Chapter 4

Experimental Techniques

In this chapter, techniques to study the structure of nucleus are presented. These techniques can be divided into two categories. The first category involve charge particle reactions. It is limited to low spin states of nuclei near the valley of stability and have modest resolution. The second category involves $\gamma$-ray spectroscopy. It offers considerable advantage over the first method e.g. it extend the range of nuclei studied beyond the valley of stability, the energy resolution attainable is considerably higher ($\sim 0.1$ keV). Also, new structures can be identified at very high spin that are not accessible by the charge particle reactions. The only limitation comes from the particle decay width, which should be negligible for the states under consideration. In the section that follows, methods of populating high spins in $\gamma$-ray spectroscopy are outlined.

4.1 Population of high spin states

Traditionally, there have been three methods of production of nuclei to high spins. These are:

1. The radioactive decay : This is the earliest available method for the production of high spins. However, this method is available to the study of only those nuclei which are produced from the $\beta$ decay of available radioactive states. The high spin states reached by this method is limited.

2. The heavy ion induced Coulomb excitation : In this process, the high spin states of a nucleus is populated by the electromagnetic interaction with another swiftly passing
nucleus. Occurrence of this process takes place only in those cases where either the relative kinetic energy of the two nuclei is insufficient or the impact parameter is large for these nuclei to come close to each other within the range of strong nuclear interaction. This process populate the nuclear states directly, which makes it a unique tool to measure the lifetimes of these states by avoiding the feeding from higher levels. Here, again the method is limited to low spin and low excitation energy. Moreover, at present with this method only those nuclei can be studied which are found to be stable in nature. However, with upcoming radioactive ion beam facilities worldwide, the range of nuclei studied by this method would be increased.

3. The heavy ion induced fusion-evaporation reaction : This method have the advantage of populating very high spin states, even in nuclei far away from the line of stability, thereby making it the most widely used method in high spin spectroscopy. Since, this method has been used in the thesis, it is described in some detail below.

In recent times, with the interest in nuclear structure of nuclei in neutron-rich side of the stability line, the fission and the transfer reaction are being used. These reactions overcome one major limitation of the fusion-evaporation reactions of populating only the neutron-deficient nuclei.

4.1.1 Heavy ion fusion

The basic steps leading to the formation of residual nuclei from the bombardment of projectile on the target is depicted is Fig. 4.1. The first step is the formation of compound nucleus (called as the complete fusion (CF) process) followed by the particle evaporation and gamma decay. In the studies of high spin states one searches for a reaction which can transfer to the nucleus the highest possible angular momentum $l$ with the largest possible cross section $\sigma$. The angular momentum available in a particular reaction depends on the momentum of the projectile $m_p v_p$ relative to the target nucleus and the impact parameter $b$, according to the relation $l = m_p v_p b$. From this relation it is evident that to achieve a high angular momentum, heavy ion projectiles are the most suitable. Although from the
Figure 4.1: Formation and decay of compound nucleus in a heavy ion reaction. The bottom left figure shows the same process in the E-I plane.
relation a high angular momentum state is also produced if the impact parameter is large, the fusion cross section decreases very rapidly for impact parameters $b > R_1 + R_2 = R$. For a given energy in the center of mass frame $E_{cm}$, using energy conservation, the maximum angular momentum $l_{\text{max}}$ can be obtained as:

$$l_{\text{max}}^2 = \frac{2\mu R^2}{\hbar^2} (E_{\text{max}} - V_c),$$

(4.1)

where $\mu$ is the reduced mass of the system, $R$ is the Coulomb barrier radius and $V_c$ is the Coulomb potential. Another factor which limits the maximum angular momentum a compound nucleus can hold depends on its probability of undergoing fission. The probability of fission is higher for heavier systems due to increase in the Coulomb repulsion and also increases with the increase in the angular momentum. It has also been observed that the estimate of $l_{\text{max}}$ as deduced from the above equation is larger than the experimental values for higher values of excitation energy $E_{\text{ex}}$ of the compound nucleus. At the excitation energies ($> 8$ MeV) of the compound nucleus, usually encountered in the heavy ion reactions, the decay probability via the particle evaporation is higher than the decay via the $\gamma$ transitions. As a result, particle emissions are preceded by the $\gamma$ emissions. Further, the emission of neutrons from the hot CN, due to the absence of Coulomb barrier, have higher probability than the emission of protons and the $\alpha$ particles. These emitted neutrons take away a large amount of energy ($\sim 8$ MeV/nucleon) but only few units of angular momentum. This leaves the residual nucleus in a state of high angular momentum. The excitation energy is still high and the decay is followed by statistical $\gamma$ emissions. These statistical $\gamma$ transitions do not take away much angular momentum thus leaving the nucleus in a dizzy state. From level density considerations, these states are often close to yrast or near yrast states of the nuclei. The nucleus then comes to the ground state following these yrast states by emitting a cascade of $\gamma$ transitions (see Fig. 4.1).

