Octupole and Quadrupole Structures in the N=88 Nucleus $^{152}\text{Gd}$

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Declaration of Authorship

I, Adivhaho Netshiya, declare that this thesis titled, ‘Octupole and Quadrupole Structures in the N=88 Nucleus $^{152}$Gd’ and the work presented in it are my own. I confirm that I have not previously in its entirety or in part submitted it at any university for a degree.

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Abstract

The spectroscopy of $^{152}$Gd has been studied using the $^{150}$Sm($\alpha$, 2n)$^{152}$Gd fusion evaporation reaction at a beam energy of 25 MeV. The emitted $\gamma$-rays were detected using the AFRODITE $\gamma$-ray spectrometer, equipped with 9 escape-suppressed clover detectors, at iThemba LABS. DCO ratios and linear polarization measurements were used to determine the spins and parities of new levels and confirm the assignments of previously established levels. We report an observation of consistent out-of-band E1 transitions decaying both to and from the K$^\pi=0^+_2$ band and the octupole band. These out-of-band E1 transitions suggest that there is strong octupole correlations between the K$^\pi=0^+_2$ and octupole band. The phenomenon of congruent band structures built between the K$^\pi=0^+_2$ band and the ground band is investigated and the results are discussed. In order to get a better insight on the microscopic behaviour of the lowest negative parity bands across the A~144 to 158 mass region, a systematic review has been carried out. The systematics of the lowest negative parity bands in the N=88 isotones are remarkably well reproduced by the quadrupole octupole coupling (QOC) model. The staggering between the even- and odd-spin energies of nuclear levels in the $\gamma$ band can provide an insight into the nature of the nuclear triaxiality. In effect, the staggering can help distinguish between $\gamma$ rigid, soft and triaxial shapes. In order to get a deeper insight into the nature of $\gamma$ bands in these nuclei, the five-dimensional collective Hamiltonian ($5$-DCH) based on the covariant density functional theory (CDFT) is used to explain the microscopic properties of the first excited K$^\pi=2^+_1$ bands, in the context of systematics.
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Chapter 1

Introduction

1.1 Introduction

The focus for this work is on $^{152}$Gd produced by the $^{150}$Sm($\alpha$, 2n)$^{152}$Gd reaction at a beam energy of 25 MeV. The nucleus has been previously studied for both low spin states and high spin states [1–4] at different energies. The most recent work on $^{152}$Gd was done by S. P. Bvumbi [4] using the $^{152}$Sm($\alpha$, 4n)$^{152}$Gd reaction at a beam energy of 45 MeV where she was able to populate low spin states and assign spins and parities to the levels as shown in Fig. 1.1.

The nucleus $^{152}$Gd, with proton number Z=64 subshell closure, belongs to a set of isotones having N=88 in the transitional region with just 6 neutrons outside the N=82 closed shell and lies just before the N=90 permanently deformed region. The isotope $^{152}$Gd is in the transitional region, consequently its nuclear collective motion will quickly evolve from vibrational to rotational motion [5]. The low lying $K^\pi=0^+_2$ bands in N=88 and 90 nuclei appear at low excitation energies [6–10] and are poorly understood [11,12]. Key to these studies is the crucial question about the legitimacy of the low lying $K^\pi=0^+_2$ bands being described as $\beta$ vibrations along the symmetry axis. The current work examines the $K^\pi=0^+_2$ band with the objective of providing more understanding. Previous studies of N=88 isotones saw consistent E1 transitions both from and to the $K^\pi=0^+_2$ bands and octupole bands, namely $^{144}$Ba [6], $^{146}$Ce [13], $^{148}$Nd [5], $^{150}$Sm [7, 14] and $^{154}$Dy [9, 15] nuclei. The experimental systematics of the low lying negative parity states in N=88 isotones are remarkably well reproduced by theoretical calculations of the quadrupole octupole coupling (QOC) model [3] as shown in Fig. 1.2.
Figure 1.1: Decay scheme obtained using the $^{152}\text{Sm}(\alpha,\,4n)^{152}\text{Gd}$ reaction for $^{152}\text{Gd}$ observed by [4].

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CHAPTER 1: INTRODUCTION

The intention to study $^{152}\text{Gd}$ is to search for octupole and quadrupole structures by investigating the out-of-band E1 transitions between the $K^\pi=0^+_2$ band and octupole band. The out-of-band E1 transitions between the $0^+_2$ band and octupole band are amongst the most critical signatures of octupole correlations [8, 9, 14, 15]. Our findings will be argued in relation to the calculations made in the region of $N=140-144$ on Uranium nuclei by R. R. Chasman [16]. The analysis will include the even-odd signature splitting of the $\gamma$ bands. The signature splitting of the even-odd $\gamma$ bands was used to determine the nature of the nuclear triaxiality [17]. The microscopic properties of these $\gamma$ bands will be theoretically interpreted with the use of the five-dimensional collective Hamiltonian (5-DCH) based on the covariant density functional theory (CDFT). We will look for structures of $\gamma$ bands and octupole negative parity bands built on the $K^\pi=0^+_2$ band “second vacuum” configurations and compare them to those built on the ground band. We compare these structures in order to see if they are congruent as seen in the neighbouring nuclei with two more neutrons ($N=90$) particularly for $^{154}\text{Gd}$ and $^{152}\text{Sm}$ [10].

The $0^+_2$ states in $^{152}\text{Gd}$ ($N=88$ nucleus) are traditionally regarded as a $\beta$-vibration by Bohr and Mottelson [18]. Emerging evidence shows that they are related to 2particle-2hole neutron states lowered into the pairing gap by configuration dependent pairing [10, 19]. J. F. Sharpey-Schafer [10] insisted that they are “pairing isomers” [20] making up a “second vacuum” which has structures built on it that are congruent to those built on the ground band.
1.2 Nuclear Spectroscopy

The study of the properties of nuclear excitations has been informative. This is due to the new technological improvements in the field of nuclear excitations. The power of the AFRODITE spectrometer has been greatly enhanced by the new digital electronics. The much improved AFRODITE spectrometer and its electronics will give detailed spectroscopy of nuclei. This will enable new structures to be found and examined that could not be studied before. The new technology will allow good statistics to be obtained in the form of \( \gamma-\gamma \) events, consequently enabling polarization assignments \( A_p \) and DCO measurements.

1.3 Thesis Structure

The introduction is here in chapter 1. The various shapes and models used in describing the behaviour of the nuclei will be discussed in chapter 2. The set up of the experiment with the equipments used and the methods used to analyse the data will follow in chapter...
3. The presentation of the results obtained is given in chapter 4 and their interpretation will be in chapter 5. The summary of the work done throughout the analysis is given in chapter 6.
Chapter 2

Nuclear Theory

2.1 Nuclear Deformations

The majority of nuclei are deformed and can take different shapes which result in them having distinguishable properties when they are excited in nuclear reactions. Therefore expansions of shapes can be described in terms of spherical harmonics $Y^\mu_\lambda(\theta, \phi)$. All shapes can be described in terms of spherical harmonics since they form a complete basis. Thus the radius of the nucleus can be represented as [21]:

$$R(\theta, \phi) = R_0 \left[ 1 + \sum_{\lambda=1}^{\infty} \sum_{\mu=-\lambda}^{\lambda} \alpha_{\lambda\mu} Y^\mu_\lambda(\theta, \phi) \right]$$

where

- $R(\theta, \phi)$ is the radius of the nucleus in the direction($\theta, \phi$).
- $R_0$ is the radius of the sphere with equal volume to the deformed nucleus.
- $\alpha_{\lambda\mu}$ is the coefficient that represent the distortions from an equilibrium spherical shape.
- $Y^\mu_\lambda(\theta, \phi)$ are the spherical harmonics in spherical polar coordinates.
- $\lambda$ indicates the multipolarity of the deformation.
- $\mu$ is an integer number taking values from -$\lambda$ to $\lambda$.

The multipole order variable $\lambda$ represent the type of deformation that is taking place in the nucleus and ranges from $\lambda=0$ to $\lambda=\infty$. The $\lambda=0$ term describes monopole deformation (sphere). The $\lambda=1$ terms are normally excluded from the sum as these correspond
CHAPTER 2: NUCLEAR THEORY

to a translation of the centre of mass. The next term \(\lambda=2\) describes quadrupole deformation taking place along the symmetry axis. The \(\lambda=3\) term describes octupole deformation and \(\lambda=4\) term describes hexadecapole deformation as shown in Fig. 2.1. The deformations with even \(\lambda\) are reflection symmetric (the same if \(r\rightarrow-r\)) and deformations with odd \(\lambda\) are reflection asymmetric (not the same if \(r\rightarrow-r\)).

![Figure 2.1: Schematic of monopole \(\lambda=0\), quadrupole \(\lambda=2\), octupole \(\lambda=3\), and hexadecapole \(\lambda=4\) deformations [7].](http://etd.uwc.ac.za/)

Most deformed nuclei are assumed to have an axis of symmetry (axial symmetry) but there are some that do not have a symmetry axis, for instance triaxial nuclei. Nuclei that are axially symmetric have all \(\alpha_{\lambda\mu}=0\) apart from \(\alpha_{00}\). Then for every \(\lambda\)-pole there is one \(\alpha_{\lambda0}\) that informs us of the deformation of the nucleus. Additionally the spherical harmonics for \(\mu=0\) are simple and are known as Legendre polynomial and are independent of \(\phi\).

Hence:

\[
R(\theta) = R_0 \left[ 1 + \sqrt{\frac{2\lambda + 1}{4\pi}} \sum_\lambda \beta_\lambda P_\lambda(\cos\theta) \right] \tag{2.2}
\]

where \(\beta_\lambda\) is the deformation parameter with a large value of \(\beta\) describing more deformed nuclear shapes.

The Lund convention [22] is generally used for the quadrupole (\(\lambda=2\)) deformation of nuclei, using two parameters \((\beta_2, \gamma)\), where \(\beta_2\) reflects the magnitude of the deformation and \(\gamma\) is an angle describing whether the nucleus is axially symmetric. The parameter \((\beta_2, \gamma)\) can be written in relation to parameters \(\alpha_{20}\) and \(\alpha_{22}\) as illustrated in equations 2.3 and 2.4 respectively.
\[ \alpha_{20} = \beta_2 \cos \gamma \]  \hspace{1cm} (2.3)

and

\[ \alpha_{22} = \beta_2 \frac{1}{\sqrt{2}} \sin \gamma \]  \hspace{1cm} (2.4)

Where \( \beta_2 \) is the total measure of the deformation, since

\[ \beta_2^2 = \sum_\lambda | \alpha_{2\mu} |^2 \]  \hspace{1cm} (2.5)

Prolate and oblate nuclear shapes have \( \gamma = 0^\circ \) and \( \gamma = 60^\circ \) respectively with the \( z \)-axis being the symmetry axis. For \( 0^\circ < \gamma < 60^\circ \) the nucleus is triaxial with its three axes having different lengths.

Figure 2.2: The lund convention schematic representing quadrupole nuclear shapes in the \((\beta_2, \gamma)\) plane. Adapted from [23].

http://etd.uwc.ac.za/
2.2 Nuclear Collective Motion

In nuclear reactions nuclei absorb energy and become excited. Some of this energy can go into promoting the total angular momentum of the nucleus to higher values. The nucleus can do this through collective motion which involves rotational motion and vibrational motion for deformed nuclei. The other way is through single particle excitation for both deformed and spherical nuclei. Nuclei near a closed shell, or at closed shells (spherical), can generate angular momentum through vibrational motion. Those that are away from closed shells (non spherical) can have rotational motion about an axis perpendicular to the symmetry axis and they can also vibrate.

2.2.1 Nuclear Rotational Motion

Collective rotational motion is experienced by deformed nuclei and it involves nucleons moving in a coherent motion. Spherical nuclei do not rotate since all their axes are axes of symmetry. If there are no observable changes then a nucleus cannot rotate since quantum mechanically an object cannot rotate around an axis of symmetry. The deformed nuclei rotate around an axis perpendicular to the symmetry axis therefore generating rotational motion. Angular momentum depends on the rotational energy. The higher the rotational energy the more angular momentum that will be generated by the nucleus.

Classically the rotational energy is given by:

$$E_{\text{rot}} = \frac{1}{2} \mathcal{J} \omega^2$$  \hspace{1cm} (2.6)

where $\mathcal{J}$ is the moment of inertia and $\vec{\omega}$ is the angular frequency given as

$$\vec{\omega} = \frac{\vec{R}}{\mathcal{J}}$$  \hspace{1cm} (2.7)

where $\vec{R}$ is the rotational angular momentum.

The combination of equations 2.6 and 2.7 gives us the following

$$E_{\text{rot}} = \frac{R^2}{2\mathcal{J}}$$  \hspace{1cm} (2.8)
Quantum mechanically the rotational angular momentum $\vec{R}$ is given by

$$ R = \sqrt{I(I+1) - K^2 \hbar} $$

(2.9)

where $K$ is the projection of the total angular momentum $\vec{I}$ onto the symmetry axis. For rotational bands with $K=0$ equation 2.9 becomes

$$ R = \sqrt{I(I+1)} \hbar $$

(2.10)

substituting equation 2.10 into 2.8 we get

$$ E_{\text{rot}}(I) = \frac{I(I+1)\hbar^2}{2J} $$

(2.11)

where $E_{\text{rot}}$ is the rotational energy of the state with angular momentum $I$ and moment of inertia $J$ [21].

In deformed even-even nuclei the ground state rotational band has $K=0$ and energy levels of only even spin and positive parity. Therefore the levels de-excite by E2 transitions with a spin change of $\Delta I=2$. Hence in $K^+=0^+$ bands, the energy of the $\gamma$-ray emitted by a rotating nucleus is the difference between the sequential nuclear states $I$ and $I-2$ respectively. The energy of an emitted $\gamma$-ray is

$$ E_\gamma(I) = E_{\text{rot}}(I) - E_{\text{rot}}(I-2) $$

$$ E_\gamma(I) = \frac{[I(I+1) - (I-2)(I-2+1)]\hbar^2}{2J} $$

(2.12)

$$ E_\gamma(I) = \frac{(2I-1)\hbar^2}{J} $$

The spacing between the energies of the $\gamma$-rays which relates to the difference between $\gamma$-ray energies is approximately given by

$$ \Delta E_\gamma(I) = E_\gamma(I) - E_\gamma(I-2) $$

$$ \Delta E_\gamma(I) = \frac{[(2I-1) - (2I-1-2)]\hbar^2}{J} $$

(2.13)

$$ \Delta E_\gamma(I) = \frac{2\hbar^2}{J} $$
which is a constant for increasing angular momentum leading to a “picket fence” $\gamma$-ray spectrum with equal spaced $\gamma$-ray peaks.

2.2.2 Nuclear Vibrational Motion

The other way in which nuclei can generate angular momentum is through vibrational motion. Vibrational motion takes place in spherical and deformed nuclei with the spherical nuclei producing excited states by one or more units of vibrational energy. This units are the vibrational quanta called phonons with each phonon having the same energy $\hbar \omega$ [24]. For quadrupole deformation each phonon has $\lambda=2$, therefore the first excited state will have one $\lambda=2$ phonon with angular momentum of $I=\lambda=2$, positive parity, $\pi=(-1)^{\lambda=2}$ and energy of $E_{2^+}=\hbar \omega_{ph}$. The are two modes of vibration in a quadrupole deformed nucleus, namely $\beta$ and $\gamma$ vibrations. The $\beta$ vibrations are orthogonal oscillations that take place along the symmetry axis also known as axial deformations generating $K=0^+$ rotational bands. The $\gamma$ vibrations take place perpendicular to the symmetry axis, breaking axial symmetry and generating $K=2^+$ rotational bands as shown in Fig. 2.3.

![Modes of vibration](http://etd.uwc.ac.za/)

**Figure 2.3:** Modes of vibration of a quadrupole deformed nucleus with $\beta$ and $\gamma$ vibrations oscillating along the symmetry axis and perpendicular to the symmetry axis respectively.

The octupole vibrational mode of collective excitation has $\lambda=3$ and negative parity, $\pi=(-1)^{\lambda=3}$. Octupole vibrations may also occur in $\lambda=2$ deformed nuclei. Figure 2.4 gives a schematic illustrating octupole vibrational mode.
2.3 Nuclear Models

2.3.1 Liquid Drop Model (LDM)

The liquid drop model (LDM) was formulated by George Gamow [25] in 1929 and advanced by N. Bohr and J. A. Wheeler [26] in 1939. This model proposes that the atomic nuclei behaves like the molecules in a drop of liquid. This is all assumed to be in the scale of subatomic particles with the fluid made up of nucleons (neutrons and protons). The nucleons are brought together by the strong nuclear force. The LDM evolved from Rutherford scattering experiments where the nuclear radii was being studied. These kinds of experiments showed near constant density of nuclei that do not depend on the number of nucleons [21]. The first evidence showing that the nucleus is a macroscopic drop of incompressible fluid were measurements performed for near constant nuclear density for all nucleons. In 1935 a German physicist C. F. V. Weizsäcker formulated a theory based on the liquid drop model. The model described the behaviour of the nuclear binding energies and consequently of the nuclear masses. This model is known as the Weizsäcker formula and is given in equation 2.14 [27].

The nuclear binding energy as a function of the mass number \( A \) and proton number \( Z \) based on the liquid drop model is given by

\[
E_b(\text{MeV}) = \alpha_V A - \alpha_S A^\frac{2}{3} - \alpha_C \frac{Z^2}{A^\frac{2}{3}} - \alpha_A \frac{(A - 2Z)^2}{A} \pm \delta(A, Z) \tag{2.14}
\]

\[
\delta(A, Z) = \begin{cases} 
+\delta_0 & \text{for } Z, N \text{ even} \\
0 & \text{for } A = N + Z \text{ is odd} \\
-\delta_0 & \text{for } Z, N \text{ odd}
\end{cases}
\]
The first positive term $\alpha_V A$ is known as the volume term and it is caused by the attracting strong forces between the nucleons [28]. The surface term $\alpha_S A^{3/2}$ is also based on the strong force, it is a correction surface to the volume term giving the surface tension constraining the drop. The term $\alpha_C \frac{Z^2}{A^{1/3}}$ describes the Coulomb repulsion between the uniformly distributed protons and is proportional to the number of proton pairs $\frac{Z^2}{R}$, whereby $R$ is proportional to $A^{1/3}$. The symmetry term $\alpha_A \frac{(A-2Z)^2}{A}$ accounts for the relative number of protons and neutrons and the reduction in the binding energy as a result of an asymmetry in $N$ and $Z$. The last term $\delta(A, Z)$ is the pairing term. This term captures the effect of the pairing interaction.

In order to calculate the binding energy the coefficients $\alpha_V$, $\alpha_S$, $\alpha_C$, $\alpha_A$ and $\alpha_p$ must be known. They are calculated by fitting the experimentally measured masses of nuclei and vary according to fitting method [29], the calculated values are as follows

$$
\begin{align*}
\alpha_V &= 15.76 \text{ MeV} \\
\alpha_S &= 17.81 \text{ MeV} \\
\alpha_C &= 0.711 \text{ MeV} \\
\alpha_A &= 23.7 \text{ MeV}
\end{align*}
$$

and

$$
\delta(A, Z) = \begin{cases} 
+33.5, & \text{MeV for } Z, N \text{ even} \\
0, & \text{MeV for } A = N + Z \text{ is odd} \\
-33.5, & \text{MeV for } Z, N \text{ odd}
\end{cases}
$$

The Weizsäcker formula can calculate the binding energy of most isotopes near stability. The formula gives good solutions for heavier nuclei but for light nuclei it produces poor results as shown in Fig. 2.5. This is due to the internal shell structure of the nucleus. It is further limited since it cannot explain the quantum behaviour like spin, dipole moments, etc.

### 2.3.2 The Spherical Shell Model

The spherical shell model description of nuclei was as a result of sharp changes observed during an experiment in the neutron and proton separation energies at the so called
nuclear magic numbers, 2, 8, 20, 28, 50, 82 and 126 [30] as shown in Fig. 2.6. These magic numbers are produced by the harmonic oscillator potential with the effects of the attractive term and spin orbit interaction as shown in Fig. 2.7. This description was further encouraged by the peaks of the first excited states in the excitation energies of even-even nuclei and sudden changes in the nuclear charge radii at the magic numbers [31]. The nuclei at these magic numbers have filled major shells and spherical shell closures. The shell model relates the nucleons as a progression of shells that are supposed to be filled by the nucleons. The filling of these shells is in accordance with the Pauli exclusion principle [32] which forbids clash of nucleons, where two or more identical fermions cannot occupy the same quantum state.

