Study of Low-Medium Spin States in ^{156}Er

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Abstract. This study investigates the low to medium spin states of the nucleus ^{156}Er through the analysis of the gamma-gamma coincidence relationships following the ^{147}Sm(^{12}C, 3n)^{156}Er reaction at 65 MeV. The experiment was performed using the African Omni-purpose Detector for Innovative Techniques and Experiments (AFRODITE) array at iThemba LABS. From the collected data, a detailed nuclear level scheme was constructed, leading to the identification of nine rotational bands. The present study confirms nearly all previously reported bands while also proposing modifications to certain band assignments. These results provide new insights into the nuclear structure of ^{156}Er and contribute to a deeper understanding of shape evolution in the $A \sim 160$ mass region.

1 Introduction

Nuclei with neutron numbers $N = 88$–92 are well-known examples for studying normal deformed states at high angular momentum [1]. These studies have helped us better understand how nuclear shapes change as angular momentum increases and how different particles align inside the nucleus.

This work focuses on the rare-earth nucleus ^{156}Er, which contains 68 protons and 88 neutrons. It lies in the middle of the rare-earth region, where nuclei transition from nearly spherical shapes to well deformed quadrupole structures. Over the last 20 to 30 years, ^{156}Er has been studied extensively [2, 3, 4], both experimentally and theoretically, particularly at high spin states due to its abundant physics. However, its structure at low to medium spin is still not fully understood, which is why there is growing interest in studying it further.

For example, Rees *et al.* [5] found that ^{156}Er might be soft in the gamma direction, meaning it can easily change between different non-axial shapes. They also suggested that $(\nu h_{9/2}, f_{7/2})$ rotationally aligned structures exist alongside the usual $\nu(i_{13/2})^2$ particle alignments seen in nuclei around mass 150-160. Before this, such a phenomenon was only seen in $^{163}\mathrm{W}$ [6] and $^{161}\mathrm{Ta}$ [7].

A review of the existing data indicates that an incorrect assignment may have led to the mischaracterisation of the abovementioned phenomenon in ^{156}Er. Therefore, accurate parity assignment is important for determining the underlying configuration and for interpreting the alignment behaviour.

In effect, this study aims to investigate the spectroscopy of ^{156}Er, particularly the band associated with the aligned $(\nu h_{9/2}, f_{7/2})^2$ configuration with the aim to best the validity of the abovementioned, which suggests that competing alignment exists in the A $\sim$ 150-160 region.

2 Experimental Method and Data Analysis

The nucleus $^{156}\mathrm{Er}$ was produced using the fusion-evaporation reaction $^{147}\mathrm{Sm}(^{12}\mathrm{C}, 3n)^{156}\mathrm{Er}$. This reaction was carried out at a beam energy of 65 MeV, chosen to maximise the cross section for the 3 neutron evaporation channel while minimising competing channels such as 2 neutron and 4 neutron reactions, thereby favouring the population of low to medium spin states in $^{156}\mathrm{Er}$. The experiment was conducted at the iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) in Cape Town, South Africa. A $^{12}\mathrm{C}$ ion beam was accelerated by the Separated-Sector Cyclotron (SSC) and delivered to a self-supporting enriched $^{147}\mathrm{Sm}$ target with a thickness of 6 mg/cm^2.

Gamma rays emitted from the excited nucleus were detected using the AFRODITE gamma-ray spectrometer. AFRODITE is an acronym for the AFRican Omnipurpose Detector for Innovative Techniques and Experiments [8]. It is an array capable of detecting both high and low energy photons with high efficiency. This is achieved by combining large volume escape-suppressed High Purity Germanium CLOVER detectors, suited for high resolution spectroscopy, with Low Energy Photon Spectrometer detectors for enhanced sensitivity to low energy transitions. At the time of the experiment, the AFRODITE array consisted of eight Compton suppressed CLOVER-type HPGe detectors arranged to optimise angular coverage and coincidence detection efficiency. Each CLOVER detector was fitted with absorbers composed of 0.15 mm of tin followed by 0.07 mm of brass. This configuration was used to suppress low energy X-rays and Compton background, thereby enhancing the clarity of the gamma-ray.

Data collection was carried out using a gamma gamma coincidence trigger and spanned five continuous days, during which approximately 1.4×10^9 gamma gamma coincidence events were recorded [3]. The raw data were then calibrated, gain matched and sorted into a symmetric gamma gamma coincidence matrix using the MIDAS[1] data acquisition system and the MTSort offline sorting package. MIDAS handled real time digitisation and event building, while MTSort converted time stamped raw events into a matrix format compatible with RADWARE[2] analysis software.