4.2 15 UD Pelletron Accelerator at IUAC

The Pelletron accelerator at IUAC is a 15 UD, 16 MV tandem accelerator of Van de Graaff type, (shown in Fig. 4.2). It was supplied by Electrostatic International Inc. (EII),
Madison, WI, USA and was installed in 1988 with the first commissioning run in 1990. For injection to a tandem, the nuclei need to be produced in the form of negative ions by attaching an extra electron to the atomic and molecular species. These negative ions are produced in the ion source by the cesium sputtering method. After their production, they are accelerated by the deck potential $V_D$ to be injected into the main tank via the injector magnet. At this stage the mass selection of the ion species is made. These negative ions are accelerated by a high positive potential $V_T$ (called as terminal potential) at the center of the tank, where they are stripped of their negative charges by the gas or foil stripper thereby getting converted into positive ions. As a result they are further accelerated with the net gain in energy of $E_{beam} = V_T[q + 1] + V_D$. Depending on the energy needed, the ions of specific charge is selected by the analyzer magnet at the bottom of the tank. The beam is then diverted to the respective beam lines by a switcher magnet.
4.3 Interaction of $\gamma$ rays with matter

As mentioned in last chapter, a $\gamma$ ray emitted from a de-exciting nucleus carries information about the decaying state like its spin, parity and mean lifetime. These information are contained in the energy of the radiation, timing of its emission and angular distribution with respect to some fixed direction in space, like beam axis. In order to extract these information, the photon has to be detected. Inside the detector, the information is converted into other usable form, like electrical pulses, which are then processed and recorded. The processes by which an electromagnetic radiation interacts with the matter are photo-electric effect, Compton effect and pair production and are described in brief below. These processes lead to partial or complete deposition of $\gamma$-ray photon energy inside the detector material and are discussed in the following sections.

4.3.1 Photo-electric effect

In this process the $\gamma$-ray photon interact with the electron of atomic shell and deposits its full energy. The kinetic energy $E_{KE}$ of the photoelectron emitted is given by the expression

$$E_{KE} = h\nu - E_b$$

(4.2)

where $\nu$ is the frequency of the photon and $E_b$ is the binding energy of the electron in a particular state. Often this process leads to the ionization of the atom but sometime also leads to an atom in an excited state which then de-excite and produce characteristic X-rays. These X-rays may leave the detector material thus resulting in an incomplete deposition of energy. The cross section $\chi_p$ for photo-electric effect decreases with increase in energy. It also depends on the atomic number $Z$ of detector material as

$$\chi_p = \frac{Z^n}{E_\gamma^{3.5}}$$

(4.3)

where the value of $n$ varies between 4 and 5 depending on the energy of photon.

4.3.2 Compton Scattering

When the energy of the $\gamma$-ray photon is between 0.1 and 1.5 MeV the Compton scattering is the most dominant form of interaction with matter. In this process the photon interacts
with a free or bound electron (called as Compton electron) in the medium. Exhibiting its particle behavior it undergoes scattering with the electron. The probability of the scattered photon to undergo a second interaction is low and therefore the photon may escape from the detector medium. Since it is the ‘Compton electron’ which deposit the energy in the medium, the result is an incomplete deposition of energy of the \( \gamma \)-ray photon. Following energy and momentum conservation relations, the energy of the scattered photon, \( E' \), is given by the following expression\(^1\)

\[
E'_\gamma = \frac{E_\gamma}{1 + \frac{E'_\gamma}{m_e c^2} (1 - \cos \theta)}
\]

where \( \theta \) is the angle of deflection (called as scattering angle) of photon from original direction. From above expressions it is clear that the maximum transfer of energy to the electron happens when the photon is backscattered, i.e. at \( \theta = 180^\circ \). In this case the energy transferred to the electron (or the energy deposited in the medium) is given by

\[
E_C|_{\theta=\pi} = \frac{2E^2_\gamma}{m_e c^2 + 2E_\gamma}
\]

This deposited energy is referred to as ‘Compton edge’ and is shown in Fig. 4.3 for a monoenergetic radiation. The figure illustrates the response of detector to a monoenergetic radiation. For a \( \gamma \) radiation above 1 MeV the Compton edge is roughly \( E_C \approx \frac{m_e c^2}{2} \) which is 0.256 MeV lower than the photopeak. Often one have a distribution of scattering angles which results in a continuous background, referred as ‘Compton background’, at lower energies (see Fig. 4.3). If the scattered photon undergoes a second interaction by photoelectric effect, a complete deposition of energy may result.

### 4.3.3 Pair Production

The process of pair production take place when the energy of \( \gamma \)-ray photon is above 1.02 MeV. In this process a \( \gamma \)-ray photon get annihilated in the presence of a nucleus and an electron and positron pair is produced. Thus the minimum energy required for the occurrence of the process is the sum of rest mass energies of electron and positron. The process occurs only in the presence of nucleus to conserve the momentum. For energy

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\(^1\)Here the binding energy of the electron is neglected.
greater than 1.022 MeV, the rest of the energy is divided into the kinetic energy of positron and electron. The positron formed in the process interacts with a surrounding electron and get annihilated thereby producing two photons each of energy 511 keV. If one of them escape out of the detector then it results in a single escape peak at energy $E_{\gamma} - m_e c^2$ in the spectrum. And if both of them escape out of the detector, it results in a double escape peak at energy $E_{\gamma} - 2m_e c^2$ in the spectrum.

### 4.3.4 Response function and size of the detector

The response of detector to a monoenergetic radiation depends on the volume of the detector medium. For a detector of small size compared to the mean free path of secondary $\gamma$ radiations, i.e. of size $\sim 2\text{ cm}$, the spectrum results from the photoelectric absorption and Compton continuum. The secondary $\gamma$ radiations resulting from the Compton effect have a low probability to interact further in the detector and thus escape out. The double escape peak for $\gamma$ radiations having energy larger than 1 MeV also get enhanced. The single escape peak is absent in this case. Thus only the photoelectric effect contributes to the photopeak counts.
If the size of detector is very large, of the order of few tens of centimeter, then the secondary $\gamma$ radiations produced will have high probability to undergo further interaction. In this case, the photopeak counts are greatly enhanced and the Compton background as well as the area under Double and Single escape peaks are reduced. In fact, in the limiting case of a very large detector nothing escapes and a complete deposition of energy results.

