2.1 In-beam Spectroscopy

The physical theory describing \( \gamma \) ray transitions between nuclear states is well understood and is frequently used to study the features of the level structures of a nucleus which is a continuation of the efforts made by physicists to understand the most important short range interaction between nucleons since the discovery of the most interesting quantum system (nucleus). 'In-beam gamma-ray spectroscopy' using nuclear reaction processes is one of the most useful and standard techniques which is used to establish the level energies, spins and parities, and the decay characteristics of levels in a nucleus under investigation. Experimental techniques in common use, the details about equipment used in in-beam gamma-ray measurements like \( \gamma \)-ray spectrometer, data-acquisitions system, the process of data analysis and the methods of constructing the decay schemes from several different types of measurements of the \( \gamma \) rays depopulating (\( \alpha, \pi \gamma \)) or (heavy ion, \( \pi \gamma \)) evaporation residues are discussed extensively in several texts \([1-9]\). Again it will be necessary to discuss several different concepts in connection with the present measurements carried out for the study of level structure of \(^{125}I\).

In practice, by means of nuclear reaction spectroscopy, rapidly spinning highly excited compound nuclei are produced by bombarding the target nuclei with a beam of energetic projectiles. The excited compound nucleus system subsequently decays by evaporating particles, and then by emission of \( \gamma \)-rays which lead finally to ground states of the residual nuclei. Various techniques of in-beam measurements of \( \gamma \)-rays for determining energies, relative intensities, multipolarities, multipole mixing ratios etc., provide valuable information about characteristics of nuclear levels which are needed to understand the level structures
of the nuclei and their interpretation in the light of theoretical models.

The nuclear structure of $^{125}\text{I}$ nucleus has been studied via in-beam $\gamma$-ray spectroscopy in fusion evaporation reactions at Variable Energy Cyclotron Centre, Calcutta, using standard experimental setup, electronics and data handling equipment commonly employed for in-beam spectroscopy.

Variable Energy Cyclotron Center (VECC) in Calcutta is a national facility for the study of the experimental nuclear physics and related fields. It has been mainly used for acceleration of alpha particles in the energy range 25-75 MeV. This accelerator provides beams in several beam lines in the experimental area for different types of measurements. Details about the parameters for this Cyclotron are given in Ref. [11]. The work for installation of Electron Cyclotron Resonance (ECR) heavy-ion source and testing of transportation of heavy ions is completed and now heavy-ion-beams are also available for the experiments. A schematic representation of the over all cyclotron facility is shown in Fig. 2.1 which shows the accelerator, experimental area, the control room, counting room and data processing room.

In-beam $\gamma$-ray spectroscopy measurements have been done in beam line-III (Fig 2.2, $30^\circ$ port). In this beam line beam focusing is achieved with the help of quadrupole magnets and no collimator is used, to avoid the background radiations ($\gamma$-rays and neutrons). A schematic representation of beam line-III is shown in Figs. 2.2 and 2.3. An overall view of the beam hall and other relevant equipments used in the beam-line for the beam transportation is shown in the picture presented in Fig. 2.4.

Beam of $\alpha$ particles from cyclotron was incident on an enriched elemental $^{123}\text{Sb}$ target. The decay $\gamma$-rays after particle emission from hot compound system were detected using high resolution HPGe detectors surrounded by Compton Suppression Shields (ACS). The signals from the detectors are pre-amplified and taken to the counting room by 50 $\Omega$ co-axial cables for further processing, recording and analysis of the data.

In the first series of experiments, $\gamma$-ray singles measurements were made for the identification of $\gamma$ rays and to determine their relative intensities. Further, to ascertain the
FIG. 2.1. VARIABLE ENERGY CYCLOTRON CENTRE (VECC)

A general lay-out of VECC showing accelerator part, experimental area, control room and data processing room.
FIG. 2.2. Schematic layout of beam transport system for channel 1, 2 & 3. The present in-beam measurements are carried out in channel 3 (35° port).
FIG. 2.3 Schematic drawing of reaction chamber and the beam-line used.
FIG. 2.4. Pictures of experimental setup at VECC showing BGO ACS's, HPGe’s, and scattering chamber and other relevant devices in the beam hall.
assignment of various γ rays to $^{125}$I, and to determine their relations with particular
cascade sequences and placement in the level scheme of $^{125}$I. γγ-coincidence measurements
were carried out with two HPGe detectors surrounded by axial BGO Compton suppression
shields. On the basis of these results γ-rays were placed in the level scheme of $^{125}$I.

The angular distributions of the γ-rays were measured in order to determine the mul­
tipolarities and the multipole mixing ratios of the γ rays and for the assignment of spins of
levels in the deduced level scheme of $^{125}$I. In addition, the relative excitation functions of
the γ rays in $^{125}$I have also been measured for isotopic identification and to supplement the
results of angular distribution measurements regarding assignment of spins of levels.

These measurements and data analysis involve several experimental techniques and the
optimization of a large numbers of parameters such as reaction, beam, target, detectors,
electronics, geometry, counting rate, statistics, measurement time, process of data acqui­sition etc. All these parameters depend upon each other so that one has to compromise
between different factors like counting rate and the amount of acceptable counting losses
etc. Details are described in the following part of this chapter.

2.2 Population of Excited States

Usually, several experimental methods like scattering, direct reactions, fusion evaporation
etc. are employed to obtain different kinds of information about the nucleus. In all these
methods the projectile nucleus interacts with the target nucleus. The interaction between
two nuclei can be roughly classified into four different categories depending upon impact
parameter 'b' or the corresponding relative angular momentum $\ell$. For interaction radius $R$
( $R$ is the closest distance of approach between the centers of the two nuclei on a grazing
trajectory ) the impact parameter is $b_{gr}$ as shown in Fig. 2.5. For $b \gg b_{gr}$ the nuclear
interaction results in Coulomb reaction, which is useful for studying the nuclear structure
of stable nuclei. At $b \sim b_{gr}$ interaction results in direct reaction like pick-up, break-up
etc., which provides considerable information on the structure of the nuclei. Scattering
experiments with low energy projectile are basically used to study the shape, size, charge
Fig. 2.5. A schematic illustration of the nuclear reactions. $R_P$ and $R_T$ are the half-density nuclear radii of the projectile and target nuclei.
distribution and overall mode of excitation of the nucleus. For impact parameters considerably smaller than \( b_{gr} \) two situations are possible, first one is the deep inelastic reaction, where, large amount of mass and energy transfer take place without formation of compound nucleus. Second one is the compound nucleus (CN) formation, where, the projectile is fused with the target nucleus and all internal degree of freedom are involved. At energies above the Coulomb barrier, there is a considerable transfer of the incident energy and momentum to the compound nucleus and the process is known as fusion reaction which provides an excellent means for the study of nuclear structure.