In this model the nucleons are confined in an attractive nuclear potential well with relatively constant potential energy inside the nucleus. The usual potential wells that are used in the spherical shell model are the harmonic oscillator, square well and Woods-Saxon potentials. The harmonic oscillator potential is favoured for its good approximate solution to nuclear problems while simple to solve. The harmonic oscillator potential is given by

\[ U(r) = \frac{1}{2} m \omega^2 r^2 \]  

\[ (2.15) \]
where $m$ is the mass of the nucleon and $\omega$ is the oscillator frequency. The resulting eigenvalues $E_{n\ell}$ from the three-dimensional harmonic oscillator potential are given by

$$E_{n\ell} = \left(2n + \ell - \frac{1}{2}\right)\hbar\omega$$

where $N$ is the oscillator quantum number, $n$ is the radial quantum number and $\ell$ is the orbital angular momentum quantum number. Unfortunately the harmonic oscillator potential produces the initial three magic numbers and the remaining disagree with the values that were observed experimentally. Since the model is unable to produce the rest of the values modifications are made to include the attractive term $\ell^2$, such that

$$U(r) = -U_0 + \frac{1}{2}m\omega^2r^2 - D\ell^2$$

The attractive term $\ell^2$ modifies the shape of the potential to an intermediate shape that lies between the square well and the harmonic oscillator potentials. The Wood-Saxon potential [33] gives a more meaningful description of the nuclear potential compared to
the infinite or finite square well and harmonic oscillator potential. It has the form

\[ V(r) = \frac{V_0}{1 + \exp\left(\frac{r - R_0}{a}\right)} \]  

(2.18)

where \( V_0 \) is the depth of the potential, \( R_0 \) and \( a \) are the radius and the surface diffuseness of the nucleus respectively. The Wood-Saxon potential will give energy levels that are the same as the harmonic oscillator potential with the \( \ell^2 \) term. If the spin-orbit interaction \((\vec{\ell} \cdot \vec{s})\) term is added on either the Wood-Saxon potential or the harmonic oscillator potential with the \( \ell^2 \) term, we would get the correct magic numbers as illustrated in Fig. 2.7. The eigenfunctions of the Wood-Saxon are not known analytically, because of this, the harmonic oscillator potential with the \( \ell^2 \) term is mostly used.

Figure 2.7: Single particle energy levels of the harmonic oscillator potential with the effects of \( \ell^2 \) term and spin-orbit interaction [34].
2.3.3 The Nilsson Model

The majority of nuclei are known to be deformed with a large number of them associated with quadrupole (λ=2) deformation. It then leads to the development of a model for deformed nuclei with quadrupole shape. This was done through the modification of the nuclear spherical potential. The spherical potential has equal radial dependence through out its three nuclear axes. It is changed to dependence along an axis to represent the spread of the nuclear matter along this axis. For instance let us consider a prolate deformed nucleus which would appear to have two equal short axes (x,y) and one long axis (z). Therefore the potential should spread further along the long axis (z).

To mathematically do this, we take the harmonic oscillator potential of the form \( U(r) = \frac{1}{2} m \omega^2 r^2 \), assuming that \( \omega_x = \omega_y \neq \omega_z \) introduces a difference in the potential along the three nuclear axis. If \( \omega_x = \omega_y > \omega_z \) the nucleus will be longer along the z-axis, while the x and y axes will be the same. Therefore the nucleus is symmetric about the z-axis with a prolate shape. If \( \omega_x = \omega_y < \omega_z \) the nucleus will be shorter along the z-axis while the x and y axes will be the same. Therefore this nucleus is symmetric about the z-axis with an oblate shape.

To be able to describe the behaviour of the above mentioned nuclei the deformed harmonic oscillator potential also known as the Nilsson model [35, 36] was introduced by S. G. Nilsson in 1955. The modified harmonic oscillator potential includes the spin-orbit (\( \hat{\ell} \cdot \hat{s} \)) and the attractive \( \ell^2 \) terms to reproduce the experimentally observed magic numbers. The potential has an axial symmetry with respect to the z-axis when used for prolate and oblate nuclei and is deformed. The modified harmonic oscillator potential or Nilsson potential for quadrupole deformed nucleus along the z-axis can be written as

\[
V = \frac{1}{2} m \left[ \omega_x^2 (x^2 + y^2) + \omega_z^2 z^2 \right] + C \hat{\ell} \cdot \hat{s} + D \ell^2
\]  (2.19)

The Nilsson model originally incorporated only quadrupole deformed axially symmetric shapes. The single particle Hamiltonian for a nucleus with symmetry axis z is [21]

\[
H = T + V
\]

\[
H = \frac{p^2}{2m} + \frac{1}{2} m \left[ \omega_x^2 (x^2 + y^2) + \omega_z^2 z^2 \right] + C \hat{\ell} \cdot \hat{s} + D \ell^2
\]  (2.20)
where $\omega_x$, $\omega_y$ and $\omega_z$ are one-dimensional oscillator frequencies in the x, y and z direction. The eigen value equation $H\Psi = E\Psi_i$ is satisfied by the Hamiltonian in equation 2.20. The Hamiltonian in equation 2.20 has a spherical limit at $\beta_2=0$. Although it is useful an alternative version needs to be introduced with nuclear deformation parameters $\delta = \frac{3}{2}\sqrt{\frac{5}{4\pi}}\beta_2$ and $\beta_2=1.057\delta$. To do this we write

\begin{align*}
\omega^2_x &= \omega^2_y = \omega^2_0\left(1 + \frac{2}{3}\delta \right) \quad (2.21) \\
\omega^2_z &= \omega^2_0\left(1 - \frac{4}{3}\delta \right) \quad (2.22)
\end{align*}

where $\omega_0$ is the oscillator frequency ($\hbar\omega_0 = 41A^{-\frac{1}{3}}$) in the spherical potential with $\delta=0$.

It is assumed that the nuclear volume remains constant as a function of $\omega_0$, which leads to the condition that $\omega_x\omega_y\omega_z$ is constant or

\begin{equation}
\omega_0 = \left(1 - \frac{4}{3}\delta^2 - \frac{16}{27}\delta^3 \right) = \text{constant} \quad (2.23)
\end{equation}

Inserting equations 2.21, 2.22, and 2.23 into 2.20 gives the Hamiltonian in terms of $r^2Y_{20}$ operator as follows

\begin{equation}
H = \frac{p^2}{2m} + \frac{1}{2m}\omega_0^2r^2 - m\omega_0^2r^2\delta^2\frac{4\pi}{5}Y_{20}(\theta, \phi) + C\hat{\ell} \cdot \hat{s} + D\hat{\ell}^2 \quad (2.24)
\end{equation}

where the coefficients $C$ and $D$ are constants of proportionality expressed in terms of parameters $\kappa = \frac{C}{2\hbar\omega_0}$ and $\mu = \frac{2D}{C}$ with $\kappa$ and $\mu$ around 0.06 and from 0 to $\approx 0.7$ respectively. The Nilsson Hamiltonian in equations 2.20 and 2.24 are both useful since they allow us to understand large and small deformations.

The Nilsson model comprises of the Nilsson diagram which correctly explains the ground state spins and parities of the majority of odd nuclei. A plot of single particle energy for protons and neutrons as a function of deformation $\varepsilon_2$ is called the Nilsson diagram. Figure 2.8 shows the Nilsson diagram for single-particle proton orbitals between the magic shell closures $Z=50$ and $Z=82$. The Nilsson diagram can be developed into a model for rotation of deformed odd-mass nuclei. Nilsson diagrams can be expressed in terms of the Nilsson orbitals with each orbit labelled as follows:

\begin{equation}
K^\pi[N, n_z, \Lambda]
\end{equation}
By definition $K = \Lambda + \Sigma = \Lambda \pm \frac{1}{2}$, where $K$ is the projection of the total angular momentum on the symmetry axis with $K = \Omega$ for a single particle model, $\Lambda$ is the component of the angular momentum along the symmetry axis and $\Sigma$ is the projection of the intrinsic nucleon spin on the symmetry axis [21]. The quantity $\pi$ is the parity of the states with negative parity indicated by dashed lines while an unbroken solid line represents positive parity. The letter $N$ is the principal quantum number of the major shell denoting the total number of oscillator quanta $N = n_x + n_y + n_z$, $n_z$ is the number of nodes along the symmetry axis, these quantum number notations are illustrated in Fig. 2.9.

**Figure 2.8:** Nilsson diagram of single-proton energies ($50 < Z < 82$) as a function of $\varepsilon_2$ [37].
2.4 Interaction of $\gamma$-Rays with Matter

In spite of the fact that countless interaction techniques are known for $\gamma$-rays in matter, just three noteworthy kinds assume a critical part in radiation measurements: photoelectric effect, Compton scattering and pair production [38, 39]. Every one of those procedures prompt the partial or total exchange of the $\gamma$-ray photon energy to electron energy. In Fig. 2.10, the line between the Compton scattering and pair production region symbolises the energy at which the two are equally probable. The line between the photonelectric effect and Compton scattering region symbolises the energy at which the two are equally probable.

![Figure 2.10: The three regions at which the three $\gamma$-ray interactions are dominant [38].](http://etd.uwc.ac.za/)
2.4.1 Photoelectric Effect

In the photoelectric effect, an electron which is bound in an atom experiences an interaction with a photon. In this interaction the incident photon totally vanishes and an energetic photoelectron is ejected out of the atom from one of its bound shells [28]. The difference between the incident photon energy \( (h\nu) \) and the binding energy of the photoelectron in its original shell \( (E_b) \) is equivalent to the kinetic energy \( E_{e^-} \) of the ejected photoelectron. Hence the kinetic energy of the photoelectron is given by [38]

\[
E_{e^-} = h\nu - E_b \tag{2.25}
\]

If a photon comes to or surpasses a threshold energy, the binding energy of the electron and the work function of the material, then the photoelectric effect will discharge photoelectrons. Most of the incident photon energy \( (h\nu) \) is carried off by the photoelectrons for \( \gamma \)-rays with energies of over a few hundred keV. A photoelectric interaction takes place creating an absorber atom with a vacancy in one of its bound shells which is occupied by the rearrangement of electrons from other shells of the atom or through capture of a free electron from the material. Another vacancy is created by the rearrangement of electrons from other shells, which is occupied by an electron from a shell with much lower binding energy. Consequently, a cascade of more characteristic X-ray emission probability declines when the absorber atomic number decreases. In a few cases, the discharge of an Auger electron may replace the characteristic X-ray in the loosing of the atomic excitation energy as shown in Fig. 2.11.

![Figure 2.11: A schematic diagram illustrating the photoelectric effect.](http://etd.uwc.ac.za)
The dominating method of absorption for $\gamma$-rays or X-rays of generally low energy is the photoelectric process. This process increases for absorber materials of high atomic number $Z$. No single analytical formula exists for the likelihood of photoelectric absorption per atom over all ranges of $E_\gamma$ and $Z$, yet an approximate estimation is

$$\tau \cong \text{constant} \times \frac{Z^n}{E_\gamma^{3.5}}$$

(2.26)

where $Z$ is the atomic number and the exponent $n$ varies between 4 and 5 over the $\gamma$-ray energy region of interest. The extreme reliance of the photoelectric absorption likelihood on the atomic number of the absorber is an essential explanation behind the prevalence of high $Z$ materials in $\gamma$-ray shields. In spite of the fact that the likelihood of the photoelectric absorption of gamma photon diminishes, as a rule with increasing energy. There are sharp discontinuities in the cross section curve which are known as absorption edges. They relate to the binding energies of electrons from atoms in the bound shells. Figure 2.12 gives a plot of the photoelectric absorption cross section for Pb.

Figure 2.12: The photoelectric effect cross section as a function of the incident photon energy for Pb [31].
2.4.2 Compton Scattering

The procedure of Compton scattering discovered in 1923 by A. H. Compton [39] happens when an inelastic scattering of an incoming incident photon by a charged particle (mostly electrons) takes place. The scattered photon shows a decrease in energy resulting in the increase of wavelength and lower frequency. In the event of Compton scattering, the incoming incident photon is redirected through an angle $\theta$ with regard to its original direction. Part of the photon energy is transferred to the recoil electron as shown in Fig. 2.13. The energy transferred can start as small as zero up to a large fraction of the incident $\gamma$-ray energy.

![Diagram of Compton scattering](http://etd.uwc.ac.za/)

The change in wavelength of the scattered photon is given by [40]

$$\Delta \lambda = \frac{h}{m_e c} \left(1 - \cos \theta\right)$$  \hspace{1cm} (2.27)

where $\lambda$ is the initial wavelength, $\lambda'$ is the wavelength after scattering, $h$ is the planck constant $= 6.626070041 \times 10^{-34} m^2 kg/s$, $m_e$ is the electron rest mass $= 0.511$ MeV, $c$ is the speed of light and $\theta$ is the scattering angle. The amount $\frac{h}{m_e c}$ is known as the Compton wavelength of the electron [41]. The change in wavelength $\Delta \lambda$ is equivalent to $2.43 \times 10^{-12} m$ for minimum change when $\theta = 0^\circ$ ($\cos \theta = 1$) and $4.86 \times 10^{-12} m$ for maximum change when $\theta = 180^\circ$ ($\cos \theta = -1$). The wavelength shift $\Delta \lambda$ is at least no less than zero and at most double the Compton wavelength of the electron. The likelihood of Compton scattering per one interaction with an atom increases linearly with atomic number $Z$, since it relies upon the number of electrons which are accessible for scattering in the target [28]. The angular distribution of photons scattered from a single free electron is given by the Klein-Nishina formula [38] as shown in equation 2.28. This formula gives the differential cross section of photons scattered from a single free electron.
\[
\frac{d\sigma}{d\Omega} = Zr_0^2 \left( \frac{1}{1 + \alpha(1 - \cos\theta)} \right)^2 \left( 1 + \cos^2\theta \right) \left( 1 + \frac{\alpha^2(1 - \cos\theta)^2}{(1 + \cos^2\theta)[1 + \alpha(1 - \cos\theta)]} \right) \]

(2.28)

Where \(\alpha = \frac{h\nu}{m_0c^2}\) and \(r_0\) is the classical electron radius. The dispersion is indicated graphically in Fig. 2.14.

**Figure 2.14:** The Compton cross section over a range of commonly encountered energies calculated using the Klein-Nishina formula.

### 2.4.3 Pair Production

Pair production is a phenomenon of nature where electro-magnetic energy is directly changed into matter. The phenomenon of pair production can be seen in Fig. 2.15. The production of an elementary particle and its anti-particle from a neutral boson refers to a photon making an electron-positron pair close to a nucleus, from a packet of electromagnetic energy (high energy photon-\(\gamma\)-ray) going through matter. It is one of the conceivable ways in which \(\gamma\)-rays interact with matter. At high energies this interaction dominates as shown in Fig. 2.10. In order for the electron-positron pair production to happen, the electromagnetic energy of the photon must be over the threshold energy,
which is equivalent to the rest mass of two electrons. The threshold energy for electron-
positron pair production is equivalent to 1.02 MeV which is two times the rest mass
of an electron (2x0.511 MeV), since the rest mass of a single electron is 0.511 MeV of
energy \([28]\). The kinetic energy of the pair is given by

\[
E_{\text{kin}} = E_\nu - 2m_0c^2 = E_\nu - 1.022\,\text{MeV}
\]

(2.29)

Figure 2.15: An illustration of pair production.
Chapter 3

Experimental Research Techniques

3.1 Reaction Choice

There are a few factors that need to be taken into consideration in order to successfully perform an experiment. These factors are beam (projectile nucleus), beam energy and the target nucleus. In this work we used the program Projected Angular Momentum Couple Evaporation (PACE4) [42] simulation code. This program was used to establish the best combination of the beam, beam energy and target nucleus that will maximize the yield of the $^{152}$Gd nucleus of interest. PACE4 uses a Monte Carlo simulation to give the predicted calculations of cross-section, the percentage yield of Heavy Ion Fusion Evaporation (HIFE) reactions and the possible contaminant nuclei. Figure 3.1 illustrates the predicted percentage yield of the $^{152}$Gd nucleus of interest and some contaminant nuclei. The vertical dotted black line indicates the chosen beam energy. Clearly, the yield of the $^{152}$Gd nucleus is 94.1% with contaminant nuclei occupying the remaining 5.9%. The choice of the beam energy also needs to consider the Coulomb barrier that needs to be overcomed by the beam (projectile) and the target nucleus in order for the nuclear reaction to take place. We used equation 3.1 [43] to calculate the Coulomb barrier for our $^{150}$Sm($\alpha$, 2n)$^{152}$Gd fusion evaporation reaction and the Coulomb barrier was found to be 17.3 MeV. The beam energy was chosen to be 25 MeV as indicated by
the dotted black line in Fig. 3.1, this is well above the Coulomb barrier indicating that
the reaction will take place.

\[ V_{cb} = \frac{1.44 Z_1 Z_2}{1.16(A_1^\frac{2}{3} + A_2^\frac{2}{3} + 2)} \]  

(3.1)

In equation 3.1, \( Z_1 \) and \( Z_2 \) are the atomic numbers of the beam and target nucleus respectively with \( A_1 \) and \( A_2 \) being the mass numbers of the beam and the target nucleus respectively. When performing an experiment we use thick (>1mg/cm\(^2\)) or thin (<0.5mg/cm\(^2\)) targets. In this experiment we used a \(^{150}\)Sm target nucleus with a thick thickness of 3.5 mg/cm\(^2\). The use of thick targets gives more events since there are more interactions consequently increasing the statistics. Thick targets stop the majority of recoils within the target without the use of backing. The \(^{150}\)Sm target nucleus has a high isotopic purity of 96%, thus decreasing the probability of obtaining contaminant nuclei.

**Figure 3.1:** PACE4 simulation for the \(^{150}\)Sm(\(\alpha\), 2n)\(^{152}\)Gd fusion evaporation reaction yields. The vertical dotted black line indicate the point where the beam was chosen.

http://etd.uwc.ac.za/
3.2 Heavy Ion Fusion Evaporation Reaction (HIFE)

The rotational states of the $^{152}$Gd nucleus of interest were excited using the fusion evaporation reaction. In fusion evaporation reactions the projectile nucleus approaches the target nucleus with a certain amount of energy. It then comes into contact with the target nucleus and they fuse together, therefore forming a compound nucleus. The projectile and target nucleus need to overcome the Coulomb barrier in order to fuse together as mentioned in section 3.1 and calculated by equation 3.1. As the projectile fuses with the target nucleus it delivers excitation energy and angular momentum to the compound nucleus. At this point the compound nucleus is at an excited state and is highly unstable. The nucleus starts to emit protons, alphas and neutrons (particles) in an attempt to de-excite to the ground state and become stable. Neutrons are uncharged particles and are preferentially favoured to be emitted first, they are then followed by charged particles, namely alphas and protons. In the process of emitting these particles the compound nucleus loses some of its excitation energy and angular momentum. Each emitted particle takes energy away from the compound nucleus causing it to de-excite into a residual nucleus which loses all of its energy and angular momentum by emitting $\gamma$-rays, therefore de-exciting to the ground state. Figure 3.2 gives a schematic representation of the fusion evaporation reaction from the point the projectile comes into contact with the target to the ground state.

![Figure 3.2: A schematic diagram showing the process of fusion evaporation reaction](44).

http://etd.uwc.ac.za/
In this work a $^4\text{He}$ projectile nucleus with 25 MeV of energy came into contact with a $^{150}\text{Sm}$ target nucleus forming an excited $^{154}\text{Gd}$ compound nucleus. The $^{154}\text{Gd}$ compound nucleus then starts to de-excite by emitting two neutrons and becomes a $^{152}\text{Gd}$ residual nucleus. The $^{152}\text{Gd}$ residual nucleus then loses all its energy and angular momentum by emitting $\gamma$-rays.

