SPECTROSCOPIC STUDY OF THE HIGH-SPIN STATES IN ^{72}Ge

BY

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Declaration

I **Faston Chilenga** hereby declare that this thesis is my work, and it has never been submitted to any other University for the award of a degree before. All materials used in this work have been cited and acknowledged.

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This thesis was supervised and approved by;

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List of Acronyms

^{72}Ge Germanium-72

DCO Directional Correlation from Oriented states

A_p Linear Polarisation Anisotropy

NSM Nuclear Shell Model

HPGe High-purity Germanium detectors

LDM Liquid drop Model

PRM Particle Rotor Model

DAL Deformation Aligned band

RAL Rotational Aligned band

E1 Electric dipole moments

E2 Electric quadrupole moments

M1 Magnetic dipole moments

AFRODITE AFRican Omnipurpose Detector for Innovative Techniques and Experiments

LEPS Low Energy Photons Spectrometer detector

ADC Analog to Digital Converter

TDC Time to Digital Converter

CAMAC Computer Automated Measurement and Control

NIM Standard Nuclear Instrumentation Module

iThemba LABS iThemba Laboratories for Accelerator Based Sciences

VME Versa Module Eurocard bus

Abstract

High spin states of ^{72}Ge were investigated using the data that was collected at iThemba LABS in Western Cape Republic of South Africa. A softaware called RadWare was used to analyse the data that was collected. 1519 keV was used as a starting excitation energy to construct the level scheme of ^{72}Ge. 1056 keV was used to link Band 3 that was constructed to Band 1 of the level scheme. The R_{DCO} was calculated and the obtained average values of R_{DCO} for E2 and E1 transitions were 0.9 and 1.2 respectively. These values were similar to the theoretical predictions. The Linear polarisation A_p was also calculated in order to assign the spin and parity. The newly assigned spin and parity are: For 580 keV, $I^\pi = 6^+$, 760 keV, $I^\pi = 8^-$, 997 keV, $I^\pi = 10^-$, and finally, 1120 keV, $I^\pi = 12^+$.

Key words: ^{72}Ge, Gating, R_{DCO}, Level scheme, Linear polarisation, RadWare.

Chapter 1

INTRODUCTION

Experimental studies of nuclear structure in exotic isotopes continue to play an important role in todays nuclear physics. Among the isotopes there comes Germanium (^{72}Ge). This is a very important isotope when it comes to everyday applications. It is among the five naturally occurring isotopes.

High-purity germanium detectors (HPGe) are the best solution for exact γ and X-ray spectroscopy. When you try to compare with other detectors like silicon, germanium is much more efficient for radiation detection, because its atomic number is much higher than silicon. The other reason is that it has lower average energy necessary to create an electron-hole pair, which is 3.6 eV for silicon and 2.9 eV for germanium[1]. Due to its higher atomic number, Ge has a much lager linear attenuation coefficient, which leads to a shorter mean free path. Moreover silicon detectors cannot be thicker than a few millimeters, while germanium can have a depleted, sensitive thickness of centimeters, and therefore can be used as a total absorption detector for γ-rays up to few MeV. In γ-spectroscopy, germanium is preferred due to its atomic number being much higher than silicon and which increases the probability of γ-ray interaction. This also provides the latter a better resolution in energy.

The spin J is an intrinsic angular momentum in the units of f_j that are associated with a particle whereby the square of it is $J(J+1)$ [2]. The spin consists of the vector as a sum of the orbital angular momentum and the intrinsic spins of its constituents. Parity is the intrinsic characteristics of the particle state under the transposition of spatial coordinates. This operation have a eigenvalue of ± 1[2]. This concept have some profound aspects and its simple operational understanding is enough for its experimental determination. The parity of a system consists of the product of the parities of its constituents. This includes the parity of orbital motion given by $(-1)^l$, as well as the intrinsic parities of the subsystems.

This work was designed primarily to construct a level scheme of band three of ^{72}Ge using 1519 keV as a starting excitation energy and 1056 keV as linkage energy between Band 3 and other Bands. Then later assign spin and parity to the excited states using the matrix data that was collected at iThemba LABS in the republic of south Africa. A spectroscopic view was made for each energy discovered by coming up with its spectrum and then later calculating its R_{DCO} and its linear polarisation (Anisotropy) in order to assign the spin and parity.

This thesis is organised as follows: Chapter 2 presents a theoretical spectroscopy of the nuclear physics behind the nucleus of ^{72}Ge. Chapter 3 presents the details of the experimental tools and techniques used in γ-spectroscopy. Chapter 4 describes the experiment and the sorting of raw data into analysable data. Chapter 5, which is the main part of this thesis, presents the results of the analysis and discusses the construction of a level scheme, and the assignment of spin and parity to new levels. Finally, Chapter 6 concludes the thesis and provides recommendations based on how the whole project has been done.

Chapter 2

THEORY

This part presents the physics background, and gives some theoretical predictions for ^{72}Ge nucleus. Three out of the four basic forces are active in the atomic nuclei. These are the strong nuclear force, which is the attractive short range force that keeps the nucleons together, repulsive Coulomb force which acts between charged particles, protons and the weak force which is responsible for the β decay. The strong and weak nuclear forces are nucleon-nucleon forces and very complicated. With such a complicated nucleon-nucleon potential, the meaningful solution for the many body problem is a difficult task. Therefore many phenomenological models have been developed to describe the nucleus. Each model works well in different type of nuclear structures, or different nucleus.

These models are classified in two groups as the independent particle or single particle models and collective models[3]. Collective models take nuclei as a whole without considering the individual nucleons. The most commonly used collective model is Liquid Drop Model (LDM) which is successful in explaining the motion of nuclei, like rotations and vibrations, where many of the nucleons contribute. Single particle models take nucleons as individual particles in the mean field potential. The most popular single particle model is Nuclear Shell Model (NSM). NSM has two different solutions for spherical nucleus and deformed nucleus. Spherical Shell model works well in spherical nuclei and describes correctly the magic numbers. However for deformed, non-spherical nucleus, NSM needs a modification for describing nuclear properties correctly, so Deformed Shell Model or Nilsson model works-well in this type of nuclei.

This work describes the Nuclear shell model and its properties, and then the liquid drop model which focuses much on the nuclear rotations and vibrations.

2.1 The Nuclear Shell Model

Nuclear shell model predicts that nucleons, protons and neutrons, move freely in orbits in mean field potential without interaction. First information of shell structure comes from magic numbers. Magic numbers for nuclear physics are 2, 8, 20, 28, 50, 82, and 126 for both protons and neutrons. Magic nucleus has several common features such as, nucleus turns out to be especially stable, it has large total binding energy than the neighboring nuclei, single particle separation energy is larger than the neighboring nuclei, lowest excitation energy is higher than the normal ones, and the number of isotopes and isotones are higher than the other stable nuclei. This common features of magic numbers are main confirmation of shell structure in nuclei. For shell model, mean field potential has two main characteristics which are potential should be relatively constant inside the heavy nuclei and potential should go to zero outside the nuclear surface[2].