Fusion reactions like \((\alpha, x\nu\gamma)\), \((\text{Heavy-Ion, } x\nu\gamma)\) are the most favourable for the excitation of very high spin states, where rapidly rotating nuclei are produced by transfer of large amount of angular momentum of the projectile [5]. Once the compound nucleus is formed after a fusion process there is a finite possibility that fission take place rather than particle and \( \gamma \) decay via high spin states. The fission probability depends on the mass of the compound nucleus and the maximum angular momentum \( \ell_{\text{max}} \) brought into the system via fusion. For rare earth nuclei \( \ell_{\text{max}} h \) exceeds 90\( h \) for a fission barrier \( B_f = 0 \) [14]. In case of \( \alpha \) particle as a projectile in the range of 30 to 50 \( MeV \), maximum angular momentum \( \ell_{\text{max}} \) lie in the range 10 to 15\( h \) is quite below the fission limit. The thermal energy of the compound nucleus is initially removed by evaporation of particles, which do not generally take much angular momentum from the system. The statistical \( \gamma \) rays emission following the particle evaporation further cools the system but carries away little angular momentum and therefore, it is expected that the residual nucleus still remains in a highly aligned state.

From a classical point of view spin distribution in the residual nucleus can be described by considering a projectile of mass number \( M \) with energy \( E \) and momentum \( p \). The orbital angular momentum \( \ell h \) corresponding to an impact radius \( b_t \) is given by

\[
b_t = \ell \frac{h}{p} = \ell \lambda
\]

where, \( \lambda = \frac{\lambda}{(2\mu E_{cm})^{1/2}} \). The maximum angular momentum \( \ell_{\text{max}} \) can be derived from the requirement of energy conservation from infinity to the distance of closest approach \( R \) between
the colliding nuclei as

$$\ell_{max}^2 = \left( 2\mu R^2 / h^2 \right) \left( E_{cm} - V_c \right)$$

(2)

where $V_c$ is Coulomb barrier ($= 1.442 \, \text{MeV}$) and

$$R = 1.36 \left( A_p^{1/3} + A_t^{1/3} \right) + 0.5 \, \text{fm} \quad [15].$$

The classical formation cross-section of compound nucleus of angular momentum $\ell$ is

$$\sigma_\ell = \pi b_{\ell+1}^2 - \pi b_\ell^2 = \pi \lambda^2 (2\ell + 1)$$

(3)

For negligible channel spin $\sigma_\ell$ becomes a spin distribution of the compound nucleus and further with assumption that negligible angular momentum is carried away in the evaporation process, $\sigma_\ell$ gives the approximate spin distribution in a residual nucleus. In quantum mechanical approach, compound nucleus formation cross-section can be deduced through the application of the Statistical Model. The partial cross-section for the formation of compound nucleus of total angular momentum $J$ ($J$ is the resultant of the incoming orbital angular momentum $\ell$ and the channel spins) and $\pi$ from the projectile nucleus with spin and parity $I_p, I_\pi$ and target nucleus with $I_t, I_t$

$$\sigma(E, J) = \pi \lambda^2 \frac{2J + 1}{(2I_p + 1)(2I_t + 1)} \sum_{s=S_2}^{S_2} \sum_{\ell=L_2}^L T_\ell(E)$$

(4)

where, $S_1 = |I_p - I_t|$, $S_2 = I_p + I_t$, $L_1 = |J - s|$, $L_2 = J + s$ and

$$\lambda(E) = \left( \frac{h^2}{2\mu E_f} \right)^{1/2}$$

Parity conservation restricts the final sum over $\ell$ (i.e. $\pi_{CN} = \pi_p \pi_t (-1)^\ell$). The $T_\ell(E)$ are the transmission coefficients for the two nuclei and are assumed to depend only on the angular momentum $\ell$ and energy $E$ and calculated from a simple Fermi function of angular momentum [27].

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For the case where the projectile and the target spin are equal to zero, equation (4) reduces to

\[ \sigma(E, J) = \pi \lambda^2 (2\ell + 1) T_{\ell}(E). \]  

(5)

The total reaction cross-section is then given by the sum of equation (5) over all \( \ell \)

\[ \sigma_t = \pi \lambda^2 \sum_{\ell=0}^{\infty} (2\ell + 1) T_{\ell}(E). \]  

(6)

Total cross-section \( \sigma_t \) may involve many mechanisms where two nuclei interact and which of these processes dominates depends on the energy, angular momentum and type of nuclei involved.

Sufficiently neutron rich target nuclei are not available, and hence, it is difficult to produce neutron rich nuclei with heavier projectile. Because of that (\( \alpha, 2n\gamma \)) reaction was chosen for studying the \( ^{125}\text{I} \) nucleus. The statistical model calculations have been done with modified version of the code CASCADE [27], to estimate the cross-section for (\( \alpha, 2n\gamma \)) reaction channel. These calculations predict that at beam energy \( E_\alpha = 29 \text{ MeV} \), (\( \alpha, 2n\gamma \)) reaction channel has maximum yield and interference from other competitive channels is negligible. Therefore, for these measurements we have selected 30 \text{ MeV} beam energy for better population of higher angular momentum states.

2.3 Reaction Chamber

In an in-beam \( \gamma \)-ray spectroscopy measurement, the geometry of the experimental set up is a very crucial factor. The distance between source and detectors generally vary from experiment to experiment depending upon the specific requirement.

