Active Collimator for the BGO Anti-Compton Shield of the HPGe Clover Detector

Biswajit Das[1,*], N. R. Khan Chowdhury[1], S. Saha[2], Md. R. S. Laskar[1], F. S. Babra[1], V. Malik[1], A. Kundu[1], P. Dey[1], S. K. Jadav[1], B. S. Naidu[1], A. T. Vazhappilly[1], S. Sihotra[3], and R. Palit[1,*]

[1]Department of Nuclear and Atomic Physics
Tata Institute of Fundamental Research, Mumbai - 400005, India
[2]School of Advanced Sciences, VIT University, Vellore-632014, India
[3]Department of Physics, Panjab University, Chandigarh-160014, India

(*) palit@tifr.res.in / biswajit.das@tifr.res.in

***Abstract*—An active collimator has been designed to replace the heavy metal collimator of the BGO anti-Compton shield to improve the performance of the hybrid Indian National Gamma Array (INGA) at TIFR, Mumbai. The active collimators of the 24 clover detectors, along with the BGO anti-Compton shields and 18 $LaBr_3$(Ce) detectors, can act as a γ-ray multiplicity filter. This configuration will be beneficial for studying weak band structures decaying by high γ-ray multiplicity events. In addition, the energy deposited in all the detectors can be added to get the sum energy for certain measurements aiming to use the hybrid array for calorimetric application. We have characterized an active collimator coupled with one of the anti-Compton shields and an HPGe clover detector with various radioactive sources. The peak-to-total ratio for the active collimator configuration is similar to the standard design with the heavy metal configuration with the ^{60}Co source. Additionally, we have evaluated the Compton cross-talk between the clover HPGe detector and the anti-Compton shield/active collimator. The total multiplicity distribution for a cascade of eleven γ-rays with an energy range of 70-2000 keV has been obtained through GEANT4 simulation. The simulation results indicate the possibility of conducting a meaningful study of decay chains with a multiplicity of twelve.**

***Keywords* — γ-ray detector development, design and characterization of an active collimator; benefits for higher multiplicity decay study in INGA; GEANT4 simulation**

I. Introduction

Gamma-ray spectroscopy continues to give new insight into the nuclear structure and remains a topic of interest over the decades [1-5]. The High Purity Germanium (HPGe) detector, having very good energy resolution is a powerful instrument for discrete γ-ray spectroscopy and remains the best apparatus for nuclear structure and astrophysics studies by making of HPGe array [6-11]. A hybrid array of Compton-suppressed Clover HPGe detectors and Cerium doped Lanthanum Bromide ($LaBr_3$(Ce)) based scintillator detectors is operational in the BARC-TIFR Pelletron Linac Facility at TIFR Mumbai for nuclear structure studies [12-15]. The array has been designed to have a maximum of 24 Compton-suppressed clover detectors and 18 $LaBr_3$(Ce) detectors. A combination of clover HPGe and $LaBr_3$(Ce) detectors array can extend the lifetime measurement from 100 pico-second to a few nano-second by the triple-fold γ-ray coincidence [16]. A heavy metal collimator made of tungsten has been placed in front of the BGO anti-Compton shields to prevent the direct hit of the γ-rays emitted from the target positions during the experiment. This heavy metal collimator reduces the false vetoes arising from an event in a reaction with high γ-ray multiplicity, where one γ-ray strikes an HPGe crystal giving a full-energy pulse, and another hits the BGO shield detector. But, the main concern of the HPGe detector is, it suffers from low peak-to-total ratio. A mono-energetic γ-ray spectrum consists of a narrow full-energy peak and a slowly varying background arising from the Compton scattering in the HPGe crystal of its surroundings. The Compton background of all the γ-rays makes it difficult to hunt for low energy γ-rays sitting on the accumulated Compton backgrounds from high-energy peaks. The Compton background is generally reduced by placing an escape-suppression shied around the Ge detector [17,18]. Events were vetoed when scattered gammas escaped from the Ge crystal and were detected in the surrounding scintillation BGO detector providing a signal. Even with a large Ge crystal and active Compton suppression, there will be residual background from incomplete suppression plus photons scattered from adjacent materials to the Ge crystal [19]. The resolving power is the overall capacity of the array to permit the identification of weak cascades of γ-rays in a complex spectrum. In order to increase the detection inefficiencies for the study of weak band structures having high multiplicity gamma decay events, the replacement of heavy metal to active collimator is our main interest for the present work.