There are three successful spherical symmetric potential that can be used in shell model. First one is Woods-Saxon potential, equation 2.1, the potential depth V_0 is around 50 MeV, radius of nuclei is $R \approx 1.1fmA^{\frac{1}{3}}$, and surface thickness $a \approx 0.5fm$. Although this potential gives shell structure it has a weakness that it cannot be used in obtaining analytical forms of wave function, it is used to determine the wave function numerically. Second potential is square well potential, equation 2.2, and third potential is harmonic oscillator potential equation 2.3. These potentials have several disadvantages such as, they do not obey the nuclear limits, and they do not have scattering states. But they have analytical solutions and like all other potentials this give the first three magic numbers correctly [2].

$$V(r) = \frac{-V_0}{1 + EXP[(r-R)/a]} \tag{2.1}$$

$$V(r) = -V_0....(r \leq R) \tag{2.2}$$

$$V(r) = \frac{1}{2}m^2\omega^2r^2 \tag{2.3}$$

2.1.1 The Shell model description for Germanium isotope

Ge isotopes exhibit a complex structure in their low energy spectra. The first excited 0_2^+ state shows an irregular behavior as function of the neutron number, as can be seen in Fig. 2.1. From ^{70}Ge to ^{72}Ge the 0_2^+ level drops in energy, rising from ^{74}Ge onwards[4]. In the semi-magic isotope ^{72}Ge which has N = 40, the 0_2^+ is below than the 2_1^+ It has been interpreted in terms of configuration mixing of regular and intruder structures, leading to a shape phase transition from oblate to spherical to prolate deformed.

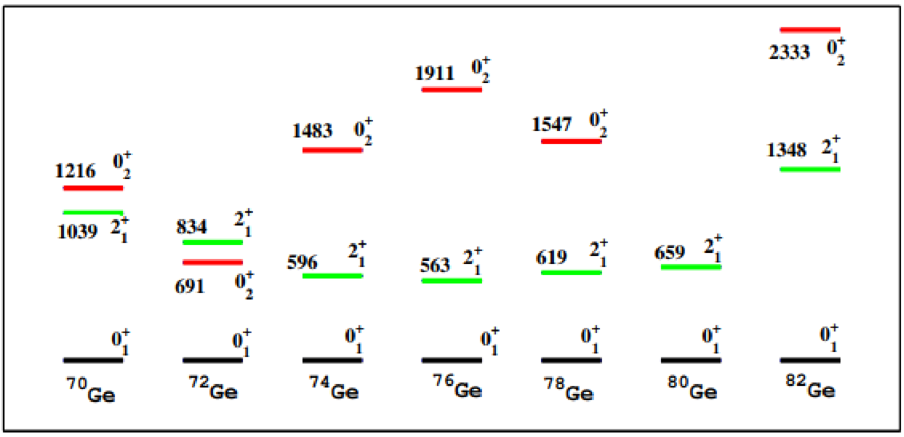

Figure 2.1: Low-lying systematics of germanium isotopes

2.2 Nuclear Properties

In order to understand the structure of the ground state and long-lived isomeric states of a nucleus, a variety of observables are needed that is spin, electromagnetic moments, size and deformation, binding energy and decay properties. The family of laser spectroscopy techniques offers a reliable probe and can determine the spin, electromagnetic moments, size and deformation of a nucleus, as it has been done in this thesis. These observables are described below.

2.2.1 Nuclear spin

The nucleons of a nucleus sit on different orbits that are characterised by an orbital angular momentum, while every nucleon has an intrinsic spin 1/2. The coupling of these two leads to the total angular momentum of a nucleon: $\mathrm{j} = \mathrm{l} \pm 1/2$. Coupling the total angular momenta of each nucleon results in the total angular momentum of the nucleus, namely the nuclear spin I.

In a nucleus with an even number of protons and neutrons, all its nucleons in the ground state are paired, leading to a nuclear spin I = 0. When there is only one unpaired nucleon in the valence space, the nuclear spin is solely determined by the total angular momentum of this single nucleon, provided that the isotope appears close to a semi-magic isotopic/isotonic chain and the single nucleon behaves in the context of the independent particle shell model. For isotopes with two valence nucleons, one proton and one neutron, the nucleon spins are coupling together to form a total angular momentum with values between $I = J_1 + J_2, J_1 + J_2 - 1, ..., |J_1 - J_2 - 1|, |J_1 - J_2|$[2].

Every nuclear spin state is also characterised by a parity, which is determined by the parity of the orbits occupied by the unpaired valence nucleons. However, parity is not an observable. It is inferred in a model-dependent way based on the calculated configuration of a nuclear state.

2.2.2 Nuclear Magnetic dipole moments

The motion of the nucleons inside a nucleus gives rise to the magnetic moment of the nucleus. The magnetic moment is a sensitive probe of the orbital occupation of the valence nucleons. There are two different contributions to the magnetic moment, the orbital movement of the charged nucleons and the intrinsic moment of all the nucleons. Thus, the magnetic moment operator can be written as [5]

$$\mu = \sum_{i=1}^{z} g_l^{\pi} l_i + \sum_{i=1}^{z} g_l^{\pi} s_i \tag{2.4}$$

where s_i is the orbital angular momentum and s_i is the intrinsic spin operator of the ith, nucleon. The factors gl and gs are the orbital and spin gyro magnetic factors respectively, which are different for protons and neutrons. The single particle magnetic moment for a nucleon in an orbital j can then be derived as[5]:

$$\mu(j = l + 1/2) = jg_l + \frac{g_s - g_l}{2} \tag{2.5}$$

$$\mu(j = l + 1/2) = jg_l + \frac{g_s - g_l}{2}\frac{j}{j+1} \tag{2.6}$$

2.2.3 Nuclear Electric quadrupole moments

The distribution of the protons and neutrons inside a nucleus give rise to the quadrupole moment of the nucleus. The quadrupole moment is a probe of the deformation of a nucleus. The quadrupole moment operator is[5]:

$$Q_z = \sum_i \frac{e_i}{e}(3z_i^2 - r_i^2) \tag{2.7}$$

where $r^2 = x^2 + y^2 + z^2$ and e_i the charge of a nucleon. Expressing the quadrupole moment in spherical coordinates as a rank 2 yields:

$$Q_2^0 = \sqrt{\frac{16\pi}{2}} \sum_i \frac{e_i}{e} r_i^2 Y_2^0(\theta_i, \psi_i) \tag{2.8}$$

The expectation value of the Q_2^0 in the nuclear state M = I is the spectroscopic quadrupole moment Q_s.

Chapter 3

EXPERIMENT AND EXPERIMENTAL TECHNIQUES

This chapter describes the experimental tools and techniques that have been used in this research project. It also describes the experiment that was done at iThemba LABS to collect the data. All the details that were used in an experiment have been explained.

3.1 The experimental methods

AFRODITE array was used to collect the matrix data in the laboratory. This array is a medium size array that is capable of detecting both high and low energy photons with a high efficiency by combining large volume escape suppressed detectors (CLOVERS) and Low Energy Photon Spectrometer (LEPS) detectors. The small pipe from left is a spectrum in which gamma ray coincidence of ^{72}Ge passes once struck. The four chambers shown are the detectors of the gamma ray coincidence, and that is where the gamma ray coincidence matrices are being collected. The matrices are taken as data to the RadWare software for analysis[6]. The diagram below shows the AFRODITE array.