3.3 Detection of $\gamma$ Radiation

3.3.1 High Purity Germanium (HPGe) Detectors

High purity photon detectors are made from hyper-pure crystals of semi-conductors Si ($Z=14$) and Ge ($Z=32$). They are reverse biased to form a depletion layer in which the photons are detected. Much larger volumes of depleted semi-conductors can be achieved with Ge. Si detectors are used to detect photons with energies less than 50 keV. Ge detectors, with high Z, are used for photons with energies greater than 50 keV. The thickness of the depletion region of this detector is given by:

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

where $V$ is the reverse bias voltage, $N$ is the net impurity concentration in the bulk semi-conductor material, $\epsilon$ is the dielectric constant and $e$ is the electronic charge. Greater depletion depths are achieved by lowering the value of $N$ at a given applied voltage through further reductions in the impurity concentration. There are two ways to reduce the net impurity concentration. The first approach to reducing the net impurity concentration is by the process of lithium (Li) ion drifting. This process has been applied in both silicon (Si) and germanium (Ge) crystals to compensate the material after the crystal has been grown. Germanium detectors developed by the lithium drifting process are denoted by Ge(Li). A major disadvantage of the Ge(Li) detector is that they have to be continuously maintained at liquid nitrogen temperature to prevent redistribution of the drifted lithium at room temperature. Furthermore, the Ge(Li) detector is highly prone to neutron damage and therefore has limitations in $\gamma$-ray spectroscopy. The second technique is zone refining, with this approach impurity levels as low as $10^9$ atoms/cm$^3$ can be achieved. This technique is applicable to germanium detectors due...
to their low melting point of 959°C and not to silicon which has a melting point of 1410°C. Detectors containing this ultrapure germanium are called High Purity Germanium (HPGe) detectors. Lithium drifting is eliminated in HPGe detectors and unlike Ge(Li) these detectors do not always need to be maintained with liquid nitrogen. A schematic showing an HPGe detector connected to the liquid nitrogen dewer is given in Fig. 3.3. The crucial performance features such as detection efficiency and energy resolution are similar for Ge(Li) and HPGe detectors. The superiority of germanium detectors over silicon spectroscopy is due to their high atomic number $Z$ ($Z=32$), which increases absorption of $\gamma$-rays through the photoelectric effect.

![Figure 3.3: Illustration of an HPGe detector connected to a liquid nitrogen dewar](http://etd.uwc.ac.za/)

### 3.3.2 Clover Detectors

Clover detectors consist of four separate coaxial n-type HPGe crystals contained together in a four-leaf clover grouping and are mounted in a cryostat [45] as illustrated in Fig. 3.4. They are the first composite detector to be used in a large array [46]. Each HPGe crystal has a length and diameter of about 70mm and 50mm respectively. The four-leaf HPGe clover crystals are $\approx 0.2$mm apart from each other increasing the probability of detecting a Compton scattered $\gamma$ transition, scattered from a neighbouring crystal. Each clover detector is housed in a bismuth germanate (BGO) Compton suppression shield which is made of a highly efficient scintillator for $\gamma$-ray detection. The good polarization sensitivity of the clover detectors enables linear polarization measurements of weak intensity transitions to be made. The clover detectors have smaller crystals, lower capacity and short drift time for electrons, therefore resulting in good energy
resolution and time response. Energy resolution of clovers at 1.4 MeV using $^{152}$Eu source are 2.6 keV with 3 $\mu$s and 3.0 keV with 2 $\mu$s shaping time constant respectively. The smaller HPGe crystals have a smaller solid angle resulting in the reduction of Doppler broadening.

![Figure 3.4: Left: A clover detector fitted into a cryostat with its cylindrical nitrogen dewar. Right: A picture of a four segmented clover detector [47].](http://etd.uwc.ac.za/)

3.3.3 BGO Compton Suppression Shields

The BGO shields are scintillator detectors housing the Clover detectors as illustrated in Fig. 3.5. They are used to suppress or reduce the unwanted Compton background from $\gamma$-rays that Compton scatter out of the detector crystals. Bismuth germanate ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$) has a high atomic number ($Z=83$) and high density of the compound ($\sim3\text{g.cm}^{-3}$) which makes it an ideal Compton suppression shield. If a $\gamma$-ray penetrates the detector crystal and does not deposit all of its energy it will then Compton scatter out of the detector crystal interacting with the BGO shield. The BGO shield and the HPGe detector operate in anticoincidence with each other eliminating $\gamma$-ray events that interact with both the shield and the detector. The elimination of these $\gamma$-ray events improves the peak-to-total (P/T) ratio of a HPGe clover crystal. In Fig. 3.6 a spectrum of a $^{60}$Co source for an unsuppressed HPGe detector shows a peak-to-total ratio of roughly 20% and for a Compton suppressed the value is roughly 60%. The Compton suppressed HPGe detector is showing an improvement of about 40% and has good energy resolution.
Figure 3.5: A schematic showing a BGO shield housing the HPGe detector, a nitrogen dewar and a pm tube.

Figure 3.6: A spectra of a $^{60}\text{Co}$ source showing the P/T ratio of an unsuppressed HPGe detector and a Compton suppressed HPGe detector. For the Compton suppressed spectrum, the background from Compton scattering is reduced and the 1173 keV and the 1332 keV photopeaks dominate [47].
3.3.4 The AFRODITE Array

The AFRODITE is an acronym that stands for African Omnipurpose Detector for Innovative Techniques and Experiments. The AFRODITE array is a $\gamma$-ray spectrometer at iThemba LABS near Cape Town, South Africa. Its structure is based on the EXOGAM at the grand Accelerator National d’Ions Lourds in France with a rhombicuboctahedron frame that has 18 squares and 8 triangular facets [48]. Among the 18 square facets, 16 can be mounted with HPGe escape-suppressed n-type coaxial clover detectors and the remaining two situated at 0° and 180° are used for beam entry and exit as shown in Fig. 3.7. The 8 triangular facets can be mounted with p-type Low Energy Photon Spectrometer (LEPS) detectors. The HPGe detectors are positioned at angles of 45°, 90° and 135° to the beam direction as illustrated in Fig. 3.8. A maximum of 16 HPGe clover detectors can be accommodated by the AFRODITE array. In this experiment we only used 9 HPGe clover detectors. We placed 5 of the detectors at angle 90° and 4 at angle 135°. The AFRODITE array can also be used with ancillary detectors, namely solar cells, DIAMANT and recoil detector [48]. The AFRODITE set-up includes the target chamber that houses the target ladder. The target chamber has aluminium windows and is placed at the centre of the AFRODITE. The target ladder has four slots, two dedicated to target materials, one for the ruby to focus the beam and the last one for an empty frame. The target is mounted on the target ladder and the ladder is used to remotely control movements of the target to certain positions inside the target chamber.

Layout of the clover detectors in the AFRODITE spectrometer [47];

- Total opening angle: $\theta=23.2^\circ$.
- Solid angle per detector: $\Omega_{Ge}=1.34\%$ of $4\pi$ (for a 0.2mm distance between crystals).
- Photo-peak efficiency for 1.33 MeV: $\epsilon_{ph,Ge}=17.8\times10^{-4}$.
- Peak-to-total ratio for 1.33 MeV: $(P/T)_{Ge}=0.30$.
- Add-back factor for 1.33 MeV: 1.56.
- Distance from the crystal surface to the target centre: $D_{tc}=196\text{mm}$.
- Distance from the detector end-cap to the crystal surface: $D_{ec}=2.0\text{mm}$.
Figure 3.7: A picture of the AFRODITE spectrometer array [47].

Figure 3.8: A diagram of the detector arrangement in the AFRODITE array [47].
3.4 Angular Distribution and Correlation of $\gamma$-Rays

3.4.1 Angular Distributions

The angular distribution $W(\theta)$ of $\gamma$-rays is a measurement of the intensity of gamma transitions as a function of the angle $\theta$ with respect to the beam direction. For angular distribution to occur, oriented nuclear states are necessary. Oriented means that the population of the $m$ substates relies solely on the magnitude of $m$ and not its sign [37].

The basic representation of the angular distribution as a function of $\theta$ is given by:

$$W(\theta) = \sum_k a_k P_k(cos\theta)$$  \hspace{1cm} (3.3)

where $W(\theta)$ is the $\gamma$-ray intensity measured at angle $\theta$ with respect to the beam direction and $a_k$ are coefficients of the corresponding Legendre polynomials $P_k(cos\theta)$ that depend upon the spins of the initial and final states from which the $\gamma$-ray transition originates and upon the multipolarity of the $\gamma$-ray transition. The quantity $k$ takes even numbers solely for preservation of parity, hence $k=0,2,...,2I$. Relative population parameters $P(|m|)$ of the angular momentum substates have to be unequal ($P(|m|)\neq P(|m'|)$) to give a non isotropic $\gamma$-ray angular distribution. Where $m$ is the magnetic quantum number ranging as $m=-I,...,I$. Emitted $\gamma$-rays from such states give angular distribution of the form [14]:

$$W(\theta) = \sum_k a_k P_k(cos\theta) = a_0 P_0(cos\theta) + a_2 P_2(cos\theta) + a_4 P_4(cos\theta) + ..., \hspace{1cm} (3.4)$$

In heavy-ion fusion evaporation reactions a Gaussian distribution of substates is formed with the population parameters $P(m)$ given by:

$$P(m) = \frac{e^{-\frac{m^2}{2\sigma^2}}}{\sum_{m'=1}^{I} e^{-\frac{m'^2}{2\sigma^2}}} \hspace{1cm} (3.5)$$

where $\sigma$ is the width of the substate distribution.
3.4.2 Angular Correlations

Angular correlation measurements involve the determination of coincident intensities of two $\gamma$-rays in a cascade detected at angles $\theta_1$ and $\theta_2$. Consider two consecutive $\gamma$-rays, $\gamma_1$ and $\gamma_2$, emitted by a de-exciting nucleus from initial state $I_i$ to a final state $I_f$ via an intermediate state $I$ as shown in Fig. 3.9.

![Figure 3.9: Schematic diagram showing transitions of two consecutive $\gamma$-rays [47].](http://etd.uwc.ac.za/)

The $\gamma$-rays are detected by two detectors placed at $\vec{k}_1$ and $\vec{k}_2$ directions at angles $\theta_1$ and $\theta_2$ with respect to the beam direction (z-axis) as illustrated in Fig. 3.10.

![Figure 3.10: Geometry set-up of angles in a directional correlation of two successive $\gamma$-rays emitted from an axially oriented state [9].](http://etd.uwc.ac.za/)
Since $\theta_1$ and $\theta_2$ are the angles of $\vec{k}_1$ and $\vec{k}_2$ with respect to the beam axis and $\phi$ is the angle between the two planes, then the angular correlation $W(\theta_1, \theta_2, \phi)$ between two $\gamma$-rays, $\gamma_1$ and $\gamma_2$ in a cascade from an axially symmetric state $I_1$ is given by [37]:

$$W(\theta_1, \theta_2, \phi) = \sum_{\lambda_1, \lambda_2} B_{\lambda_1} \left( I_1 \right) A_{\lambda_1, \lambda_2} \left( \gamma_1 \right) A_{\lambda_2, \lambda_1} \left( \gamma_2 \right) H_{\lambda_1, \lambda_2, \lambda_2} \left( \theta_1, \theta_2, \phi \right)$$

(3.6)

where the indices $\lambda, \lambda_1$ and $\lambda_2$ are integers limited by the spins and multipolarities of the $\gamma$-ray transitions. $B_{\lambda_1} \left( I_1 \right)$ are orientation parameters that depend on the substate population parameters [37]:

$$B_{\lambda_1} \left( I_i \right) = (2I + 1) \sum_m (-1)^{I+1} (I - m) \lambda_0 > P(m)$$

(3.7)

The coefficient $A_{\lambda_1, \lambda_2}$ are defined as:

$$A_{\lambda_1, \lambda_2} = \left[ F^{\lambda_1, \lambda_2}_{\lambda}(L_1 L_2 I_f I_i) + 2\delta F^{\lambda_1, \lambda_2}_{\lambda}(L_1 L_2 I_f I_i) + \delta^2 F^{\lambda_1, \lambda_2}_{\lambda}(L_1 L_2 I_f I_i) \right] \frac{1}{1 + \delta^2}$$

(3.8)

The coefficients have information of the nuclear wave function, multipolarities, spins of the states and mixing ratios of the transitions. DCO measurements are performed by comparing the angular function $W(\theta_1, \theta_2, \phi)$ with an experimentally measured intensity $I_{\gamma_1 \theta_1 \theta_2}$, therefore we are able to get information about the $\gamma$-ray multipolarity of $\gamma_1$ or $\gamma_2$ from data.

### 3.5 Directional Correlations of $\gamma$-Rays from Oriented States (DCO)

The directional correlation of $\gamma$-rays from oriented states (DCO) is a method used to determine the multipole order (dipole or quadrupole) of a $\gamma$-ray transition. This is done by measuring the ratio ($R_{DCO}$) of two angular correlation functions $W(\theta_1, \theta_2, \phi)$ and $W(\theta_2, \theta_1, \phi)$. The DCO ratio from two angular correlation functions is given by:

$$R_{DCO} = \frac{W(\theta_1, \theta_2, \phi)}{W(\theta_2, \theta_1, \phi)}$$

(3.9)
where $W(\theta_1, \theta_2, \phi)$ is the angular correlation of $\gamma_1$ detected at $\theta_1$ in coincidence with $\gamma_2$ detected at $\theta_2$ and $W(\theta_2, \theta_1, \phi)$ is the angular correlation of $\gamma_1$ detected at $\theta_2$ in coincidence with $\gamma_2$ detected at $\theta_1$ as illustrated in Fig. 3.10. The experimental DCO ratio ($R_{DCO}$) of a $\gamma$-ray transition is given by:

$$R_{DCO} = \frac{I_{\gamma_1}(\text{Gated}_{\gamma_2})}{I_{\gamma_1}(\text{Gated}_{\gamma_2})}$$

(3.10)

where $I_{\gamma_1}(\text{Gated}_{\gamma_2})$ is the intensity of $\gamma_1$ detected at $\theta_1$ gated on $\gamma_2$ detected at $\theta_2$ and $I_{\gamma_1}(\text{Gated}_{\gamma_2})$ is the intensity of $\gamma_1$ detected at $\theta_2$ gated on $\gamma_2$ detected at $\theta_1$. In the current set-up of the AFRODITE spectrometer array, angles $\theta_1$ and $\theta_2$ are 45° or 135° and 90° respectively, with $\phi$ being approximately 15° on average. We treat angles 45° and 135° as one because of symmetry.

### 3.6 Linear Polarization Measurements

Linear polarization measurements can be used to determine the electric (E) or magnetic (M) nature of a $\gamma$-ray transition [49]. When $\gamma$-rays are linearly polarized, the angular distribution function of the scattered $\gamma$-rays depends on their outgoing direction $\theta$ with respect to the beam axis and on their electric field direction with respect to the reaction plane. Linear polarization of $\gamma$-rays can be defined in terms of their angular distribution function as [49]:

$$P(\theta) = \frac{W(\theta, \zeta = 0) - (\theta, \zeta = 90)}{W(\theta, \zeta = 0) + (\theta, \zeta = 90)}$$

(3.11)

it is the difference between the angular distribution function when their electric field is in or parallel to the reaction plane $W(\theta, \zeta=0^\circ)$ and when it is perpendicular to the reaction plane $W(\theta, \zeta=90^\circ)$ as shown in Fig. 3.11. Where $\theta$ is the angle of the outgoing $\gamma$-rays with respect to the beam axis. Clover detectors allow linear polarization measurements to be made [4]. They can be used for a wide range of things including to scatter incident $\gamma$-rays, an analyzer and a counter to detect $\gamma$-rays. Therefore enabling the clover detectors to measure the number of $\gamma$-rays scattered perpendicular ($N_\perp$) and parallel ($N_\parallel$) to the
The experimental linear polarization anistropy $A_P$ is defined by the difference between $N_\perp$ and $N_\parallel$ with respect to the beam direction divided by their sum:

$$A_P = \frac{a N_\perp - N_\parallel}{a N_\perp + N_\parallel}$$

where $a$ is the normalization constant found by taking the ratio of $N_\parallel$ to $N_\perp$ for unpolarized $\gamma$-rays and is given by:

$$a = \frac{N_\parallel}{N_\perp}$$

The polarization sensitivity $Q_k$ relates $P(\theta)$ and $A_P$:

$$A_P = Q_k P(\theta)$$

The polarization anistropy has a positive sign for stretched electric transitions and negative sign for stretched magnetic transitions, and the opposite for unstretched transitions.
3.7 Data Analysis

3.7.1 Energy Calibration

Before the experiment, energy calibration measurements were performed using a radioactive $^{152}$Eu source. In order to obtain enough counting statistics the $^{152}$Eu source ran for approximately 1 hour. The crystals of each clover detector collect data independently, hence energy calibration measurements were conducted to associate the channels to their relative energies. The calibration can be of a linear fit or a quadratic fit or a higher order polynomial fit. The energy calibration coefficients for this work are obtained through the quadratic equation given in equation 3.15.

$$E = a_0 + a_1 x + a_2 x^2$$  \hspace{1cm} (3.15)

Where $E$ is the energy of a $\gamma$-ray detected by the clover detector, $a_0$ represents the offset in keV and is the intercept on the energy axis, $a_1$ is the dispersion keV/channel which represents rate in change of energy, $a_2$ represents non-linearity and $x$ is the channel number [51]. Equation 3.15 can be mapped on a linear energy equation $E=0.5x'$ with $x'$ channels as shown in Fig. 3.12. The energy calibration coefficients have to be corrected if gain drift has been observed.

![Figure 3.12: The schematic mapping of the quadratic equation $E=a_0 + a_1 x + a_2 x^2$ and the linear equation $E=0.5x'$ [47].](http://etd.uwc.ac.za/)

Once the $^{152}$Eu source run has been sorted using MIDAS MTsort program and any gain drift has been corrected for by use of equation 3.16 and 3.17 together with Radware program [52], the $\gamma$-ray energies and the relative intensities of the source run $\gamma$-rays are
then saved in a .sto file. The Radware SOURCE program [52] is used to combine the .sto file and the .sou file (source data file) to form the .sin file. The Radware ENCAL program [52] is used to fit energy calibration and uses the output file from SOURCE (.sin file) as its input. ENCAL reads the data in the .sin file and perform polynomial fits to the energy calibration, therefore giving the energy calibration file as an output.

\[
a' = a \frac{P_h - P_1}{P_h + S_h - P_1 - S_1}
\]

(3.16)

\[
b' = \frac{1}{2} \frac{P_1 S_h - P_h S_1}{P_h + S_h - P_1 - S_1} + b \frac{P_h - P_1}{P_h + S_h - P_1 - S_1}
\]

(3.17)

Where \(a'\) and \(b'\) are the new calibration coefficients, \(a\) and \(b\) are the initial calibration coefficients, \(P_1\) and \(P_h\) are the reference peaks with \(S_1\) and \(S_h\) being the corresponding peak shifts.

### 3.7.2 Efficiency Calibration

After the experiment, efficiency calibration measurements of the AFRODITE clover detectors were made. A \(^{152}\)Eu radioactive source was used to perform these measurements. Most detectors are less than 100% efficient, so it is critical to have an accurate amount of the detector efficiency in order to relate the number of pulses counted to the number of \(\gamma\)-rays incident on the detector [4]. There are various sorts of efficiencies for \(\gamma\)-ray detectors, such as absolute efficiency, intrinsic efficiency, relative efficiency and photopeak or full energy peak efficiency. Some of these efficiencies can be defined as follows [37]:

The photopeak efficiency is given by:

\[
E_{ph} = \frac{N_{peak}}{\Omega N_{emitted}}
\]

(3.18)

where \(N_{peak}\) is the number of \(\gamma\)-rays in the photopeak, \(\Omega\) is the solid angle covered by the detector and \(N_{emitted}\) is the number of \(\gamma\)-rays emitted by the source.

The absolute efficiency is given by:
\[ E_{abs} = \frac{N_{det}}{\Omega N_{emitted}} \quad (3.19) \]

where \( N_{det} \) is the number of events detected.

The relative efficiency is given by:

\[ E_{rel} = \frac{(E_{ph}\Omega)_{detector}}{(E_{ph}\Omega)_{NaI}} \quad (3.20) \]

where \((E_{ph}\Omega)_{NaI} = 1.244 \times 10^{-3}\) for a NaI detector of 7.6 cm length and 7.6 cm diameter at a distance of 25 cm from the source. We obtained the .sin file from the \(^{152}\)Eu source run by using the methods used to obtain the .sin file in section 3.7.1. The Radware EFFIT program [52] uses input data taken from the .sin file to determine the relative efficiency curves for clovers at 90° and at 135°. Figure 3.13 gives the relative efficiency curve for 9 AFRODITE clover detectors obtained using a \(^{152}\)Eu source. The EFFIT program uses different equations to describe the efficiency at different energies and gives the efficiency calibration file as an output.

