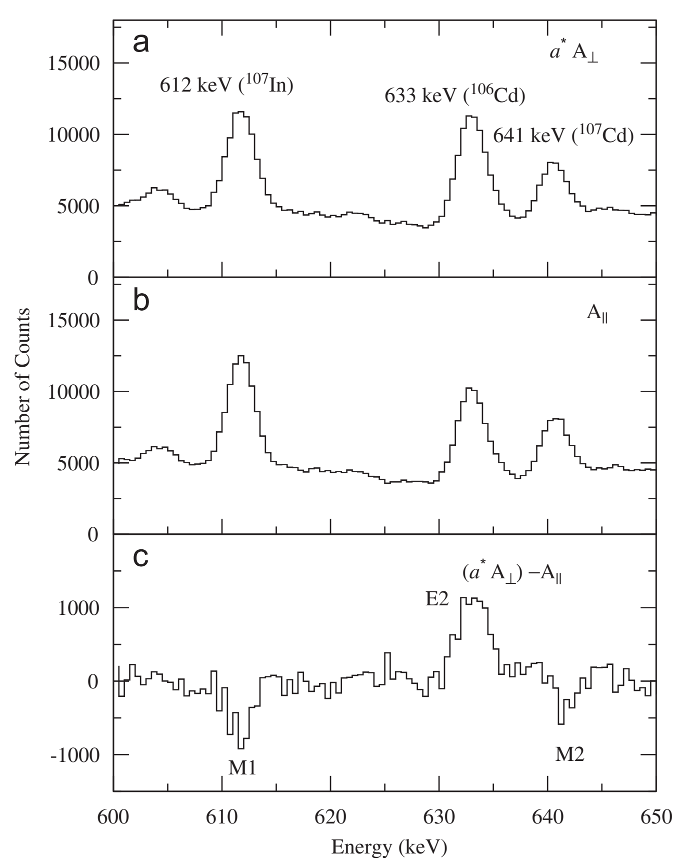

Fig. 8. Coincidence spectra from crystals of a Clover at 90° using the reaction ^{94}Mo(^{16}O,*xnyp*) at beam energy of 70 MeV. Normalized spectra of (a) perpendicular and (b) parallel scattering, and (c) difference of spectra shown in (a) and (b).

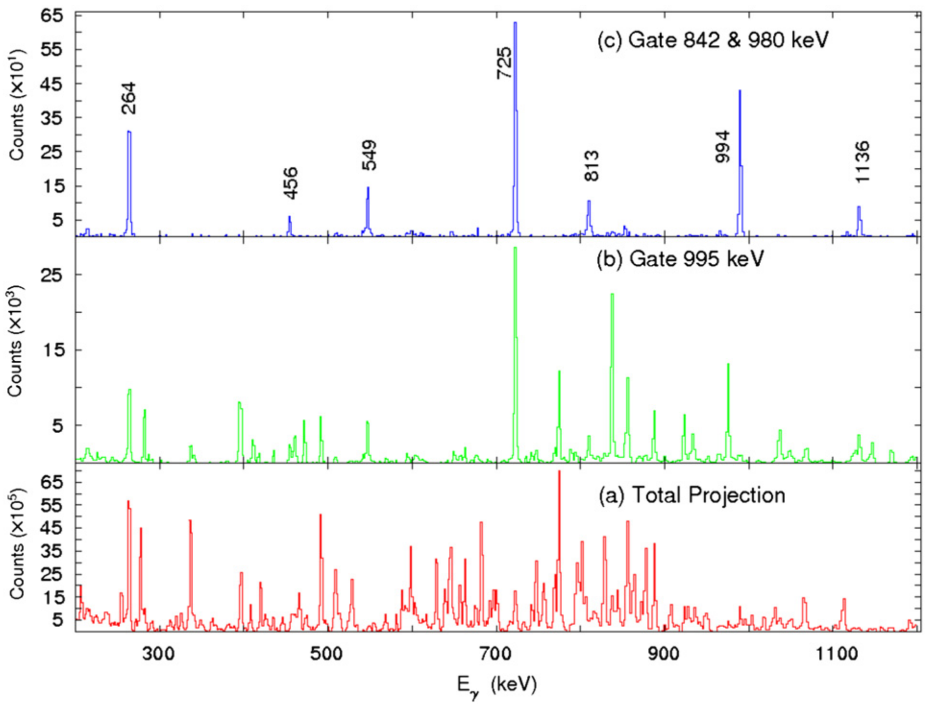

Fig. 9. Typical $\gamma-$ray spectra from the reaction ^{75}As(^{28}Si,$p3n$) at $E_{lab}=120$ MeV, (a) total projection spectrum, (b) coincidence spectrum with gate on the 995 keV transition and (c) coincidence spectrum with double gate on the 842 and 980 keV transitions in ^{98}Rh.

