The Practice of Gamma-Ray Spectroscopy: Here and Now

Rajarshi Raut

1 Introduction

The many-body complex system called the nucleus exhibits myriad intriguing phenomena, particularly in its excited states. The practice of γ-ray spectroscopy aspires observation and decipherment of these many phenomena manifested by the excited nuclei. The tools and the techniques herein have extensively evolved over several decades to their current form that can now unravel even the rarest and the most exotic idiosyncrasies in the nuclear panorama. This article aspires to provide an overview on γ-ray spectroscopy through discussions on its essential components. The first is population of nuclei in their excited states, and de-excitations therefrom, that causes emission of radiations. The next component of the pursuit is the detection of the emitted γ-rays that is based on their interactions with the detector, chosen for the purpose. The subsequent step is to process the detection, obtained in the form of a pulse from the detector, for retrieving information of interest. And, finally, the acquired information needs to be converted into data that are stored for eventual processing and analysis in order to conclude on the physics being aspired in the relevant study.

The study of nuclear excitations commences with the production of the nuclei in their excited states, typically accomplished through nuclear reactions carried out at the accelerators. One of the most commonly used one is compound nucleus (CN) fusion-evaporation reactions. Herein, an energetic projectile, delivered by the accelerator, bombards on a static target nucleus and, depending on the beam energy and other factors (cross section etc.), fuses to form a compound system. The compound nucleus is an extremely energetic system and tends to de-excite, initially through emission of light particles, such as neutron, proton and alpha and eventually through

R. Raut (✉)
UGC-DAE Consortium for Scientific Research, Kolkata Centre, Kolkata 700106, India
e-mail: rajarshi.raut@gmail.com

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emission of γ-rays. The practice of γ-ray spectroscopy is essentially about detecting these γ-rays to infer on the level structure of the emitting nuclei. The details can be looked up in a range of texts such as by Regan [1] and Casten [2].

2 Detection

At the basis of detection of radiations is their interaction with the detection medium (matter). A γ-ray incident on a medium may or may not interact therein. If it does, there are different possible mechanisms with varying impact on the end-result of detection. The γ-ray can undergo photoelectric absorption or Compton scattering or, in case of high energy γ-rays $\geq$1.02 MeV, pair production. The photoelectric interaction dominates at the lowest energies while the pair production gains significance only at the highest ones. The Compton scattering remains the most probable mechanism of interaction for a wide range of incident γ-ray energies. As far as the spectroscopic objectives are concerned, of only pertinence is whether, as the result of one or more interactions, the full energy of the incident γ-ray is completely contained in the medium.

The solid state detectors, with higher matter density than the gas based ones and with increased probability of interaction, have emerged to be of preference in the practice of γ-ray spectroscopy. These detectors can be of scintillators or semiconductors [3, 4]. In γ-ray spectroscopy, some of the earliest measurements were based on NaI(Tl) and BaF_2 scintillators that are merited with superior detection efficiency. However, the scintillator detectors are plagued with poor energy resolution that come in the way of their usage for spectroscopic goals.

The advent of semiconductor based detectors revolutionized the practice of γ-ray spectroscopy through improved energy resolution, to typical values of $\sim$2 keV at $\sim$1 MeV, and has unleashed the era of modern spectroscopy wherein even the most complex excitation pattern of the nuclei could be deciphered. The semiconductor detectors are basically junction diodes of Si or Ge wherein the depletion region represents the active volume of the detector. Ge ($Z = 32$) is of preference in γ-ray detection, compared to the Si ($Z = 14$). The semiconductor junction detectors are operated under a reverse bias voltage effecting into the depletion region getting extended to almost the entire crystal volume. An interacting radiation create electron-hole pairs therein and these migrate under the existing (reverse bias) electric field towards their respective collector ends. The signal that results encodes information of interest on the detected radiation. The Ge material used for the detectors is High Purity Ge (HPGe), characterized with $\sim 10^{10}$ impurity atoms/cm^3 [3]. This facilitates an increased width of the depletion region for a given bias voltage and ensures maximizing the active volume of the detector. The Ge based detectors, however, need to be operated at liquid nitrogen temperature (77 K) in order to restrict the thermally generated leakage current.