For very high count rate pile up is always large and due to that, true information is lost and spurious events increase the volume of the data. Secondly, high count rate always increases the random rate in case of coincidence measurements. A poor count rate, on the other hand worsens the signal to background ratio. Therefore, a compromise is necessary for optimum count rate. On the basis of these points beam current used was \( \sim 2\mu A \), and two different reaction chambers were used in these experiments.
In case of γ-ray singles measurements the effects of γγ-summing and Doppler broadening are pronounced when detectors are placed close to target. Therefore, for singles measurements, keeping these points in mind, sufficient gap of 25 cm was kept between target and detectors. To meet these requirements, a cylindrical reaction chamber of radius 17 cm, made of aluminum sheet of 2.5 mm thickness was used. The provision for fixing the angular position of HPGe detectors is made by mounting a circular scale graduated in angles, on the reaction chamber. The centre of the scale lies vertically above, on the axis of the reaction chamber, passing through the centre of the target. A schematic diagram of the reaction chamber for singles experiments is shown in Fig. 2.3.

In the case of γγ—coincidence measurements the coincidence rate, depends on the product of the absolute efficiencies of the detectors, and the beam current. The coincidence rate can be increased either by increasing the beam current or by decreasing the distance between target and detector. In first case, the random event rate increases as the square of the total event rate. So increasing the beam current is not a favourable alternative. In the second case, since the coincidence rate is proportional to the solid angles (i.e inversely proportional to the square of the distance between detector and target ) subtended by the detectors, it can be increased by decreasing the distance between the target and detectors. Therefore, for coincidence measurements a very close geometry is required for high coincidence efficiency. For this purpose a small reaction chamber with two windows of lucite, shown in picture (Fig. 2.4) was used for γγ—coincidence measurements. The target-detector distance in these experiments was ~ 5 cm.

In both the reaction chambers there was an arrangement for mounting the targets on a movable target-ladder passing through the centre of the chamber. Five targets with proper target frames can be mounted at the same time on this target ladder, and any particular target can be positioned at the centre of the reaction chamber by moving target ladder forward and backward. The corresponding positions for each target-center aligned with the center of the beam lines were marked on a scale fixed outside the chamber for monitoring and adjustment. The reaction vacuum in the chamber and connecting beam tube sections
was maintained by an oil-diffusion vacuum pump backed by a rotary pump.

2.4 Targets

The targets were prepared by depositing the powder of enriched elemental \(^{123}\text{Sb}\) uniformly on a 500 \(\mu\text{g/cm}^2\) thick mylar foil in a centrifuge. The thickness of the target \(^{123}\text{Sb}\) was \(\approx 10 \text{ mg/cm}^2\). The effective area of the target was large (\(\approx 15 \text{ mm diameter}\)). The mylar foil with the deposited target was mounted on a target holder frame made of thicker mylar sheet of 0.5 mm thickness. The target holder was in turn mounted on the target ladder in a reaction chamber.

2.5 Beam Focusing and Alignment

Before starting the measurements, the alignment of the centre of the reaction chamber and the axis of the beam tube was examined carefully. The position of the target-ladder for which the alumina \((\text{Al}_2\text{O}_3)\) and the target centers coincide with the centre of the reaction chamber were marked on a calibrated scale attached to the chamber. The beam line after the main gate valve, and the reaction chamber were evacuated up to \(10^{-6} \text{ Torr}\) by oil-diffusion pumps backed by rotary pumps, before opening the gate valve. The beam of \(\alpha\)-particles was focused on the thin fluorescent wafer of alumina marked with four concentric circles of diameters 4, 8, 12 and 16 mm, which was positioned at the centre of the reaction chamber. A closed circuit television (TV) camera was focused at the alumina to view the beam profile at control room of the cyclotron. The \(\alpha\)-particle beam was focused to a size of \(\approx 3 \text{ mm}\) at the centre of alumina using quadrupole magnets and then the ladder was moved such that the alumina was replaced by the target. Beam current was set at \(\approx 2nA\). The beam passing through the target was dumped on a thick tantalum foil in the Faraday Cup (FC) at the end of the beam-line at \(\approx 3 \text{ meter distance}\) from the target.

The beam dump was well shielded by blocks of paraffin and lead to suppress the back-
ground of neutrons and γ-rays arising from the beam-dump. Since the beam was well focused to a small size (≈ 3 mm dia.) and no slits or collimator were used in the beam line, there was no other source of background radiation due to the beam.

2.6 Gamma-ray Spectrometer

The γ-ray spectrometer used for various experiments in this work includes detectors, electronics and the data acquisition system that receives, handles, sorts and stores the information delivered by the detectors. In this spectrometer high efficiency HPGe detectors with BGO Compton suppression shields and a large number of nuclear instrument modules (NIM), high density modules and computer automated measurement and control (CAMAC) system to interface the computer for data processing and data storage have been used. Details are described in the following.

2.6.1 Detectors

In the in-beam measurements in this work γ-rays were detected with two ORTEC n-type coaxial High Purity Germanium (HPGe) detectors. The efficiency of the detectors used were 25% relative to a 7.6 cm x 7.6 cm NaI(Tl) scintillation detector at 25 cm distance. Typically energy resolution of the detectors was 2.6 keV (FWHM) at 1.33 MeV.

In order to reduce the continuum background due to Compton scattered γ rays escaping from the HPGe detector, BGO Compton suppression shields were used with both HPGe detectors in the γγ—coincidence measurements.

These anti Compton shields (ACS) are of axial (symmetric) design employing BGO scintillator (Bi₄Ge₃O₁₂) with small NaI(Tl) scintillator in front (Fig. 2.6). In the front end of the shields NaI(Tl) scintillator is used as active collimator for detection of back scattered γ rays from HPGe detectors, because NaI(Tl) scintillator has very high scintillation efficiency (≈ 3 times of BGO) for these back scattered low energy photons with energies ≤ 250 keV. The γ—ray absorption coefficient of BGO is very large because of high Z (= 83 ) of bismuth and high density (7.13 g/cm³) of the bismuth germanate. High Z scintillators are particularly
desirable for reducing detector volume requirements. The high absorption coefficient for \( \gamma \) rays does not only have a positive influence on the size of the detector but also improves the spatial resolution of a system. Weight and size limitation are important considerations in the design of detectors and hence BGO scintillator is very useful in such design where space is limited and optimum stopping power is required. Eight photomultiplier tubes (PMT) are optically coupled to each BGO shield. The side view of the BGO shield and assembly of eight PMT's are shown in Fig. 2.6. The HPGe detectors were surrounded by the BGO Compton suppression aluminum as shown in picture (Fig. 2.4). The outputs of all the PMT's coupled to BGO are connected together to provide the veto signal for suppression of the Compton background in the HPGe detector. The performance of detectors with ACS shields was tested with standard sources of \(^{60}\text{Co}\) and \(^{137}\text{Cs}\) placed at the position of the target in the reaction chamber. Suppressed and unsuppressed HPGe spectra were recorded and Compton suppression factor and the peak-to-total ratio were calculated. Compton suppression factor defined as the ratio of the unsuppressed to the suppressed spectrum was \( \approx 6 \), and for \(^{60}\text{Co}\) source peak-to-total \((P/T)\) ratio obtained was 15.1 without ACS shield, and it improved by a factor of 4 with ACS shield.

