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Nuclear structure at high spin using multidetector gamma array and ancillary detectors

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Abstract. A multidetector gamma array (GDA), for studying nuclear structure was built with ancillary devices namely gamma multiplicity filter and charged particle detector array. This facility was designed for in-beam gamma spectroscopy measurements in fusion evaporation reactions at Inter-University Accelerator Centre, New Delhi. Description of the facility and in-beam performance with two experimental studies done are presented. This array was used in a number of nuclear spectroscopic and reaction investigations.

Keywords. Hyperpure germanium; multiplicity detector, charged particle detector; nuclear structure; γ-ray spectroscopy; empirical shell model.

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1. Introduction

Atomic nucleus is an interesting many-body system bound by strong interaction. Complexities in understanding nuclear structure in terms of an effective nucleon–nucleon interaction, is due to finite number of nucleons in the system. Nucleus has both collective and single-particle excitations. Time-scale of nuclear collective excitations and single-nucleonic excitations are similar, resulting in simultaneous excitation of both modes in nucleus.

Common theme of the nuclear structure is to understand effective nucleon–nucleon force, which provides a wide variety of phenomena in nuclear physics. Many features of this effective interaction, strong dependence on spin, isospin and relative momenta of interacting nucleons, were extracted from experiments. Microscopic approaches in understanding nuclear structure rely on static mean-field description, based on Hartree–Fock [1], Hartree–Fock–Bogolyubov [2] or relativistic mean field theory [3] to describe nuclear properties by density-dependent effective *N*–*N* interaction.

Population of nuclei under extreme conditions, i.e., at high excitation energy and at large angular momentum using heavy-ion fusion evaporation reactions enabled study of the nuclear behaviour by recording gamma decay in nuclei. This study is done by measuring properties of discrete γ-ray transitions (their energies, intensities, linear polarization, angular distribution etc.) at and above the yrast line. These investigations were possible due to the availability of heavy-ion beams and gamma detector arrays (GDA). Results of such investigations were interpreted using various nuclear models.

Scientific community in this country needed gamma-spectroscopy facility with ancillary detectors to pursue nuclear structure physics. Ancillary tagging tools enhance sensitivity of selecting reaction channels of nuclei populated in small cross-section. In this paper, we present tools developed at IUAC for this purpose and two experimental studies done using them.

2. Gamma detector array

Co-axial hyperpure germanium (HPGe) detector of *n*-type with 25% efficiency is used for this purpose as it has good energy resolution. Photopeak-to-total for this detector is ∼20% which is useful for full energy γ-transitions. For a $\gamma\gamma$ coincidence measurement, only 4% events are full energy events. Thus, it is necessary to improve signal-to-background ratio. This is achieved by detecting Compton scattered γ-rays coming out of HPGe detector by another scintillator detector and cancelling those signals while recording data. Employing this anti-Compton shield, peak to total improves to ∼50%, increasing coincidence efficiency of the spectrometer.

Increase in coincidence rate is achieved by using an array of Compton-suppressed HPGe detectors. In an array of N detectors, two-fold coincidence rate is $N(N-1)/2$ times the rate of two detectors. Therefore, arrays with large number of gamma detectors were built over the past decades worldwide. A review of these arrays is in [5].

2.1 *Gamma detector array at IUAC*

Gamma detector array (GDA) [6,7], at Inter-University Accelerator Centre (IUAC) is specially designed for γ-ray spectroscopic study. This array consists of twelve Compton-suppressed *n*-type HPGe detectors. HPGe detectors with anti-Compton shields (ACS) are mounted on two support structures on either side of 30° beam line in IUAC beamhall. Support structures are movable on rails giving access to mount target in scattering chamber. Each support structure holds six detectors in two rows, 25° above and below the horizontal plane with three detectors in each row at 45°, 99° and 153° in-plane angles. These make approximately 50°, 98° and 144° actual angles respectively with respect to beam direction. There are four detectors in each of these angles. Schematic lay-out of HPGe detectors in GDA set-up at IUAC is presented in figure 1.

Automatic liquid nitrogen filling system [8] was made in-house which filled detectors once a day using solenoid-operated pneumatic valves controlled by PT100 sensors. Bias supplies of HPGe and ACS, pre-amplifier power supply for both the detectors were custom-made [9] to get better reliability. Analogue electronics processing was set up to record energy and time from all the twelve suppressed Ge detectors and ancillary detector signals (BGO multiplicity, pulsing timing...) as and when $\gamma\gamma$ coincidence occurred.