Although from the point of view of $\gamma$-ray spectroscopy large detectors are better, but a detector of such a large dimension is unrealistic. The most often used detectors are of intermediate size. In these detectors the photopeak counts are still higher than of the small detectors. However, in this case both Single and Double escape peaks are present.

### 4.4 Detection of $\gamma$-radiation

As mentioned in the previous section that the deposition of energy of $\gamma$-radiation is an indirect process. The incoming photon during an interaction produces an energetic electron. The interaction time is very small and can be considered as instantaneous. It is these secondary electrons which finally losses their energy in the medium and produces an electron-hole pair which constitute an electric charge $Q$. These charges are collected by the application of electric field and form the basic signal carrying the information about the detected photon. Time required for collection of charges depends on the type of detector, for example a semiconductor detector has a collection time of about few nanosecond while for a gas detector it is few milliseconds. The amplitude of the signal pulse is proportional to the energy of radiation deposited. In the subsections below, the parameters which define the efficacy of a detection system are described.

#### 4.4.1 Resolution of a detector

In $\gamma$-ray spectroscopy, one of the important criteria is the resolution of detector. It defines how good a detector is in resolving two close lying transitions. In general if two transitions are closer than the full width at half maximum (FWHM) of detector, it would be difficult
to resolve them. The formal definition of resolution of a detector is

\[ R = \frac{FWHM}{C}. \]  \hspace{1cm} (4.6)

In the Poisson limit, the above definition becomes

\[ R_{Poisson}^1 = \frac{2.35K}{KN^{1/2}} = \frac{2.35}{N^{1/2}} \]  \hspace{1cm} (4.7)

where \( C \) is the pulse height, \( N \) is the average number of charge carriers produced per interaction and \( K \) is a proportionality constant. A lower value of \( R \) implies better resolution. From above equation it can be inferred that larger the value of \( N \) better will be the resolution. This is the case for semiconductor detectors and hence are the preferred detectors for \( \gamma \)-ray spectroscopy. In above expression, FWHM represents the fluctuation in the charge collection process and is of statistical in origin. There are other sources of fluctuation, like coming from the drift in the operating characteristics of the detector, random noise from the detector and electronics. The total FWHM therefore can be written as:

\[ FWHM_{total}^2 = FWHM_{statistical}^2 + FWHM_{noise}^2 + FWHM_{drift}^2 + .. \]  \hspace{1cm} (4.8)

Other than the sources discussed above, the data acquisition system also has certain inherent capacity to resolve close lying transitions. This limitation comes during the digitization process in the ADC’s (Analog to Digital Conversion). During digitization process, the pulses having an amplitude (or \( \gamma \)-ray of corresponding energy) within a certain range, say \( \Delta A (\Delta E) \), are thrown into the same channel. For a good ADC it means that \( \Delta E \ll R \). This can be achieved with 8k or 16k ADC’s.

4.4.2 Efficiency of the detection system

The efficiency of a \( \gamma \) detector is defined by the ratio of number of photons recorded \((n_r)\) to the number of photons impinged \((n_i)\) on it in a certain time interval.

\[ \epsilon_i = \frac{n_r}{n_i} \]  \hspace{1cm} (4.9a)

This efficiency is usually called the intrinsic efficiency of the detector. For a detection system the solid angle coverage of the system also comes into picture and the above
The definition is accordingly modified. The absolute detection efficiency is the ratio of the number of photons recorded \( n_r \) to the number of photons produced \( n_p \) in a reaction.

\[
\epsilon_a = \frac{n_r}{n_p} = \epsilon \frac{\Omega}{4\pi}
\]

where the factor \( \frac{\Omega}{4\pi} \) is called as geometrical efficiency. From above equation it is clear that by increasing the solid angle coverage the efficiency of the system can be increased. Photon detection are often used for precision measurements of \( \gamma \) energies. For these measurements, only those events which increase the number of photopeak counts \( n_{ph} \) are of consideration. The absolute photopeak peak efficiency \( \epsilon_{ph} \) of a detector is defined as

\[
\epsilon_{ph} = \frac{n_{ph}}{n_p}
\]

For an array of detectors, the total photopeak efficiency is defined as the sum of absolute photopeak efficiencies of the individual detectors

\[
\epsilon_{ph(total)} = \sum_k \epsilon_{ph}(k)
\]

The number of events \( N_\gamma \) recorded for a \( \gamma \) transition, with yield \( y_\gamma \) in the reaction, can be written as

\[
N_\gamma = \epsilon_\gamma(\gamma)y_\gamma d\Omega
\]

where the dependence of efficiency on the transition energy is shown. In case of coincidence events (described in Section 5.1) the efficiency of the system, now called as 'coincidence efficiency', is given by the product of individual efficiencies of transitions.