2.6.2 Electronics and Data Acquisition System

The technology of detection of nuclear radiations has made a tremendous advances during past few years. It is noticed in past few years that there has been an increasing complexity and volume of the nuclear data and the information generation in nuclear process due to progress and development in technology of the measuring equipments. In a typical nuclear process, the information is converted into electric pulses with the help of detectors and then various pulse processing techniques are used to extract information about the nuclear process. For example pulse height analysis provides information about the energy of the incident radiation. These signals are then interfaced to the data acquisition system using NIM modules and CAMAC crate, which transfers them to the computer for further analysis and storage. We have used conventional experimental set-up for in-beam \( \gamma \)-ray
FIG. 2.6. BGO Compton Suppression Shield of symmetric type used in the present experiment. The upper parts show the side view of BGO CSS. The lowest part represents a schematic view of HPGe with BGO (NaI) CSS.
measurements details of which are mentioned below.

A. Electronics

The signals from the detectors contain information about both energy as well as the time of interaction of radiation with the detector. The information about the energy dissipated in the detector is contained in the amplitude of the detector pulse whereas the time-information is inherent in the rising part of the pulse. In the HPGe photon detectors, the energy lost by a photon interacting with the detector results in creation of electron-hole pairs. A charge sensitive pre-amplifier built in with detector assembly integrates the charge and provides a voltage pulse whose amplitude is a measure of the energy. Two identical outputs are available from pre-amplifier of each HPGe detector, for energy and time measurement.

The signals from the bismuth germanate (BGO) scintillation detectors were obtained by adding the signals from the anodes of all the photo-multiplier tubes coupled to the scintillator. The photomultiplier pulses thus obtained were used only to derive the timing information because they were used only for the purpose of suppression of Compton background in the HPGe detectors, with BGO scintillator serving as anti-Compton shield.

The electronic setup was configured using the NIM standard and the CAMAC standard modular instrumentation. Most of the electronic modules used in this work are from EG&G ORTEC, designed in accordance with the above standards. The signals from the preamplifiers were transported by low loss cables of 50Ω characteristic impedance to the counting room for further processing. For singles measurements of γ—ray energies and relative intensities, the preamplifier signal was amplified by ORTEC 572 spectroscopy amplifier and its unipolar output with a shaping time of 3μ sec was used.

In the γγ-coincidence experiments both energy and time information was processed as shown in the block diagram of Fig 2.7. For the purpose of timing, the signals from the preamplifiers of the HPGe detectors and the BGO scintillation detectors were amplified and shaped by timing filter amplifiers and fed to the inputs of an Octal Constant Fraction Discriminator (CFD), CF8000. Fast NIM standard logic pulses from the outputs of
FIG. 2.7. Typical block diagram of $\gamma\gamma$-coincidence set-up using HPGe detectors with Anti Compton Shields.

1. HPGe
   - EG&G ORTEC Hyper Pure Germanium Detector
2. BGO ACS
   - Harshaw’s Bismuth germanate Anti compton Shield
3. Amp 572
   - ORTEC Model 572 Linear Amplifier
4. OCT. CF. DISC.
   - ORTEC Model CF 8000 Octal Constant Fraction Discriminator
5. ADC
   - ORTEC AD413A Analog to Digital Converter
6. MCA
   - PC-based ORTEC & OXFORD Multi-Channel Analyzer
7. TAC 567
   - ORTEC Model 567 Time to Amplitude Converter
   - ORTEC Model 416A Gate and Delay Generator
9. TFA 474
   - ORTEC Model 474 Timing Filter Amplifier
10. ns delay 425A
    - ORTEC Model 425A nanosecond delay r
11. Del Amp 427A
    - ORTEC Model 427A microsecond delay amplifier
12. GG8010
    - ORTEC Model GG8010 Octal gate generator
13. CO4020
    - ORTEC Model CO4020 logic unit
the CFD were in turn fed to an octal logic delay unit to adjust the delay as well as the width of the logic pulses. A quad logic module (model C04020) was used to perform the coincidence and anti-coincidence functions as required for the experiments. The logic signals derived from the HPGe and BGO detectors were set such that the output ($X$) of the logic module C04020 appeared only when the HPGe signal (A) was not accompanied by the corresponding BGO signals (B), to achieve Compton suppression (Fig. 2.7). The suppressed fast logic signals from HPGe detectors thus obtained were further delay matched, and the coincidence output of these was used to generate MASTER PULSE for LIST data. Positive TTL outputs of model C04020 corresponding to the Compton suppressed signals of HPGe detectors were used as gates for simultaneous recording of the singles energy spectra of the HPGe detectors. The MASTER pulse for the LIST data and the GATE pulses for the singles were delay matched with respect to the corresponding analog pulses using Gate and Delay Generator modules.

The energy signals from the preamplifiers of the HPGe detectors were amplified by spectroscopy amplifiers, suitably delayed and fed to the analog inputs of the models AD413A CAMAC quad ADC for LIST, and a PC based MCA for simultaneous singles data (Fig. 2.7). In the coincidence experiments, the shaping time of the spectroscopy amplifiers was reduced to 2 μsec to achieve higher event rate. The time distribution of the HPGe detectors was also simultaneously obtained using additional fast NIM logic outputs from the CFD and a time-to-amplitude converter (TAC). The output of the TAC was fed to one of the analog inputs of the CAMAC quad ADC.

B. Data Acquisition System

PC based data acquisition systems were used for acquiring singles spectra, as well as the multiparameter LIST mode data for $\gamma\gamma$-coincidence experiments.