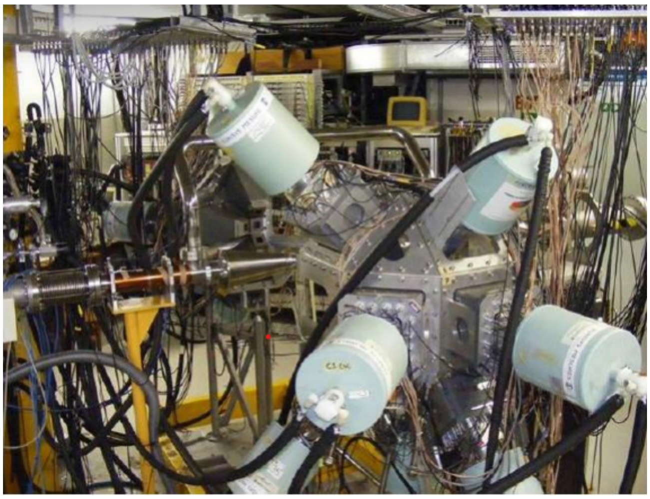

Figure 3.1: The AFRODITE array

The clover detectors consist of four n-type high power Ge crystals packed together in a common cryostat. Each element of a clover detector has its own pre-amplifier which allows energies deposited in more than one element due to Compton scattering to be added. The primary advantage of using clover detectors over single crystal detectors, is the increased photo-peak sensitivity in the add-back mode for γ-rays above 1 MeV[7]. In addition, the clover detectors are used as the four-fold Compton polarimeter to allow the measurements of the linear polarisation of the γ-rays.

Germanium detectors are semiconductor diodes having a p-n structure in which the intrinsic region is sensitive to ionising radiation, such as γ-rays. The device is mounted under reverse bias to increase the depletion region of diodes. When a photon interacts with the material within the depleted volume of a detector, electron hole pairs are produced. These charge carriers are then converted to a voltage pulse. The number of carriers is proportional to the γ-ray energy and the height of the voltage pulse. Therefore, the pulse height is proportional to the γ-ray energy. The voltage pulses are recorded and saved[7].

RadWare is a software that was used to analyse the matrix data. It is a powerful, user-friendly software package for interactive graphical analysis of gamma-ray coincidence data. It is used by many physicists around the world as they study the structure of the atomic nucleus and analyze the results of their experiments. This project shall use three commonly used Radware programs which include; **gf3**, and **escl8r**[6].

GF3 is a general spectrum manipulation, fitting and analysis program for one dimension spectra. It is a least-squares peak-fitting program designed primarily for use in analyzing gamma-ray spectra from Germanium detectors[6]. However, it can also be used to analyze other types of spectra, such as those from Si(Li) electron detectors and silicon surface barrier detectors, and under some circumstances may even be used to extract lifetimes from time spectra.

There are three different versions of gf3 included in the RadWare package, but they differ only in the user interface. The standard command-only version is called gf3, while gf3x is a version that also incorporates a very simple X-windows menu system. xmgf3 is a Motif-GUI version that is significantly more user-friendly, at the cost of some speed. This documentation describes the typed commands, and so is intended primarily for the standard command-only version, but of course the functionality of the commands does not depend on the user interface in any way[6].

ESCL8R is an interactive program for graphics-based analysis of gamma-gamma data for the deduction of level schemes. It allows fast and easy inspection of the gamma-gamma matrix, making use of parameterized values of the peak-shapes, peak-widths, detector efficiency and energy calibrations. It uses the two-dimensional background-subtraction algorithm. It also displays a proposed level scheme which is modified continually as the analysis proceeds. This level scheme is used to calculate expected results for comparison with the observed experimental data. Least-squares fits to the matrix may be performed to extract the optimum energies and intensities of transitions in the level scheme, with up to 500 parameters fitted simultaneously[6].

3.2 The experiment

High spin states in ^{72}Ge were set at a beam energy of 30 MeV[1]. At an incident energy of 30 MeV the dominant residual nuclei were found to be ^{72}Ge representing 93% and ^{70}Ge representing 3%, where the figures in parentheses denote an approximate percentage of the total cross-section. The data also included γ-rays emitted following the Coulomb excitation of ^{70}Zn represnting 4%.

Coincident γ-rays were measured with the AFRODITE spectrometer array comprising nine Compton suppressed Clover detectors and five four-fold segmented Low-Energy Photon Spectrometers (LEPS). The Clovers were positioned in two rings, at 90$\circ$ relative to the beam direction (five Clovers) and at 135 (four Clovers). Two LEPS were placed at 90 and three at 45[1]. The master event trigger demanded a two or higher fold coincidence between any of the detectors, in coincidence with the radio-frequency signal from the cyclotron. The coincidence time window was set to 150 ns. Under these conditions, and during some 50 hours of beam time, a data set of $\approx$868 million coincident events was acquired.

3.3 Construction of γ-γ matrices

Performing gain matching coefficients from the gain-drift and Doppler shift corrections that were available, helped so much to sort data into an $E_{\gamma1}$-$E_{\gamma2}$ matrices. Two γ-rays $E_{\gamma1}$ and $E_{\gamma2}$ are said to be in coincidence if they are detected within the coincidence time frame. The γ-rays detected in coincidence plays a big role in a coincidence activity. In this project the $E_{\gamma1}$-$E_{\gamma2}$ coincident matrix consisted of a two dimensional matrix of γ-γ events with $E_{\gamma1}$ on the x and y-axes and coincidence counts on the z-axis[7].

Assuming you have a coincident event of three γ-rays, e.g $E_{\gamma1}$, $E_{\gamma2}$ and $E_{\gamma3}$ The possible coincidence pairs one can form are: $(E_{\gamma1},\ E_{\gamma2})$, $(E_{\gamma2},\ E_{\gamma1})$, $(E_{\gamma1},\ E_{\gamma3})$, $(E_{\gamma3},\ E_{\gamma1})$, $(E_{\gamma2},\ E_{\gamma3})$ and $(E_{\gamma3},\ E_{\gamma2})$[7].

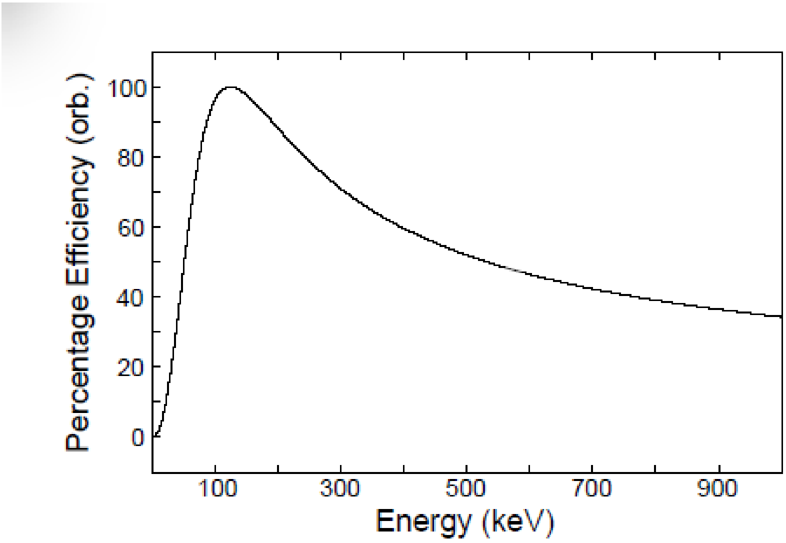

Figure 3.2: The normalised efficiency of the clover detectors as function of γ-ray energy.