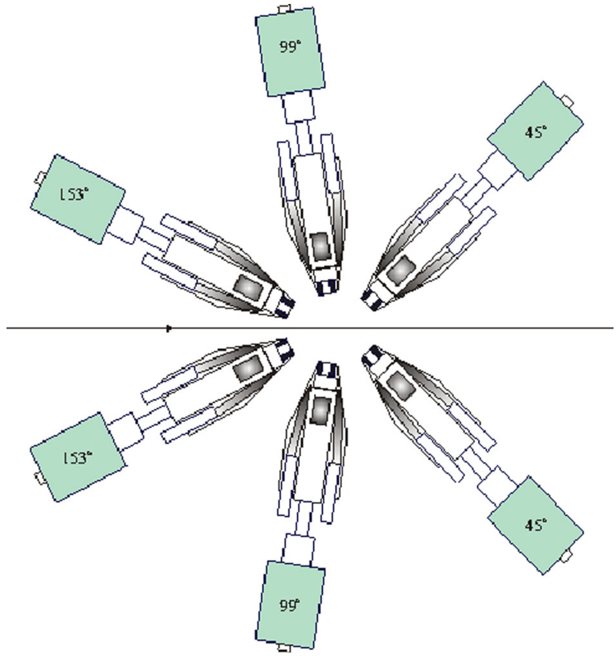

Figure 1. Schematic of the orientation of HPGe detector in GDA [4].

These signals were fed to custom-made data acquisition system *Freedom* [10] which was later used for data reduction.

We recorded γ-ray fold of nuclear reaction using multiplicity filter made of BGO scintillator. This tool enhances the resolving power of the gamma detector array in fusion evaporation reaction. The multiplicity filter array consisted of 14 bismuth germanium oxide (BGO) (38 mm × 75 mm, hexagonal shape) detectors, seven above and seven below the scattering chamber in a honey comb structure arrangement, mounted at a distance of 4 cm from the target. It covered ∼35% of the total solid angle at the target (figure 2) and each BGO detector covered nearly equal solid angle. This BGO array [11] was used as total energy and/or gamma multiplicity filter (figure 2).

3. Nuclear structure at high spins of ^{217}Ra

There has been a resurgence in spectroscopic studies of radium isotopes in the neighbourhood of neutron magic number 126. Shell model was successful in describing properties of 'magic' nuclei, i.e., nuclei with N or Z equal to 82 or 126. Nuclear structure of nuclei around ^{208}Pb is understood in terms of effective interactions. At higher spins, however, particle–hole excitation plays role. Ra isotopes show an abrupt change in excitation spectrum, from individual particle excitations to collective excitations with increasing neutron number from ^{217}Ra to ^{218}Ra. In a study of $N = 126$ nucleus ^{214}Ra [12], a small Compton-suppressed gamma detector array and conversion electron spectrometer were used. It is shown that high spin states can be understood in terms of empirical shell model

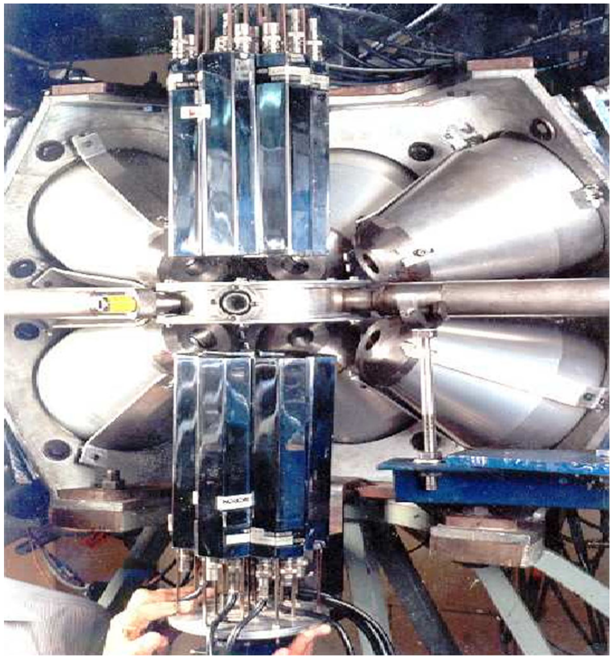

Figure 2. Inside view of GDA with scattering chamber and fourteen-element BGO multiplicity filter.