The data for measurements of energies, relative intensities, angular distributions and excitation functions of $\gamma$-rays were acquired in the singles mode using PC based MCA. The $\gamma\gamma$-coincidence information was deduced from the LIST mode data acquired with another
PC based system interfaced to a CAMAC quad ADC through a CAMAC Crate.

The amplitudes of the analog pulses from the spectroscopy amplifiers and time-to-amplitude converter contain the requisite information regarding energy as well as time. The analog-to-digital converter (ADC) measures the maximum amplitude of an analog pulse and converts that value to a digital number. The digital output of the ADC is a proportional representation of the analog amplitude at the ADC input. In the singles mode, the digital outputs for sequentially arriving pulses at the ADC input are fed to a computer and sorted into a histogram. This histogram corresponds to the energy spectrum for singles coming from the spectroscopy amplifier and time spectrum for those coming from the time-to-amplitude converter. In the list mode, several ADC's operate together and the pulse heights of the mutually coincident analog signals received at the inputs of the ADC's are registered at a time by sequential readout of the digital outputs of all the ADC's on the arrival of the corresponding MASTER pulse. This pulse height information is stored in the memory of the computer and subsequently sorted into histograms with gating conditions configured in the software.

Singles spectra for energy spectroscopy were acquired using EG&G ORTEC plug-in ADC Card (Model No. TRUMP-8K-W3) in conjunction with an IBM-compatible personal computer (PC). Conversion gains of 4096 or 8192 channels were used in the experiments. Data acquisition and analysis were carried out using MAESTRO program based on WINDOWS95 operating system from EG&G ORTEC. For the acquisition of LIST data in coincidence experiments, the EG&G ORTEC Model AD413A CAMAC quad 8k ADC was used with CAMAC readout. It is a multiplexed, four input, 13 bit, successive-approximation ADC. Each input is dc-coupled and accepts analog pulses in the linear range from 0 to +10 Volt from the spectroscopy amplifiers or time-to-amplitude converter. The MASTER gate signal from the Electronic Setup (Fig. 2.7) was applied to the common GATE input of the quad ADC (AD413A) for the coincidence operation. The operation and control of the ADC was done via CAMAC using a PC based software. A menu driven, user friendly software, beta release 1.0, developed by the Computer staff of the Variable Energy Cyclotron Centre
(VECC) was used for the on-line acquisition and analysis of LIST data. This program runs on IBM PC with WINDOWS 95 operating system. This software comprises four modules: (i) data acquisition (ii) spectrum generation (iii) one and two dimensional graphic display (iv) a control program to initiate and supervise all these operations. The control of several processes is user defined like number of parameters, size and dimension of the spectrum to be collected, start, halt, stop, preset time for acquisition, writing of the spectra in the Hard Disc of PC, etc.

It was essential to perform some on-line analysis to assure the quality of the acquired data. Three parameters were measured in each event viz. (i) $E_{\gamma_1}$, (ii) $E_{\gamma_2}$, and (iii) $t_{\gamma_1\gamma_2}$ (time interval between $\gamma_1$ and $\gamma_2$) This data was saved in the Hard Disc of the PC in LIST MODE. The energy gated spectra with selected time windows were generated by off-line sorting of the LIST DATA using Beta release 1.0. The sorted spectra were analysed using an off-line analysis program NSCSORT which runs in DOS environment. This program has several in-built features such as multiple peak fitting, choice of parameters for fitting function, energy and efficiency calibration, peak area calculation, choice of multi-order background selection during peak area calculation, error in area etc., which are necessary for analysis of the $\gamma$-ray spectra.

2.7 Singles Measurements

Singles spectra were measured with detector placed at a distance of 25 cm from the target in order to determine the energies and relative intensities of the decaying $\gamma$ rays from $^{125}$I.

2.7.1 Energy Measurements

For the identification of $\gamma$ rays from product nuclei, $\gamma$ ray singles spectra were recorded
with HPGe detectors for a long duration for better statistical accuracy (minimum 10,000 counts are needed in peak area for 1% accuracy [6]). In these energy measurements the detector was placed at an angle of 90° with respect to the beam axis to minimise the effect of Doppler shift. Energy calibration of HPGe detector was done with standard γ energy sources for a wide energy range. Before starting the experiments the calibration spectra were recorded with standard sources $^{57}$Co, $^{60}$Co, $^{133}$Ba and $^{152}$Eu, by mounting them at target position. After the experiment with beam, again calibration spectra were recorded to check any kind of shift in energy and there was but no noticeable shift was observed in the energy spectra. In order to identify background radiation, singles spectra were recorded without beam before the starting and at the end of the measurements. Later on these background spectra were subtracted from those recorded with beam on target after normalizing with the real time of ADC’s. The centroids for all photopeaks of accurately known energies were determined by proper peak fitting [8] with computer program NSCSORT for all γ rays. A calibration function of second degree polynomial was calculated [12,13,16] by the quadratic fit and energy calibration with an accuracy of about 0.1 keV in γ ray energies. After that, off line analysis was carried out for all the spectra and results are reported in the next chapter of the thesis.

### 2.7.2 Intensity Measurements

First of all efficiency calibration spectra are recorded (in energy range ≈ 100 to 1408 keV) for both the detectors with standard sources of $^{133}$Ba and $^{152}$Eu whose γ-ray emission rates are known very precisely, by placing them in same geometry in which the measurements have to be carried out with the target $^{123}$Sb. After peak fitting, proper area was calculated for each of known peaks and efficiency curve was fitted by standard function discussed in Ref. [17]. A relative efficiency curve for one of the HPGe detectors obtained in these measurements is shown in Fig. 2.8.
FIG. 2.8. Relative full energy peak efficiency curve for one of the HPGe detectors in this work.
Intensity measurements were carried out by placing detectors at an angle of 55° w.r.t the beam axis to minimise the effect of anisotropy of the angular distribution of the $\gamma$ rays of different multipolarities.

2.8 Angular Distribution

Angular distribution measurements of $\gamma$ rays emitted from nuclear states produced in nuclear reactions provide a very powerful tool in nuclear spectroscopic studies. Results of these measurements provide vital information regarding multipolarities and multipole mixing ratios of the $\gamma$ rays and spins of the excited states in the nucleus of interest, which is the main objective of these measurements. Experimental results of multipole mixing ratios $'\delta'$ can be compared with the theoretically predicted values of multipole mixing ratios based on various nuclear models, which provide the means for testing the validity of these nuclear models.