In this work, the heavy metal collimator of the BGO anti-Compton shield of a clover detector has been replaced

https://doi.org/10.1051/epjconf/202328810004

by an active collimator of BGO crystal to improve the performance of the hybrid Indian National Gamma Array (INGA) at TIFR, Mumbai. We have designed and tested one of the anti-Compton shields coupled with the active collimator and an HPGe clover detector with various radioactive sources. The benefits of the use of active collimators for higher multiplicity events in INGA setup have been demonstrated through GEANT4 simulation.

II. INSTRUMENTATION AND EXPERIMENTAL SETUP

The active collimator detector consists of Bismuth Germanium Oxide (BGO) crystal and has been manufactured by SCIONIX [20]. The choice of BGO crystal as an active collimator is because of its high density (7.12 gm/cm^3), very good radiation hardness (the parameters remain stable for high radiation dose [21]), high scintillation efficiency, cost-effectiveness, non-hygroscopic, and mechanically strong. The BGO crystal produced ~9000 photons per 1 MeV gamma energy deposition. The crystal emits scintillation photons of a wavelength range of 375-650 nm with a peak at 480 nm [21]. The active collimator consists of 8 BGO crystals, which are coupled with same type of Photo Multiplier Tubes (PMT: Hamamatsu R9880-10) fabricated by SCIONIX, Holland [20]. Each BGO crystal has a cross-sectional dimension of 3.35 cm × 1.7 cm. The whole assembly of the BGO crystals and PMTs of the active collimator are encapsulated within an aluminum encasing having a thickness of 0.5 mm. A schematic diagram of the cross-sectional, side view, with Al housing and actual image, have been shown in Fig. 1.

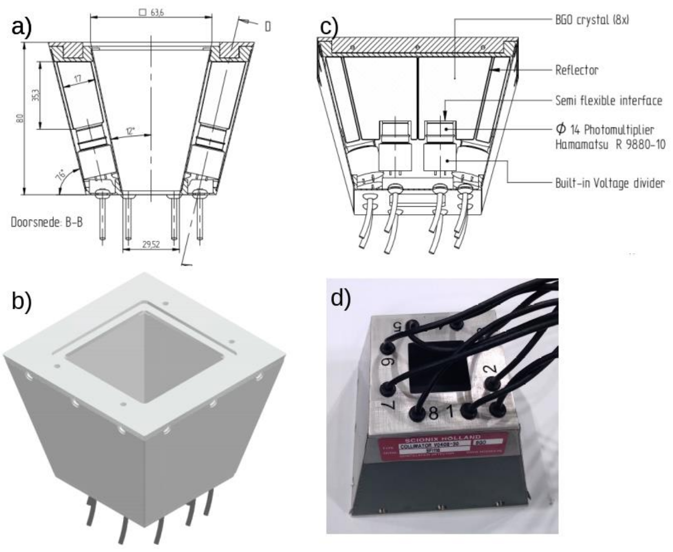

Fig. 1. Schematic of active collimator: a) cross-sectional middle view, b) one side view, c) with Al housing. d) Ensembles active collimator used in the experiment.