The coincidence pairs are represented in a matrix, by coordinates $(x; y; z)$ and the pair $(E_{\gamma1},\ E_{\gamma2})$ corresponds to coordinates $(E_{\gamma1},\ E_{\gamma2},\ Z_{\gamma12})$ while the pair $(E_{\gamma2},\ E_{\gamma1})$ correspond to coordinates $(E_{\gamma2},\ E_{\gamma1},\ Z_{\gamma21}$[7].The coordinate Z_{12} represents the number of instances the pair $(E_{\gamma1},\ E_{\gamma2})$ is found in the data. Similarly Z_{21} represents the number of situations the pair $(E_{\gamma2},\ E_{\gamma1})$ is detected in the data. If the matrix is symmetric, that is $Z_{12} = Z_{21}$, for every instance a coincidence pair $(E_{\gamma1},\ E_{\gamma2})$ is detected, the coincidence count coordinate z,is incremented.

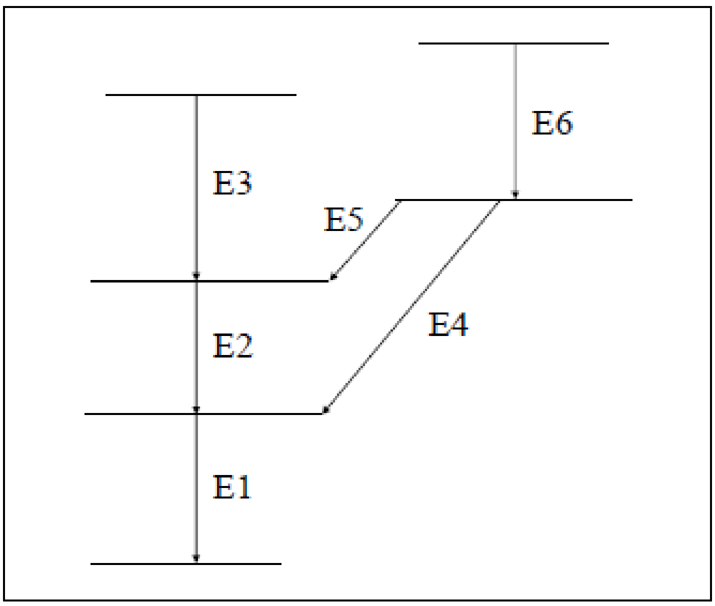

Figure 3.3: A simple level scheme of 5 transitions.

In general the matrix is constructed by incrementing the corresponding coincidence counts, for example, Z_{12}, for a specific pair each time this pair is found in the data. In this experiment data were sorted into two matrices. The first one was a symmetric γ-coincidence matrix which was used to construct the level scheme. The second was an asymmetric directional correlation (DCO) matrix, used in assigning spin and parity to nuclear states.

3.4 Gating

Gating is a way of identifying whether a γ-ray is in coincidence with other γ-rays. Gating on a particular γ-ray energy, only γ-rays that are in coincidence with the gated one are being displayed. This refers to the slicing of a region around a γ-ray energy E_γ on the x or y axis in a E_γ-E_γ matrix and projecting all the γ-rays in coincidence with the γ-ray with energy E into a one-dimensional spectrum.

By working on the different gates on different γ-ray energies, the level scheme of a nucleus can be constructed. Consider a simple level scheme shown in figure 3.3. If a gate is set on the transition $E1$, all the other γ-rays in this level scheme are seen in the spectrum because they are in coincidence, which means they belong to the same decay path as the $E1$ transition. However if the gate is set on the transition $E2$, then $E3$, $E5$ and $E6$ will be seen but $E4$ will not be seen in the spectrum because it is not in coincidence with $E2$ as they do not belong to the same decay path. With such gating analysis, one can locate and place the γ-rays and build a level scheme.

3.5 Construction of the Level Scheme

The construction of the level scheme is done from the analysis of the coincidence relationships between the detected γ-rays by means of gating with the use of the ESCL8R software program[6]. Usually one starts with a few already-known transitions, and by gating on these, γ-rays in coincidence are observed in the spectrum and are placed according to the coincidence relation between them. Thus a level scheme can be built. In this work the previously known level scheme of ^{72}Ge was taken from [8] and is shown in figure 4.1 With γ-coincidence analysis several new transitions were placed in the ^{72}Ge level scheme which are discussed in the chapter 5.

3.6 DCO ratios

The Directional Correlation from Orientated states (DCO) method can be used to determine the multipolarity of γ-ray decays and to infer the spin of states in a level scheme. The DCO ratio measurement is similar to angular distribution measurements and is often used with small arrays or when γ-rays with small intensities are measured. To determine the multipolarities of the γ-ray transitions in ^{72}Ge, the coincident events were sorted into an asymmetric matrices with data from the 90^0 detectors on one axis and 135^0 detectors on the other axis. In this work, the R_{DCO} were measured by gating on known multipolarity (E2) transitions and measuring the ratios of coincidence intensity I at two angles 90^0 and 135^0 according to the expression [9]:

$$R_{DCO} = \frac{W(135^0, 90^0)}{W(90^0, 135^0)} \tag{3.1}$$

where $W(135^0; 90^0)$ is an angular correlation function and denotes the intensity of a γ-ray detected at 135^0 when a gate is set on an E2 γ-ray detected by a detector at 90^0 with respect to the beam direction.

According to the theory, when a gate is set on a known stretched $E2$ transition, the R_{DCO} ranges from 0.6 to 1.0 values are observed for the known $E2$ and $E1$ transitions respectively, and when a gate is set on a known stretched $E1$ transition, the R_{DCO} values ranging from 1.0 to 1.6 values are found for known $E2$ and $E1$ transitions respectively. For this work,the R_{DCO} values for newly observed transitions were measured and compared with the theoretical predictions that were calculated using the code *DCOplot* as described in [10] for the purpose of determining the multipolarity of the transitions.

3.7 Linear Poralisation measurement of γ-rays

The R_{DCO} values do not produce a difference between electric and magnetic transitions. Hence, it was necessary to perform the linear polarization measurements to deduce the electric or magnetic character of the transition to allow the assignment of spin and parity to levels. At iThemba labs where data was collected, clover detectors situated perpendicular to the beam direction were used as Compton polarimeters to scatter the incident γ-rays. Two $E_\gamma - E_\gamma$ matrices were constructed. One of it contained γ-rays scattered perpendicular to the beam direction in coincidence with any detected γ-ray, and the other one had γ-rays scattered parallel to the beam direction in coincidence with any detected γ-ray. The linear polarization anisotropy P, is defined as

$$P = \frac{A}{Q} \tag{3.2}$$

A is determined on the basis of the experimental asymmetry between vertically and horizontally scattered γ-rays given by [9]

$$A_p = \frac{aN_V - N_H}{aN_V + N_H} \tag{3.3}$$

where N_V and N_H are the number of γ-rays scattered in vertical and horizontal directions respectively and a is the polarisation sensitivity of the detector crystals, typically very close to 1. It is noted that, when the anisotropy measurement is negative, then the parity on that particular excited energy is negative. If the anisotropy is positive, then the parity of that excited state is also positive.