The sorted matrix formed the basis for both the initial and present analyses. The RADWARE software suite was used for further offline processing: `GF3` was used for peak fitting of the gamma ray spectra, while `ESCL8R` was used to construct and update the level scheme of $^{156}\mathrm{Er}$. While the initial analysis produced a preliminary level scheme, the present secondary analysis focused on a more detailed investigation of Band 9, whose structure and spin parity assignments remained partially unresolved in previous work [5]. Gated coincidence spectra were used to verify known transitions and to explore possible new or extended placements within the band structure. The outcomes of this analysis will guide future Directional Correlation of Oriented States ratio measurements, which are expected to confirm multipolarities and refine spin parity assignments in $^{156}\mathrm{Er}$.

[1]`http://nnst.dl.ac.uk/MIDAS/manual/MTsort/edoc033`

[2]`http://radware.phy.ornl.gov/rw/esclev/esclev.html`

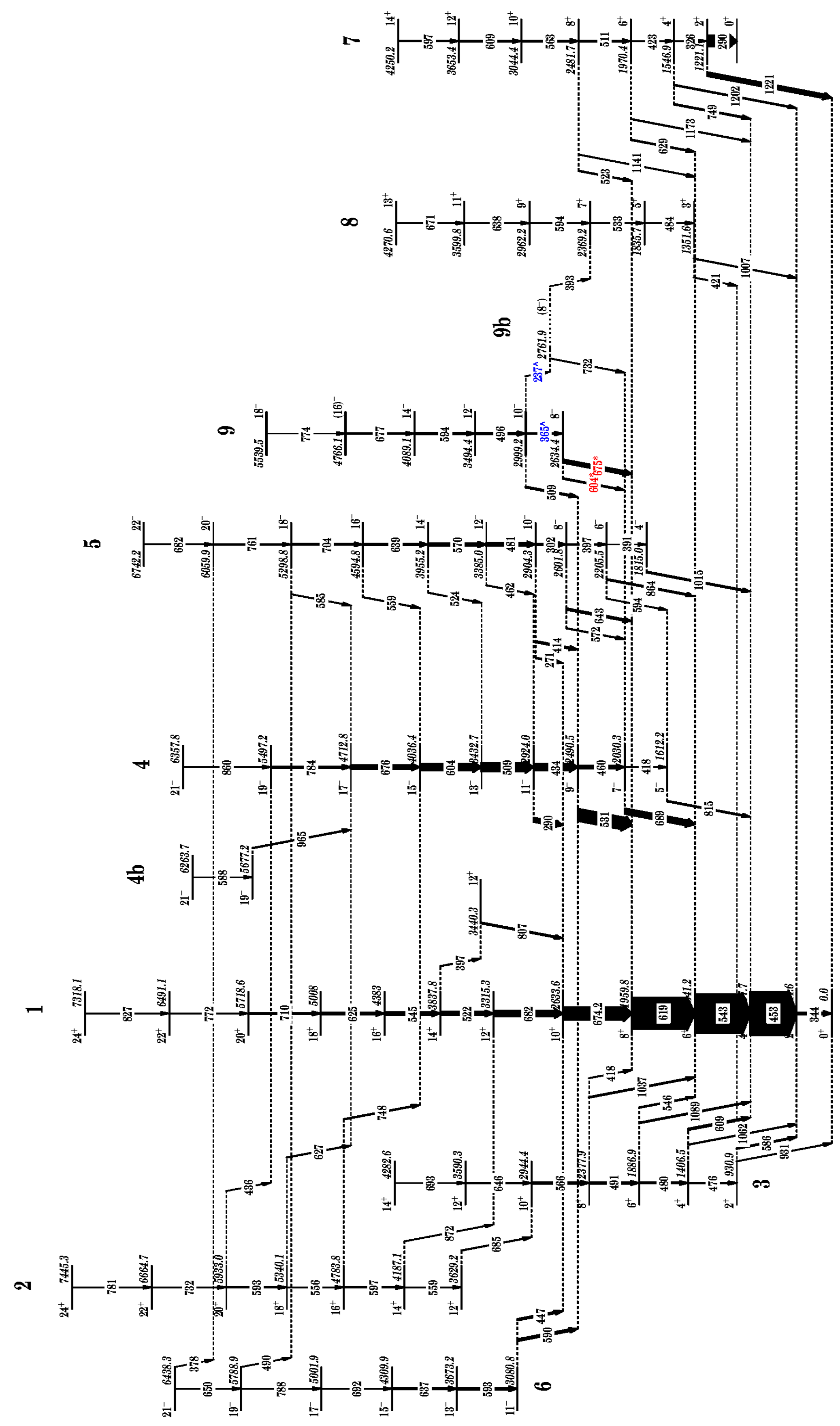


Figure 1: Level scheme deduced for ^{156}Er. Transition energies are in keV, with arrow widths proportional to the measured relative intensities. Newly observed transitions are shown in red with an asterisks(*) and updated transitions from previous work in blue with a caret ().