2.8.1 Angular Distribution Function

Nuclear orientation is produced either by static or dynamic methods such as optical pumping, radio frequency methods, resonance fluorescence, Coulomb excitations and nuclear reactions etc. [4]. In the nuclear reaction spectroscopy at the usual beam energy, in reactions like ($\alpha$, xn) and (Heavy-Ion, xn) the incoming particle brings in large linear momentum along the beam axis and a large angular momentum aligned in the plane perpendicular to the beam axis and consequent formation of a strongly oriented compound nucleus with respect to the beam axis [5]. The linear and angular momentum of the compound system are well preserved through particle and $\gamma$ decays [18–20]. The neutrons evaporated from compound nucleus system before a particle stable state is reached, carry away small amount of angular momentum, and furthermore the neutrons are emitted in approximately random directions. High energy gamma radiations may be emitted from the hot compound nucleus system, which are mostly E1 transitions and do not results in appreciable deorientation of the first observed state, generally denoted as 'initial' state in the final nucleus. It is,
therefore, reasonable to assume that the initial nuclear state produced in this manner is strongly aligned. The highly aligned initial state gives rise to a cascade of $\gamma$ rays leading finally to the ground state and as a result, each successively lower level is expected to have a lower spin value than that of the preceding state. Angular distribution for a $\gamma$-ray transition $J_i \rightarrow J_f$, where $J$ represents the spin of the nuclear state is usually expressed as [23].

$$W(\theta) = 1 + A_2 P_2(\cos \theta) + A_4 P_4(\cos \theta),$$

(7)

where, $\theta$ is the angle of the detector, $P_2$ and $P_4$ are Legendre polynomials and $A_2$, $A_4$ are the alignment parameters (or anisotropy coefficients) which depend on the degree of spin alignment of the residual state with spin $J_i$.

For the case of complete alignment $A_2$, $A_4$ have maximum values and angular distribution is expressed as

$$W(\theta) = 1 + A_2^{\text{max}} P_2(\cos \theta) + A_4^{\text{max}} P_4(\cos \theta),$$

(8)

The experimentally observed alignment parameters ($A_2$ & $A_4$) are always smaller than those for perfect alignment and it is due to loss of alignment resulting from emission of particles and $\gamma$ rays. Therefore, angular distribution of a transition $J_i \rightarrow J_f$ emitted from a partially aligned state can be expressed in term of attenuated alignment parameters as

$$W(\theta) = \sum_{k=\text{even}} \alpha_k A_k^{\text{max}} P_k(\cos \theta),$$

(9)

where, $k = 0, 2, 4$ and $\alpha_k$ are attenuation coefficients which describe the actually observed orientation in an experiment and defined as $\alpha_k = \frac{A_k^{\text{exp}}}{A_k^{\text{max}}}$; $A_k^{\text{max}}$ are the alignment coefficient for perfect aligned state [26].

The degree of alignment of a state with angular momentum $J$ can be expressed in terms of statistical tensor $\rho_k(J)$ as

$$\rho_k(J) = (2J + 1)^{1/2} \sum_m (-)^{J-m} \langle J m J - m|k0 \rangle P_m(J)$$

(10)

where $\langle J m J - m|k0 \rangle$ is a Clebch-Gordan coefficient and $P_m(J)$ is the population parameter, discussed in the following.
A nuclear state possessing angular momentum \( J \), may have several magnetic substates with different values of \(|m|\) (\( m \) is the projection of angular momentum \( J \) on the beam axis); \(|m| = 0, 1, 2, ..., J\), for integer values of \( J \) and \(|m| = \frac{1}{2}, \frac{3}{2}, ..., J\) for the half integer values of \( J \).

In case of oriented nuclei, the nuclear spins are oriented with respect to a preferred direction, which is conveniently taken as an axis of quantization. The nuclei with spin along this axis and opposed to it are equal in number. The population \( P(m) \) for each pair of magnetic substates corresponding to positive and negative values of a particular \( m \) are equal although the \( P(m) \) values of the pairs of substates are different. The compound nucleus produced by a spinless projectile on a spinless target has a complete plane alignment of \( P(m) \).

J. O. Rasmussen and T. Yamazaki have pointed out [21,23] that there may be many substates distributions which will lead to the same angular distribution. However, it is reasonable to expect Gaussian distribution of substates for the initial state since that state is fed by large no of paths and none of them is dominant [21,22] and same is not true for lower spin states as most of these are fed by higher spin states only. The real distribution of magnetic substates of the initial state is not important as long as initial state corresponds to a fairly good alignment which depends on the process of its formation and the probability of population of substates \( m \) is expressed as [25].

\[
P_m(J) = \frac{\exp \left( -\frac{m^2}{2\sigma^2} \right)}{\sum_{m=-J}^{J} \exp \left( -\frac{m'^2}{2\sigma^2} \right)}
\]

(11)

where, \( \sigma \) is the width parameter for the Gaussian distribution of these states.

For a complete aligned state statistical tensor can be expressed as

\[
B_k(J) \equiv \begin{cases} 
(2J + 1)^{1/2} (-)^J J(J+1) |0\rangle |k0\rangle & \text{for integral spin.} \\
(2J + 1)^{1/2} (-)^{J-1/2} J_{1/2} J - \frac{1}{2} |\rangle |k0\rangle & \text{for half integral spin.}
\end{cases}
\]

and, then in eqn. (9) attenuation coefficients \( \alpha_k(J) \) can be written in terms of \( B_k(J) \) and \( \rho_k(J) \) as
\[ \alpha_k(J_i) = \frac{\rho_k(J_i)}{B_k(J_i)} \]  

and then, angular distribution function \( W(\theta) \) in eqn. (7) can be described with equations (12) and (10). And thereafter, the angular distribution coefficients \( A_k \) can be expressed in terms of the statistical tensor as

\[ A_k(J_i L_i L_2 J_f) = \rho_k(J_i) f_k(J_i L_i L_2 J_i) \]  

where, \( f_k \) are functions of multipoles \( L_1, L_2 \) and the spins \( J_i \) and \( J_f \) of the initial and final states of the transition. The summation over \( k \) is restricted to even values and extends to its maximum value given by

\[ k_{\text{max}} = \min \{ 2J_i, (L_1 + L_2) \} \]  

where \( L_1 \) is the lowest multipole and \( L_2 \) is the next higher multipole. In case of pure multipole transition \( L_1 = L_2 \) and \( k_{\text{max}} \) is then given by \( 2J_i \) or \( 2L_1 \) which ever is minimum. 