Q is the polarization sensitivity for clover detectors measured [9] as

$$Q = Q_0[0.31 + 7x10^{-5}E_\gamma] \tag{3.4}$$

where E is in keV and Q_0 is the polarization sensitivity for an ideal polarimeter given by

$$Q_0 = \frac{1+\alpha}{1+\alpha+\alpha^2} \tag{3.5}$$

where $\alpha = \frac{E_\gamma keV}{511}$

The linear polarization measurements do not depend on the multipolarity of gating transition. This is the reason why it did not matter if a gate was set on a quadrupole or a dipole transition. The A_p measured values were compared to the calculated A_p values using the code POLAR [11] when assigning spin and parity to the levels. The code POLAR is a program designed to predict the A_p value of a transition depending on its multipolarity and its character. This is why the transitions with positive A_p values were interpreted as stretched electric or unstretched magnetic, and those with negative A_p values were interpreted as stretched magnetic or unstretched electric transitions.

Chapter 4

RESULTS AND DISCUSSION

In this chapter, the outcomes of the objectives have been outlined and discussed. The placement of gamma energies has been confirmed through energy spectrum. Other new γ-rays have been placed in the level scheme. The chapter also discusses the spin and parity assignment from levels, the DCO ratio and polarization measurements of γ-transitions.

4.1 The Level Scheme

The figure below gives a spectroscopic view of a Band 3 of ^{72}Ge level scheme plus other Bands that were done by other researchers. After the level scheme, a discussion and an analysis is made based on the results of the constructed level scheme.

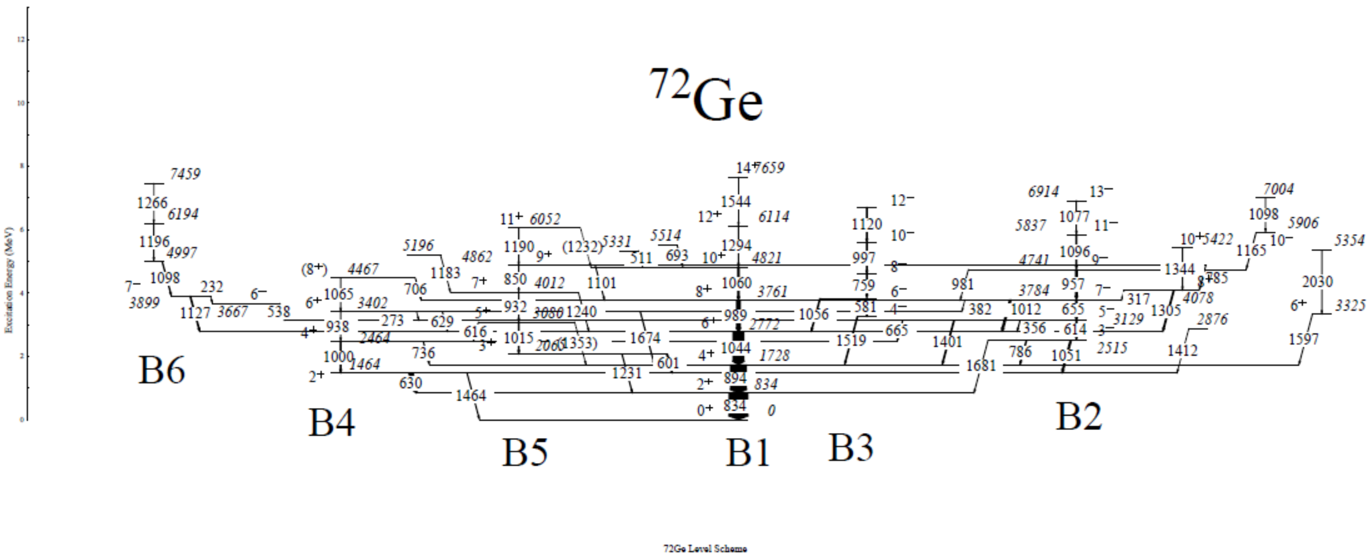

Figure 4.1: The constructed level scheme of ^{72}Ge

The first step of data analysis was to confirm the existing level scheme and extend it to construct band 3 of the existing level scheme. Band 3 of the level scheme was constructed by using the energy 1519 KEV as a starting energy. This was done through gating on the new band and then γ-energy was assigned by adding 1519 KeV and corresponding energy 1729 KeV from Band 1. This gave 3248 KeV as the energy to be assigned. After that the starting spin and parity from 1729 KeV of Band 1 was added. The starting $I^{\pi} = 4^{-}$ as shown in figure4.1.

The second γ-ray was discovered after gating on 1519 KeV, to examine the γ-ray. The energy was discovered as 580 KeV from the histogram window. For it to be added to the Band 3, this 580 KeV was added to the previous level energy 3248 KeV to give 3828 KeV. The spin and parity assignment was +2 of the previous spin but of the same negative parity. In this case, the $I^{\pi} = 6^{-}$ as referred to figure4.1.

After assigning 580 KeV, the new γ-ray was discovered in the histogram window. This was done by gating on the 580 KeV in the Band 3 of the level scheme, then the new γ-ray was discovered as 760 KeV. This was assigned by adding it to the previous level energy 3828 KeV giving out 4588 KeV. The spin and parity assignment was +2 of the previous spin with the same negative parity. Therefore, the $I^{\pi} = 8^{-}$ at 760 KeV.

From 760 KeV the next γ-ray was discovered after gating on 760 KeV on Band 3 of the level scheme . The new γ-ray was coincidence on the histogram window as 997 KeV. The energy was assigned by adding it to the previous level energy 4588 KeV to produce 5585 KeV. The existing spin was added by 2 to give new spin as 10 with a negative parity. So the $I^{\pi} = 10^{-}$ at 997 KeV.

The final energy according to Band 3 of the ^{72}Ge level scheme, was discovered by gating on 997 KeV of the level scheme. The new γ-ray was shown on the histogram window as 1120 KeV. To assign it, the γ-ray was added to previous level energy 5585 KeV to give out 6705 KeV as the new level energy. A 5585 KeV spin was added by 2 to produce 12 as the new spin with a negative parity. Hence, the $I^{\pi} = 12^{-}$ at 1120 KeV as on figure 4.1.

4.2 Coincidence Spectrum of 580 keV

After assignment of the γ-rays, the coincidence spectrum were produced for each energy to show the peaks of the γ-energy discovered. Gating on 1519 KeV as a starting point, 580 KeV that was assigned was seen, which means it was possible to view the coincidence spectrum of that seen energy. As the shown in figure 4.2, a gate set on 1519 keV produces a spectrum that gives 3 strong peaks of 580 keV.