### 4.5 High Purity Germanium (HPGe) detectors

Germanium detectors belong to a class of semiconductor detectors known for their superior energy resolution as compared with gas detectors or scintillators. The superior energy resolution is due to the fact that a comparatively low energy, \( \sim 3 \, eV \), is needed to create a charge pair (in this case an electron-hole pair). This translates into a higher number of charge pairs created for a given incident radiation and therefore a relatively lower fluctuation. The energy needed to create a charge pair is slightly lesser in Ge.
than Si at both room temperature and at 77 K. Another important parameter which is of consideration is the active volume of the detector determined by the thickness $d$ of the depletion region. The thickness $d$ depend on the bias voltage $V$ applied and the concentration of impurity $N$ as

$$d = \left(\frac{2eV}{\epsilon N}\right)^{\frac{1}{2}}$$

(4.13)

where $\epsilon$ is the dielectric constant of the medium. From above equation it is clear that for increasing the thickness of the depletion region the parameter which can be varied is the concentration of impurity $N$. For getting a thickness of $d \sim 10 \text{ mm}$ at an applied voltage of $1000 \text{ V}$ it has to be of the order of $1 \text{ part in } 10^{12}$. To achieve such a low concentration of impurity there are two approaches available. The first approach is to add an impurity of opposite type after the crystal formation, which would compensate for the impurity already present. This approach is tested for both Silicon and Germanium by a process called lithium ion drifting. The germanium detectors fabricated by this process are called Ge(Li). The disadvantage these detectors have is that they have always to be maintained at liquid nitrogen temperature. In addition, they are highly prone to the neutron damage and therefore not suitable for in-beam spectroscopy. The second approach to get a low value of $N$ is to make a hyper pure crystal by a technique called zone refining. By this technique the impurity concentration can be made as low as $10^9 \text{ atoms/cm}^3$. However, this technique can only be applied to germanium, which is due its lower melting point (959° C) as compared with silicon (1410° C). The detectors made with this method are called Hyper Pure Germanium (HPGe) detectors. Unlike Ge(Li) these detectors need not always be maintained at liquid nitrogen temperature and can be annealed at elevated temperature to nullify the effect of neutron damage. Another advantage of germanium over silicon is its high atomic number $Z$ which enhances the absorption of $\gamma$ radiation via photoelectric effect.

The major disadvantage of germanium detectors in comparison with scintillator detectors are their poor timing properties. The major factors which limit the timing resolution of a germanium detector (which may be few tens of nanosecond) are the charge
collection time and the variable shape of pulse rise from event to event. In spite of these
deficits they are now the most important tool for study in γ-ray spectroscopy due to their
superior energy resolution which compensate for these deficits.

4.6 Gamma Detector Arrays

Ge detectors started a new era in γ-ray spectroscopy. It was possible to investigate
high spin states by γ-γ coincidence method using two Ge detectors. To look for weakly
populating states the number of such coincidences have to be large\(^2\). For having such
a high statistics data, the detection efficiency of the system has to be improved. One
way is to increase the interaction probability of not only the primary γ radiation but also
that of the secondary radiations thereby increasing the photopeak events. This can be
achieved by increasing the thickness of Ge crystal. But in practice growing a large crystal
is always difficult. Further, the collection time in a large Crystal is always large with
poorer time resolution. Another way is to have large solid angle coverage. This again can
be achieved in two methods. First by increasing the dimension of front face of the crystal
leaving the thickness same. But this introduces problems like poorer energy resolution
and increased multiple hit events. The poorer energy resolution is due to the acceptance
of events having highly Doppler-broadened transitions emitted from moving nuclei. Again
this method also involves making a large crystal which have the same problems mentioned
above. The second way to increase solid angle coverage is to have a number of detectors
arranged in a specific geometry. This arrangement is called an array. In this case the
problem of Doppler-broadening and multiple hit events do not get enhanced as compared
with that of a single large detector.

4.6.1 Early Arrays

With the advent of Ge(Li) detectors in late sixties [1], it was for the first time possible
to extend the study to high spin structures of nuclei. This is due to good resolution of

\(^2\) For example, for the determination of various properties of a transition having relative intensity of 5
% of the most intense transition in a nucleus, while the cross section of the nucleus being itself about 10
%, the number of γ-γ coincidences should be of the order \(10^9\) counts.
Ge(Li) which makes it possible to filter out cascade of $\gamma$ transitions in a complex level scheme. Early arrays consisted of two to a few Ge(Li) detectors. But a low peak to total ratio of these early detectors limited their ability to identify weak transitions.

### 4.6.2 First generation $\gamma$ detector arrays

The solution of low peak to total ratio can be achieved if the events corresponding to Compton escaped $\gamma$-rays are suppressed. This can be achieved by increasing the active volume of the detector which increases the photopeak efficiency. But the major breakthrough came with the idea of using an anti-Compton shield (ACS) made of NaI detectors surrounding the Ge detector. These NaI detectors are then used to produce a veto signal for the Compton escape events. This increases the peak to total ratio. However, the efficiency of the system reduces drastically and to overcome this problem the number of detectors with ACS were increased. This led to the development of first generation $\gamma$ detector arrays. The first such array was built in 1980 in Risø, in Denmark [2]. The array was called TESSA (the Escape Suppressed Spectrometer Array) and consisted of 5 Ge(Li) of 25 % relative efficiency with NaI(Tl) escape suppression shield.

### 4.6.3 Second generation $\gamma$ detector arrays

Second generation arrays made two improvements over the arrays of first generation. First was the use of BGO ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$) instead of NaI(Tl) which has three times better efficiency per interaction. This made it possible to reduce the size of suppression shield and thereby increasing the number of Ge detectors. Second was the use of n-type Ge detectors which reduces the dead layer between the Ge detector and the scintillator. HERA (high-energy resolution array) built at Lawrence Berkeley National Laboratory (LBNL) in early 1980's was such an example [3]. It consisted of 21 HPGe of $\sim$ 25 % efficiency arranged in three rings along with the BGO suppression shield. HERA made a big impact on the study of nuclear structure. For the first time it was possible to have a meaningful $\gamma$-$\gamma$-$\gamma$ data and the possibility of using double gates. In the free space of the array 44 BGO elements were used for the measurement of multiplicity.
4.6.4 Third generation $\gamma$ detector array

The goal for making an ultimate $4\pi$ array of escape suppressed Ge detectors led to the development of third generation detectors GAMMASPHERE [4] and EUROBALL [5]. In order to achieve the aim, a few points were taken in consideration:

1. Full peak efficiency of the array: The efficiency of the array is limited by the total solid angle coverage of the Ge detectors. Therefore to have large efficiency the design of the array should be such that the free space left should be minimized.