The efficiency at low energies is:

\[ \log(\text{eff}) = A + B \log \left( \frac{E_\gamma}{E_1} \right) + C \log \left( \frac{E_\gamma}{E_1} \right)^2 \quad (3.21) \]

The efficiency at high energies is:

\[ \log(\text{eff}) = D + E \log \left( \frac{E_\gamma}{E_2} \right) + F \log \left( \frac{E_\gamma}{E_2} \right)^2 \quad (3.22) \]

where \( A, B \) and \( C \) describe the efficiency at low energies, \( D, E \) and \( F \) describe the efficiency at high energies, \( E_\gamma \) is the \( \gamma \)-ray energy, and the constants \( E_1 \) and \( E_2 \) have the values 100 keV and 1 MeV respectively. The parameter \( C \) is by default a fixed zero.

The complete functional form for the efficiency is:

\[ \text{eff} = \exp \left[ (A + Bx + Cx^2)^{(-G)} + (D + Ey + Fy^2)^{(-G)} \right]^{(-\frac{1}{G})} \quad (3.23) \]

where \( G \) is an interaction parameter, \( x = \log \left( \frac{E_\gamma}{E_1} \right) \) and \( y = \log \left( \frac{E_\gamma}{E_2} \right) \).
3.7.3 Construction of $\gamma$-$\gamma$ Matrices and the $^{152}$Gd Level Scheme

The data collected during the experiment (in beam data) is sorted using MIDAS MTsort program. After sorting the data we ran it on MIDAS to get spectra and matrices. A matrix is a two-dimensional $E_{\gamma 1}, E_{\gamma 2}$ energy histogram with the energy of one photon on one axis and the energy of a coincident photon on the other axis [47]. A matrix is sometimes referred to as a plot of the number of coincidences vs $E_{\gamma 1}$, and simultaneously vs $E_{\gamma 2}$, the energies of the coincident quanta registered by the first and the second detectors respectively [47]. Figure 3.14 gives a representation of a two-dimensional matrix of the $^{152}$Gd nucleus of interest. We used the Radware program eg2rad to convert the matrix into a .m4b file which is a readable Radware format and can be analyzed using gf3 program. The matrix dimensions after conversion are 4095x4095 channels with a dispersion of 0.5 keV per channel. The Radware graphical analysis package escl8r uses the efficiency and energy calibration files, the projection spectra (x and y), the
Figure 3.14: A contour plot of a $\gamma-\gamma$ correlation matrix for the $^{152}$Gd nucleus. The orange colours correspond to the higher-intensity $\gamma$-rays, with respect to the cyan colour, which correspond to the lower intensity $\gamma$-rays.

background spectrum and the matrix as input files to build the decay scheme of $^{152}$Gd nucleus. To build a level scheme we had to analyze the projection spectra for coincidence $\gamma$-rays by gating on $\gamma$-ray transitions. If $\gamma$-rays are detected by different detectors within a short period of time [7] then they are said to be in coincidence with each other. This enables detection of $\gamma$-rays that belong to one decay path in the same nucleus. In order to identify the $\gamma$-rays that are in coincidence with a particular photopeak, a gate needs to be set on the ungated spectrum or on the total projection. The energy gated upon disappears as that energy cannot be in coincidence with itself unless there is a random, doublet or triplet. Analysing different gated spectra with a gate set on different $\gamma$-ray energies permits building of a level scheme with interconnected energies and intensities of the $\gamma$-rays as shown in Fig. 3.15. Normally, one starts with a few already known transitions and levels. Each transition is characterised by quantum properties namely, parity, spin and angular momentum. The transitions between the energy levels can be dipole, quadrupole or mixed.
3.7.4 \( \gamma \)-Ray Selection Rules

The conservation of angular momentum (L) has provided an enormous amount of information on the structure of nuclei and plays an important role in the \( \gamma \)-ray decay process. A stationary nucleus in a definite quantum mechanical state makes a transition to a lower energy state during gamma decay and emits a single photon. Both the initial \((I_i)\) and final \((I_f)\) states of the nucleus will have a definite angular momentum and parity \((\pi)\), so the photon must connect the two states and conserve both parity and angular momentum \([53]\). The conservation of angular momentum and parity are different and the conservation of each has a different effect on the possible properties of the emitted photon. Given known values of the spins of initial and final state of the nucleus, the angular momentum carried by the photon can take any value in the range:

\[
| I_i - I_i | \leq L \leq | I_i + I_i | \quad (3.24)
\]

Transitions with \( \Delta I=L \) are called stretched transitions and unstretched when \( \Delta I \neq L \). The multipolarity of the photon gives the amount of angular momentum carried by the photon. The parity of the photon depends on both the angular momentum and the nature (electric (E) or magnetic (M)) of the transition and is given by:
\pi(EL) = (-1)^L \quad (3.25)

\pi(ML) = (-1)^{L+1} \quad (3.26)

The electric and magnetic multipole radiation can also be described as $2^L$ pole radiation, with $L=1$ for dipole, $L=2$ for quadrupole and so on. The $\gamma$-ray selection rules are summarized in table 3.1.

**Table 3.1:** $\gamma$-ray selection rules and multipolarities [9].

<table>
<thead>
<tr>
<th>$L$</th>
<th>Multipolarity</th>
<th>Transition type</th>
<th>Parity change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dipole</td>
<td>Electric dipole (E1)</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnetic dipole (M1)</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>Quadrupole</td>
<td>Electric quadrupole (E2)</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnetic quadrupole (M2)</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>Octupole</td>
<td>Electric octupole (E3)</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnetic octupole (M3)</td>
<td>No</td>
</tr>
<tr>
<td>$L$</td>
<td>$2^L$</td>
<td>Electric $2^L$-pole</td>
<td>No for even $L$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Yes for odd $L$</td>
<td>Yes for even $L$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No for odd $L$</td>
<td>No for odd $L$</td>
</tr>
</tbody>
</table>
Chapter 4

Experimental Results

4.1 The decay scheme of $^{152}\text{Gd}$

The $^{152}\text{Gd}$ nucleus was populated using the $^{150}\text{Sm}(\alpha, 2n)^{152}\text{Gd}$ reaction with the use of the AFRODITE spectrometer. A total of $1 \times 10^9 \gamma$-$\gamma$ events were obtained in one weekend of beam time. The in beam data was sorted using MIDAS MTsort [54], after sorting we used Radware to construct a decay scheme. The present analysis established the already existing decay scheme of $^{152}\text{Gd}$ as seen by [1–4, 55] for both low spin and high spin states. The analysis also extended the decay scheme of $^{152}\text{Gd}$ by 33 new transitions, 26 levels and 2 new bands as shown in Figs. 4.1 and 4.2. The 33 new additional transitions are composed of 25 out-of-band and 8 in-band transitions. In the process of populating the $^{152}\text{Gd}$ nucleus of interest other contaminant nuclei were observed and their decay schemes were built and are given in this chapter in section 4.3. The DCO ratios and polarization anistropy measurements were conducted and their values are in Appendix A. Using those measurements and $\gamma$-ray selection rules we were able to assign spins and parities to the nuclear levels. Figures. 4.1 and 4.2 show the negative and positive parity bands respectively, the complete decay scheme is given in Appendix B.
CHAPTER 4: EXPERIMENTAL RESULTS

Figure 4.1: Partial decay scheme of $^{152}$Gd for negative-parity states from the $^{150}$Sm(α, 2n) reaction, with the newly observed states and γ-rays shown in red.

http://etd.uwc.ac.za/
FIGURE 4.2: Partial decay scheme of $^{152}$Gd for positive-parity states from the $^{150}$Sm(α, 2n) reaction, with the newly observed states and γ-rays shown in red.
4.2 DCO Ratios and Linear Polarization Plots

The DCO ratios and polarization anisotropy $A_P$ measurements performed in this study are contained in the table of $\gamma$-rays in Appendix A, shown in Figs. 4.3 and 4.4. To perform DCO ratio measurements we use the matrix at 90° (matrix90°) and the matrix at 135° (matrix135°). The two matrices are just collections of the $\gamma-\gamma$ events detected by clover detectors at 90° and at 135°. Figure 4.5 shows a spectrum of a matrix at 90° used to perform DCO ratio measurements. If the gate is set on a stretched quadrupole transition in the matrices, then the $R_{DCO}$ value for dipole transition is $\sim 0.56$ and for quadrupole transition is $\sim 1.05$. For gates set on stretched dipole transitions, the corresponding $R_{DCO}$ values are $\sim 1.1$ and $\sim 1.8$ respectively [56]. Figure 4.3 gives a plot of $R_{DCO}$ versus $\gamma$-ray energies for quadrupole and dipole transitions.

![Figure 4.3: Plot for measured DCO ratios ($R_{DCO}$). The $R_{DCO}$ for previously established transitions are in black while the $R_{DCO}$ for newly established transitions are in red. In blue are the $R_{DCO}$ of transitions that were observed previously but their $R_{DCO}$ could only be measured here in this work.]

The DCO ratio measurements for some of the $\gamma$-rays could not be measured since the statistics were insufficient but for most the measurements were performed. We conduct measurements for polarization anisotropy ($A_P$) using clover detectors placed at...
90° with respect to the beam axis. These clover detectors detect $\gamma$-$\gamma$ events scattered perpendicular and parallel to the emission plane inside the clover detectors and contain them in matrices referred to as vertical and horizontal matrices respectively. The two matrices contain unpolarized and polarized projection. For linear polarization anisotropy ($A_P$) measurements we used the polarized projection as shown in Fig. 4.6. In Fig. 4.4 the stretched and unstretched electric $\gamma$-ray transitions have measured $A_P > 0$ and $A_P < 0$ respectively. For stretched and unstretched magnetic transitions the measured values are $A_P < 0$ and $A_P > 0$ respectively [57]. Electric and magnetic transitions scatter perpendicular and parallel to the emission plane respectively.

**Figure 4.4:** Plot for measured polarization anisotropy ($A_P$). The $A_P$ for previously established transitions are in black while the $A_P$ for newly established transitions are in red. In blue are the $A_P$ of transitions that were observed previously but their $A_P$ could only be measured here in this work.
Figure 4.5: A spectrum constructed from a matrix used for $R_{DCO}$ ratio measurements. The transitions in black belong to the $^{152}$Gd nucleus of interest. The 122 keV and 248 keV transitions in blue belong to the $^{154}$Gd compound nucleus. The 334 keV and 227 keV transitions in green and brown are contaminant $\gamma$-rays belonging to the $^{150}$Sm and $^{153}$Gd respectively.
Figure 4.6: A polarized projection spectrum used for polarization measurements. The transitions in black belong to the $^{152}$Gd nucleus of interest. The 334 keV and 248 keV transitions in green and blue are contaminant $\gamma$-rays belonging to the target nucleus $^{150}$Sm and $^{154}$Gd compound nucleus respectively.
4.3 The contaminants

Simulation performed using PACE4 has predicted that the total cross-section of the $^{150}\text{Sm}(\alpha, 2n)^{152}\text{Gd}$ reaction at 25 MeV is 1013mb. The $^{152}\text{Gd}$ nucleus of interest constitutes about 94.1% of the total cross-section with the remaining cross-section occupied by contaminant nuclei. In this nuclear reaction the contaminants that were populated are $^{153}\text{Gd}$, $^{150}\text{Sm}$, $^{156}\text{Gd}$, $^{154}\text{Gd}$, and $^{150}\text{Gd}$ see Figs. 4.7 and 4.8. The de-excitation of the compound nucleus to the ground state by shedding particles results in contaminant nuclei being populated. The analysis of the contaminants did not produce any new transitions since the cross-section was very small. For analysis purpose of the data the decay schemes of contaminant nuclei were built in order to separate the transitions belonging to the contaminant nuclei from those that belong to the $^{152}\text{Gd}$ nucleus of interest. This made it easy to identify $\gamma$-ray transitions that do not belong to the nucleus of interest during the building process of the decay scheme of $^{152}\text{Gd}$ shown in Figs. 4.1 and 4.2.

![Diagram of decay schemes](http://etd.uwc.ac.za/)

**Figure 4.7:** The decay schemes of $^{150}\text{Sm}$, $^{156}\text{Gd}$, $^{154}\text{Gd}$ and $^{150}\text{Gd}$ contaminant nuclei extracted from $^{150}\text{Sm}(\alpha, 2n)^{152}\text{Gd}$ reaction.
Figure 4.8: The decay scheme of $^{153}$Gd contaminant nucleus extracted from $^{150}$Sm(α, 2n)$^{152}$Gd reaction.
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4.4 The positive parity bands.

4.4.1 Band 1 (The ground state band)

The current work confirms this band up to $I^π=16^+$. All the transitions in this band have $R_{DCO} \sim 1$ and $A_P > 0$ consistent with E2 character.

4.4.2 Band 2 ($0^+_2$ Band)

This band is known as the $0^+_2$ band and is described by [18] as a $\beta$-vibrational band. Recent evidence by [10, 19] suggests that the $0^+_2$ states in $N=88$ and $N=90$ are 2p-2h neutron states lowered into the pairing gap by configuration dependent pairing. It is argued that they are “pairing isomers” [20] forming a “second vacuum” [10]. The isotones of $N=88$ show strong E1 transitions from the $0^+_2$ band to the octupole band [4, 7, 8, 13, 58] suggesting that the bands are related. The work done on this band by [2] established it up to $I^π=16^+$. In this work we were able to observe this band up to $I^π=10^+$ with no new transitions observed. The DCO ratios and $A_P$ values of all the in-band transitions were measured and found to be $R_{DCO} \sim 1$ and $A_P > 0$, thus implying that they are stretched E2 transitions. This is consistent with the measurements that were carried out by previous in beam work [4]. It is worth noting that the DCO ratio and $A_P$ value of the 315 keV ($2^+ \rightarrow 0^+$) have been measured for the first time in this study. The out-of-band transition 931 keV ($2^+ \rightarrow 0^+$) was observed by [4, 55] but its DCO ratio could not be determined. In the present work we were able to measure both the DCO ratio and $A_P$ value for the 931 keV transition and they are 0.952(13) and 0.109(76) respectively. Both the DCO ratio and the $A_P$ value of the 587 keV ($2^+ \rightarrow 2^+$) could not be measured previously by [1–4, 55] but in this work we were able to measure them as 0.741(4) and 0.063(4) respectively. We measured the DCO ratio of 159 keV ($4^+ \rightarrow 3^-$) as 0.633(20) for the first time in this work indicating that it is of E1 character. The rest of the DCO ratios and $A_P$ value measurements were done mainly by [4] and are in agreement with the present measurements performed here in this work as shown in Appendix A table A.2.

http://etd.uwc.ac.za/
4.4.3 Band 3

The study of this band did not provide new transitions. In the current work the band is populated up to $I^\pi=20^+$ with previous work done by [2] populating it up to its highest spin $I^\pi=48^+$. The band is known as the S band and interacts with the ground band, in doing so it crosses the ground band. The DCO ratios and $A_P$ value measurements contributed three and two measured values respectively as shown in table A.3.

4.4.4 Band 4

The current information did not enable us to observe new gamma transitions or levels in this band but allowed us to measure the DCO ratios and $A_P$ values of four previously observed transitions which had not been measured before. The newly measured DCO ratios and $A_P$ values are for 519 keV ($11^+ \rightarrow 9^+$), 534 keV ($13^+ \rightarrow 11^+$), 1075 keV ($7^+ \rightarrow 6^+$) and 996 keV ($11^+ \rightarrow 10^+$) transitions. The DCO ratio for the 519 keV transition is 1.382(110) and the $A_P$ value is measured to be 0.013(54), therefore 519 keV is of E2 character. For the 1091 keV ($3^+ \rightarrow 2^+$) transition the DCO ratio and the $A_P$ value were found to be 0.779(18) and -0.054(53) respectively indicating that the 1091 keV transition is M1. The 1075 keV ($7^+ \rightarrow 6^+$) transition linking bands 4 and 1 has 0.566(24) and -0.156(86) as the DCO ratio and $A_P$ value respectively. These measured values of 1075 keV are consistent with magnetic nature of the first order (M1). The last of the newly measured transitions on this band is 996 keV with a DCO ratio and $A_P$ value of 0.389(98) and -0.156(86) respectively, linking bands 4 and 1 with an M1 transition.

4.4.5 Band 5

This band has three newly observed transitions, two of which are in-band transitions and one is an out-of-band transition. This band was previously seen up to $I^\pi=8^+$ by [4]. In this study we have extended it up to $I^\pi=12^+$. The two in-band transitions are 504 keV ($10^+ \rightarrow 8^+$) and 549 keV ($12^+ \rightarrow 10^+$) $\gamma$-rays. The DCO ratios and $A_P$ values of the two transitions could not be determined due to low statistics. In Figs. 4.9 (a) and (b), we have set multiple gates at 1236 keV ($8^+ \rightarrow 6^+$) and at 464 keV ($8^+ \rightarrow 6^+$) in order to observe spectra showing $\gamma$-rays in coincidence with the 504 keV and the 549
keV transitions. The transitions in Figs. (a) and (b), labelled in black belong to other bands in our nucleus of interest, in green and blue are contaminants belonging to $^{153}$Gd and $^{156}$Gd respectively. The insert spectra in Figs. (a) and (b), starting from 450 keV show the newly observed 504 keV and 549 keV transitions of the 1236 keV and 464 keV gates respectively. The newly observed out-of-band 585 keV ($8^+ \rightarrow 7^-$) transition linking bands 5 and 14 has an $A_P$ value of 0.118(2) but its DCO ratio could not be determined due to low statistics. The $A_P$ value of this transition indicates that it is of electric nature which is consistent with change of spin and parity. Gates placed at 504 keV ($10^+ \rightarrow 8^+$) on band 5 and at 411 keV ($7^- \rightarrow 5^-$) on band 14 gives spectra shown in Figs. 4.10 (a) and (b) confirming the newly observed 585 keV. Previously the DCO ratio and $A_P$ values of the 464 keV ($6^+ \rightarrow 4^+$) and 1243 keV ($6^+ \rightarrow 4^+$) transitions could not be measured by [1–3, 55]. In the current work we report that we were able to measure the DCO ratios and $A_P$ values of the two transitions, therefore making it possible to fairly assign the multipolarity of these transitions. The DCO ratio and $A_P$ value for 464 keV are 0.85(2) and 0.24(10) respectively, this is consistent with the 464 keV $\gamma$-ray being a stretched E2. A DCO ratio of 1.092(91) and $A_P$ value of 0.240(104) have been measured for the 1243 keV ($6^+ \rightarrow 4^+$) transition, linking bands 5 and 1, this is consistent with the $\Delta I=2$ expected for a pure E2 transition.
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Figure 4.9: (a) The gate was placed at 1236 keV out-of-band transition in band 5 showing the coincidence spectrum of the newly observed transitions 504 keV and 549 keV in red. (b) The gate was placed at 464 keV in band 5 showing the coincidence spectrum. The newly observed transitions 504 keV and 549 keV are in red.

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Figure 4.10: Multiple gates were constructed to examine the 585 keV out-of-band transition linking band 5 and 14. (a) The gate was set at 504 keV in band 5 showing the coincidence spectrum. The newly observed 585 keV transition is in red while the transitions in black belong to other bands. The γ-ray transition in green is a contaminant belonging to the target nucleus $^{150}$Sm. The insert spectrum starting from 450 keV shows the newly observed 585 keV transition of the same gate. (b) The coincidence spectrum of the $^{150}$Sm(α, 2n)$^{152}$Gd reaction was obtained by setting a gate at 411 keV transition in band 14. The newly observed 585 keV out-of-band transition is labelled red in the spectrum with the transitions in black belonging to the other bands in our $^{152}$Gd nucleus of interest. The insert spectrum starting from 450 keV shows the newly observed 585 keV transition of the same gate.