The detector has 8-channel outputs, which are further converted to one from OR condition. The BGO crystals have a small self-activity caused by minor contamination of the ^{207}Bi. However, few BGO crystals incidentally have higher internal radioactive background with activity up to 10 Bq/kg [22]. This background contribution is because of the ^{210}Po contamination and has a technological origin. The Clover HPGe detector has been surrounded by BGO anti-Compton shield. A collimator made of heavy metal in front of each BGO anti-Compton shield has been placed to stop the direct hit of γ-rays in the BGO crystal. In this experiment, the set-up has been made with two configurations, one is with heavy metal collimator, and other one is with a BGO active collimator detector. The geometry of the setup with HPGe clover, active collimator, and BGO anti-Compton shield detectors has been shown in Fig. 2. The PMTs of the active collimator have been biased at +900 V through a voltage divider. The gains of all the photo-multiplier tubes within the BGO annulus are matched identically by adjusting the high voltage of each individual PMT. This is accomplished by placing a mono-energetic γ-ray source (^{137}Cs) on each side of the BGO annulus. We have used the standard radioactive source like ^{241}Am, ^{57}Co, ^{137}Cs, and ^{54}Mn for energy calibration of the BGO anti-Compton shield and active collimator. A ^{60}Co source has been used for further characterization of the active collimator. We used weak sources to avoid pile-up and other count rate dependent effects. The detector noise has also been checked for the BGO element by using a ^{241}Am source which emits a primary γ-ray at 59.4 keV and the threshold is safely set at 15-20 keV. The experimental raw signals have been processed and digitized with a XIA-LLC based Digital Data Acquisition System with a 12-bit, 100 MHz, PIXIE-16 module connected in a PCI/PXI crate. The γ-ray energy and time information have been extracted by pulse processing through DAQ and were transferred to a host PC by a controller module connected in the same PCI/PXI crate. The experimental data have been acquired by a software, TIFR Digital Data Acquisition Software for Nuclear Structure Studies (TIDES) [23].

III. GEANT4 SIMULATION

The GEometry ANd Tracking 4 (GEANT4, version 4.10.05) simulation toolkit has been used for making the geometry and Monte-Carlo calculation [24]. G4Sphere, G4Box, G4Tubs, G4Trd, G4Polycone, G4Polyhedra, G4UnionSolid, and G4SubtractionSolid classes have been used to construct the different parts of the detector and the set-up. The GEANT4 geometry of one of the HPGe clover detectors with active collimator and BGO shield has been shown in Fig. 2. The simulation of the INGA with 24 Compton-suppressed HPGe clover detectors has been thoroughly studied by Saha, et al [14]. Later on, the simulation code has been extended by adding 18 $LaBr_3$(Ce) detectors with INGA to make it hybrid. The placement of $LaBr_3$(Ce) and clover HPGe detectors can be found in the Ref. [15,25]. The 24 BGO-shielded HPGe clover detectors have been arranged at different angles with respect to the beamline along with the 18 $LaBr_3$(Ce) detectors (2″ x 2″) in 4π geometry. We have simulated the responses of a Compton-suppressed clover detector with an active collimator. In the simulation code, we have replaced all the heavy metals with the active collimators in order to study the combined performance of the hybrid INGA. In PhysicsList of GEANT4 simulation, we have included the classes of all possible interaction mechanisms of γ-ray, electron and positron with matter. The γ-ray photons, electrons, and positrons are expected to be produced on the path of γ-ray while interacting with the matter. The considered interaction mechanisms for the γ-photons are photoelectric effect, Compton scattering, pair production, and Rayleigh scattering. The electrons and positrons which produced during interaction can undergo multiple scatterings, ionization, and emit Bremsstrahlung radiation. In addition, the positron can undergo annihilation with the material's electrons. For γ-ray interaction with matter, the considered process classes have been used in physics list are G4PhotoElectricEffect, G4ComptonScatte-ring, G4Gamma-Conversion, and G4RayleighScattering.