A γ-ray spectrum is characterized by full-energy peaks and Compton background. The latter is required to be restricted for ensuring spectroscopic objectives. The

HPGe detectors are conventionally used with an Anti Compton Shield (ACS) for the purpose. The ACS is a scintillator based detector, typically using BGO (Bismuth Germanium Oxide) or NaI(Tl). The idea is to detect the Compton scattered photons, from the HPGe crystal, in the surrounding ACS and reject those events through a logic implementation during the pulse processing. The application of the ACS to reduce the Compton background is called an active shielding. The background also has a component from interaction of high energy γ-rays of cosmic origin, or other ambient sources, with the detector medium and efforts to reduce the same are based on what is called the passive shielding. This is implemented through housing the experimental setup in a canopy of high-Z material or by setting up the experiments in underground laboratories.

Apart from its efficiency and energy resolution, the timing characteristics of a detector are of extensive considerations particularly in the context of the settings in the pulse processing circuitry as well as its application in the investigation of nuclear level structure. The pulse resulting from a detector is characterized by a rise time, an (voltage) amplitude and a decay time. The amplitude depends on the number of charge carriers produced in the detector, following the interaction of a radiation therein and thus encodes the energy deposited in the process. The rise time reflects the time of collection of the charge carriers following their production in the radiation interaction. The rise time provide a marker to the so called "time of detection" that is applied for defining of timing correlations (coincidence, anti-coincidence) between different detectors in a setup and facilitates identification of the events of interest. For instance, the signals resulting from the HPGe detector and the corresponding ACS, following one Compton event that deposits energy in both, need to be correlated in time to be identified as resulting from the interaction of the same γ-ray in the two detectors (and thus to be rejected).

Larger detector volume would result into better efficiency and the same is implemented through composite HPGe detectors such as the clover. A HPGe clover has four HPGe crystals enclosed in a common cryostat. The packing of the crystals is close and indicates a realistic possibility that in the event of an incident γ-ray undergoing Compton scattering in one of the crystals, the scattered photon, carrying the residual energy, would go and interact with one or more of the adjacent crystals and cumulatively deposit the entire incident energy in the clover detector. This possibility translates into an increased efficiency, as was aspired for HPGe detectors, through what is called the addback mode of operating the clover. The clover detector is now a basic tool routinely applied for γ-ray spectroscopy measurements in this country as well as across the globe.

3 Processing

The next step towards arriving at the aspired physics is processing of the signal obtained from the detector. Such a signal is generally extracted from the preamplifier of the detector. The preamplifier is the first component of the pulse processing

circuitry that is typically positioned very close to the detector. In fact for the HPGe detectors, the preamplifier is located inside the enclosure common to the crystals, albeit the latter are in vacuum while the preamplifier board is not, so as to facilitate easy access for maintenance. The preamplifier signal of a HPGe detector is characterized by a rise time of $\sim$ tens of ns, amplitude of $\sim$ tens of mV/MeV, and a decay time extending to $\sim$ tens of μs. The amplitude is proportional to the amount of charge carriers produced from a radiation interaction with the detector medium, and the energy deposited in the process. The preamplifier signal has to be processed for extracting information of primary interest on the detected radiation. These are the energy deposited by the radiation in the detector medium and the time of detection. For many decades, pulse processing has been implemented through use of modular electronics fabricated as per one of the global standards, such as the NIM (Nuclear Instrument Module) and the CAMAC (Computer Automated Measurement And Control).

The energy information from the preamplifier signal comes through its processing by a spectroscopy amplifier. The module is set to amplify the preamplifier pulse, through a gain factor, as well as filter/shape it for faithful extraction of pulse height, that represents the energy deposited in the corresponding detection. The pulse processing for extracting the timing information from the detector pulse output principally proceeds through application of modules such as a Timing Filter Amplifier (TFA) and a Constant Fraction Discriminator (CFD) to generate a time marker that is independent of the amplitude and the rise time of a detector pulse and represents the time of detection. The time marker facilitates identification of correlations between different detectors in the setup and that of the events of interest. For instance, the correlation between the HPGe and the corresponding ACS helps identifying the Compton events and implement the Compton suppression. The Compton suppressed time marker resulting from a Compton suppressed HPGe is typically used to define an event trigger in an array of such detectors. An event is the fulfillment of a condition subject to which the data is acquired. An event in an array of detectors typically corresponds to a user defined multiplicity of detectors firing in coincidence, within a time window, manifested in an overlap between their time markers. The pulse processing techniques elaborated in this section have been and are being routinely practiced in the country, both using commercially available modules as well as modules developed herein.