calculation by taking six valence protons in ^{214}Ra to be in orbitals $1h_{9/2}$, $2f_{7/2}$ and $1i_{13/2}$. As one adds neutrons to ^{214}Ra to obtain ^{215}Ra, ^{216}Ra, etc., high-spin yrast states in these nuclei will be built up by coupling of six proton states in ^{214}Ra with neutron states in $2g_{9/2}$, $1i_{11/2}$ and $1j_{15/2}$ orbitals available after the magic number 126. High-spin yrast states in nuclei near closed shell are formed by maximum orbital alignment of the valence

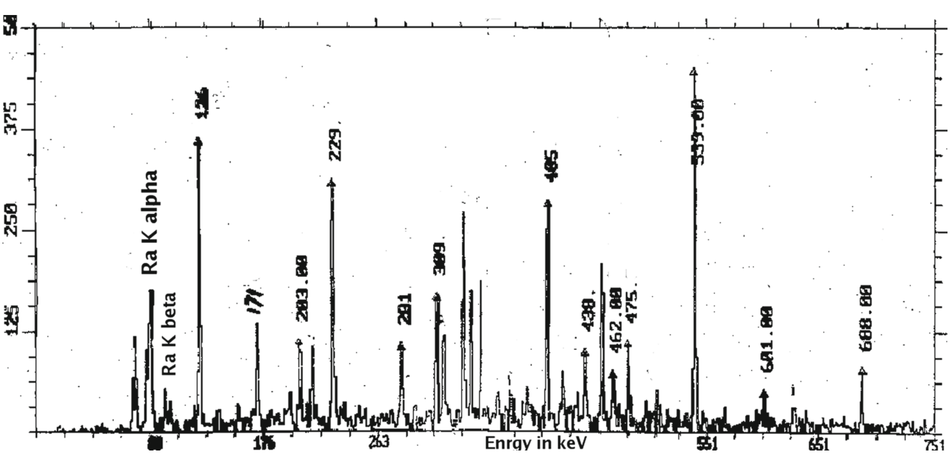

Figure 3. Coincident spectrum with 335 keV, γ showing the presence of ^{216,217}Ra in $\gamma\gamma$ data.

nucleons. Six proton states of ^{214}Ra are known. It will be of great interest to study high-spin states of ^{217}Ra and correlate them with coupled states of ^{211}Pb and ^{214}Ra. The earlier published work in ^{217}Ra [13–16] were not significant as they used a relatively small Ge array. ^{218}Ra excitation spectrum is vibrational in nature having quadrupole and octupole excitations. The above studies of ^{217}Ra gives mutually inconsistent level structure.

3.1 *Experiment*

High spin states were populated in ^{217}Ra using ^{209}Bi(^{11}B, 3n)^{217}Ra reaction with 65–78 MeV incident beam energy from 15 UD Pelletron [17] at Inter-University Accelerator Centre, New Delhi. The rolled ^{209}Bi target thickness was 3.5 mg/cm^2. Beam was pulsed at 4 MHz to measure lifetimes of nuclear isomers by electronics method. GDA used in the present work has improved the quality of coincidence spectra, enabling us to identify and place several weak transitions in ^{217}Ra. We studied nuclear structure of ^{216}Ra at high spin [18] as it was also populated in the above-mentioned reaction.

Coincident events were grouped in two sets based on detector angles: effective angle of Ge with respect to the beam direction, i.e., (1) 50°, 98° and (2) 98°, 144°. This angle-dependent data enabled measurement of directional correlations from oriented state (DCO) ratios [19] to get multipolarity (quadrupole or dipole) of γ-transition. Since a number of γ-rays were found to have similar energies in ^{215,216,217}Ra, a detailed comparison of $\gamma\gamma$ coincidence data for these γ-rays at three projectile energies, 65, 70, 78 MeV were done. Optimum projectile energy for the coincidence study of ^{217}Ra was found to be 65 MeV. Some γs of ^{217}Ra are common with ^{216}Ra like 335 keV (figure 3). Some transitions (330, 405 and 438 keV) appear more than once in the excitation spectrum. Intensity balance was difficult due to side feeding. Fold distribution recorded from the above reaction BGO multiplicity filter is shown in figure 4. Photopeak-to-background of γs belonging to fusion evaporation reaction improves (in comparison to $\gamma\gamma$ coincidence spectrum) when at least three or more γs are detected in BGO multiplicity filter in coincidence with $\gamma\gamma$ in Ge array. This is illustrated from the present experimental data in figure 5. Raw $\gamma\gamma$ coincidence spectrum is scaled down (0.4) to match the background of both spectra in order to compare peak-to-background in both spectra. Raw $\gamma\gamma$ coincidence spectrum is given as an offset of 6keV to guide the eye. One can note that in fold-gated spectrum, γs (613, 688 keV) associated with high multiplicity reaction of ^{216}Ra have more photopeak-to-background compared to raw spectrum, while γs with low multiplicity (773 keV) are suppressed. This spectrum demonstrates how BGO multiplicity filter enhances the resolving power of GDA.