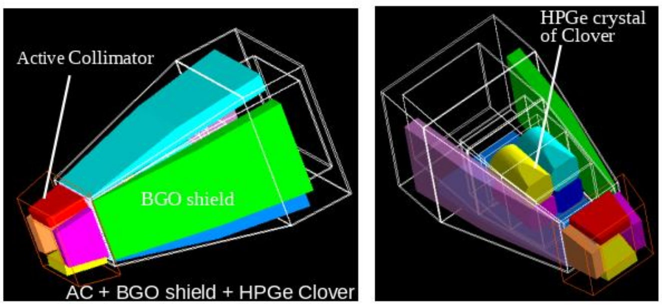

Fig. 2. GEANT4 Geometry of one of the HPGe clover detectors with an active collimator and BGO anti-Compton shield (left), and the same with one BGO slab taken out to show the internal part of the detector setup.

IV. ANALYSIS AND RESULT

The characterization of the BGO as an anti-Compton shield of HPGe clover detector in INGA setup has been studied in our previous work [14]. Here, we have studied the effect of γ-ray detection performance while replacing the heavy metal collimator with an active collimator. Also, how this replacement will be effective for a large array of HPGe clover detectors has been simulated. The experimental data have been sorted by a MultipARameter time-stamped based COincidence Search (MARCOS) [12,26] code, developed at TIFR, and used to generate the matrix. The energy calibration of the BGO anti-Compton shield and active collimator has been done with the single γ-ray energy emitting radioactive sources. The photo-peak energies were plotted against their corresponding channel numbers and then fitted with a quadratic function. The calibration fits are depicted and the calibration parameters are tabulated. The responses of the crystals have been found almost linear with the γ-ray energy. The energy resolution of the active collimator has been found to be ~18.8 % at 662 keV. We have tested the performance of the HPGe clover detector with three different configurations, i) HPGe+BGO Compton shield, ii) HPGe + BGO Compton shield + heavy metal, and iii) HPGe + Compton shield + active collimator. The γ-ray energy spectrum of ^{60}Co in the third configuration has been shown in Fig. 3. The Peak-to-total ratios have been obtained (Table-I) in anti-coincidence mode along with the BGO annular shield.

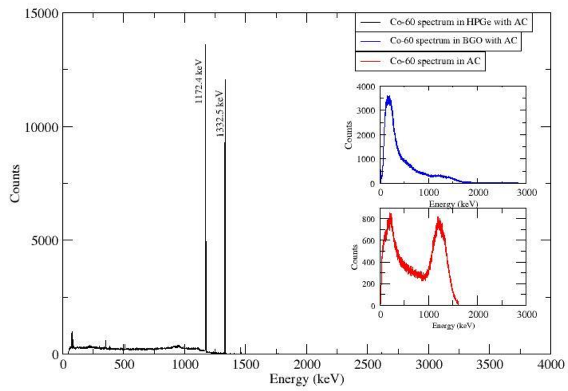

Fig. 3. Measured γ-ray spectrum of ^{60}Co in the HPGe Clover detector (shown in black). In inset, γ-ray spectrum of: BGO anti-Compton shield (blue) and active collimator (red).

Table-I: The performance of the different configurations of the setup with ^{60}Co point source has been placed at the target position.

Configuration	P/T ratio
HPGe (no veto)	0.224
HPGe + BGO (without HM)	0.343
HPGe + BGO + HM	0.429
HPGe + BGO + AC	0.439

The table demonstrates that the replacement has not had an impact on the detection capability of the HPGe clover detector in single-mode measurements. However, it does prove effective in coincidence measurements for improving detection efficiency, especially in scenarios involving higher-order multiplicity events or cascade gamma decay. This enhancement results in an increased coincidence efficiency. Figure 4 displays the coincidence spectrum of 60Co using an HPGe clover detector configuration in conjunction with one active collimator/BGO shield. The coincidence spectrum of ^{60}Co obtained between active collimator/BGO anti-Compton shield and one HPGe clover detector configuration has been shown in Fig. 4(inset). This indicates that there is an impact of active collimation in the coincidence measurements.