4.4.6 Band 6 ($0^+_3$)

The $0^+_3$ band in $^{152}$Gd was previously observed by [55] and has also been reported in another N=88 isotope [14]. This band lies at a higher excitation energy compared to the $0^+_2$ band as seen in both $^{152}$Gd and $^{150}$Sm [14, 55]. The analysis performed on this band did not yield any new transitions and observed the band up to $I^\pi=2^+$. Previous studies by [55] observed the 271 keV ($2^+ \rightarrow 0^+$), 703 keV ($0^+ \rightarrow 2^+$) and 703 keV
(2^+ \to 0^+) transitions but could not measure their DCO ratios and A_P values because of low statistics. The present analysis assigned a DCO ratio of 0.858(24) and A_P value of 0.166(94) to the 271 keV transition and this is consistent with the transition being an E2. For the 703 keV (0^+ \to 2^+) transition we have the DCO ratio and A_P value as 0.750(37) and 0.265(66) respectively. The 703 keV transition can be assigned to an E2 multipolarity. The second 703 keV (2^+ \to 0^+) transition on this band has a DCO ratio and A_P value of 0.777(62) and 0.505(55) respectively. This two measured values indicate that the transition is E2.

4.4.7 Band 7

We managed to extend this band up to spin 8^+, the band consists of two in-band and three out-of-band transitions. The newly observed in-band transitions are 437 keV (6^+ \to 4^+) and 765 keV (8^+ \to 6^+). The DCO ratios and A_P values of the two in-band transitions could not be measured. A gate was set at 779 keV (3^- \to 2^+) allowing us to measure the DCO ratio and A_P value of the newly observed out-of-band 684 keV (4^+ \to 3^-) transition as 0.716(69) and 0.113(167) respectively. The transition is of E1 multipolarity, which is consistent with ΔI=1 and the change in parity. For the 490 keV out-of-band transition, the DCO ratio and A_P value could not be measured. The last of the newly observed transitions on this band is 964 keV (6^+ \to 4^+) having a DCO ratio and A_P value of 0.901(126) and 0.070(120) respectively. The DCO ratio and A_P value of this transition give an indication that it is a stretched E2.

4.4.8 Band 8

In this newly observed band, we report the 504 keV (12^+ \to 10^+), 635 keV (14^+ \to 12^+) and 572 keV (10^+ \to 8^+) transitions for the first time. The DCO ratios of these transitions were measured to be 0.822(112), 0.750(79) and 1.153(33) respectively. The statistics were very low and we were unable to measure the A_P values. The DCO ratios of this transitions show that the transitions are of order two (quadrupole transitions), most likely E2.
4.4.9 Band 9

This band has only one in-band 696 keV transition, which is observed here for the first time. The DCO ratio and $A_P$ value of this transition could not be measured due to low statistics. However we have managed to measure the DCO ratio and $A_P$ value of a previously observed transition of $\gamma$-ray energy 727 keV ($7^+ \rightarrow 6^+$) [4]. The DCO ratio and $A_P$ value of this transition could not be measured by [1–3, 55, 59] but here for the first time we measured them as 0.419(95) and -0.026(145) respectively. The results are consistent with this transition being of M1 character.

4.4.10 The positive parity states not assigned to bands (10, 11, 12, and 13)

4.4.10.1 States 10

This states consist of out-of-band transitions and no in-band transitions, they are included for completeness. The analysis of these states brought about two newly observed transitions of $\gamma$-ray energies 1331 keV ($8^+ \rightarrow 6^+$) and 753 keV ($8^+ \rightarrow 7^+$). The $A_P$ values of the 1331 keV and 753 keV transitions are -0.645(45) and 0.459(87) respectively. We could not measure the DCO ratio of these transitions since the statistics were low. The $\gamma$-ray transition 1315 keV ($6^+ \rightarrow 4^+$) was seen by [4] but the DCO ratio and $A_P$ value could not be measured. The present analysis observed the DCO ratio and $A_P$ value of this 1315 keV transition to be 0.813(77) and 0.073(13) respectively. The DCO ratio and $A_P$ value of this transition are consistent with it being a stretched E2. The newly measured DCO ratio and $A_P$ value of the previously observed 793 keV ($4^+ \rightarrow 3^-$) transition are 0.503(82) and 0.032(99), and this is consistent with the 793 keV $\gamma$-ray being of E1 character.

4.4.10.2 States 11

The analysis done on these states produced two new transitions and provided DCO ratio and $A_P$ value measurements of previously observed linking transitions. The two newly observed transitions are 855 keV and 819 keV. We could not measure the DCO ratio and $A_P$ value of the 819 keV transition due to low statistics making it difficult to assign...
\(\gamma\)-ray multipolarity. The DCO ratio of the 855 keV transition could not be measured due to low statistics but the \(A_P\) value was measured as 0.737(96). We were able to measure the DCO ratios and \(A_P\) values of 1002 keV (12\(^+\) → 10\(^+\)) and 1495 keV (2\(^+\) → 2\(^+\)). We deduced a DCO ratio of 0.853(86) and \(A_P\) value of 0.206(96) for the 1002 keV transition. Our measurements yielded a DCO ratio of 0.538(104) and \(A_P\) value of 0.220(63) for the 1495 keV transition. We therefore assign the 1002 keV transition to be an E2 and 1495 keV to be an E1. The assignment of 1002 keV as an E2 is consistent with the DCO ratio and \(A_P\) value measurement as well as \(\Delta I = 2\). For the 1495 keV transition the assignment is consistent with \(\Delta I = 1\) and DCO ratio together with \(A_P\) value.

4.4.10.3 States 12

The work done on these states showed one new transition, which is the 618 keV (12\(^+\) → 11\(^-\)). A gate was placed on the 483 keV transition in band 14 to observe the newly populated 618 keV transition as shown in Fig. 4.11. The DCO ratio and \(A_P\) value of 618 keV are 0.676(44) and 0.415(87) respectively, making it possible to assign the transition as an E1. The analysis was also able to measure the DCO ratio and \(A_P\) value of the 1348 keV (4\(^+\) → 2\(^+\)) observed by [55] as 0.829(100) and 0.478(76) respectively. The two values indicate that the assignment of the 1348 keV \(\gamma\)-ray should be E2.
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Figure 4.11: Coincidence spectrum corresponding to gate placed at 483 keV transition. The newly observed 618 keV transition is in red and the transitions in black belong to other bands in our $^{152}$Gd nucleus of interest.
4.4.10.4 States 13

In this states we established three new transitions, namely 444 keV \((8^+ \rightarrow 6^+)\), 941 keV \((6^+ \rightarrow 4^+)\) and 834 keV \((8^+ \rightarrow 6^-)\). The transition 444 keV is a lone in-band transition with a DCO ratio of 0.768(75), the \(A_P\) value could not be determined due to low statistics. A spectrum showing the newly observed 444 keV \(\gamma\)-ray transition with a gate set at 941 keV is shown at Fig. 4.12. The second newly observed transition is the 941 keV, the transition has a DCO ratio and \(A_P\) value of 0.754(87) and 0.03(90) respectively. A gate placed at 527 keV \((4^+ \rightarrow 4^+)\) shows the \(\gamma\)-ray transition of the 941 keV as illustrated in Fig. 4.13. The states built on \(\gamma\)-ray transitions 834 keV and 444 keV are enclosed in parantheses since we could not measure the DCO ratios and \(A_P\) values of the two transitions.

![Figure 4.12](http://etd.uwc.ac.za/)


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**Figure 4.13:** Coincidence spectrum from the $^{150}$Sm($\alpha$, 2$n$)$^{152}$Gd reaction obtained by placing a gate on the 527 keV transition. The newly observed 941 keV transition is labelled in red. Transitions labelled in black belong to other bands in our $^{152}$Gd nucleus of interest. The insert spectrum starting from 850 keV shows the newly observed 941 keV transition of the same gate.

**4.5 The negative parity bands**

**4.5.1 Band 14 (Octupole band)**

This band has been observed by [1–3, 55] with [1] observing it up to $I^\pi=27^-$. The present analysis has allowed us to observe this band up to $I^\pi=15^-$. We report only two new transitions decaying out of this band namely the 212 keV ($7^- \rightarrow 6^+$) and the 192 keV ($3^- \rightarrow 2^+$) linking the octupole band (band 14) and the $0^+_2$ band (band 2). The DCO ratio of the 212 keV transition could not be measured since the transition was weakly populated but its $A_P$ value was measured to be 0.249(109). Its $A_P$ value is consistent with $\Delta I=1$ electric transition, we therefore suggest an assignment of an $E1$ to this transition. We place a gate on the 386 keV transition in band 2 and obtain a spectrum showing the newly observed 212 keV transition as shown in Fig. 4.14. The newly observed 192 keV transition has a DCO ratio and $A_P$ value of 0.412(7) and

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0.067(99) respectively, consequently the transition is an E1. A gate was placed on the 344 keV transition in band 14 and a coincidence spectrum showing the newly observed 192 keV was obtained as illustrated in Fig. 4.15. These E1 transitions between the $0^+_2$ band and the octupole band indicate that there is a structural relationship between them as suggested by Sheline [60].

**Figure 4.14:** The spectrum showing the newly observed 212 keV out-of-band transition in red obtained by placing a gate on the 386 keV transition in band 2. The transitions in black belong to other bands in the $^{152}$Gd nucleus of interest. The insert spectrum starting from 100 keV shows the newly observed 212 keV transition of the same gate.
4.5.2 Band 15

The highest spin observed in this band by the current work is $I^\pi=14^-$ with [1] observing it up to $I^\pi=40^-$. The DCO ratios and $A_P$ values of some of these transitions were measured by [4] and gave an indication that band 15 is a negative parity structure. The 364 keV ($8^- \rightarrow 6^-$) transition was observed by [4] but could not measure the DCO ratio and $A_P$ value of this transition. In this work we measured them to be 0.918(30) and 0.104(97) respectively. These measurements are consistent with this transition being a stretched E2. The in-band transitions of this band with $R_{DCO} \sim 1$ and $A_P > 0$ are in accordance with the assignment of E2.
4.5.3 Band 16

This band was established by [4] as a negative parity structure up to \( I^\pi = 17^- \). The present work observed it up to \( I^\pi = 13^- \) with no new transitions. The DCO ratios and \( A_P \) values of the 554 keV and 734 keV transitions were measured, the multipolarities of the transitions are E2 and E1 respectively. The 703 keV and 774 keV transitions could not be assigned \( \gamma \)-ray multipolarity due to lack of statistics.

4.5.4 Bands 17 and 18

We treat bands 17 and 18 jointly since the two bands are signature partners. The two bands are joined together by low energy cross band M1 transitions. In this work we observed band 17 up to \( I^\pi = 12^- \) with [4] establishing it up to \( I^\pi = 16^- \). The 995 keV (8\(^-\) → 7\(^-\)) transition decaying out of band 17 was previously observed by [4] but the DCO ratio and \( A_P \) value could not be measured. The respective DCO ratio and \( A_P \) value of the 995 keV \( \gamma \)-ray are 0.460(85) and -0.110(25) measured in this study and are consistent with this transition being an M1. We observed band 18 up to \( I^\pi = 17^- \) in this work and we were unable to extend it with new transitions.

4.5.5 The negative parity states not assigned to bands (19, 20 and 21)

4.5.5.1 States 19

These states have only out-of-band transitions and no in-band transitions. The are six newly observed transitions in these states. The newly observed transitions are 842 keV (5\(^-\) → 3\(^-\)), 1548 keV (6\(^-\) → 4\(^+\)), 1118 keV (7\(^-\) → 5\(^-\)), 1431 keV (7\(^-\) → 5\(^-\)), 1356 keV (9\(^-\) → 8\(^+\)) and 711 keV (9\(^-\) → 8\(^+\)). The DCO ratio and \( A_P \) value of the 1356 keV were measured to be 0.606(125) and 0.076(104) respectively. The DCO ratio and \( A_P \) value of the 1356 keV \( \gamma \)-ray transition suggest that it is an E1 consistent with \( \Delta I = 1 \). The 730 keV (11\(^-\) → 9\(^-\)) transition was previously observed by [4] but was unable to measure its DCO ratio and \( A_P \) value. This work measured them to be 1.160(10) and 0.200(11), the transition is then assigned to be a pure stretched E2. The spin and parity of these states are enclosed in parantheses since the intensities of the transitions were very low and the DCO ratio together with the \( A_P \) value could not be measured. A gate
was placed in band 14 on the 779 keV ($3^- \to 2^+$) transition in order to see a spectrum of the newly observed 842 keV transition as shown in Fig. 4.16.

![779 keV Gate in band 14](image)

Figure 4.16: A spectrum showing the newly observed 842 keV transition with a gate placed on the 779 keV transition in band 14. The insert spectrum starting from 750 keV shows the newly observed 842 keV transition of the same gate.

4.5.5.2 States 20

These states consist of three newly observed transitions, namely the 1329 keV ($9^- \to 8^+$), 715 keV ($1^- \to 0^+$) and 220 keV ($2^- \to 3^-$). The DCO ratio and $A_P$ value of the 1329 keV transition are 0.31(105) and 0.202(110) respectively, indicating that it is an E1. The DCO ratio and $A_P$ value of the 220 keV transition were not measured since the statistics were insufficient. The DCO ratio and $A_P$ value measurements of the 715 keV transition are 0.666(26) and 0.107(11) respectively. The DCO ratio together with the $A_P$ value indicate that the $\gamma$-ray multipolarity of the 715 keV transition is E1, consistent with the change of spin and parity. A gate was placed at 703 keV ($0^+ \to 2^+$) transition in band 6 showing a spectrum confirming the existence of the 715 keV transition as shown in Fig. 4.17.
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4.5.5.3 States 21

The 967 keV ($6^- \rightarrow 5^-$) transition is one of two newly observed transitions in these states, its DCO ratio and $A_P$ value could not be measured due to low statistics. The existence of the 967 keV was confirmed by setting a gate at 716 keV ($5^- \rightarrow 4^+$) in band 14 as illustrated in Fig. 4.18. The analysis also produced the newly observed 887 keV ($6^- \rightarrow 5^-$) transition. The DCO ratio and $A_P$ value of this transition could not be measured.
Figure 4.18: A gated spectrum confirming the newly observed 967 keV transition in red. The gate was placed on the 716 keV transition in band 14. The transitions in black belong to other bands in the $^{152}$Gd nucleus of interest. The insert spectrum starting from 900 keV shows the newly observed 967 keV transition of the same gate.
Chapter 5

Discussion

5.1 Octupole and Quadrupole Structures

The behaviour of the transitional rare earth nuclei with N=88 varies according to the number of protons. In the $^{152}$Gd nucleus of interest belonging to the heavier N=88 nuclei, consistent E1 transitions were observed from the $0^+_2$ band to the octupole band and vice versa. These interleaving E1 transitions may perhaps be indicating that the two bands are associated and share some characteristics. They suggest that the $0^+_2$ band has a level of octupole deformation and may form reflection asymmetric structures with the octupole band [61]. In Fig. 5.1 the $0^+_2$ band and the octupole band become signature partner bands from spin 3 to 7 and start splitting from spin 8 and upwards. This behaviour demonstrates that there is a structural relationship between the two bands as suggested by Sheline [60]. The signature partnering of the two bands maybe interpreted as a suggestion of octupole deformation of the $0^+_2$ states in $^{152}$Gd. A schematic Hamiltonian with pairing forces and particle-hole octupole-octupole forces was used by Chasman [16] to calculate the properties of the $0^+_2$ states in light U nuclei. He found that the $0^+_2$ states have significant octupole correlations and the ground states are quadrupole deformed. The are two ways of determining the degree of octupole deformation in the $0^+_2$ band.
CHAPTER 5: DISCUSSION

Figure 5.1: Plot of excitation energy minus rigid rotor, plotted as a function of spin for the ground band, the octupole band and the $0^+_2$ band.

The first criteria used would be the rotational frequency ratios ($\omega^-/\omega^+$) used in [61] and defined in equations 5.1 and 5.2 [15].

$$\omega^- (I)/\omega^+ (I) = 2 \frac{E(I+1)^- - E(I-1)^-}{E(I+2)^+ - E(I+2)^+} (I_{even})$$  \hspace{1cm} (5.1)

$$\omega^- (I)/\omega^+ (I) = 0.5 \frac{E(I+2)^- - E(I-2)^-}{E(I+1)^+ - E(I-1)^+} (I_{odd})$$  \hspace{1cm} (5.2)

Where $\omega^-$ is the rotational frequency of the octupole band and $\omega^+$ is that of the $0^+_2$ band. The rotational frequency ratio for structures with permanent octupole deformation would be one ($\omega^-/\omega^+ \approx 1$). Figure 5.2 gives the rotational frequency ratios as a function of spin plotted for $^{152}$Gd. The plot gives the pairing of the octupole band with the $0^+_2$ band and the ground band, plotted here in this work and also by [8, 14, 15]. The two plots will be compared to a known octupole deformed nucleus $^{224}$Ra [62]. In Fig. 5.2 the pairing of the $0^+_2$ band with the octupole band satisfies $\omega^-/\omega^+ \approx 1$, whereas pairing the ground band with the octupole band gives poor results.

The rotational frequency ratio of the $0^+_2$ band is $\approx 1$ indicating that the band is octupole deformed and may form reflection asymmetric structures with simplex quantum number...
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Figure 5.2: The rotational frequency ratios as a function of spin(I) for the pairing of the octupole band with the ground band and the $0^+_2$ band [8, 15] compared with a known octupole deformed $^{224}$Ra nucleus [62].

$s=1$ as reported by [16], not the ground band as indicated by [63]. The poor pairing of the ground band with the octupole band is an indication that the ground band is not octupole deformed. The rotational frequency ratio plots agree with the calculations made by Chasman [16]. The calculations showed that the $0^+_2$ band is octupole deformed and advocated for the ground band being quadrupole deformed. This means that the $0^+_2$ band is an octupole structure and the ground band might be a quadrupole structure as articulated by Chasman [16]. The second criteria for determining the level of octupole deformation in the $0^+_2$ band is to take the energy difference ($\Delta E$) between the $0^+_2$ band and the octupole band by use of equation 5.3 [15]. Given that octupole deformation is stable with change of spin then $\Delta E \approx 0$. This is seen in Fig. 5.3 were the pairing of the $0^+_2$ band with the octupole band gives $\Delta E \approx 0$. We also paired the ground band with the octupole band as shown in Fig. 5.3.

$$\pm \Delta E(I) = E(I) \pm \frac{E(I + 1) \pm E(I - 1) \pm}{2} \quad (5.3)$$

Figure 5.3 shows that pairing the $0^+_2$ band with the octupole band satisfies $\Delta E \approx 0$ [62] much better than pairing the ground band with the octupole band. The pairing of the $0^+_2$ band and the ground band with the octupole band is compared to the pairing of the
ground band with the octupole band in $^{224}_{88}$Ra$_{136}$ a well known octupole deformed nucleus [62]. The fact that pairing the $0^+_2$ band with the octupole band gives $\Delta E \approx 0$ indicates that stable deformation is taking place and the $0^+_2$ band is an octupole structure. It is again evident that pairing the ground band with the octupole band argues for the ground band being a quadrupole structure. Calculations similar to those of Chasman [16] need to be performed to determine the nature of this band.

![Energy difference graph](http://etd.uwc.ac.za/)

**Figure 5.3:** Energy differences ($\Delta E(I)$) between the negative and positive parity states [8, 15], compared to a known octupole deformed $^{224}_{88}$Ra nucleus [62]. For structures with permanent octupole deformation, this ratio would be $\approx 0$.