2. Energy resolution: Apart from the intrinsic resolution of Ge which is $\sim 2$ keV at 1332 keV, the Doppler broadening of radiation emitted from the recoiling nuclei decreases the resolution. To reduce this effect opening solid angle of individual detectors should be reduced which means placing the detectors relatively far from the center. This in turn means increasing the number of detectors to cope with the decreased efficiency due to decrease in solid angle coverage.

3. Isolated hit probability: In a cascade of $m$ $\gamma$-rays it is desirable to detect as many gamma rays as possible. This implies that for $f$ fold detection all the $f$ $\gamma$-rays should be detected by individual detectors of the array. An event corresponding to the detection of two $\gamma$-rays of a cascade by the same detector results in the background and therefore a loss of event. To reduce such losses the isolated hit probability should be increased. An isolated hit probability is defined as the probability in which the $\gamma$ transitions emitted in a cascade are detected by different detectors. This probability increases with the granularity of the array.

In GAMMASPHERE, 70 out of 110 detectors have longitudinal segmentation, which increases both the energy resolution and the isolated hit probability. The full energy peak efficiency of the array is about 10%. In EUROBALL, the solution to increase the granularity was the use of composite detectors, like clover [6] and cluster [7]. Both arrays have there advantages and disadvantages. GAMMASPHERE have high symmetry which facilitate the data analysis considerably whereas EUROBALL have higher efficiency due to cluster and high polarization sensitivity due to clover detectors.
4.6.5 Fourth generation $\gamma$ detector array

We are now about to enter the domain of fourth generation $\gamma$ detectors where individual detectors are made of highly segmented Ge-detectors. Due to their large granularity, Doppler broadening of the $\gamma$-ray is highly reduced. By tracking of individual Compton events, the total energy of the incident photon can be reconstructed with superior peak to total ratio without the use of anti-Compton shield.

Arrays of this type are currently under development, i.e. AGATA in Europe and GRETA in USA [8, 9].

4.6.6 Clover detectors

Clover detectors were the first composite detectors used in EUROBALL setup. A clover detector consists of four HPGe crystals placed in four quadrants of a square as shown in Fig. 4.4 and housed in a cryostat. The diameter and length of each crystal is about 50 mm and 70 mm respectively and are tapered at the edges. Each of the crystals can be used as an independent detector. This increases the granularity of the clover detector compared with a conventional HPGe detector. Since the crystals are closely packed with a small
gap of 0.2 mm, there is a high probability of detecting a Compton-scattered $\gamma$ transition scattered from a neighboring crystal. If the crystals are used as independent detectors the $\gamma$ transitions corresponding to these events are added to the Compton background. To get back these events, the clover is used in an addback mode, which can be two fold, three fold or four fold. The addback mode of $n$ ($\leq 4$) fold is defined as a mode of operation of clover detectors in which the energies of $\gamma$ transitions of $n$ crystals firing simultaneously are added together. This is done offline where the information about the firing of each crystal is stored on event by event basis. The above method of getting the photopeak events back in addback mode is possible due to high isolated hit probability of the clover detector. The photopeak efficiency of a clover is about six times that of a single crystal when used in the addback mode. In Fig.4.5, the ‘addback factor’ is plotted as a function of energy. It is defined as the ratio of the photopeak efficiency of a clover in addback mode to the photopeak efficiency of a clover in singles mode. From the figure, it is observed that the ratio is close to one at lower energies which is due to the fact that the cross section of Compton scattering at these energies is very less. Due to the removal of events from the Compton background when the clover is used in addback mode, the background is considerably reduced. This is illustrated in Fig. 4.6, with data taken from $^{60}$Co source.

The clover detectors have the following advantages over the conventional HPGe detectors of same volume:

a) Since the crystals of a clover detector behave as an independent detector their opening angle is relatively small in comparison to a HPGe detector having the same dimension of a clover. This reduces the Doppler broadening of $\gamma$ transitions emitted from short lived states. The average opening angle of the four crystals can be defined as an effective opening angle of the clover.

b) The probability of isolated hit event in a clover is higher than in HPGe. This is again due the small effective opening angle of clover.

c) The total efficiency of a clover in the addback mode is same to that of HPGe of same volume. Since it is difficult to grow a single large crystal, the use of composite detector, like clover, made it possible to increase the effective volume of the detector and hence an increase in efficiency of detection.
Figure 4.5: A figure showing the variation of addback factor with energy.

Figure 4.6: A comparison of Compton background in $^{60}$Co data spectrum in singles and addback mode. Left figure a) is without the suppression of escape events by ACS whereas right figure b) is with the suppression of escape events by ACS.
4.6.7 Anti-Compton Shield

In Section 4.6.2, the advantages of having a Compton suppression data were mentioned. In the design of an ACS, one important parameter is the amount of anti-Compton material in a particular direction surrounding the Ge crystal. This depends on the energy of Compton scattered photon. From Eq. 4.4 it is clear that placing the anti-Compton material in the forward direction improves the lower energy part of the spectrum while material in the backward direction improves the higher energy part of the spectrum. From the Eq. 3.23 of Chapter 3

\[ \frac{d\sigma}{d\Omega}(\nu, \chi) = \frac{\gamma^2}{2} \left( \frac{E}{E_0} \right)^2 \left[ \frac{E_0}{E} + \frac{E}{E_0} - 2 \sin^2 \nu \cos^2 \chi \right] \]

(4.14)

it can be seen that to achieve the same suppression in all direction relatively small amount of material is needed in the backward direction\(^3\).