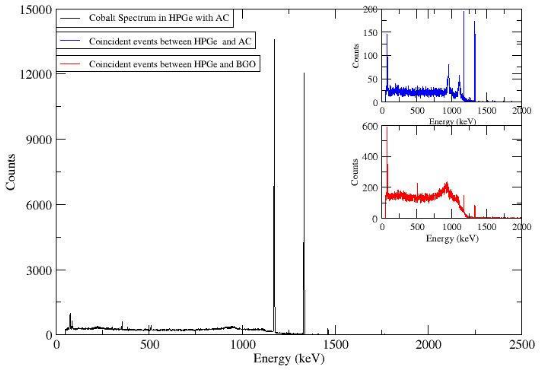

Fig. 4. The ^{60}Co γ-ray spectrum of HPGe clover detector (shown in black). In inset, the HPGe clover γ-ray spectrum in coincidence with Active Collimator (blue), in coincidence with BGO anti-Compton shield (red).

In the simulation, we have generated a cascade of 11 γ-rays in the range of 70 keV to 2 MeV. The multiplicity has been obtained from the simulation in INGA setup consisting of 24 Compton suppressed HPGe clover,18 $LaBr_3$(Ce) detectors with 24 active collimators has been shown in Fig.5.

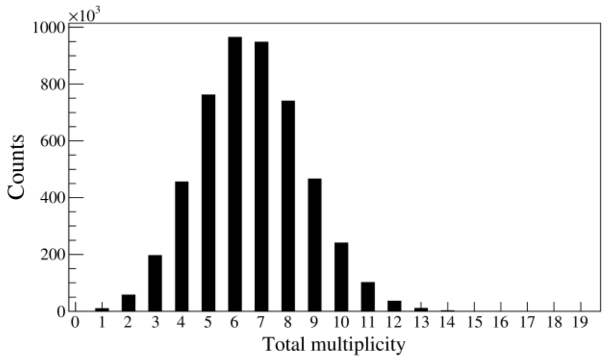

Fig. 5. Simulated multiplicity of the hybrid INGA consisting 24 HPGe clover, 24 BGO anti-Compton shield, 18 $LaBr_3$(Ce), and 24 active collimator.

V. Conclusions

The performance of an active collimator with a HPGe clover detector surrounded by BGO Compton-shield has been designed and tested experimentally. The characterization of the active collimator has been done. The benefits of the presence of active collimators instead of heavy metal collimators has been discussed through GEANT4 simulation for a hybrid array consisting of 24 Compton-suppressed clover detectors and 18 $LaBr_3$(Ce) detectors. With an inner layer of BGO shield detectors, we can not only use it as a veto circuit but also it allows a measure of the total γ-ray energy and the efficiency in higher order multiplicity of the γ-rays. The active collimator will be efficient for those nuclear γ-ray spectroscopy experiment where higher-order multiplicity gate is the matter of concern. We can use the inner active collimator to select events associated with long cascades of γ-rays, which are generally the cascades involving high spin states and increases the detection efficiency. The limitation of using the active collimator is the detection of γ-ray events in lower multiplicity of high energy, where there is a chance of Compton scattering of the γ-ray from active collimator and to HPGe clover crystal and hence the Compton background increases.

Acknowledgment

This work is supported by the Department of Atomic Energy (DAE) and Department of Science and Technology (DST), Government of India, under project No. 12-R&D-TFR-5.02-0200, and IR/S2/PF-03/2003-II, respectively. The author would also like to thank Infosys-TIFR Leading Edge Travel Grant.

References

[1] P. Gorodetzky, J. J. Kolata, J. W. Olness, A. R. Poletti, and E. K. Warburton, "Gamma-Ray Spectroscopy in A ≈ 40 Nuclei via Heavy-Ion-Induced Reactions: High-Spin States in ^{40}K and ^{41}Ca", Phys. Rev. lett. **31**, 17 (1973).