3.2 *Empirical shell model calculations*

We calculated empirical excitation energies of ^{217}Ra in terms of six proton states from ^{214}Ra coupled with three neutron states from ^{211}Pb i.e., added energies of levels from ^{214}Ra and ^{211}Pb, whose spins make up to total spin in ^{217}Ra, gives the excitation energy for that nuclear level. The values of zeroth-order levels of ^{217}Ra in terms of coupled stretched states by these two nuclei are compared with the data obtained from this experiment and they agree well. Shell model configurations of a majority of the newly found high-spin states in ^{217}Ra were obtained by following this method.

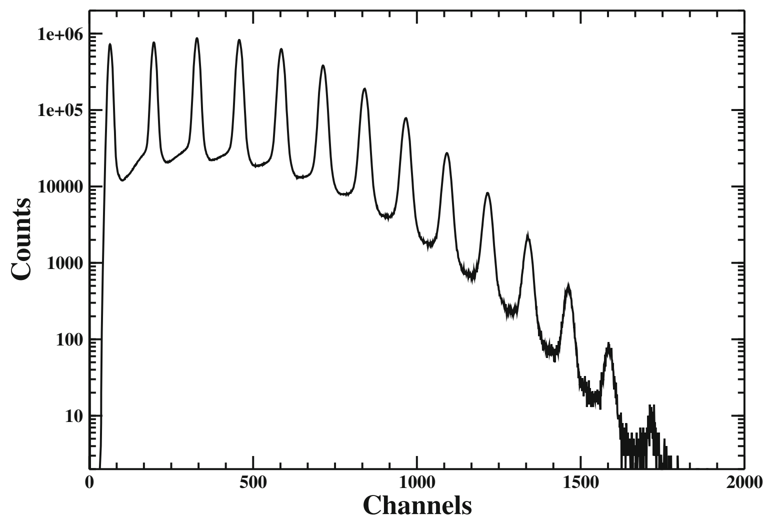

Figure 4. Fold distribution recorded in the fusion evaporation reaction ^{209}Bi(^{10}B, 3n) at 65 MeV using GDA and BGO multiplicity filter.

4. Charged particle detector array

In heavy-ion fusion evaporation reactions competition between proton, α and neutron evaporation leads to dispersion of reaction channels, particularly for high angular

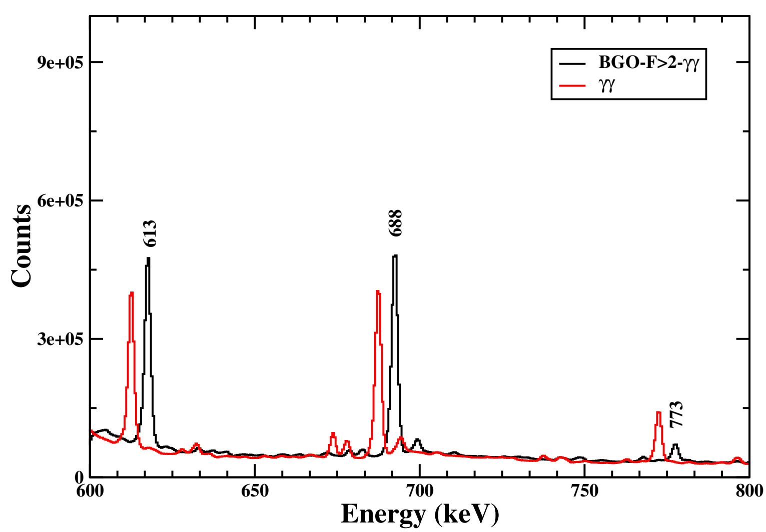

Figure 5. $\gamma\gamma$ coincidence spectrum from Ge array with and without BGO multiplicity filter detecting more than two γs, from the fusion evaporation reaction ^{209}Bi(^{10}B, 3n) at 65 MeV using GDA.