Polarization measurements were carried out for the $\gamma-$rays emitted in the ^{94}Mo(^{16}O,$xnyp$) reaction at beam energy of 70 MeV [34]. Data were collected in $\gamma-\gamma$ coincidence mode. The Clover detector ring at 90° was used to measure the linear polarization of $\gamma-$rays as the anisotropy is maximum at this angle. The coincidence information between two neighboring crystals of any Clover detector was extracted from the individual crystal energy signals. The geometrical factor '$a(E_\gamma)$' measured for all detectors [17] using a ^{152}Eu source was found to be 0.98(2) on an average. Fig. 8(a) shows the $\gamma-$ray coincidence spectrum of normalized Compton scattered events in perpendicular plane from one 90° Clover detector in coincidence with any other detector in the array. Fig. 8(b) shows the spectrum of parallel coincidence events. The polarization sensitivity of the Clover detector is clearly indicated in Fig. 8(c) which shows difference of spectra Fig. 8(a) and (b). The electric quadrupole (E2) type 633 keV γ transition of ^{106}Cd [35] has more coincidences in perpendicular scattering than in parallel scattering. It is the other way round for magnetic dipole type 612 keV transition in ^{107}In [34] and the magnetic quadrupole type 641 keV of ^{107}Cd [36].

For studying triple $\gamma-$ray correlations, excited states in ^{98}Rh were populated [37] using the ^{75}As(^{28}Si,p3n) fusion-evaporation reaction at a bombarding energy of 120 MeV. The ^{75}As target was of thickness $\sim 3\,mg/cm^2$ and it had a backing of $\sim 10\,mg/cm^2$ thick Pb. The de-exciting $\gamma-$rays were detected using 18 Clover detectors. A total of ~300 million triple or higher fold coincidence events were recorded during the experiment. The offline analysis was done using both *Ingasort* [29] and *Radware* [38] software. The data were sorted into $4k \otimes 4k$ symmetrised $E_\gamma - E_\gamma$ matrices and $E_\gamma - E_\gamma - E_\gamma$ cube by selecting data with gating on the prompt peak (coincidence time 100 ns) in time spectrum. Fig. 9 gives the total projection spectrum from cube, coincidence spectra of ^{98}Rh with gate on the 995 keV $\gamma-$ray and double gates on the 842 and 980 keV $\gamma-$rays. The higher fold data from INGA (over earlier arrays in the country) allows analysis using multi-gamma gates. The sensitivity of the coincidence analysis is enhanced in double gated spectra and it is especially useful for placement of two $\gamma-$transitions of nearly equal energy.

4. Summary and outlook

INGA facility at IUAC allows high resolution $\gamma-$ray spectroscopy with significantly higher efficiency. Using the array, different aspects of the high-spin study, i.e., lifetime of nuclear levels, linear polarization of γ transitions, and angular correlation by DCO ratios can be carried out. As a part of first campaign, $\gamma-$ray nuclear spectroscopy experiments and lifetime measurements by Doppler shift attenuation method were performed [31,34,39]. This Compton-suppressed Clover Ge detector array comprises of in-house developed systems for cooling detectors, bias supplies, analogue signal processing units, ADCs and data acquisition system. The combination of the recoil separator HYRA and multi-detector Clover Ge array, used with stable beams from the Pelletron and Linear accelerator, will provide many new research opportunities in areas of nuclear structure, reactions and astrophysics. A number of ancillary detectors, i.e., charged particle detector, neutron detector, recoil distance device [40], and LEPS are being developed for this facility.

Acknowledgments

The authors would like to thank the members of INGA Principal Investigating Coordination Committee for making the detectors available. We are indebted to students and faculty of various universities and institutes for helping in installation and testing of sub-systems of the array. This work was funded by the Department of Science and Technology, Government of India (No. IR/S2/PF-03/2003-I), and University Grants Commission. We are thankful to the Pelletron staff for providing excellent beam during all experiments of the campaign and Prof. Nirmal Singh of Panjab University for providing the experimental data.

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