A schematic cross sectional view of an anti-Compton shield (ACS) is shown in Fig. 4.7. The Clover is surrounded with 16 BGO scintillators.

\(^3\)Here the direction is defined in the direction of \(\gamma\) ray.
4.7 Indian National Gamma Array (INGA)

Indian National Gamma Array (INGA) [10, 11] at IUAC in its phase III has the provision of placing 24 Clover detectors along with anti-Compton shield (ACS) at five different angles (see Table 4.1). The total photopeak efficiency of the array is about 5%. It also has the provision of placing 6 Low Energy Photon Spectrometer (LEPS) detectors at two different angles. A front view of INGA at IUAC is shown in Fig. 4.8. Also is shown the relative position of array in Beam Hall II with respect to the recoil separator HYRA in Fig. 4.9. The diameter of the structure is 1 m. The distance between the target position and the Ge crystals is 24 cm. The array can be divided into two parts, the forward hemisphere\(^4\) and the backward hemisphere. These hemispheres are mounted on separate platforms which are in turn mounted on movable platforms. These movable platforms move on a pair of guide rails and are controlled by a remote motor controller. The forward hemisphere is attached with the beam line while the backward one is free to

\(^4\text{although strictly not a hemisphere}\)
move along the beam line. The reaction chamber is a 5.08 cm diameter cylindrical glass tube to minimize the attenuation of γ-rays and is connected to the beam line at both the switching magnet and HYRA end. A removable collimator with a current readout of diameter 5 mm is placed at a distance of 1.5 m upstream from the target position. The filling of the clover dewars is done regularly at an interval of 12 hrs. For automatic filling of all the dewars at regular intervals a PC based ‘Autofill’ controller system has been developed [12].

4.7.1 Target Chamber

The target chamber used in the INGA at IUAC consists of a cylindrical glass chamber of 5.08 cm diameter attached to the beam line with Wilkinson seal. The target is mounted on a target ladder shown in Fig. 4.10. The target ladder is a circular aluminum plate of diameter 4.3 cm and thickness 0.5 mm with a circular hole of diameter 2 cm. It is attached by two stainless steel rods of thickness 4 mm and 3.5 cm apart to an adapter.
Table 4.1: Orientation of detectors in INGA.

<table>
<thead>
<tr>
<th>Detector position</th>
<th>Orientation of detectors $\theta; \phi$</th>
<th>Number of detectors</th>
<th>Shape of plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward Hemisphere</td>
<td>$32^{\circ}; 0^{\circ}, 90^{\circ}, 180^{\circ}, 270^{\circ}$</td>
<td>4 clovers</td>
<td>Hexagon</td>
</tr>
<tr>
<td>21 to 24</td>
<td>$32^{\circ}; 0^{\circ}, 90^{\circ}, 180^{\circ}, 270^{\circ}$</td>
<td>4 clovers</td>
<td>Hexagon</td>
</tr>
<tr>
<td>17 to 20</td>
<td>$57^{\circ}; 45^{\circ}, 135^{\circ}, 225^{\circ}, 315^{\circ}$</td>
<td>4 clovers</td>
<td>Pentagon</td>
</tr>
<tr>
<td>28 to 30</td>
<td>$61^{\circ}; 0^{\circ}, 90^{\circ}, 180^{\circ}$</td>
<td>3 LEPS</td>
<td>Trapezium</td>
</tr>
<tr>
<td>Backward Hemisphere</td>
<td>$90^{\circ}; 0^{\circ}, 45^{\circ}, 90^{\circ}, 135^{\circ}$</td>
<td>4 clovers</td>
<td>Rectangle</td>
</tr>
<tr>
<td>9 to 16</td>
<td>$90^{\circ}; 0^{\circ}, 45^{\circ}, 90^{\circ}, 135^{\circ}$</td>
<td>4 clovers</td>
<td>Rectangle</td>
</tr>
<tr>
<td>25 to 27</td>
<td>$119^{\circ}; 0^{\circ}, 90^{\circ}, 180^{\circ}$</td>
<td>3 LEPS</td>
<td>Trapezium</td>
</tr>
<tr>
<td>5 to 8</td>
<td>$123^{\circ}; 45^{\circ}, 135^{\circ}, 225^{\circ}, 315^{\circ}$</td>
<td>4 clovers</td>
<td>Pentagon</td>
</tr>
<tr>
<td>1 to 4</td>
<td>$148^{\circ}; 0^{\circ}, 90^{\circ}, 180^{\circ}, 270^{\circ}$</td>
<td>4 clovers</td>
<td>Hexagon</td>
</tr>
</tbody>
</table>

Figure 4.10: A view of the target ladder used in the INGA experiments at IUAC.
Figure 4.11: A schematic figure illustrating the orientation of INGA with respect to laboratory axis. Only 90° ring is shown and the position of forward and backward hemispheres are indicated.

which is compatible with the flange at the HYRA side.