momentum input. In such cases, a large number of exit channels are populated, making selection of a particular reaction channel difficult. Large cross-sections for charged particle emission lead to many channels with similar γ-ray multiplicities which makes it difficult to separate by γ-ray multiplicity of the reaction. In such cases, charged particle identification enhances selection of reaction channel [20–23]. Charged particle coincidence removes large γ-ray background from fission. Charged particle emission from fission fragments is low, relative to fusion evaporation reaction.

4.1 *CPDA in GDA*

Charged particle detector array (CPDA) at IUAC consists of 14 charged particle detectors (CPD) arranged in two truncated hexagonal pyramids. The bases of both pyramids lie in a horizontal plane with each detector having a trapezoidal shape. Two hexagonal detectors at the top and bottom together with trapezoids cover nearly 90% of 4π [24]. Cross-sectional view of CPDA in the scattering chamber having a target is shown in figure 6. There are four CPDs in forward angles (0–60°), four in backward angles (120–180°) and six around 90°. Each CPD is made of plastic phoswich detectors, optical guide, and PMT with bias circuit. Scattering chamber, analogue processing electronics, CPDA unit including plastic phoswich and optical guide were custom-fabricated in IUAC.

4.2 *Rotational bands in* ^{65}*Zn*

Proton and neutron number of this nucleus are in fpg shell and lie between two spherical magic gaps 28 and 50. Spherical shapes are expected for light nuclei, having N or/and Z, close to 28. Nuclei with $N,\ Z \approx 29$–40 exhibit a wide variety of behaviours. Besides spherical shapes, prolate, as well as oblate and triaxial deformations, co-exist

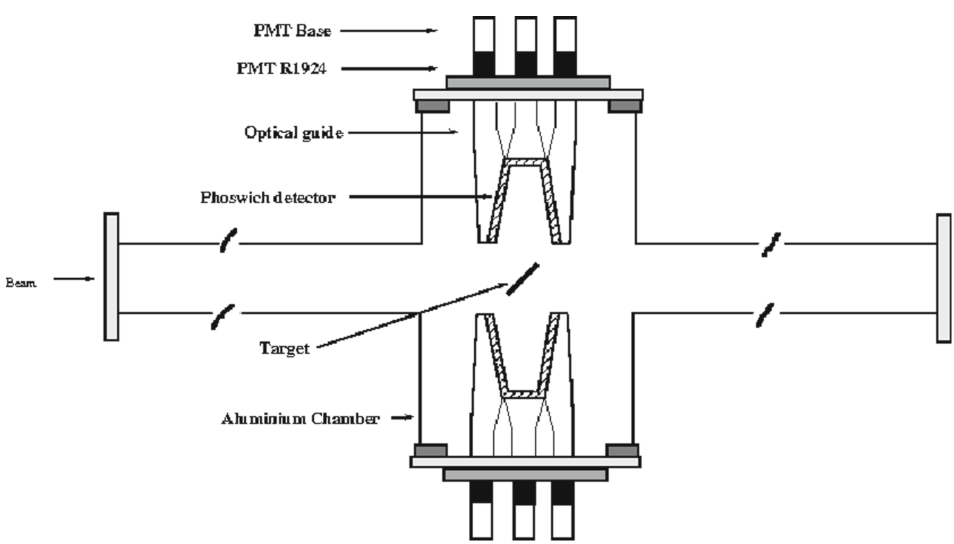

Figure 6. Cross-sectional view of CPDA in the scattering chamber inside a GDA.

at low excitation energy. At high spin one finds alignments of quasiparticles resulting in shape changes. The data of lower mass nuclei in this region indicate mostly single-particle excitations, due to the proximity of $N = Z = 28$ single-particle magic gap. However, nuclei near mid-shell exhibit highly collective bands with large quadrupole moments. Nuclei in transitional region of these two limits are expected to have complicated structure with both single-particle and collective states. In this context, we studied high spin states of ^{65}Zn. Positive-parity structure in this nucleus is based on the $g_{9/2}$ orbital. Spectroscopic measurements were performed and results of the experiments are interpreted using collective models.