### 5.2 Congruent band Structures

The concept of congruence was seen in the transitional rare earth region specifically for the N=90 nuclei $^{154}$Gd and $^{152}$Sm [10]. The level schemes of $^{154}$Gd and $^{152}$Sm were treated as two different sets of congruent levels. The first congruent set was based on structures built on the ground band and the second set on structures built on the $0^+_2$ band as shown in Fig. 5.4. The $0^+_2$ band and the structures built on it were lowered by the excitation energy of the $0^+_2$ bandhead for both nuclei as illustrated in the figure. They were lowered in order to level them to their corresponding ground band and a congruency between structures built on the $0^+_2$ band and those built on the ground band was observed. The congruency of the structures built on the $0^+_2$ band with respect to
those built on the ground band is outstanding. In the figure, the data for $^{154}$Gd is a combination of $(\alpha, 2n)$ and $(\alpha, 4n)$ reactions. For $^{152}$Sm it is a combination of $\beta$ decay, $(\alpha, 2n)$ and Coulomb excitation reactions [64–67]. The congruent structures of these even-even nuclei in the transitional rare earth region are taken as an indication that the $0^+_2$ band is a second vacuum as stated by [10, 19, 68]. This means that the $0^+_2$ states are 2particle-2hole neutron states lowered into the pairing gap by configuration dependent pairing [10, 19, 68]. Traditionally the $0^+_2$ states are regarded as $\beta$-vibration by Bohr and Mottelson [18]. It has been suggested that the occurrence of these low-lying $0^+_2$ states in the N=88 and 90 nuclei is due to shape co-existence [64, 65]. The $0^+_2$ states are also said to be pairing isomers [20]. The congruency that is observed in the even-even N=90 nucleus $^{154}$Gd would be anticipated to occur in N=88 nucleus $^{152}$Gd [68]. The current work in Figs. 4.1 and 4.2 shows some few level structures built on the $0^+_2$ band but no band structures built on it. In addition, Fig. 5.5 shows the band structures that are built on the ground band and no band structures built on the $0^+_2$ band. Due to the fact that the are no band structures built on the $0^+_2$ band, we are unable to test the assumption that the are congruent structures built on the $0^+_2$ band and ground band in N=88 nuclei $^{152}$Gd nucleus. The absence of congruent structures in N=88 $^{152}$Gd nucleus may be caused by the deformation. The N=90 $^{154}$Gd and $^{152}$Sm nuclei are more deformed than the N=88 $^{152}$Gd and $^{150}$Sm nuclei. This means that the N=90 $^{154}$Gd and $^{152}$Sm have completely different band structures and decay pattern. Amusingly in the N=90 $^{152}$Sm nucleus, we see a second octupole band ($K^\pi=0^-$) with enhanced E1 transitions decaying to the $0^+_2$ band which we do not see in the N=88 $^{150}$Sm nucleus.
Figure 5.4: The congruency between structures built on the (a), (c) ground states and the (b), (d) first excited \( 0^+_1 \) states lowered by 681 keV for \( ^{154}\text{Gd} \) and by 685 keV for \( ^{152}\text{Sm} \) so that the \( 0^+_1 \) and the \( 0^+_2 \) are at the same level in the figure [10].
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Figure 5.5: The structures built on the ground state band are in black and in green. The structures in black were extracted from the current work obtained by the $^{150}\text{Sm}(\alpha, 2n)^{152}\text{Gd}$ reaction and in green were extracted from [4], obtained by the $^{152}\text{Sm}(\alpha, 4n)^{152}\text{Gd}$ reaction. In blue are the $0^+_2$ states with no structures built on them lowered by 615 keV so that the $0^+_1$ and $0^+_2$ are at the same level.
5.3 Systematic Comparison of $^{152}$Gd to other N=88 Isotones and $^{152}$Sm N=90 Isobar.

Direct comparisons (in the context of the systematics of the region) have been performed in this section in order to better understand the structural behaviour of bands that are being investigated in this work, namely the octupole and $K^\pi=0^+_2$ bands. The number of protons in N=88 isotones plays a crucial role in the systematics of these nuclei. Figure 5.6 shows a few N=88 isotones and their behaviour with increasing proton number. The $1^-_1$ states move below the $3^-_1$ states for lower Z ($Z<60$) and for higher Z ($Z>60$), the $1^-_1$ states move above the $3^-_1$ states [3] as shown in Fig. 5.6. It is clear in both Figs. 5.6 and 5.7 that at $Z=60$ the $1^-_1$ and the $3^-_1$ states nearly become degenerate in energy. The $3^-_1$ states increase in energy with increasing proton numbers. The $1^-_1$ states move further up from the $3^-_1$ states as the proton numbers increase as illustrated in Fig. 5.6. The above systematics of the low lying negative parity states in N=88 isotones are successfully explained by the quadrupole octupole coupling (QOC) model [3].

Additionally, the presence of strong E1 decays between the $K^\pi=0^+_2$ bands and the lowest negative parity bands in these nuclei suggest that there are enhanced octupole correlations [8, 15] between the bands. In light N=88 nuclei ($Z<60$) and in medium N=88...
nuclei \(60 \leq Z \leq 63\) E1 transitions are observed from the \(K^\pi=0^+_2\) bands to the octupole bands \([6–8, 13, 14, 58]\) as seen in Fig. 5.7 (a), (b), (c), and (d). In the nucleus of interest \(^{152}\text{Gd}\) which belongs to heavier \(N=88\) nuclei \((Z>63)\) E1 transitions were observed both from and to the \(K^\pi=0^+_2\) band and octupole band, with those decaying from the octupole band being reported for the first time in this study, see Figs. 4.1 and 4.2. In this study, we have also determined that these types of E1 decays are not only unique to heavier \(N=88\) isotope nuclei but have also been observed in the neighbouring \(N=90\) \(^{152}\text{Sm}\) with two more neutrons as shown in Fig. 5.8. The strength of these E1s in \(^{152}\text{Gd}\) and \(^{152}\text{Sm}\) isobar nuclei may be determined by comparing the branching ratios of out-of-band E1 transitions to in band E2 transitions to give a ratio of \(B(E1)/B(E2)\) taken between the \(K^\pi=0^+_2\) bands and the octupole bands. The branching ratios of E1s in \(^{152}\text{Gd}\) and \(^{152}\text{Sm}\) isobars are measured and recorded in table 5.1, plotted in Fig. 5.9. The strength of E1s in \(^{152}\text{Gd}\) and \(^{152}\text{Sm}\) isobars could not be conclusively compared due to the lack of \(B(E1)/B(E2)\) data points as seen in Fig. 5.9. In the \(^{154}\text{Dy}\) nucleus with two more protons than \(^{152}\text{Gd}\), E1 transitions have been observed from the octupole band to the \(K^\pi=0^+_2\) band \([9, 15]\). The observation of E1 transitions from the octupole bands to the \(K^\pi=0^+_2\) bands in heavier \(N=88\) nuclei \(^{152}\text{Gd}\) and \(^{154}\text{Dy}\) \([15]\) is due to the increase in excitation energy of the octupole band as shown in Figs. 5.6 and 5.7. The E1 transitions both from and to the \(K^\pi=0^+_2\) bands and octupole bands in \(N=88\) isotope nuclei indicate that the \(K^\pi=0^+_2\) bands have permanent octupole deformation \([9, 15]\). In the light \(N=88\) nuclei E1 transitions have been observed from the ground bands to the octupole bands starting at spin \(8^+\) upwards \([6, 13, 58, 69]\). This associates the light nuclei with static octupole deformation of the ground bands from spin \(8^+\) and above as shown in Fig. 5.7 (a), (b) and (c) \([8]\). For medium \(N=88\) nuclei the E1 transitions start at spin \(10^+\) upwards \([7]\) showing static octupole deformation of the ground bands from spin \(10^+\) and above \([8]\) as shown in Fig. 5.7 (d). In heavier \(N=88\) nuclei E1 transitions from the ground bands to the octupole bands have not been observed \([15, 70]\) as shown in Fig. 5.7 (e), (f) and (g). This leads to the suggestion that the ground bands in heavier \(N=88\) nuclei are quadrupole deformed \([8]\).
Figure 5.7: Partial decay schemes of N=88 nuclei (a)\(^{144}\)Ba [6], (b)\(^{146}\)Ce [13], (c)\(^{148}\)Nd [58], (d)\(^{150}\)Sm [14], (e)\(^{152}\)Gd [4], (f)\(^{154}\)Dy [15] and (g)\(^{156}\)Er [70] showing strong E1 transitions. The E1 transitions from the 0\(^+_2\) bands to the octupole bands are in red, from the octupole bands to the 0\(^+_2\) bands are in blue and from the ground bands to the octupole bands are in green.
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Figure 5.8: Partial decay scheme of $^{152}\text{Sm}$ N=90 nuclei with E1 transitions from the $0^+_2$ band to the octupole band in red and from the octupole band to the $0^+_2$ band in blue.

Table 5.1: Measured B(E1)/B(E2) branching ratios of E1 transitions both from and to the K$^\pi$=0$^+_2$ bands and octupole bands in $^{152}\text{Gd}$ and $^{152}\text{Sm}$ isobars. Transitions from the K$^\pi$=0$^+_2$ bands are labelled 0$^+_2$ and from the octupole bands are labelled oct.

<table>
<thead>
<tr>
<th>Transitions</th>
<th>E$_\gamma$ (keV)</th>
<th>B(E1)/B(E2)($10^{-9}$fm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+_2$ (10$^+ \rightarrow 9^-$)</td>
<td>361</td>
<td>143.69(7.50)</td>
</tr>
<tr>
<td>$0^+_2$ (8$^+ \rightarrow 7^-$)</td>
<td>258</td>
<td>97.61(4.78)</td>
</tr>
<tr>
<td>$0^+_2$ (6$^+ \rightarrow 5^-$)</td>
<td>197</td>
<td>111.99(5.08)</td>
</tr>
<tr>
<td>$0^+_2$ (4$^+ \rightarrow 3^-$)</td>
<td>159</td>
<td>46.96(2.85)</td>
</tr>
<tr>
<td>Oct (7$^+ \rightarrow 6^-$)</td>
<td>212</td>
<td>1.09(4.19)</td>
</tr>
<tr>
<td>$0^+_2$ (12$^+ \rightarrow 11^-$)</td>
<td>198</td>
<td>4521.87(506.37)</td>
</tr>
<tr>
<td>$0^+_2$ (10$^+ \rightarrow 9^-$)</td>
<td>200</td>
<td>1252.07(140.07)</td>
</tr>
<tr>
<td>$0^+_2$ (13$^- \rightarrow 12^+$)</td>
<td>161</td>
<td>871.41(97.48)</td>
</tr>
<tr>
<td>Oct (2$^+ \rightarrow 0^+$)</td>
<td>316</td>
<td>11829.19(1344.37)</td>
</tr>
</tbody>
</table>
The first excited $0^+_2$ states in the $N=88$ and 90 nuclei are found to occur at very low excitation energies of less than 900 keV. A lot of interpretations have been made in an attempt to try and explain the systematics of the $0^+_2$ states since they are not clearly understood [11, 12]. The low lying $0^+_2$ bands in $N=88-90$ nuclei are as a result of the crossing of the $\frac{1}{2}^+_2[660]$ and $\frac{1}{2}^-_2[505]$ Nilsson neutron orbitals as seen in Fig. 5.10. The minimum excitation energy of the $0^+_2$ bandhead for the $N=88$ nuclei was observed at the nucleus of interest $Z=64$ ($^{152}\text{Gd}$) as shown in Fig. 5.11. This is caused by the crossing of the $\frac{5}{2}^-_2[532]$ prolate orbital and the $\frac{3}{2}^+_2[413]$ weakly oblate orbital at proton number $Z=64$. 

**Figure 5.9:** B(E1)/B(E2) ratios for E1 transitions between the K$^\pi=0^+_2$ bands and the octupole bands in $^{152}\text{Gd}$ and $^{152}\text{Sm}$ isobars.
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Figure 5.10: Portion of the Nilsson diagram for neutrons. The low lying $\beta$ bands observed in the N=88-90 nuclei are due to the crossing of the bold $\frac{1}{2}[660]$ and $\frac{11}{2}[505]$ orbitals [3].

Figure 5.11: Systematics of the bands built on the first excited $0^+_2$ states in various N=88 nuclei [3, 14].

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5.4 Systematics of \( \gamma \) bands in N=88 Isotones Compared to Solutions of the 5DCH-CDFT

The five-dimensional collective Hamiltonian based on the covariant density functional theory (5DCH-CDFT), which can simultaneously treat the quadrupole vibrational and rotational excitations is expressed in terms of two deformation parameters \( \beta \) and \( \gamma \), and the three Euler angles (\( \phi, \theta, \Psi \) \( \equiv \Omega \)) \([71, 72]\). The five-dimentional collective Hamiltonian is given by \([44]\):

\[
\hat{H}_{\text{coll}}(\beta, \gamma) = \hat{T}_{\text{vib}}(\beta, \gamma) + \hat{T}_{\text{rot}}(\beta, \gamma, \Omega) + V_{\text{coll}}(\beta, \gamma)
\]

(5.4)

where the term \( \hat{T}_{\text{vib}}(\beta, \gamma) \) is the vibrational kinetic energy, \( \hat{T}_{\text{rot}}(\beta, \gamma, \Omega) \) is the rotational kinetic energy and \( V_{\text{coll}}(\beta, \gamma) \) is the collective potential. The 5DCH-CDFT has been developed and extensively applied to describe the nuclear collective properties at low spins, such as the phase transitions, shape evolutions and many others in different regions \([73–76]\). In the 5DCH-CDFT calculations, with the collective parameters determined by the CDFT, the excitation energies and the collective wave functions for each value of the total angular momentum I can be obtained by diagonalizing the 5DCH. The 5DCH-CDFT was used in this work in order to describe the properties of the low-lying excitations in \( ^{152}\text{Gd} \) even-deformed nucleus in relation to \( ^{150}\text{Sm}, ^{154}\text{Dy} \) and \( ^{156}\text{Er} \) N=88 isotones as shown in Fig. 5.12. Figure 5.12 (a), (c), (e) and (g) gives the systematic plots of excitation energy (minus the energy of a rigid rotor) of rotational levels built on the ground state, \( 0^+_2 \) and \( \gamma \) bands compared to solutions of the 5DCH-CDFT in Fig. 5.12 (b), (d), (f) and (h). In most cases there is good agreement between the experimental data and the theoretical calculations of the 5DCH-CDFT for even-odd \( \gamma \) and \( 0^+_2 \) bands for N=88 nuclei, see Fig. 5.12. Some notable experimental features that are well reproduced by the 5DCH-CDFT calculations are \([44]\):

(a) The energy spacings between the ground, the \( \gamma \) and the \( 0^+_2 \) bands is fairly comparable.

(b) All the unperturbed members of the \( \gamma \) bands, more especially the odd spin members, appear to track the ground state bands as expected.

(c) The energy splitting between the even-odd spin members of the \( \gamma \) bands is well reproduced by theory.
(d) There is an evident band crossing observed between the $\gamma$ bands and the $0^+_2$ bands in N=88 isotones, see Fig. 5.12.

This work was able to extend the even $\gamma$ band (band 5) by two in-band transitions as shown in Fig. 4.1. The work also established in Figs. 5.12 (e) and 5.16 (c) that there is a signature splitting of the $\gamma$ bands (band 4 and band 5) up to spin $11^+$ as noticed in the neighbouring $^{154}$Dy nucleus by [77]. At spin $11^+$ the two $\gamma$ bands start to converge and this is taken as a sign of band mixing or change in the $\gamma$ bands. The presence of even-odd signature splitting of the $\gamma$ bands in Figs. 5.12 (e) and 5.16 (c) indicates that there is a possibility of $\gamma$ deformation in $^{152}$Gd nucleus. The splitting of the $\gamma$ bands in $^{152}$Gd seems to be moderate unlike in some other N=88 isotones which is substantial and can indicate permanent $\gamma$ deformation [78]. Gamma bands are expected to track the intrinsic configuration [79], in most cases the ground band they are based on. This is found to be the case for nearly all the $\gamma$ and ground state bands as shown in Fig. 5.12 (a), (c), (e) and (g) with just a couple exceptional cases where the even $\gamma$ bands deviate from the trend. The deviation of the even $\gamma$ bands in Fig. 5.12 (a) and (g) is due to band mixing which is as a result of band crossing between the even $\gamma$ band and the $K^{\pi}=0^+_2$ band.

The $\gamma$ bands have moments-of-inertia that are similar to those of the grounds bands, this is why they are seen to constantly track the ground bands through out the $^{150}$Sm–$^{156}$Er N=88 isotones as illustrated in Figs. 5.12 and 5.13. Figure 5.13 shows the theoretical moments-of-inertia of the $\gamma$ bands mimicking the behaviour of the experimental $\gamma$ bands, their moments-of-inertia are comparable to those of the ground bands. The most visible observation in the figure is that the theoretical bands rise rapidly in moment-of-inertia than the experimental ones. These difference between theory and experiment might be due to an assumption of adiabatic approximation of the collective Hamiltonian [72, 81].

The agreement between theoretical results and experimental data can be improved by using the empirical ab formula of moments-of-inertia [82] which is responsible for the fourth order effect of the collective Hamiltonian. Regardless of the slight differences indicated before, the general agreement between theory and experimental data is very good.

The signature splitting between the even and odd $\gamma$ bands has been proposed as a
method of differentiating between the $\gamma$ rigid and $\gamma$ soft triaxial shapes \[17\]. Figure 5.14 gives the experimental structures of $^{152}$Gd nucleus compared with $\gamma$ rigid and $\gamma$ soft structures. From Fig. 5.14 it is clear that the $^{152}$Gd nucleus could be identified as a $\gamma$ soft.

The pattern displayed by the experimental structures is $2^+_\gamma$, $(3^+_\gamma-4^+_\gamma)$, $(5^+_\gamma-6^+_\gamma)$,... often taken to be characteristics of a $\gamma$ soft triaxial nucleus \[83, 84\]. For $\gamma$ rigid triaxial shapes

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a pattern of \((2^+_γ, 3^+_γ), (4^+_γ, 5^+_γ), (6^+_γ, 7^+_γ), \ldots\) is expected \[83, 84\]. An additional method of determining the soft or rigid triaxiality of \(^{152}\text{Gd}\) nucleus is by calculating the potential energy surface (PES) using the constrained triaxial covariant density functional theory with the density functional PC-PK1 \[81\] in the \(β-γ\) plane as shown in Fig. 5.15. Figure 5.15 gives the PESs for \(N=88\) isotones from \(^{150}\text{Sm}–^{156}\text{Er}\). The red dots from the PESs show the ground state shape of the nuclei. These nuclei show prolate-like shape in their ground states but show more or less different softness/rigidity in the \(β\) and \(γ\) directions. The PESs around the global minimum of \(^{152}\text{Gd}\) nucleus of interest in Fig. 5.15 is soft in the \(γ\) direction, therefore \(^{152}\text{Gd}\) is a \(γ\) soft triaxial nucleus. For the \(^{150}\text{Sm}–^{156}\text{Er}\) \(N=88\) isotope nuclei, with increasing protons, the PES around the global minimum becomes
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Figure 5.14: Comparison of the energy of the ground state band and energy staggering of (a) the experimental $\gamma$ bands in $^{152}$Gd, (b) the $\gamma$ rigid asymmetric-rotor model with $\gamma=30^\circ$ and, (c) the $\gamma$ soft rotor model with $\bar{\gamma}=30^\circ$ [78].

more rigid in the $\beta$ direction and a little bit softer in the $\gamma$ directions, as shown in Fig. 5.15.

The signature splitting of $\gamma$ bands can be measured using the staggering parameter $(S(I))$ [78] given by equation 5.5.

$$S(I) = \frac{[E(I) - E(I-1)] - [E(I-1) - E(I-2)]}{E(2^+)}$$ (5.5)

Where $E(I)$, $E(I-1)$ and $E(I-2)$ are the excited energy levels for the $\gamma$ bands at spins, I, I-1 and I-2 respectively. The $E(2^+_1)$ indicates the energy of the first excited $2^+_1$ state [44]. The energy staggering parameter in equation 5.5 was used to measure the splitting of the $\gamma$ bands in $^{152}$Gd nucleus. For an ideal axially symmetric rotor, this staggering parameter is a constant $S(I)=0.333$ and for a harmonic vibrator it shows a staggering behaviour with its absolute value being 1.0 and $S(4)=-1$. In Fig. 5.16 the experimental energy staggering parameters for the $\gamma$ bands of $^{150}$Sm, $^{152}$Gd nucleus of interest, $^{154}$Dy and $^{156}$Er N=88 isotones are plotted as functions of spin, in comparison with theoretical calculations of the 5DCH-CDFT. In the figure the calculated $S(I)$ satisfactorily reproduces the experimental data not only in the staggering behaviour but also in the absolute amplitude. The staggering parameter $S(I)$ shows an evident even-odd staggering with $S(4)\sim1$, indicating that there is a distinguishable vibrational character of the $\gamma$ bands.

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Figure 5.15: Potential energy surfaces (PESs) of N = 88 isotones in the β-γ plane. Minima are marked with red symbols, circles and triangles represent the global and secondary minima, respectively. The energy spacing in the contour lines is 0.25 MeV [80].

This is in agreement with their potential energy surfaces with slightly quadrupole deformed minimum and γ-soft character. The amplitude of S(I) increases with spin for $^{150}$Sm and $^{156}$Er but decreases for $^{152}$Gd and $^{154}$Dy.