4.7.2 Alignment of the array

An array can be considered as a rigid body having six degrees of freedom. Three of them are the translational degrees of freedom and correspond to the position of the center of array. While the other remaining three are the rotational degrees of freedom defining its orientation with respect to some standard set of axes. These rotational degrees of freedom can be the Euler angles. The body set of axes of the INGA are defined as three mutually perpendicular axis $x'$, $y'$, $z'$. The $z'$ axis is perpendicular to the plane of 90° detectors and point out from the backward hemisphere, the $x'$ and $y'$ axes lie in the plane passing through the detectors at position 13th and 11th respectively. The laboratory set of axes are defined with respect to beam direction. The beam direction is chosen as the $z$ axis, vertical direction to the ground as the $y$ axis and the $x$ axis lie in the plane of ground in the direction demanded by the right handedness of coordinate system. The origin of the laboratory set of axes is chosen as the target position. The alignment of an array is defined as translating the position of its center to the target position and the alignment of the body set of axes parallel to the laboratory axes. Following steps were undertaken for the alignment:-
a) First the center of array was positioned at an arbitrary position along the $z$ axis. This was done using wires joined at diametrically opposite ends of the array. The point where the wires intersect is the array center and it was positioned along the beam axis with the help of theodolite.

b) Aligning the $y$ axis along the $y'$ axis: This was done by dropping a plumb wire from the center of a small hole on the top plate (position A) of 90° ring (see Fig. 4.11) and passing through a small hole on the bottom plate exactly at the diametrically opposite position (position C) of former hole. With the help of screws, called as ‘adjustment screws’ which joins the array platform and the moving platform, the array is rotated till the plumb wire passes exactly through the center of the bottom hole. In this situation the wire also passes through the center of the array and can be checked through a theodolite. Additionally, spirit levels were put on the top flat surface of the 90° ring in both $x$ and $z$ axes to ensure its parallelness with respect to the plane of ground. The rotation of the array was carried out about the $x$ axis and $z$ axis iteratively till the alignment of $y$ axis parallel to $y'$ axis was achieved. After the end of this exercises, the $y'$ axis was parallel to the $y$ axis and $x'$ and $z'$ axes lie in the plane of $x$ and $z$ axis. This make the front face of both hemisphere vertical.

c) Alignment of $z'$ axis along the $z$ axis: The rotation of the array was carried about the $y$ axis (the vertical axis) for aligning the $z'$ axis parallel to $z$ axis. To check this two plumb wires from the edges of the 90° ring (position B and D in Fig. 4.11) are dropped. A line was drawn joining the points on the ground where these plumbs meet and the angle this line made with the beam axis was noted. In the case of $z'$ axis aligned parallel to $z$ axis the above angle is 90°.

d) Positioning the individual hemispheres along the beam line: The position of the forward hemisphere was kept fixed with respect to the HYRA entrance quadrupole to provide adequate clearance for mounting detectors in situ. This also fixes the target position as all the detectors in forward hemisphere must point to this target. The movable backward hemisphere was now positioned such that the remaining detectors in the backward hemisphere also pointing towards the target. A proximity switch was mounted on the guide rails so that the backward hemisphere could be brought back to the same position with
an accuracy of ± 0.2 \text{mm}.

4.7.3 Alignment of ACS plates

The ACS plates are necessary to take care of manufacturing defects in the structure. It ensures that each detector faces the center and is at the prescribed distance. With the help of adjustment screws, the ACS plates are aligned perpendicular to the line joining the center of the array and the center of plate. Also with the help of ACS plates, the distance of ACS from the center of the array is adjusted. This is done by using a pointed rod attached to a plate at its center. The length of the pointed section of the rod is equal to the sum of the radius of array and the thickness of ACS plate. Three such rods are inserted into the array at an angle of 90° with each other in the \textit{xy} plane. In the event of perfect alignment the tips of the rods meet at the center of the array. In other cases adjustment is done via ‘adjustment screws’ of ACS till the tips of the rods meet at the center within a certain limit (± 2 \text{mm}).

4.8 Data Processing and Acquisition

The signals coming from the detectors carry information in the form of pulse amplitude, the shape of the pulse and the relative timing of the pulse. The job of a data processing and acquisition system (DAS) is to extract these information and record them on a storage medium for further offline analysis. The basic components of the system are:

1. Front end electronics.

2. Data acquisition and storage.

In the front end electronics, the signals are processed before any information contained in them could be digitized. After digitization the information, which is now called ‘datum’ is stored on a hard disk. This collection and storage of data can be done either as histograms for individual detectors or in the list mode format (which means collection and storage on event by event basis). Often, the data acquired have multiple parameters for which the list mode format is the best available option. The storage of the data is done in a
4.8.1 Front end electronics
Pulse processing and Compton suppression

The front end electronics of the DAS is associated with the processing of the pulse in a form suitable for digitization. Here it is ensured that the digitization of signals associated with an event takes place only if a certain set of conditions are satisfied. The timing signals from the detectors, which are converted into logic signals during signal processing, are used to test these conditions.

A block diagram of electronics for the pulse processing and Compton-suppression is shown in Fig. 4.12. From a clover detector, four preamplifier outputs corresponding to each crystal are obtained. These outputs are used in both energy and timing channels. In the energy channel, the signals are amplified and shaped by spectroscopy amplifiers,
of shaping time $\sim 3\mu s$, before they are fed into ADCs for digitization. In the timing channel, the conditions for the selection of events are checked. The first process is the conversion of an analog signal into a NIM logic signal which is achieved by constant fraction discriminator (CFD). For a CFD to work better, i.e. to have less amplitude walk, the rise time of the pulse has to be small. Therefore, before the signal undergoes a logic conversion in CFD, it is amplified and shaped by timing filter amplifier (TFA), especially made for the purpose of achieving fast rise time ($\sim 10$ ns). The width of logic signals from CFD is kept at 50 ns. The threshold of CFD is kept just above the noise level. This adjustment is done online using a CRO. Timing signals from all the four crystals and ACS are converted into logic signals. The second process in the timing channel is the satisfaction of conditions. For the INGA without ancillary detectors this translates into two conditions. First one is the identification of Compton escape events and second is the information about the status of data acquisition system. Later condition is discussed in next section. For the former condition an anti-coincidence between the 'OR'ed of clover timing signals and ACS timing signal is demanded, i.e. $\text{Ge}.\overline{\text{ACS}}$. The 'OR'ed clover signal is delayed by 100 ns before it is 'AND'ed with the signal from ACS in the anti-coincidence mode. The delay to clover signal is adjusted such that it is well contained within the ACS signal, which is 500 ns wide, as shown in Fig. 4.13 so that any walk in the clover timing channel can be taken care of. The anti-coincidence is achieved in coincidence module. Presence of signal in ACS is an indication of an Compton escape event and by the above condition these events are removed from being recorded.