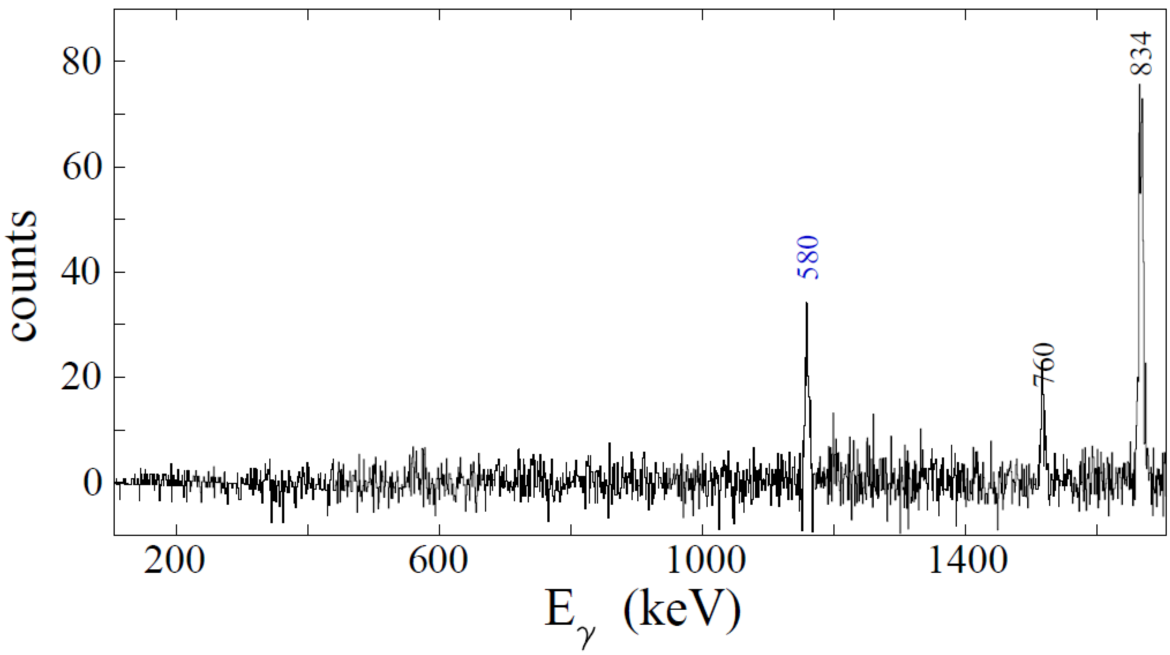

Figure 4.2: 580 keV coincidence spectrum

4.3 Coincidence Spectrum of 760 keV

760 keV is a γ-energy that was discoverd gating 580 keV. Therefore, Gating on 580 keV, the 760 keV that was assigned was been displayed, which means a coincidence spectrum of 760 keV could be viewed after writing it in gf3. As the shown in figure 4.3, a gate set on 580 keV produces a spectrum that gives more than 3 strong peaks of 760 keV.

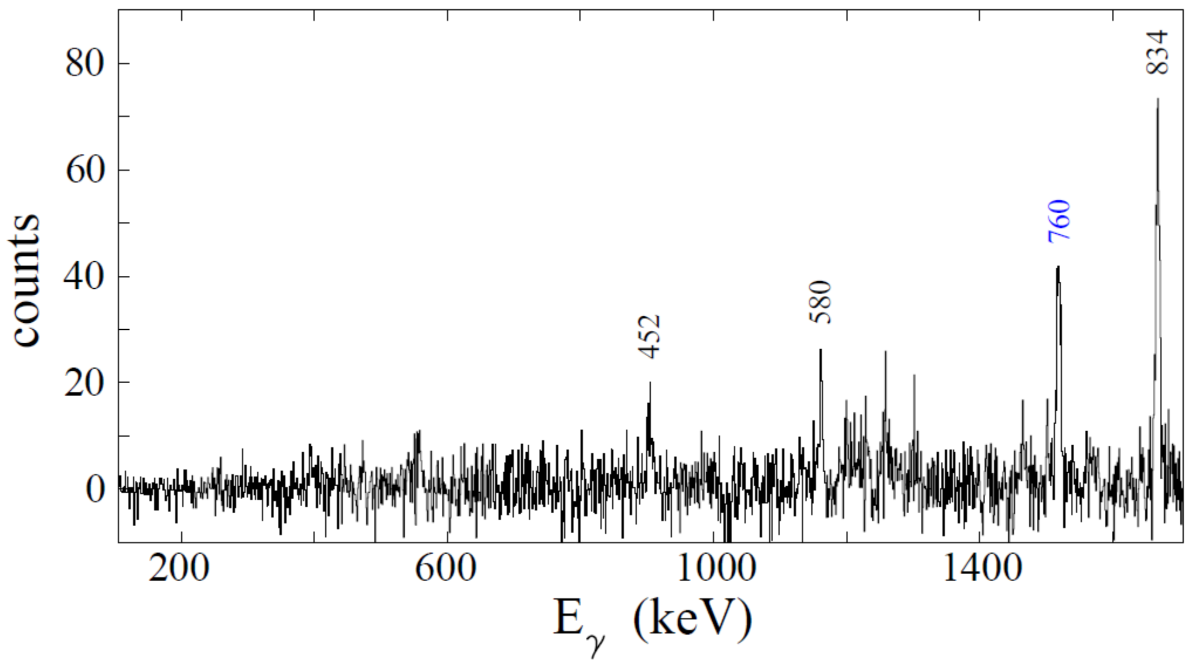

Figure 4.3: 760 keV coincidence spectrum

4.4 Coincidence Spectrum of 997 keV

A gate set on the γ-ray 760 keV with the excitation energy 4588 keV, displayed the γ-energy of 997 keV in the histogram window. This energy has an excitation energy (E_{ex}) of 5585 keV, Upon writing on the gf3 the plotted spectrum showed peaks of this energy of the band 3 of the ^{72}Ge level scheme. The figure 4.4 shows the peaks for 997 keV γ-energy.