Theoretical calculations of the 5DCH-CDFT were also used to predict the branching ratios of the γ bands in $^{150}$Sm–$^{156}$Er N=88 isotones as seen in Fig. 5.17. An important advantage of using collective models is that their calculations are parameter free. The
Figure 5.16: The experimental staggering parameter $S(I)$ for the $\gamma$ bands in the $N = 88$ isotones, in comparison with the calculated results of the 5DCH-CDFT [80].

A detailed explanation and theory of branching ratios is well documented in [50]. In Fig. 5.17 a systematic comparison between theory and experiment has been made for out-of-band to in-band branching ratios $\frac{B(\text{E2}; I_{\gamma} \rightarrow (I-2)_{g})}{B(\text{E2}; I_{\gamma} \rightarrow (I-2)_{\gamma})}$ for even $I$ and $\frac{B(\text{E2}; I_{\gamma} \rightarrow (I-1)_{g})}{B(\text{E2}; I_{\gamma} \rightarrow (I-2)_{\gamma})}$ for odd $I$, for $\gamma$ bands with respect to the ground bands. The vertical lines shown in the figure represent error bars for the odd spin members, which imply that the $B(\text{E2})$ value with a correct mixing ratio $\delta$ associated with the $I_{\gamma} \rightarrow (I-1)_{g}$ transitions lies anywhere within the limit. The minimum points of the vertical lines correspond to $\delta=1$ with the maximum corresponding to a pure E2. Furthermore, the experimental and theoretical results show a significant degree of staggering between $\frac{B(\text{E2}; I_{\gamma} \rightarrow (I-1)_{g})}{B(\text{E2}; I_{\gamma} \rightarrow (I-2)_{\gamma})}$ for odd $I$ and $\frac{B(\text{E2}; I_{\gamma} \rightarrow (I-2)_{g})}{B(\text{E2}; I_{\gamma} \rightarrow (I-2)_{\gamma})}$ for even $I$ as shown in Fig. 5.17. The overall agreement between the experimental and theoretical results is outstanding.
Figure 5.17: The calculated branching ratios for out-of-band to in-band transitions, $B(E2; I_γ \rightarrow (I-2)γ)/B(E2; I_γ \rightarrow (I-1)γ)$ for even $I$ and $B(E2; I_γ \rightarrow (I-2)γ)/B(E2; I_γ \rightarrow (I-1)γ)$ for odd $I$, for the $γ$ bands in $N=88$ isotones, in comparison with the available data.

The lowest value of the vertical lines, for $B(E2)$ values of odd spin members of the $γ$ bands correspond to $δ=1$ while the highest correspond to a pure $E2$.

In Fig. 5.18 the experimental $γ$-bandhead energies are plotted as a function of atomic number and compared to theoretical calculations. The experimental and theoretical $γ$-bandhead energies in $N=88$ nuclei decrease in energy with increasing proton numbers as illustrated in Fig. 5.18. This is consistent with the observation that the PES around the global minimum becomes softer in the $γ$ direction from $^{150}\text{Sm}$ to $^{156}\text{Er}$ for $N=88$ isotonic chain as shown in Fig. 5.15. The large strength of $γ$ vibrations are as a result of two pairs of states $\left( ^{5/2}_2[413],[^{1+}_2[411]) \right)$ and $\left( ^{3/2}_2[411],[^{1+}_2[411]) \right)$ in Nilsson proton orbitals as shown in Fig. 5.19. The lowest lying $γ$ bands appear at $Z=66-68$ since the two proton orbital pairs are found to be contributing at these proton numbers. At $Z=68$ ($^{156}\text{Er}$) the $2^+$ state of the even $γ$ band is energy degenerate with the $0^+_2$ state. Zolnowski [3] argued
that the $\gamma$ vibrational bandhead in $Z=70$ ($^{158}\text{Yb}$) when located should show an upturn in energy. Larger strength of $\gamma$ vibrations on the side of neutrons are found to occur at $\left(\frac{3}{2}^{-}[523],\frac{1}{2}^{-}[521]\right)$ and $\left(\frac{5}{2}^{-}[523], \frac{1}{2}^{-}[521]\right)$ in Nilsson neutron orbital pairs expected for $N\approx 98$.

**Figure 5.18:** $\gamma$ bands systematics for several $N=88$ nuclei [80].

**Figure 5.19:** Portion of Nilsson diagram for protons. Bold orbitals are those which are responsible for low lying $\gamma$ bands at $Z=66-68$ [3].
Chapter 6

Conclusion

The $^{152}$Gd nucleus of interest was populated through the $^{150}$Sm($\alpha$, 2n)$^{152}$Gd fusion evaporation reaction performed at iThemba LABS using the AFRODITE spectrometer array. A total of 25 out-of-band transitions, 8 in-band transitions, 26 levels and 2 new bands have been newly established in this work. Linear polarization (AP) and Directional Correlations from Oriented states (DCO) measurements were performed for both newly and previously observed transitions, with these measurements we assigned spins and parities to the transitions. In some N=88 isotone nuclei $^{144}$Ba [6], $^{146}$Ce [13], $^{148}$Nd [58] and $^{150}$Sm [14], E1 transitions have been observed from the K$^\pi$=0$^+_2$ bands to the lowest negative parity bands. However, this is not the case for heavier (Z>63) N=88 isotone nuclei. In heavier N=88 isotone nuclei more specifically $^{154}$Dy [15], E1 transitions have been observed from the lowest negative parity band to the K$^\pi$=0$^+_2$ band [15]. In this work E1 transitions have been observed from the K$^\pi$=0$^+_2$ band to the lowest negative parity band and from the lowest negative parity band to the K$^\pi$=0$^+_2$ band as shown in chapter 4, Figs. 4.1 and 4.2. These types of E1s are not only found in $^{152}$Gd (N=88) nucleus but have also been observed in the $^{152}$Sm (N=90) isobar. The E1 decays from the lowest negative parity bands to the K$^\pi$=0$^+_2$ bands are due to the increase in excitation energy of the lowest negative parity bands in heavier N=88 nuclei. These E1 transitions in N=88 isotones between the K$^\pi$=0$^+_2$ bands and the lowest negative parity bands show that the two bands are structurally related and have octupole correlations since they become signature partner bands at certain spins as shown in Fig. 5.1. The K$^\pi$=0$^+_2$ band has been identified as an octupole structure following its display of considerable octupole correlations with the octupole band [8, 15], consequently forming a simplex s=1
[63, 85, 86] alternating parity band. In lighter (Z<60) and medium (60≤Z≤63) N=88 nuclei E1 transitions were also observed from the ground bands to the lowest negative parity bands associating the ground bands with static octupole deformation beyond 8+ [6, 13, 58] and 10+ [7, 8] respectively. These E1 transitions were not observed in the 152Gd nucleus of interest and other heavier (Z>63) N=88 nuclei [4, 15, 70] indicating a decrease in deformation as proton number increases. In 152Gd the relative strengths of the E1 decays and the behaviour of the Kπ=0+ 2 band advocates for, however does not verify the Chasman evaluation of the ground band being quadrupole deformed. The analysis of the γ bands in 152Gd showed large signature splitting at lower spins. At high spins the signature splitting seem to decrease significantly and the even-odd γ bands start to converge at spin 11+ as shown in Fig. 5.12 (e). It follows from this argument, that the γ bands when observed at higher spins should be signature partner bands. The signature splitting of the even-odd spin members of the γ band provides information on the nature of the nuclear triaxiality [78]. The experimental structures of the γ bands were compared to those of γ rigid and γ soft triaxial shapes. The pattern displayed by the experimental structures is of γ soft triaxial nucleus as shown in Fig. 5.14. This was further confirmed by the potential energy surface (PES) around the global minimum of the 152Gd nucleus which is softer in the γ direction as seen in Fig. 5.15. The γ bands in N=88 isotones decrease in energy for heavier nuclei and increase in energy for lighter nuclei. The comparison of the experimental even-odd γ bands systematics to the theoretical solutions of the 5DCH/CDFT showed outstanding agreement between experiment and theory in most instances with just a few exceptional cases. The lowest negative parity states in N=88 nuclei increase in energy with increasing proton numbers as shown in Fig. 5.6. The systematics of the Kπ=0+ 2 states are effectively explained by the quadrupole octupole coupling (QOC) model [3]. We were unable to establish congruent band structures built between the Kπ=0+ 2 band and the ground band in this work of 152Gd as shown in Fig. 5.5, though the neighbouring 152Sm and 154Gd [10] isotopes showed congruency between the two bands. The lack of congruent band structures in N=88 152Gd might be due to the deformation of this nucleus eventually resulting in different decay pattern and band structures from those seen in N=90 152Sm and 154Gd.
Appendix A

Directional Correlation from Oriented states (DCO) and Linear Polarization ($A_p$) measurements.

The terms used in this Appendix are:

- $E_\gamma$ → Energy of the $\gamma$-ray.
- $I^\pi_i$ → Is the spin and parity of the initial level.
- $I^\pi_f$ → Is the spin and parity of the final level.
- $R_{DCO}$ → Is the ratio of directional correlation from oriented states between matrix at 135° and at 90°.
- $A_p$ → Linear polarization measurements.
- $\gamma$-Mult → Is the multipolarity of the $\gamma$-ray.
- Band → Gives the initial and final band of the transition.
- Gate on → Refers to where the gate was placed when the $R_{DCO}$ measurements were taken.
- $^{\text{a}}$ → Insufficient statistics to measure $\gamma$-ray intensity.
- $^{\text{b}}$ → Multipolarity could not be determined.
## Appendix A: DCO RATIOS AND A_P MEASUREMENTS

### Table A.1: Band 1

<table>
<thead>
<tr>
<th>E_γ (keV)</th>
<th>I^+_m → I^+_f</th>
<th>R_{DCO}</th>
<th>A_p</th>
<th>γ-Mult.</th>
<th>Band</th>
<th>Gated on</th>
</tr>
</thead>
<tbody>
<tr>
<td>344</td>
<td>2^+ → 0^+</td>
<td>0.943(1)</td>
<td>0.216(1)</td>
<td>E2</td>
<td>1</td>
<td>Quadrupole</td>
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<tr>
<td>411</td>
<td>4^+ → 2^+</td>
<td>0.938(1)</td>
<td>0.140(1)</td>
<td>E2</td>
<td>1</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>472</td>
<td>6^+ → 4^+</td>
<td>0.734(1)</td>
<td>0.149(1)</td>
<td>E2</td>
<td>1</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>519</td>
<td>8^+ → 6^+</td>
<td>0.947(2)</td>
<td>0.158(2)</td>
<td>E2</td>
<td>1</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>553</td>
<td>10^+ → 8^+</td>
<td>0.936(3)</td>
<td>0.146(3)</td>
<td>E2</td>
<td>1</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>584</td>
<td>12^+ → 10^+</td>
<td>0.783(5)</td>
<td>0.081(2)</td>
<td>E2</td>
<td>1</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>616</td>
<td>14^+ → 12^+</td>
<td>0.755(70)</td>
<td>0.182(39)</td>
<td>E2</td>
<td>1</td>
<td>Quadrupole</td>
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<tr>
<td>644</td>
<td>16^+ → 14^+</td>
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### Table A.2: Band 2

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<th>γ-Mult.</th>
<th>Band</th>
<th>Gated on</th>
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<tr>
<td>315</td>
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<td>0.119(76)</td>
<td>E2</td>
<td>2</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>352</td>
<td>4^+ → 2^+</td>
<td>0.908(112)</td>
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<td>E2</td>
<td>2</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>386</td>
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<td>0.921(12)</td>
<td>0.220(14)</td>
<td>E2</td>
<td>2</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>470</td>
<td>8^+ → 6^+</td>
<td>0.909(2)</td>
<td>0.120(2)</td>
<td>E2</td>
<td>2</td>
<td>Quadrupole</td>
</tr>
<tr>
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<td>10^+ → 8^+</td>
<td>0.857(7)</td>
<td>0.160(6)</td>
<td>E2</td>
<td>2</td>
<td>Quadrupole</td>
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<tr>
<td>271</td>
<td>0^+ → 2^+</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>931</td>
<td>2^+ → 0^+</td>
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<td>2→1</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>587</td>
<td>2^+ → 2^+</td>
<td>0.741(5)</td>
<td>0.063(4)</td>
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<td>2→1</td>
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<tr>
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<td>4^+ → 4^+</td>
<td>0.665(8)</td>
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<td>2→1</td>
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<tr>
<td>441</td>
<td>6^+ → 6^+</td>
<td>0.782(37)</td>
<td>0.501(28)</td>
<td>M1</td>
<td>2→1</td>
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<tr>
<td>159</td>
<td>4^+ → 3^+</td>
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<td>M1</td>
<td>2→14</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>197</td>
<td>6^+ → 5^+</td>
<td>0.875(26)</td>
<td>0.138(81)</td>
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<td>2→14</td>
<td>Dipole</td>
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<td>8^+ → 7^+</td>
<td>0.762(78)</td>
<td>0.331(79)</td>
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<td>2→14</td>
<td>Quadrupole</td>
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<tr>
<td>361</td>
<td>10^+ → 9^−</td>
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<td>2→14</td>
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<tr>
<td>391</td>
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<td>Quadrupole</td>
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### Table A.3: Band 3

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<th>E_γ (keV)</th>
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<th>R_{DCO}</th>
<th>A_p</th>
<th>γ-Mult.</th>
<th>Band</th>
<th>Gated on</th>
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<tr>
<td>451</td>
<td>14^+ → 12^+</td>
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<td>0.298(95)</td>
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<tr>
<td>496</td>
<td>16^+ → 14^+</td>
<td>0.861(19)</td>
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<td></td>
<td>3</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>553</td>
<td>18^+ → 16^+</td>
<td></td>
<td>0.400(9)</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>639</td>
<td>20^+ → 18^+</td>
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<td></td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>557</td>
<td>12^+ → 10^+</td>
<td>0.801(40)</td>
<td></td>
<td></td>
<td>3→2</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>696</td>
<td>16^+ → 14^+</td>
<td></td>
<td></td>
<td></td>
<td>3→1</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>605</td>
<td>18^+ → 16^+</td>
<td>0.703(44)</td>
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<td>3→1</td>
<td>Quadrupole</td>
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### Table A.4: Band 4

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<th>R$_{DCO}$</th>
<th>$A_p$</th>
<th>$\gamma$-Mult.</th>
<th>Band</th>
<th>Gated on</th>
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<tr>
<td>428</td>
<td>$5^+ \to 3^+$</td>
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<td>$^a$</td>
<td>$^b$</td>
<td>4</td>
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</tr>
<tr>
<td>440</td>
<td>$7^+ \to 5^+$</td>
<td>1.156(61)</td>
<td>$^a$</td>
<td>$^b$</td>
<td>4</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>476</td>
<td>$9^+ \to 7^+$</td>
<td>$^a$</td>
<td>$^a$</td>
<td>$^b$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>519</td>
<td>$11^+ \to 9^+$</td>
<td>1.382(110)</td>
<td>$^a$</td>
<td>$^b$</td>
<td>4</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>534</td>
<td>$13^+ \to 11^+$</td>
<td>1.002(93)</td>
<td>0.069(60)</td>
<td>E2</td>
<td>4</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>506</td>
<td>$3^+ \to 2^+$</td>
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<td>$^a$</td>
<td>$^b$</td>
<td>4–2</td>
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<tr>
<td>1107</td>
<td>$5^+ \to 4^+$</td>
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<td>-0.048(13)</td>
<td>$^b$</td>
<td>4–1</td>
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</tr>
<tr>
<td>1091</td>
<td>$3^+ \to 2^+$</td>
<td>0.779(18)</td>
<td>-0.054(53)</td>
<td>M1</td>
<td>4–1</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>679</td>
<td>$3^+ \to 4^+$</td>
<td>$^a$</td>
<td>-0.272(84)</td>
<td>$^b$</td>
<td>4–1</td>
<td></td>
</tr>
<tr>
<td>634</td>
<td>$5^+ \to 6^+$</td>
<td>$^a$</td>
<td>-0.113(49)</td>
<td>$^b$</td>
<td>4–1</td>
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<tr>
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<td>0.566(24)</td>
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<td>4–1</td>
<td>Quadrupole</td>
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<td>$^a$</td>
<td>$^b$</td>
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### Table A.5: Band 5

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<th>R$_{DCO}$</th>
<th>$A_p$</th>
<th>$\gamma$-Mult.</th>
<th>Band</th>
<th>Gated on</th>
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<td>$4^+ \to 2^+$</td>
<td>0.816(22)</td>
<td>0.309(67)</td>
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<td>5</td>
<td>Quadrupole</td>
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<tr>
<td>447</td>
<td>$6^+ \to 4^+$</td>
<td>0.727(12)</td>
<td>0.250(98)</td>
<td>E2</td>
<td>5</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>464</td>
<td>$8^+ \to 6^+$</td>
<td>0.848(17)</td>
<td>0.236(95)</td>
<td>E2</td>
<td>5</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>504</td>
<td>$10^+ \to 8^+$</td>
<td>$^a$</td>
<td>$^a$</td>
<td>$^b$</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>549</td>
<td>$12^+ \to 10^+$</td>
<td>$^a$</td>
<td>$^a$</td>
<td>$^b$</td>
<td>5</td>
<td></td>
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<tr>
<td>766</td>
<td>$2^+ \to 2^+$</td>
<td>0.688(32)</td>
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<td>$^b$</td>
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<td>Quadrupole</td>
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<tr>
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<td>1.092(91)</td>
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<td>Quadrupole</td>
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<tr>
<td>585</td>
<td>$8^+ \to 7^+$</td>
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<td>0.118(2)</td>
<td>$^b$</td>
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<td>794</td>
<td>$8^+ \to 6^+$</td>
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<td>$^a$</td>
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### Table A.6: Band 6

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<th>R$_{DCO}$</th>
<th>$A_p$</th>
<th>$\gamma$-Mult.</th>
<th>Band</th>
<th>Gated on</th>
</tr>
</thead>
<tbody>
<tr>
<td>271</td>
<td>$2^+ \to 0^+$</td>
<td>0.858(24)</td>
<td>0.166(94)</td>
<td>E2</td>
<td>6</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>703</td>
<td>$2^+ \to 0^+$</td>
<td>0.777(62)</td>
<td>0.505(55)</td>
<td>E2</td>
<td>6–1</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>388</td>
<td>$2^+ \to 2^+$</td>
<td>$^a$</td>
<td>$^a$</td>
<td>$^b$</td>
<td>6–2</td>
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<tr>
<td>974</td>
<td>$4^+ \to 4^+$</td>
<td>$^a$</td>
<td>0.009(65)</td>
<td>$^b$</td>
<td>6–1</td>
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</tr>
<tr>
<td>703</td>
<td>$0^+ \to 2^+$</td>
<td>0.750(37)</td>
<td>0.265(66)</td>
<td>E2</td>
<td>6–2</td>
<td>Quadrupole</td>
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### Table A.7: Band 7

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<th>$I_i^\pi \rightarrow I_f^\pi$</th>
<th>$R_{DCO}$</th>
<th>$A_p$</th>
<th>$\gamma$-Mult.</th>
<th>Band</th>
<th>Gated on</th>
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<tr>
<td>765</td>
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<td>\textsuperscript{b}</td>
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<td>0.920(99)</td>
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<td>7→2</td>
<td>Quadrupole</td>
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<td>684</td>
<td>$4^+ \rightarrow 3^-$</td>
<td>0.716(69)</td>
<td>0.113(167)</td>
<td>E1</td>
<td>7→14</td>
<td>Dipole</td>
</tr>
<tr>
<td>964</td>
<td>$6^+ \rightarrow 4^+$</td>
<td>0.901(126)</td>
<td>0.070(120)</td>
<td>E2</td>
<td>7→2</td>
<td>Quadrupole</td>
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### Table A.8: Band 8

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<th>$E_\gamma$(keV)</th>
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<th>$A_p$</th>
<th>$\gamma$-Mult.</th>
<th>Band</th>
<th>Gated on</th>
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<tr>
<td>504</td>
<td>$12^+ \rightarrow 10^+$</td>
<td>0.822(112)</td>
<td>\textsuperscript{a}</td>
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<td>8</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>635</td>
<td>$14^+ \rightarrow 12^+$</td>
<td>0.750(79)</td>
<td>\textsuperscript{a}</td>
<td>\textsuperscript{b}</td>
<td>8</td>
<td>Quadrupole</td>
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<tr>
<td>572</td>
<td>$10^+ \rightarrow 8^+$</td>
<td>1.153(33)</td>
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### Table A.9: Band 9