[2] P. S. Haskins, F. E. Dunnam, R. L. Coldwell, A. C. Rester, R. B. Piercey, M. L. Muga, H. A. Van Rinsvelt, R. W. Smart, H. J. M. Aarts, J. D. Fox, L. C. Dennis, and C. B. Saw, "In-beam gamma-ray spectroscopy of ^{82}Sr", Phys. Rev. C **32**, 6 (1985).

[3] J. A. Cameron, M. A. Bentley, A. M. Bruce, R. A. Cunningham, W. Gelletly, H. G. Price, J. Simpson, D. D. Warner, and A. N. James, "High-spin gamma spectroscopy of recoil-separated ^{49}Cr, ^{49}V, and ^{46}T", Phys. Rev. C **44**, 5 (1991).

[4] A. Gade, R. V. F. Janssens, D. Bazin, P. Farris, A. M. Hill, S. M. Lenzi, J. Li, D. Little, B. Longfellow, F. Nowacki, A. Poves, D. Rhodes, J. A. Tostevin, and D. Weisshaar, "In-beam γ-ray spectroscopy of ^{62,64}Cr", Phys. Rev. C **103**, 014314 (2021).

[5] P . Dey, D. Negi, R. Palit, P. C. Srivastava, Md. S. R. Laskar, B. Das, F. S. Babra, S. Bhattacharya, Biswajit Das, K. Rojeeta Devi, R. Gala, U. Garg, S. S. Ghugre, E. Ideguchi, S. Kumar, A. Kundu, G. Mukherjee, S. Muralithar, S. Nag, S. Nandi, Neelam, M. Kumar Raja, R. Raut, R. Santra, A. Sharma, S. Sihotra, A. K. Singh, R. P. Singh, and T. Trivedi, "Experimental investigation of high-spin states in ^{90}Zr", Phys. Rev. C **105**, 044307 (2022).

[6] S. Akkoyun, et al., "AGATA—Advanced GAmma Tracking Array", Nucl. Instrum. Meth. A **668**, 26 (2012).

[7] R. Palit, "Recent results from digital INGA at BARC–TIFR Pelletron Linac Facility and future plans", Pramana **83**, 719-728 (2014).

[8] C. Louchart-Henning, G. Henning, J. Gerl, N. Pietralla, and the DESPEC collaboration, "Simulations for DEGAS detectors at FAIR", GSI Scientific Report, NUSTAR-GS-05 (2013).

[9] I. Y. Lee, "The GAMMASPHERE", Nucl. Phys. A **520**, 641 (1990).

[10] J. Simpson, "The Euroball Spectrometer", Z. Phys. A **358**, 139 (1997).

[11] J. Eberth, G. Pascovici, H. G. Thomas, N. Warr, D. Weisshaar, D. Habs, & Miniball Collaboration. "MINIBALL A Ge detector array for radioactive ion beam facilities". Progress in Particle and Nuclear Physic **46**(1), 389-398 (2001).

[12] R. Palit, S. Saha, J. Sethi, T. Trivedi, S. Sharma, B. S. Naidu, S. Jadhav, R. Donthi, P. B. Chavan, H. Tan, and W. Hennig, "A high speed digital data acquisition system for the Indian National Gamma Array at Tata Institute of Fundamental Research", Nucl. Instrum. Methods Phys. Res. A **680**, 90 (2012).

[13] R. Palit, S. Saha, J. Sethi, T. Trivedi, B.S. Naidu, P.B. Chavan, R. Donthi, S. Jadhav, "Performance of Indian National Gamma Array (INGA) Coupled with a Fast Digital Data Acquisition System for Nuclear Structure Studies", Journal of Physics: Conference Series **420** (2013) 012159.

[14] S. Saha, R. Palit, J. Sethi, S. Biswas and P. Singh, "Geant4 simulation study of Indian National Gamma Array at TIFR", JINST **11**, P03030 (2016).