4.3 *Experiment*

We populated ^{65}Zn, using ^{52}Cr(^{16}O, $2pn$) reaction at a beam energy of 65 MeV provided by 15 UD pelletron accelerator at the IUAC. In the above reaction, beam was impinged on a natural (85% abundance) target of thickness 1 mg/cm^2 backed by 7 mg/cm^2 thick gold foil. GDA and CPDA were used for recording $\gamma\gamma$ coincidence data. For each coincidence event, signals from HPGe and CPDA were recorded in the form of energy and time, from all HPGe detectors and multiplicities of charged particle and α. This data were useful to create matrices of $\gamma\gamma$ with or without coincidence of charged particles. Thus, spectra of different reaction channels were created.

The $\gamma\gamma$ coincidence relationship for ^{65}Zn was derived from a $4k\times4k$ matrix with a coincidence of $2p$. A comparison of a typical projected γ-spectrum from total matrix

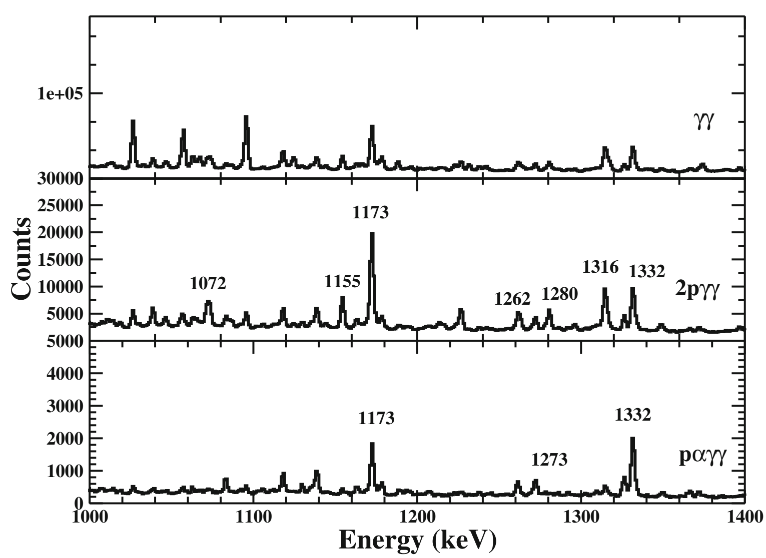

Figure 7. In-beam $\gamma\gamma$ coincidence spectra without and with coincidence of charged particles ($p\alpha$ and $2p$) from the reaction of ^{16}O on ^{52}Cr. Reaction channel selection power of CPDA from $\gamma\gamma$ coincidence spectrum can be noted by the enhancement of peak-to-background, for γs which are labelled by their respective energies, in the bottom two panels.

(where no charged particle condition is used) with that of a $2p$-gated and $p\alpha$-gated spectra are shown in figure 7. The γs emitted by ^{65}Zn is marked in $2p$-gated spectrum while γs emitted by ^{62,63}Cu are marked in $p\alpha$-gated spectrum. Selective power of CPDA gate is amply evident from charged particle coincidence spectra as photopeak-to-background for γs of selected nuclei is better than in raw spectrum. Leak-through of contaminant peaks into $2p$-gated data arose from occasional mis-identification of a low-energy α-particle as a proton in CPD located at backward angles relative to the beam axis.

Decay scheme of ^{65}Zn derived from this work can be found in [25,26]. Using DCO ratios measured for γs, spins of various levels were identified. This work confirms almost all states reported in the earlier experiment [27]. A total of 20 unreported states and 42 new γ-transitions were observed and placed in level scheme. Level scheme is extended to an excitation energy of 10.57 MeV and spin-parity of $(41/2^+\hbar)$.

5. Conclusions

A set of tools were developed to study nuclear structure, which include GDA, BGO multiplicity filter and plastic phoswich CPDA at IUAC. Both ancillary detectors, when they detect signal in coincidence with GDA, enhances the resolving power of the spectrometer by increasing peak-to-background of $\gamma\gamma$ spectrum compared to raw spectrum. Support systems, automatic liquid nitrogen filling system, bias supplies, analogue processing electronics, data acquisition system and offline analysis codes were developed in-house. The design features of this facility enabled several users across the country to study various nuclear phenomena for two decades.

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