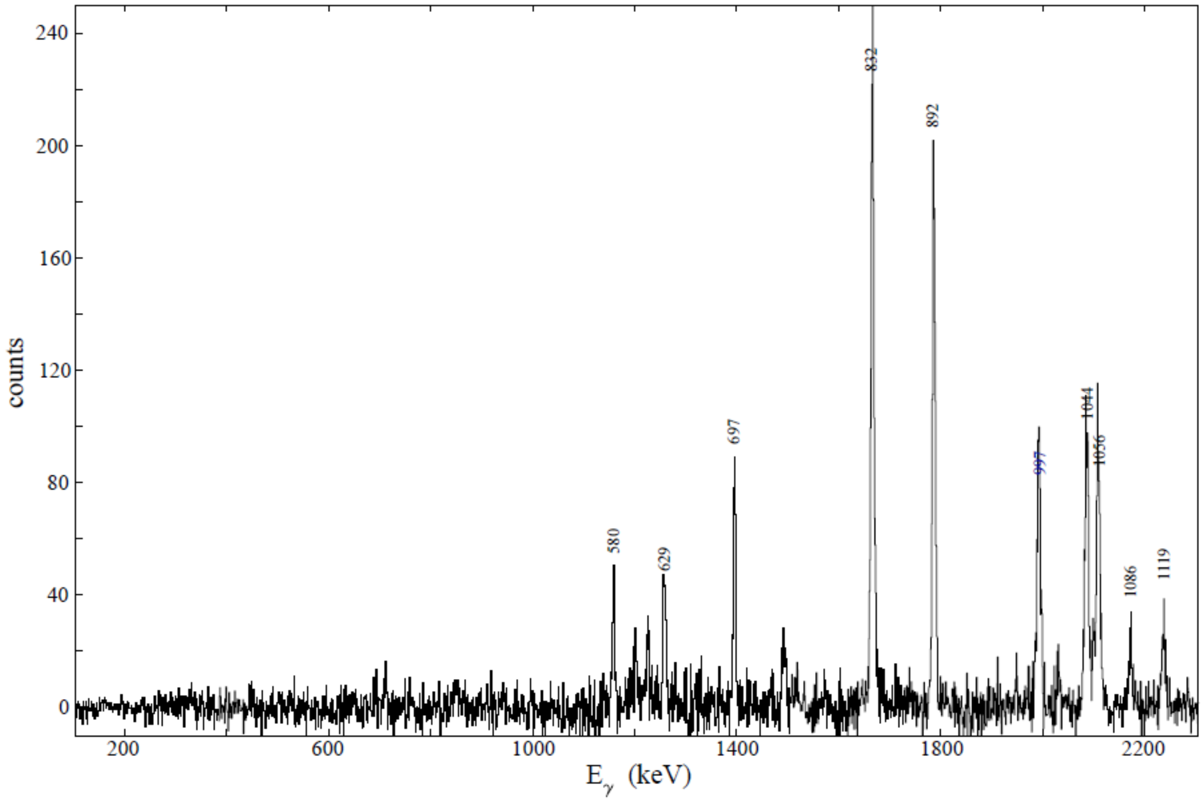

Figure 4.4: 997 keV coincidence spectrum

4.5 Coincidence Spectrum of 1120 keV

A gate set on the γ-ray 997 keV with the excitation energy 5585 keV, showed a γ-energy 1120 keV in the histogram window. This energy had an excitation energy of 6705 keV. Upon writing it on the gf3 in RadWare, the plotted spectrum showed peaks of this energy of the band 3 of the ^{72}Ge level scheme. The figure 4.5 shows the peaks for 1120 keV γ-energy.

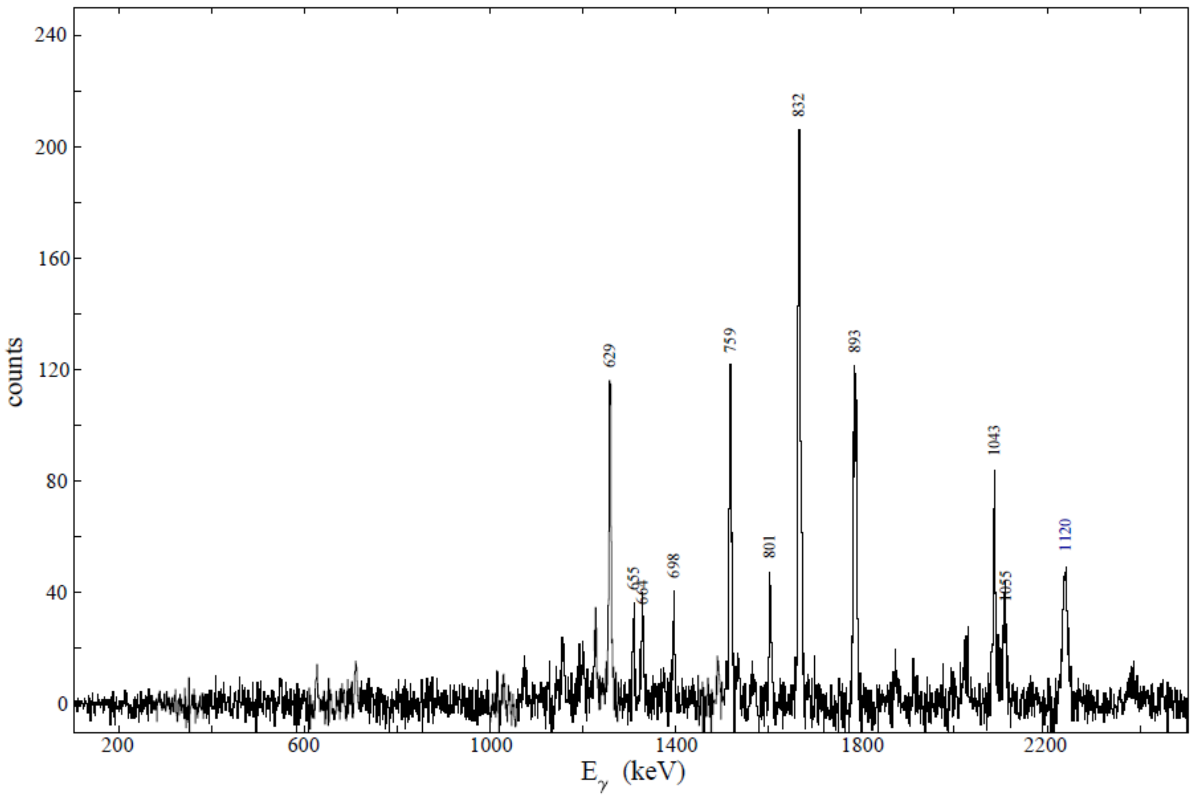

Figure 4.5: 1120 keV coincidence spectrum

4.6 Summary for energy spectra

Different gates for both E1 and E2 transitions were set at different γ-energies. These energies provided peaks that were used to come up with the R_{DCO} values as well as the linear polarisation (Anisotropy). These peaks provided the yield that was used to fulfill the objective of assigning spin and parity to the γ-energies in the level scheme. The figure 4.6 below provides a summary of how the each γ-energy was plotted to provided details for analysis.