The function \( f_k \) can be written in terms of Racah coefficients and the multipole mixing ratio as

\[ f_k(J_i L_1 L_2 J_f) = \frac{1}{1 + \delta^2} \times \left[ F_k(J_f L_1 L_2 J_i) + 2\delta F_k(J_f L_1 L_2 J_i) + \delta^2 F_k(J_f L_1 L_2 J_i) \right] \]  

where,

\[ F_k(J_f L_1 L_2 J_i) = (-)^{J_f - J_i - 1} [(2L_1 + 1)(2L_2 + 1)(2J_i + 1)]^{1/2} \times \langle L_1 L_2 - 1 | k0 \rangle W(J_i L_i L_2; kJ_f) \]  

here \( W(J_i L_i L_2; kJ_f) \) is Racah coefficient and \( \delta \) (mixing ratio) is the ratio of amplitude of mixed multipole transition defined as

\[ \delta \equiv \frac{\langle J_f | L_2 | J_i \rangle}{\langle J_f | L_1 | J_i \rangle} \]  

In case of pure multipole transition \( \delta = 0 \), and \( f_k \) (15) reduced to simple form

40
\[ f_k(J_f L_1 L_1 J_i) = (-)^{I_f - I_i - 1}(2L_1 + 1)(2J_i + 1)^{1/2} \]
\[ \times \langle L_1 L_1 - 1 | k0 \rangle W(J_i J_f L_1 L_1; k J_f) \]  
(18)

From equations (12), (13) and (15), for a state which is partially aligned can be expressed in terms of the attenuation coefficients \( \alpha_k \) as

\[ A_k(J_1 L_1 L_1 J_f) = \alpha_k(J_i) B_k(J_i) f_k(J_1 L_1 L_1 J_i) \]  
(19)

The values of the \( A_k \) coefficients \((k = 2, 4)\) are tabulated by several authors [23,24]. Coefficients \( F_k \) and \( B_k F_k \) also reported in Ref. [24] for \( J \) values up to 26 for integral spin and for \( J \)-values up to \( \frac{51}{2} \) for half integral spins for dipole and quadrupole transitions. Using these tables the value of \( A_k^{\text{max}} \) can be estimated for various transition of pure as well as mixed multipolarity.

The angular distribution coefficients \( A_k \) for partial alignment can be determined using \( A_k^{\text{max}} \) values provided the attenuation coefficients \( \alpha_k \) are evaluated. As mentioned above, values of \( \alpha_k \) depend on the angular momentum \( J \) of the \( \gamma \) emitting state and its distribution over \( m \) substates. With the assumption of Gaussian distribution of the \( m \)-substates, the attenuation coefficients \( \alpha_k \) have been tabulated by Der. Mateosian and Sunyar [24] for \( k = 2, 4 \), for integral and half integral values of \( J \) up to 26 and \( \frac{51}{2} \) respectively and for \( \sigma / J \) values ranging from 0.1 to 0.2.

2.8.2 Angular Distribution of Gamma-rays

The \( \gamma \) ray angular distributions have been studied by in-beam \( \gamma \) ray spectroscopy in the fusion-evaporation reaction \( ^{123}\text{Sb}(\alpha, 2n \gamma)^{125}\text{I} \), with a beam energy of 30 MeV. The \( \gamma \) ray angular distributions were measured in singles at five angles 30°, 45°, 60°, 75° and 90° with respect to beam with two HPGe detectors (details are mentioned earlier) placed at 25 cm from the target. One HPGe was used as a movable detector for measuring angular distribution and the other HPGe detector served as a monitor and kept on a fixed position during all these measurements. The data were normalized using the monitor detector which
was placed in fixed geometry at an angle -55° with respect to beam direction.

2.8.3 Process of Analysis

The angular distribution coefficients were extracted by performing a least square fit to the data at five angles (i.e. \( W(\theta)_{\text{expt}} \) using equation (7)). The experimental angular distribution coefficients were compared with the expected values of these coefficients evaluated using \( A_k^{\text{max}} \) and \( \alpha_k \) values obtained from the tables from Ref. [23]. The values of \( A_k^{\text{max}} \) were multiplied with \( \alpha_k \) in order to obtain the theoretical \( W(\theta) \) i.e. \( W(\theta)_{\text{th}} \). For each transition with all possible spin sequences the most likely mixing ratio and value of \( \sigma \) are evaluated with function \( \chi^2(\delta) \) from the following relation

\[
\chi^2 = \frac{1}{F} \sum \left| \frac{W_{\text{th}}(\theta_i, J_i, J_f, \delta) - W_{\text{expt}}(\theta_i)}{\Delta W_{\text{expt}}(\theta_i)} \right|^2
\]

where \( W_{\text{th}}(\theta_i) \) is the theoretical angular distribution at an angle \( \theta_i \) and \( W_{\text{expt}}(\theta_i) \) is experimental distribution with standard deviation \( \Delta W_{\text{expt}}(\theta_i) \). \( F \) is the number of degrees of freedom. Chi-square is calculated for different values of mixing ratio (\( \delta \)) and quantities \( \sigma/I \), and minimum of \( \chi^2 \) is searched to obtain the best fit.

2.8.4 Statistical Concept of Chi-square Analysis

The concept of least squares fit is built on the hypothesis that the optimum description of a set of data is one which minimizes the weighted sum of squares of deviations of the data \( x_i \) from the fitting function \( f(x_i) \). This weighted sum is characterized by the variance of the fit \( s^2 \), which is an estimate of the variance of the data \( \sigma^2 \). In testing a theoretical hypothesis against \( n \) number of experimental measurements say for example the intensity of a \( \gamma \)-ray, \( W_{\text{expt}}(\theta) \) the theoretical predictions \( W_{\text{th}}(\theta) \) for each experimental data point is used to compute by \( s^2 \)

\[
s^2 = \sum_{i=1}^{n} \left[ \frac{W_{\text{expt}}(\theta_i) - W_{\text{th}}(\theta_i)}{\sigma(\theta_i)} \right]^2
\]

The variance of the fit \( s^2 \) is also characterized by the statistic \( \chi^2 \) and theory can be tested by comparing \( s^2 \) with appropriate confidence levels of \( \chi^2 \). For example comparison
of $s^2$ with the 0.1% confidence levels results in a true theory being rejected in 0.1% of the considered cases. A very large value of $s^2$ generally indicates a false theory.