4 Data

The principal hardware for data acquisition is an ADC (Analog-to-Digital Converter) that reads-out the amplitude information of the amplifier pulse and facilitates recording the same as a number (channel number) in the data file. An ADC is characterized by a resolution, expressed in bits such as 12-bit, 13-bit, 14-bit, and indicates the maximum of the channel number it can generate. For instance, a 13-bit ADC can give out a maximum channel number of $2^{13} - 1 = 8191$. Apart from reading-out the amplitude information from the amplifier pulse, as a record of the energy deposited

in the corresponding detector, the time of detection is also to be recorded in the data, particularly if an array of detectors is used for measurements. The Time-to-Digital Converter (TDC) is used for the purpose. The timing record is made from the time difference between a signal representing the time of detection in each detector, that triggers an event, with respect to a common signal and converting this difference into a channel number of the TDC. The commonly used format of the acquired data is the list mode format. Data in this format is an event-by-event record of the energy and the timing of the detections along with the identity of the detector elements, that constitute the event.

The advent of digital signal processing, and its applications in nuclear physics experiments, has revolutionized the methodology of processing and acquisition during the recent years. The technology, merited with fast processing and increased throughput, has facilitated acquisition of enhanced event rates that typically characterize the large array of detectors set up for γ-ray spectroscopy measurements. The Nuclear Physics group at the **UGC-DAE CSR**, has made significant contributions in the development and implementation of digitizer based pulse processing and data acquisition for nuclear structure studies in the country [5].

5 Data Reduction and Analysis

The first step in the data processing exercise is the energy calibration of the (ADC) channel numbers. The energy calibration is facilitated by the use of standard radioactive sources, such as ^{60}Co, ^{152}Eu, ^{133}Ba, ^{137}Cs, with known characteristic γ-ray energies. For an array of γ-ray detectors, the energy calibration is followed by what is called gain matching. It is necessary that the energy represented in a given channel number for a detector in the array is identical to the energy represented by the same channel number recorded for any other detector in the array. The unambiguous assignment of observed γ-ray transitions to a nucleus populated in an experiment typically follows γ-γ coincidence information. The analysis of data acquired in γ-ray spectroscopy measurements, that are targeted at probing the level structure of nuclei, proceeds through construction of varied kind of matrices, symmetric as well as asymmetric, so as to extract different measurables therefrom. These include, apart from identifying the coincidence relationships between the observed transitions, their angular correlations and the linear polarization of the γ-rays. The correlation and the polarization measurements facilitate in assigning the multipolarity and electromagnetic character of the transitions and thus the spin-parities of the associated levels. Another measurement of much significance is that of level lifetimes and the same is extracted through a variety of methods, depending on the lifetimes being addressed. Significant developments have recently been made in the relevant domain [6, 7] and have resulted in determination of level lifetimes with reduced uncertainties. Further details, on data analysis for γ-ray spectroscopy can be found in several papers and review articles, such as the ones by Regan [1] and Bhowmik [8].