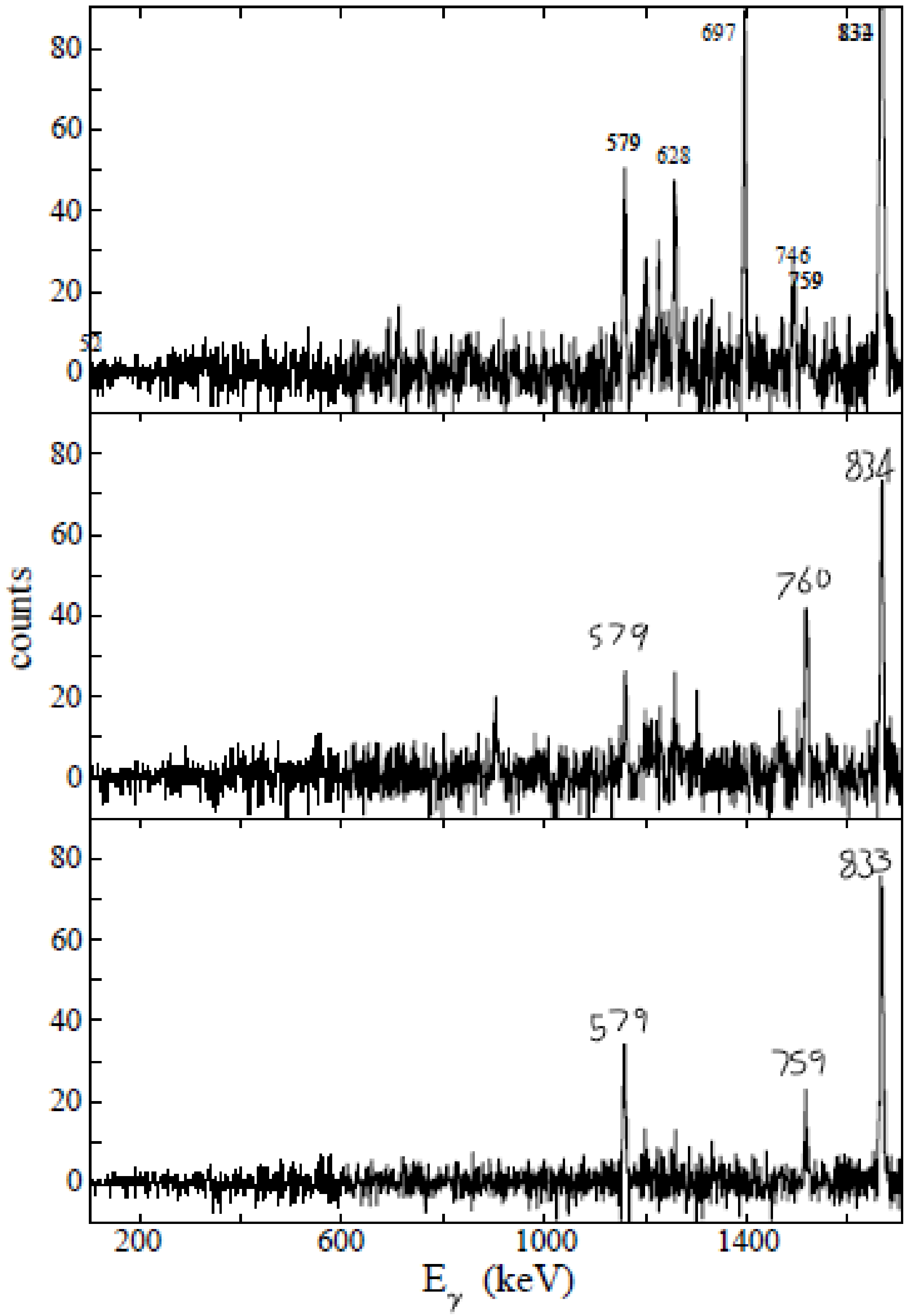

Figure 4.6: 580 keV, 760keV and 997 keV coincidence spectra

4.7 DCO measurements

To determine the multipolarities of new transitions, the DCO ratios (R_{DCO}) defined in eq.**??** were measured using the known stretched $E2$ transitions as gates. The R_{DCO} for a number of transitions with known stretched $E2$ multipolarities were measured to provide the reference values for the current detector configuration.

The theoretical R_{DCO} values were calculated using the code *DCOplot* [10], and were compared to the measured R_{DCO} values in order to determine the multipolarity of transitions. According to the theory, the values of R_{DCO} is based on two ranges with $E2$ ranging from 0.6 to 1.0 and $E1$ ranging form 1.0 to 1.6 transitions respectively. The obtained average values of R_{DCO} for E2 and E1 transitions were 0.9 and 1.2 respectively. These values are very similar to the theoretical average values where $R_{DCO}(E2) = 0.8$ and $R_{DCO}(E1) = 1.3$.

4.8 Linear Polarisation measurements (Anisotropy)

The linear polarization measurements are used to deduce the electric and magnetic character of γ-ray transitions. When the multipolarity of a transition is combined with the electric or magnetic character of the transition, the spin and parity of a new level can be assigned if it decays to a level of known spin and parity. The linear polarization measurements were performed following Eq.?? which is described in section 4.5. Since the linear polarization measurements do not depend on the multipolarity of the gate, the A_p values were determined using stretched $E2$ or $E1$ transitions as gates and the results are given in table 4.1.

4.9 Spin and parity assignments

In this work the spin-parity was assigned to the new levels and to the established levels of Band 3 which were not previously assigned. The spin-parity assignment was performed using the deduced multipolarities and character of linking transitions to the levels for which the spin-parity was known. The theoretical DCO ratios and theoretical polarization (Anisotropy) values were calculated for important transitions. The objective was to compare them with the measured values when assigning spin and parity to the levels.

Table 4.1: Spin and parity assignment to different discovered energies

E_γ(keV)	E_{ex}(keV)	$I_i^\pi \rightarrow I_f^\pi$	Gate	R_{DCO}	A_p	P
580	3828	$6^- \rightarrow 6^+$	E2	0.996	0.18	0.81
760	4588	$8^- \rightarrow 8^-$	E1	1.04	-0.14	-0.74
997	5585	$10^- \rightarrow 10^-$	E1	1.27	-0.06	-0.35
1120	6705	$12^- \rightarrow 12^+$	E1	1.257	0.06	0.38

From the table 4.1, it is noted that amongst the four level energies, two energies have maintained their parities as positives, and the other two energies have new parity being assigned to them. These are negative parities. This comes due to calculation of the linear polarisation (Anisotropy) of the energies.

For the energies with a negative parity, the number of γ-rays scattered in vertical direction was less than the number of γ-rays scattered in the horizontal directions even if the γ-rays scattered in vertical direction were multiplied by the polarisation sensitivity. On the other hand, the energies with positive parity had the number of γ-rays scattered in vertical direction being greater than the number of γ-rays scattered in horizontal direction.

These number of γ-rays were obtained from the yield of each γ-energy after running slice in RadWare. For example, 580 keV which falls under excitation energy of 3828 keV, had a positive parity being maintained because it had the number γ-rays scattered in vertical direction being more than that of horizontal direction.

Chapter 5

CONCLUSION

This part provides a summary of the thesis findings, and the discussion being made. At the same spot it gives a site for further studies and highlights some challenges the researcher encountered.

The primary objective of this thesis was to have a spectroscopic study of the nucleus of Germanium,^{72}Ge to be precise. On this objective, a level scheme for band 3 of ^{72}Ge was constructed. The starting energies used for constructing the level scheme were 1519 keV which was used to construct the level scheme, and 1056 keV which was used to link band 3 with band 1 which links to band 2, 4, 5 and 6. The data for this thesis was collected at iThemba LABS of the Republic of South Africa.

Apart from a level scheme, spectra for each γ-energy were plotted and the peaks discovered were used to find the values of R_{DCO} and Anisotropy (A_p). The R_{DCO} and Anisotropy (A_p) values were used to assign spin and parity to the γ-energies. The results were found by looking at the sign the value of linear polarisation (A_p) carries. If the linear polarisation (A_p) has a negative value, it means that the parity for that γ-energy is negative. If the linear polarisation (A_p) has a positive value, it means that the parity is positive.

All the objectives were achieved, whereby the level scheme was drawn and the spin and parity were assigned. After the assignment, the results were compared with theoretical predictions.

Despite the project being successful, there were some drawbacks during the process. The first drawback was that, the researcher had limited time to work on the thesis as it had only a period of three months. On the same period, the researcher was also attending classes including assignments and examinations, which led to having a lot of pressure on the research project. The next researcher to work on a project similar to this must prepare in advance, in fact they must start working on it from the first semester in order to fulfill all the objectives in the specified period.

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