The pulse processing and Compton suppression is carried out in a home made compact module called as 'Clover electronics module' [13] (see Fig. 4.12). This double width module have NIM outputs consisting of four base line corrected spectroscopy amplifiers with selectable gain range (2, 4, 6 MeV for pulse of height 10V) by jumper settings. One module contains in all five TFA's and CFD's for four crystals of a clover and ACS. Timing and energy inputs are given through rear panel. Outputs obtained from the rear panel are individual CFD's of crystals and ACS. Pile Up Rejection (PUR) signal is also given through the rear panel. The online adjustments like, walk adjustment, lower level threshold adjustment (LLTH) and the corresponding monitors are provided in the front
Figure 4.13: In above figure, logic of Compton-suppression is depicted. The presence of ACS signal forbids the clover signal to pass through.

As described in the introduction of this section, a master signal refers to the satisfaction of certain set of conditions and its presence at the master input of ADC serve as an information to the data acquisition system that the data can be digitized and collected. In γ-ray spectroscopy this means the selection of event on the basis of fold, or the selection on the basis of channel or other criteria. Along with these conditions one additional criterion which has to be taken into consideration is the status of data acquisition system, whether it is busy or not. In Fig. 4.14, an electronics diagram for the generation of master gate in the experiments held with INGA is shown.

The idea is to have an analog sum of all the timing signals (which are logical signals), coming from the detectors after the satisfaction of Compton suppression condition. The event can then be discriminated on the basis of number of logical signals making up the analog sum. This is achieved by a combination of three 16 Channel Discriminators
Figure 4.14: Electronics diagram for the generation of master gate.
(Phillips 7106), each one producing 100 mV per input pulse. Outputs of all three Discriminators are then added in Phillips 744 Linear sum modules. The summed output is then given to the Hex discriminator (Phillips 711) having discriminator levels adjusted to pass only the pulses with required heights (or voltages). The heights correspond to the folds to be selected. The output of Hex discriminator is AND’ed with the BUSY signal in anti-coincidence mode, i.e. Ge.ACS.BUSY, coming from the Trigger Generator. The presence of pulse in the BUSY indicates the inability of data acquisition system to accept the event. Once the condition of BUSY is satisfied the signal is given to the Trigger Generator, which now act as a receiver, to generate a signal which is now called as a Master Signal. At the same time it synchronizes all the ADC’s in the system. A view of the electronic set up used in INGA at IUAC is shown in Fig. 4.15.

4.8.2 Data acquisition and storage

The acquisition of data starts from the digitization in analog to digital converter (ADC). The data were digitized by 14 bit 8 channel ADC’s [14] and 12 bit TDC’s (Phillips 7186). For acquiring the data from INGA, a dedicated data acquisition system (DAS) has been
developed. The DAS consists of three CAMAC crates each containing 8 ADC's and one TDC module, from where the events are read in parallel with an event identification tag for each event. The process of reading and storing is accomplished by a new List Processor cum Crate Controller (LPCC) CAMAC module [15] fabricated at IUAC. The synchronization of crates is done by Trigger generator (TG) [16]. The fragmented events from each of the CAMAC crates are assembled and reconstructed to form an entire event by a multi-crate data acquisition program CANDLE [17] which is run on a dedicated PC with Linux operating system.

The data from INGA is written in the buffer list mode format (i.e. event by event). The number of parameters are 113, with four energy and one timing parameters per detector from 22 detectors of the array and three parameters for the event identification from each of the three CAMAC crates.

4.9 Target Preparation

For an experiment held with INGA, an isotopically enriched $^{94}$Mo target with a gold backing was prepared in the Target laboratory at IUAC. Since the enriched target was in the form of foil, the rolling procedure was adopted to obtain the required thickness of 1 mg/cm². The rolling machine at IUAC, consists of two roller's, made of a very hard material (Tantalum), which are connected with rotatable shafts powered by an electric motor. The motor is then controlled manually.

The isotopically enriched $^{94}$Mo foil was rolled to a slightly higher thickness than the desired value. It was then rolled with a gold foil also prepared by the rolling method with thickness slightly higher than the desired value. The thickness of both molybdenum and gold foil were chosen to be slightly higher than the desired value because of the decrease in the thickness while rolling together.

Points taken in consideration while preparing the molybdenum target were

1) Mo has a very high melting and boiling point, which make its preparation from the evaporation method quite difficult.

2) The enriched material was found to be quite soft as compared with the natural one.
This can be due to the impurities settled on the natural material for its long exposure to air.

3) The sticking properties of enriched molybdenum material on gold was found to be better than the natural molybdenum.

4) Since the expansion coefficients of molybdenum and gold are different, the final target is found to be curled severely. It was flattened gently by pressing between the paper sheets or glass slides and mounted on the target frame with glue.
Bibliography