6 The Indian National Gamma Array

The Indian National Gamma Array (INGA) has been the principal tool for pursuing nuclear structure studies, with in-beam γ-ray spectroscopy, in this country for around two decades now. It is an array of Compton suppressed HPGe clover detectors setup by a collaboration of Institutes and Universities across the nation. The participating organizations include **UGC-DAE CSR**, TIFR (Mumbai), SINP (Kolkata), VECC (Kolkata), IUAC (New Delhi), BARC (Mumbai) and several others. The user community for this facility is a widespread one and extends to institutions outside the country as well. The facility is set up at regular intervals in one of the accelerator centers in the country, VECC, IUAC and TIFR. The facility has evolved in its merits through the many experimental campaigns that have been hosted since its commencement. The first setup was at the Pelletron LINAC Facility (then TIFR-BARC Pelletron) at TIFR, in around 1999–2000 and consisted of 8–9 Compton suppressed clover detectors. The subsequent campaign at IUAC (then NSC), around 2002–2003, was again based on 8 Compton suppressed clovers as well as certain ancillary detectors for charged particles, neutrons, and recoils that facilitated improved identification of the reaction channel of interest. These campaigns of INGA were largely based on commercially available pulse processing electronics of NIM standards and CAMAC based data acquisition hardware, albeit the acquisition software were developed at BARC and IUAC, respectively, for the first and the second programmes. The acquisition program used in the first campaign was AMPS, developed at BARC, while the one used during the second campaign, at IUAC, was CANDLE. This was followed by a significant development at IUAC wherein compact clover electronics modules were designed and fabricated such that each such module could support the pulse processing of one clover along with its ACS. These modules were put to use in the INGA campaign at VECC cyclotron, during 2004–06, with 8–10 Compton suppressed clovers [9]. The data acquisition used in this campaign was CAMAC-based and running on the LAMPS [10] software, developed at BARC as an updated linux version of the previous AMPS code. A major augmentation in the number of detectors followed, and the next INGA campaign at IUAC, during 2008–09 [11], had around 22–24 Compton suppressed clover detectors in the setup. The compact electronics modules, which had been developed earlier, significantly helped in sustaining the campaign. The data acquisition hardware, apart from the commercially available modules, also consisted of ADCs fabricated at IUAC and was supported by an updated version of CANDLE. The next major stride in the history of INGA was taken during its campaign at TIFR, during 2009–13, with around 24 Compton suppressed clover detectors. Herein, a digitizer based data acquisition system was used as a maiden instance in the practice of γ-ray spectroscopy in the country [12]. The use of digital signal processing manifolded the merits of the facility that could now handle increased event rates characterizing the large array of detectors. The following and the most recent campaigns of INGA have progressed simultaneously at both IUAC and VECC. The one at IUAC has around 16 Compton suppressed clovers. It is largely based on the same infrastructure of the previous campaign hosted therein,

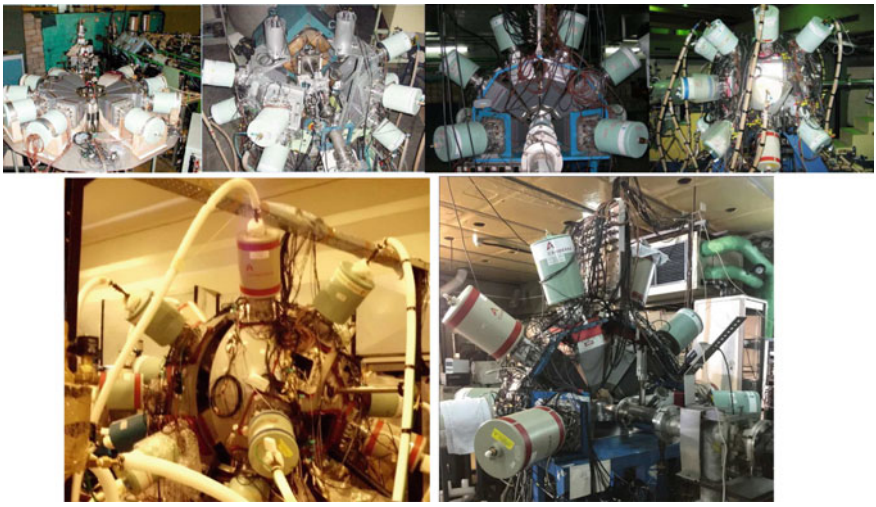

Fig. 1 The detector setups during different INGA campaigns. In the upper panel, from left to right, is the first INGA st TIFR, second campaign at IUAC, third campaign at VECC, and following campaign at IUAC. The lower panel shows the setups at two recent campaigns, at TIFR on the left and at VECC on the right

back in 2008, but with an improved data acquisition system, running on CANDLE, and facilitated with capabilities for handling higher event rates. The campaign at VECC has been based on around 8 Compton suppressed clover detectors and upto 2 LEPS, for detecting x-rays and low energy γ-rays. Most importantly, this experimental programme at VECC has been supported by a digitizer based pulse processing and data acquisition system that is conceptualized and implemented by **UGC-DAE CSR** [5], as one of the major developments in the progress of INGA and has been effectively used in over 30 experiments at VECC. That was a very short history of the INGA facility through its evolution into the current being. Figure 1 shows the photographs of the detector setups in the different campaigns. Efforts are in progress to better the facility, to increase its usage, and to explore the current frontiers of nuclear structure research by exercising the many developments that have been accomplished in the process.

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