2.8.5 Error in Mixing Ratio

There is a probability distribution $P(x_i)$ for each measurable quantity $x_i$ which is characterized by mean value $\mu(x)$ (the measured experimental value) and the variance $\sigma^2(x)$. The Gaussian distribution is most important probability distribution for use in statistical analysis of the experimental data [8,28] and for this case the error, (i.e standard deviation) $\Delta x$ is equal to $\sigma$ has the meaning that there is a 32% chance that the experimentally observed value $\mu(x)$ differs from the true value by more than $\Delta x$. The estimate of the error on the constant value of a parameter which has been determined by fitting procedure should correspond to the standard deviation.

Spin hypotheses leading to $\chi^2$ distributions lying above the 0.1% probability limit were rejected [25]. The multipole mixing ratios $\delta$ for transitions of mixed multipolarities were determined from the minimum $\chi^2$ in the $\chi^2$ vs arctan($\delta$) plots. The errors in the values of $\delta$ were taken at 1% probability limit [25].

2.9 Coincidence Measurements

$\gamma\gamma$-coincidence spectroscopy is an experimental technique of considerable importance to the construction of level scheme. These measurements are required for isotopic identification by establishing a connection between cascade $\gamma$-rays and those known from $\beta$-decay measurements. Level scheme of a nucleus is established on the basis of coincidence relations between decaying $\gamma$ rays from its bound states. The procedure for determining the coincidence relation in the $\gamma$ rays decaying from the product nuclei is based on coincidence methods [2,3,9], whereby, two or more $\gamma$ rays emitted in one nuclear event, within the resolving time of electronic unit are recorded. The order of energy levels in the level scheme are fixed by intensity considerations of the coincidence $\gamma$-rays (i.e $\gamma$-ray cascade). Generally, in a level scheme many sequences of levels are possible depending upon the internal configuration of the nucleus, and therefore, several $\gamma$-cascades are usually observed in a nucleus.
Fig. 2.9 Typical $\gamma\gamma$ time spectrum collected using two HPGe detectors in the $^{123}\text{Sb}(\alpha, 2\gamma)^{125}\text{I}$ reaction at 30 MeV. Small asymmetry observed is due to slow rise time pulses in one of the detectors.
In coincidence measurements two HPGe detectors were placed at 90° w.r.t the beam axis, at a distance of 10 cm from the target. We have avoided the exact 180° angle between the two detector to reduce the possibility of detecting annihilation γ rays. Reliable efficiency (Fig. 2.8) and energy calibration curves were determined before starting the experiment, with standard sources as used in case of singles measurements. Approximately $10^6$ coincidence events were stored on a hard disc of a PC in list-mode. Various energy and time spectra were projected for various gate settings by off-line sorting of the LIST data. A typical time spectrum projected with integral γ-ray spectra shows the prominent $\gamma\gamma$ prompt peak (FWHM = 20 ns) presented in Fig. 2.9. Details about experimental setup and electronics have been given earlier. The geometrical arrangement of the experimental setup for coincidence measurement is shown in picture presented in Fig. 2.4.

2.10 Excitation Function Measurements

Decay process of a γ-ray transition from initial state $J_i$ to final state $J_f$ is well understood and has a well establish physical theory [10]. In general, it is the spin $J_i$ of the initial state which is unknown, and usually determined by γ-ray angular distribution measurements as discussed above. The principle of the experiments for the angular distribution of γ-ray is that if spin $J_f$ of the final state and mixing ratio $\delta$ of the populating transition are known, than the spin of the initial state $J_i$ may be determined. In general several spin choices may be consistent with the data obtained from angular distribution measurements and it becomes difficult to predict the correct spin for the initial state and therefore, different types of experiments are required to resolve these ambiguities in spin assignment. The relative excitation function measurements of the decaying γ rays are very useful tools used in resolving these ambiguities in spin assignment.

The excitation energy $E_x$ for a compound nucleus produced by alpha particle bombardment is given as

$$E_x = E_{cm} + Q_{fusion}$$  \hspace{1cm} (22)
where, $Q_{\text{fusion}}$ denotes the $Q$-value for complete fusion and $E_{\text{cm}}$ is the energy in centre-of-mass system. The average loss in the excitation energy of the compound nucleus by every neutron evaporation is about 10 to 14 MeV and average excitation energy $E_x$ of the residual nucleus is about 5 MeV. A proper choice of $E_\alpha$ for a given reaction leads mainly to a particular reaction channel ($\alpha, xn$) as described earlier in section. Increase of the $\alpha$-particle energy results is an increase of the angular momentum which is brought into the compound nucleus system (equation 2). The angular momentum changes due to neutron evaporation are negligible. This favours a relatively larger population of high-spin states at higher $\alpha$-particle energies as the neutron evaporation does not influence the angular momentum distribution very much. Thus dependence of the $\gamma$-ray intensity on the projectile energy is used to evaluate the spin of the residual state.

The intensities of the $\gamma$ rays from high spin states increase more rapidly than those from low spin states as the incident alpha particle energy increases. The slope of the curve giving the $\gamma$-ray intensity of a given line as a function of the $\alpha$-particle energy is useful in limiting the spin value of the level from which the $\gamma$-line originates. Following Taras and Haas [25], who have reviewed the technique of making spin assignments, it can be stated that if slopes are clearly separated then each successively higher member of a cascade must have the spin $J_i \geq J_F + 1$ but if the separation is not clear then possible spin values of $J_i \geq J_F$ must be considered.

In the present study of excitation functions the detectors were placed at an angle of 55° with respect to the beam direction in order to avoid Doppler shifts. Singles $\gamma$-ray spectra were recorded at four different beam energies in energy range 25 to 33 MeV. Corresponding relative excitation function plots ($\frac{I_j(E)}{I_j(\text{ref})}$ Vs $E_\alpha$) for different sequences of transitions are given in chapter III. These were used to supplement the results of angular distribution measurements and to establish spin assignments for levels in $^{125}$I.
REFERENCES