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<th>$E_\gamma$(keV)</th>
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<th>$R_{DCO}$</th>
<th>$A_p$</th>
<th>$\gamma$-Mult.</th>
<th>Band</th>
<th>Gated on</th>
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<td>696</td>
<td>$9^+ \rightarrow 7^+$</td>
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<tr>
<td>534</td>
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<tr>
<td>727</td>
<td>$7^+ \rightarrow 6^+$</td>
<td>0.419(95)</td>
<td>-0.026(145)</td>
<td>M1</td>
<td>9→2</td>
<td>Quadrupole</td>
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<tr>
<td>649</td>
<td>$7^+ \rightarrow 8^+$</td>
<td>\textsuperscript{a}</td>
<td>\textsuperscript{a}</td>
<td>\textsuperscript{b}</td>
<td>9→1</td>
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<tr>
<td>1168</td>
<td>$7^+ \rightarrow 6^+$</td>
<td>\textsuperscript{a}</td>
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### Table A.10: States 10

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<th>$R_{DCO}$</th>
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<th>$\gamma$-Mult.</th>
<th>Band</th>
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<tr>
<td>1266</td>
<td>$2^+ \rightarrow 2^+$</td>
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<td>991</td>
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<td>\textsuperscript{b}</td>
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<tr>
<td>679</td>
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<td>\textsuperscript{a}</td>
<td>\textsuperscript{b}</td>
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<tr>
<td>597</td>
<td>$4^+ \rightarrow 2^+$</td>
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<td>\textsuperscript{a}</td>
<td>\textsuperscript{b}</td>
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<td>793</td>
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<td>1160</td>
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<tr>
<td>1315</td>
<td>$6^+ \rightarrow 4^+$</td>
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<td>0.073(13)</td>
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<td>10→1</td>
<td>Quadrupole</td>
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<tr>
<td>1331</td>
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<td>753</td>
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<td>0.459(87)</td>
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### Table A.11: States 11

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<th>$R_{DCO}$</th>
<th>$A_p$</th>
<th>$\gamma$-Mult.</th>
<th>Band</th>
<th>Gated on</th>
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</thead>
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<tr>
<td>1495</td>
<td>$3^- \rightarrow 2^+$</td>
<td>0.538(104)</td>
<td>0.220(63)</td>
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<td>1304</td>
<td>$6^+ \rightarrow 2^+$</td>
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<tr>
<td>819</td>
<td>$10^+ \rightarrow 8^+$</td>
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<tr>
<td>855</td>
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<td>0.737(96)</td>
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<tr>
<td>1002</td>
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<td>0.206(96)</td>
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### Table A.12: States 12

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<th>$R_{DCO}$</th>
<th>$A_p$</th>
<th>$\gamma$-Mult.</th>
<th>Band</th>
<th>Gated on</th>
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<td>1348</td>
<td>$4^+ \rightarrow 2^+$</td>
<td>0.829(100)</td>
<td>0.478(76)</td>
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<td>12→1</td>
<td>Quadrupole</td>
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<tr>
<td>623</td>
<td>$2^+ \rightarrow 2^+$</td>
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<tr>
<td>618</td>
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### Table A.13: States 13

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<th>$R_{DCO}$</th>
<th>$A_p$</th>
<th>$\gamma$-Mult.</th>
<th>Band</th>
<th>Gated on</th>
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<td>0.768(75)</td>
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<td>941</td>
<td>$6^+ \rightarrow 4^+$</td>
<td>0.754(87)</td>
<td>0.013(90)</td>
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<td>13→2</td>
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</tr>
<tr>
<td>834</td>
<td>$8^+ \rightarrow 6^-$</td>
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<tr>
<td>1428</td>
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<td>0.400(95)</td>
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<tr>
<td>841</td>
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<tr>
<td>649</td>
<td>$2^+ \rightarrow 3^-$</td>
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<tr>
<td>1368</td>
<td>$4^+ \rightarrow 4^+$</td>
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### Appendix A: DCO Ratios and A<sub>p</sub> Measurements

Table A.14: Band 14

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<tr>
<th>E&lt;sub&gt;γ&lt;/sub&gt; (keV)</th>
<th>I&lt;sup&gt;+&lt;/sup&gt;&lt;sub&gt;i&lt;/sub&gt; → I&lt;sup&gt;+&lt;/sup&gt;&lt;sub&gt;f&lt;/sub&gt;</th>
<th>R&lt;sub&gt;DCO&lt;/sub&gt;</th>
<th>A&lt;sub&gt;p&lt;/sub&gt;</th>
<th>γ-Mult.</th>
<th>Band</th>
<th>Gated on</th>
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</thead>
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<tr>
<td>344</td>
<td>5&lt;sup&gt;-&lt;/sup&gt; → 3&lt;sup&gt;-&lt;/sup&gt;</td>
<td>0.943(4)</td>
<td>0.270(3)</td>
<td>E2</td>
<td>14</td>
<td>Quadrupole</td>
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<tr>
<td>411</td>
<td>7&lt;sup&gt;-&lt;/sup&gt; → 5&lt;sup&gt;-&lt;/sup&gt;</td>
<td>&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.355(2)</td>
<td>&lt;sup&gt;b&lt;/sup&gt;</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>452</td>
<td>9&lt;sup&gt;-&lt;/sup&gt; → 7&lt;sup&gt;-&lt;/sup&gt;</td>
<td>0.761(8)</td>
<td>0.053(38)</td>
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<td>14</td>
<td>Quadrupole</td>
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<tr>
<td>483</td>
<td>11&lt;sup&gt;-&lt;/sup&gt; → 9&lt;sup&gt;-&lt;/sup&gt;</td>
<td>0.759(8)</td>
<td>0.240(31)</td>
<td>E2</td>
<td>14</td>
<td>Dipole</td>
</tr>
<tr>
<td>524</td>
<td>13&lt;sup&gt;-&lt;/sup&gt; → 11&lt;sup&gt;-&lt;/sup&gt;</td>
<td>1.231(99)</td>
<td>&lt;sup&gt;a&lt;/sup&gt;</td>
<td>&lt;sup&gt;b&lt;/sup&gt;</td>
<td>14</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>600</td>
<td>15&lt;sup&gt;-&lt;/sup&gt; → 13&lt;sup&gt;-&lt;/sup&gt;</td>
<td>&lt;sup&gt;a&lt;/sup&gt;</td>
<td>&lt;sup&gt;b&lt;/sup&gt;</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>366</td>
<td>3&lt;sup&gt;-&lt;/sup&gt; → 4&lt;sup&gt;+&lt;/sup&gt;</td>
<td>&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.172(33)</td>
<td>&lt;sup&gt;b&lt;/sup&gt;</td>
<td>14→1</td>
<td>Quadrupole</td>
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<tr>
<td>779</td>
<td>3&lt;sup&gt;-&lt;/sup&gt; → 2&lt;sup&gt;+&lt;/sup&gt;</td>
<td>0.764(10)</td>
<td>0.482(9)</td>
<td>E1</td>
<td>14→1</td>
<td>Quadrupole</td>
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<tr>
<td>716</td>
<td>5&lt;sup&gt;-&lt;/sup&gt; → 4&lt;sup&gt;+&lt;/sup&gt;</td>
<td>0.795(5)</td>
<td>0.104(3)</td>
<td>E1</td>
<td>14→1</td>
<td>Quadrupole</td>
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<tr>
<td>653</td>
<td>7&lt;sup&gt;-&lt;/sup&gt; → 6&lt;sup&gt;+&lt;/sup&gt;</td>
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<td>0.409(2)</td>
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<td>14→1</td>
<td>Quadrupole</td>
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<tr>
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<td>0.083(3)</td>
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<td>14→1</td>
<td>Quadrupole</td>
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<td>0.474(81)</td>
<td>E1</td>
<td>14→1</td>
<td>Dipole</td>
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<tr>
<td>456</td>
<td>13&lt;sup&gt;-&lt;/sup&gt; → 12&lt;sup&gt;+&lt;/sup&gt;</td>
<td>0.774(49)</td>
<td>0.238(100)</td>
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<td>14→1</td>
<td>Dipole</td>
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<tr>
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<td>14→2</td>
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<td>0.249(109)</td>
<td>&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>Quadrupole</td>
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<tr>
<td>971</td>
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<tr>
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<td>0.506(34)</td>
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<td>14→1</td>
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Table A.15: Band 15

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<th>R&lt;sub&gt;DCO&lt;/sub&gt;</th>
<th>A&lt;sub&gt;p&lt;/sub&gt;</th>
<th>γ-Mult.</th>
<th>Band</th>
<th>Gated on</th>
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<td>8&lt;sup&gt;-&lt;/sup&gt; → 6&lt;sup&gt;-&lt;/sup&gt;</td>
<td>0.918(30)</td>
<td>0.104(97)</td>
<td>E2</td>
<td>15</td>
<td>Quadrupole</td>
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<tr>
<td>354</td>
<td>10&lt;sup&gt;-&lt;/sup&gt; → 8&lt;sup&gt;-&lt;/sup&gt;</td>
<td>0.934(14)</td>
<td>&lt;sup&gt;b&lt;/sup&gt;</td>
<td>15</td>
<td>Quadrupole</td>
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<tr>
<td>456</td>
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<td>0.888(14)</td>
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<td>15</td>
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<td>15</td>
<td>Quadrupole</td>
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<td>947</td>
<td>6&lt;sup&gt;-&lt;/sup&gt; → 6&lt;sup&gt;-&lt;/sup&gt;</td>
<td>0.846(41)</td>
<td>&lt;sup&gt;a&lt;/sup&gt;</td>
<td>&lt;sup&gt;b&lt;/sup&gt;</td>
<td>15→1</td>
<td>Quadrupole</td>
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<td>1.010(8)</td>
<td>-0.081(25)</td>
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<td>15→1</td>
<td>Quadrupole</td>
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<td>-0.066(101)</td>
<td>E1</td>
<td>15→1</td>
<td>Quadrupole</td>
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<td>&lt;sup&gt;b&lt;/sup&gt;</td>
<td>15→14</td>
<td>Dipole</td>
</tr>
<tr>
<td>659</td>
<td>8&lt;sup&gt;-&lt;/sup&gt; → 7&lt;sup&gt;-&lt;/sup&gt;</td>
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<td>&lt;sup&gt;b&lt;/sup&gt;</td>
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Table A.16: Band 16

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<th>R&lt;sub&gt;DCO&lt;/sub&gt;</th>
<th>A&lt;sub&gt;p&lt;/sub&gt;</th>
<th>γ-Mult.</th>
<th>Band</th>
<th>Gated on</th>
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<td>0.755(8)</td>
<td>0.564(8)</td>
<td>E2</td>
<td>16</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>734</td>
<td>11&lt;sup&gt;-&lt;/sup&gt; → 10&lt;sup&gt;+&lt;/sup&gt;</td>
<td>0.750(26)</td>
<td>0.425(73)</td>
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<td>16→1</td>
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<tr>
<td>703</td>
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<td>0.228(88)</td>
<td>&lt;sup&gt;b&lt;/sup&gt;</td>
<td>16→1</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>774</td>
<td>13&lt;sup&gt;-&lt;/sup&gt; → 11&lt;sup&gt;-&lt;/sup&gt;</td>
<td>1.066(90)</td>
<td>&lt;sup&gt;a&lt;/sup&gt;</td>
<td>&lt;sup&gt;b&lt;/sup&gt;</td>
<td>16→14</td>
<td>Quadrupole</td>
</tr>
</tbody>
</table>
## Appendix A: DCO RATIOS AND $A_p$ MEASUREMENTS

### Table A.17: Band 17

<table>
<thead>
<tr>
<th>$E_\gamma$(keV)</th>
<th>$I^i_1 \rightarrow I^f_1$</th>
<th>$R_{DCO}$</th>
<th>$A_p$</th>
<th>$\gamma$-Mult.</th>
<th>Band</th>
<th>Gated on</th>
</tr>
</thead>
<tbody>
<tr>
<td>283</td>
<td>$10^- \rightarrow 8^-$</td>
<td>$^{a)}$</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>352</td>
<td>$12^- \rightarrow 10^-$</td>
<td>1.474(100)</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>17</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>995</td>
<td>$8^- \rightarrow 7^-$</td>
<td>0.460(85)</td>
<td>-0.110(25)</td>
<td>17→14</td>
<td>Quadrupole</td>
<td></td>
</tr>
<tr>
<td>827</td>
<td>$10^- \rightarrow 9^-$</td>
<td>0.693(98)</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>17→14</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>147</td>
<td>$10^- \rightarrow 9^-$</td>
<td>$^{a)}$</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>17→18</td>
<td></td>
</tr>
<tr>
<td>191</td>
<td>$12^- \rightarrow 11^-$</td>
<td>0.536(81)</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>17→18</td>
<td>Quadrupole</td>
</tr>
</tbody>
</table>

### Table A.18: Band 18

<table>
<thead>
<tr>
<th>$E_\gamma$(keV)</th>
<th>$I^i_1 \rightarrow I^f_1$</th>
<th>$R_{DCO}$</th>
<th>$A_p$</th>
<th>$\gamma$-Mult.</th>
<th>Band</th>
<th>Gated on</th>
</tr>
</thead>
<tbody>
<tr>
<td>307</td>
<td>$11^- \rightarrow 9^-$</td>
<td>$^{a)}$</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>411</td>
<td>$13^- \rightarrow 11^-$</td>
<td>0.733(23)</td>
<td>0.236(6)</td>
<td>18</td>
<td>Quadrupole</td>
<td></td>
</tr>
<tr>
<td>520</td>
<td>$15^- \rightarrow 13^-$</td>
<td>$^{a)}$</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>605</td>
<td>$17^- \rightarrow 15^-$</td>
<td>$^{a)}$</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>161</td>
<td>$11^- \rightarrow 10^-$</td>
<td>1.222(55)</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>18→17</td>
<td>Dipole</td>
</tr>
<tr>
<td>220</td>
<td>$13^- \rightarrow 12^-$</td>
<td>0.953(55)</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>18→17</td>
<td>Dipole</td>
</tr>
<tr>
<td>680</td>
<td>$9^- \rightarrow 7^-$</td>
<td>0.760(22)</td>
<td>0.351(290)</td>
<td>18</td>
<td>Quadrupole</td>
<td></td>
</tr>
<tr>
<td>1019</td>
<td>$11^- \rightarrow 10^+$</td>
<td>0.773(67)</td>
<td>0.081(105)</td>
<td>18→1</td>
<td>Quadrupole</td>
<td></td>
</tr>
<tr>
<td>1132</td>
<td>$9^- \rightarrow 7^-$</td>
<td>$^{a)}$</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>18→14</td>
<td></td>
</tr>
<tr>
<td>988</td>
<td>$11^- \rightarrow 9^-$</td>
<td>1.093(53)</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>18→14</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>505</td>
<td>$11^- \rightarrow 11^-$</td>
<td>1.308(86)</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>18→14</td>
<td>Dipole</td>
</tr>
<tr>
<td>844</td>
<td>$13^- \rightarrow 12^+$</td>
<td>$^{a)}$</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>18→1</td>
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### Table A.19: States 19

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<th>$E_\gamma$(keV)</th>
<th>$I^i_1 \rightarrow I^f_1$</th>
<th>$R_{DCO}$</th>
<th>$A_p$</th>
<th>$\gamma$-Mult.</th>
<th>Band</th>
<th>Gated on</th>
</tr>
</thead>
<tbody>
<tr>
<td>842</td>
<td>$5^- \rightarrow 3^-$</td>
<td>$^{a)}$</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>19→14</td>
<td></td>
</tr>
<tr>
<td>1356</td>
<td>$9^- \rightarrow 8^+$</td>
<td>0.606(125)</td>
<td>0.076(104)</td>
<td>19→1</td>
<td>Quadrupole</td>
<td></td>
</tr>
<tr>
<td>711</td>
<td>$15^- \rightarrow 13^-$</td>
<td>$^{a)}$</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>19→14</td>
<td></td>
</tr>
<tr>
<td>1118</td>
<td>$7^- \rightarrow 5^-$</td>
<td>$^{a)}$</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>19→14</td>
<td></td>
</tr>
<tr>
<td>1548</td>
<td>$6^- \rightarrow 4^+$</td>
<td>$^{a)}$</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>19→1</td>
<td></td>
</tr>
<tr>
<td>1431</td>
<td>$7^- \rightarrow 5^-$</td>
<td>$^{a)}$</td>
<td>$^{a)}$</td>
<td>$^{b)}$</td>
<td>19→14</td>
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<tr>
<td>730</td>
<td>$11^- \rightarrow 9^-$</td>
<td>1.160(10)</td>
<td>0.200(11)</td>
<td>19→14</td>
<td>Quadrupole</td>
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</table>
Table A.20: States 20

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<tr>
<th>E(_\gamma) (keV)</th>
<th>(I^e_i \rightarrow I^e_f)</th>
<th>(R_{DCO})</th>
<th>(A_p)</th>
<th>(\gamma)-Mult.</th>
<th>Band</th>
<th>Gated on</th>
</tr>
</thead>
<tbody>
<tr>
<td>1032</td>
<td>(9^- \rightarrow 8^+)</td>
<td>0.472(118)</td>
<td>0.051(50)</td>
<td>E1</td>
<td>20→1</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>1329</td>
<td>(9^- \rightarrow 8^+)</td>
<td>0.31(105)</td>
<td>0.202(110)</td>
<td>E1</td>
<td>20→1</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>1203</td>
<td>(5^- \rightarrow 3^-)</td>
<td>)(^a)</td>
<td>)(^a)</td>
<td>)(^b)</td>
<td>20→14</td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>(2^- \rightarrow 3^-)</td>
<td>)(^a)</td>
<td>)(^a)</td>
<td>)(^b)</td>
<td>20→14</td>
<td></td>
</tr>
<tr>
<td>715</td>
<td>(1^- \rightarrow 0^+)</td>
<td>0.666(26)</td>
<td>0.107(11)</td>
<td>E1</td>
<td>20→6</td>
<td>Quadrupole</td>
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</table>

Table A.21: States 21

<table>
<thead>
<tr>
<th>E(_\gamma) (keV)</th>
<th>(I^e_i \rightarrow I^e_f)</th>
<th>(R_{DCO})</th>
<th>(A_p)</th>
<th>(\gamma)-Mult.</th>
<th>Band</th>
<th>Gated on</th>
</tr>
</thead>
<tbody>
<tr>
<td>1298</td>
<td>(4^- \rightarrow 2^+)</td>
<td>)(^a)</td>
<td>0.497(161)</td>
<td>)(^b)</td>
<td>21→1</td>
<td></td>
</tr>
<tr>
<td>967</td>
<td>(6^- \rightarrow 5^-)</td>
<td>)(^a)</td>
<td>)(^a)</td>
<td>)(^b)</td>
<td>21→14</td>
<td></td>
</tr>
<tr>
<td>951</td>
<td>(8^- \rightarrow 8^+)</td>
<td>1.045(85)</td>
<td>0.089(0.164)</td>
<td>E1</td>
<td>21→1</td>
<td>Quadrupole</td>
</tr>
<tr>
<td>896</td>
<td>(10^- \rightarrow 9^-)</td>
<td>)(^a)</td>
<td>0.084(122)</td>
<td>)(^b)</td>
<td>21→14</td>
<td></td>
</tr>
<tr>
<td>887</td>
<td>(6^- \rightarrow 5^-)</td>
<td>)(^a)</td>
<td>)(^a)</td>
<td>)(^b)</td>
<td>21→14</td>
<td></td>
</tr>
</tbody>
</table>
Appendix B

Full decay scheme of $^{152}$Gd

Figure B.1 gives the full decay scheme of the $^{152}$Gd nucleus, the newly observed transitions and states are in red while the previously observed transitions and states are in black. The DCO ratios and $A_P$ values were measured for both newly and previously observed transitions. This is done to assign spins and parities to the states and assign multipolarity to the $\gamma$-rays. We enclosed some states in parentheses since their spins and parities could not be determined due to insufficient statistics.
Figure B.1: The decay scheme of the $^{152}\text{Gd}$ from the $^{150}\text{Sm}(\alpha, 2n)^{152}\text{Gd}$ reaction, with the newly observed states and $\gamma$-rays shown in red.
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