[15] Biswajit Das, S. Saha, A. Kundu, Md S. R. Laskar, P. Dey, R. K. Santra, D. Negi, F. S. Babra, R. Donthi, S. Jadhav, B. S. Naidu, A. T. Vazhappilly, S. Sihotra, R. Palit, "Measured and Geant4 Simulation Performance of the Hybrid Array of Compton Suppressed HPGe Clover and $LaBr_3$(Ce) Detectors at TIFR", Jl. of the Instrum. Soc. of India, **51**, 1-4 (2021) ISSN No. 0970-9983.

[16] Md. S. R. Laskar, R. Palit, E. Ideguchi, T. Inakura, S. N. Mishra, F. S. Babra, S. Bhattacharya, D. Choudhury, Biswajit Das, B. Das, P. Dey, U. Garg, A. K. Jain, A. Kundu, D. Kumar, D. Negi, S. C. Pancholi, S. Rajbanshi, and S. Sihotra, "Enhanced B(E3) strength observed in ^{137}La", Phys. Rev. C **104**, L011301 (2021).

[17] M. P. Carpenter, T. L. Khoo, I. Ahmad, R. V. F. Janssens, T. Lauritsen, G. A. Annan, A. M. Baxter, M. E. Bleich, S. Harfenist, E. F. Moore, M. Torelli, D. W. Visser, "Test and performance of a BGO Compton-suppression shield for GAMMASPHERE", Nucl. Instrum. Methods A **353**, 2(1994).

[18] F. Camera, A. BraCCO, M. Mattiuzzi, G. Lo BianCo, M. Pignanelli, J. J. Gaardhoje, l. G. Bearden, Z. Zelazny, A. Maj, "The response of a HPGe detector with a BGO shield to high energy γ-rays" Nucl. Instrum. Methods A **351**, 401-405 (1994).

[19] S. K. Mattews and L. E. Ussery, "The performance ofa single-crystal BGO Annulus as a Compton-Suppression detector", **LA-UR-91-3443 DE92**,003872.

[20] SCIONIX, Holland webpage, http://scionix.nl/.

[21] Peter Kozma and Petr Kozma Jr, "Radiation resistivity of BGO crystals due to low-energy gamma-rays", Nucl. Instrum. Methods A **501**, 449 (2003).

[22] D. N. Grigoriev, V. F. Kazanin, G. N. Kuznetcov, I. I. Novoselov, P. Schotanus, B. M. Shavinski, S. N. Shepelev, V. N. Shlegel, Ya. V. Vasiliev, "Alpha radioactive background in BGO crystals", Nucl. Instrum. Methods A **623**, 999 (2010).

[23] Md. S. R. Laskar, Abraham T Vazhappilly, R. Palit, S. Jadhav, R. Donthi, B. S. Naidu, F. S. Babra, P. Dey, Biswajit Das, B. Das, C. S. Palshetkar, L. P. Singh, and H. Tan, "TIFR Digital Data Acquisition Software for Nuclear Structure Studies (TIDES)", Proceedings of the DAE Symp. on Nucl. Phys. **63** (2018).

[24] S. Agostinelli et al. And GEANT4 collaboration, "GEANT4: a simulation toolkit", Nucl. Instrum. Meth. A **506**, 250 (2003).

[25] Biswajit Das, S. Saha, R. Palit, A. Kundu, P. Dey, V. Malik, S. K. Jadav, B. S. Naidu, A. T. Vazhappilly, and S. Sihotra, "Cross-talk estimation of the hybrid γ-ray detector array through GEANT4 simulation", Proceedings of the DAE Symp. on Nucl. Phys. **66** (2022) 1082.

[26] R. Palit and S. Saha, "Investigation of exotic modes of spinning nuclei near ^{90}Zr", Pramana **82** (2014) 649.