3 Results

Nine rotational bands were identified in ^{156}Er, with observed states extending up to a maximum spin-parity of 24^+. This was achieved using a ^{12}C beam at 65 MeV and a ^{147}Sm target via the fusion-evaporation reaction $^{147}\mathrm{Sm}(^{12}\mathrm{C}, 3n)^{156}\mathrm{Er}$.

A new configuration of Band 9 was established. The 365 keV gamma-ray, previously believed to connect the 2998 keV level in Band 9 to the yrast 10^+ state in Band 1, was observed to feed a newly identified band head.

Coincidence relationships observed in the gated spectra provide additional evidence regarding the structure of Band 9. The 495.8 keV transition is observed in coincidence with the 604.2 keV transition, but not with the 603.7 keV transition. The 365 keV transition appears in coincidence with both the 495.8 keV and 604.2 keV transitions. Additionally, the 674.7 keV transition is observed in coincidence with the 365 keV transition, whereas the 674.2 keV transition is not.

Alignment analysis as a function of rotational frequency was performed for Bands 1, 2, 4, 5, and 9. Band 9 exhibited an alignment of approximately 7.5 $\hbar$. Alignments are shown in Figure 4a.

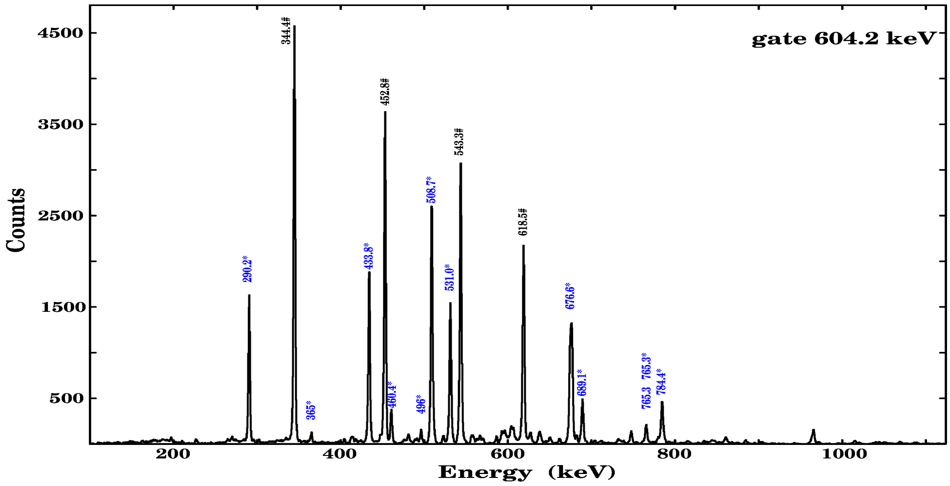


Figure 2: Spectrum gated on the 604.2 keV transition. Transition belonging to ^{156}Er are shown in blue and marked with an asterisk (*). Transitions belonging to the ground-state band are in black and marked with a hash symbol (#)

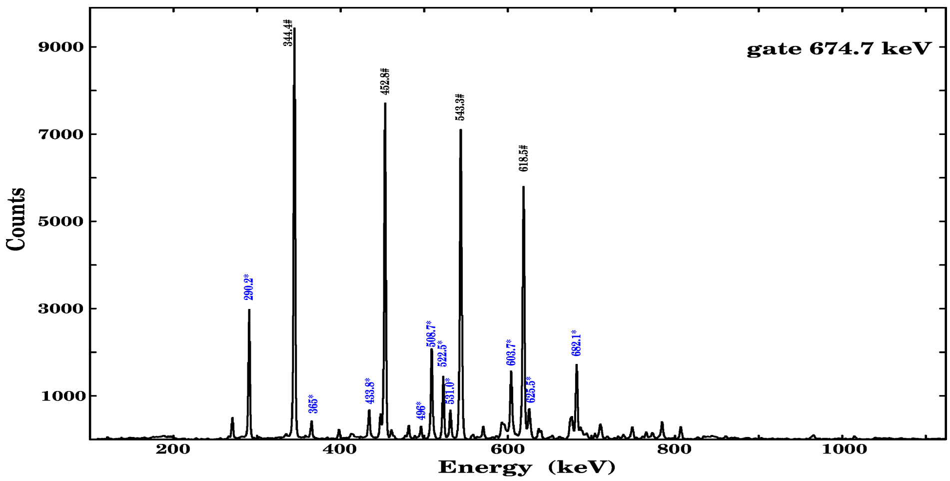


Figure 3: Spectrum gated on the 674.7 keV transition. Transition belonging to ^{156}Er are shown in blue and marked with an asterisk (*). Transitions belonging to the ground-state band are in black and marked with a hash symbol (#)

Discussion

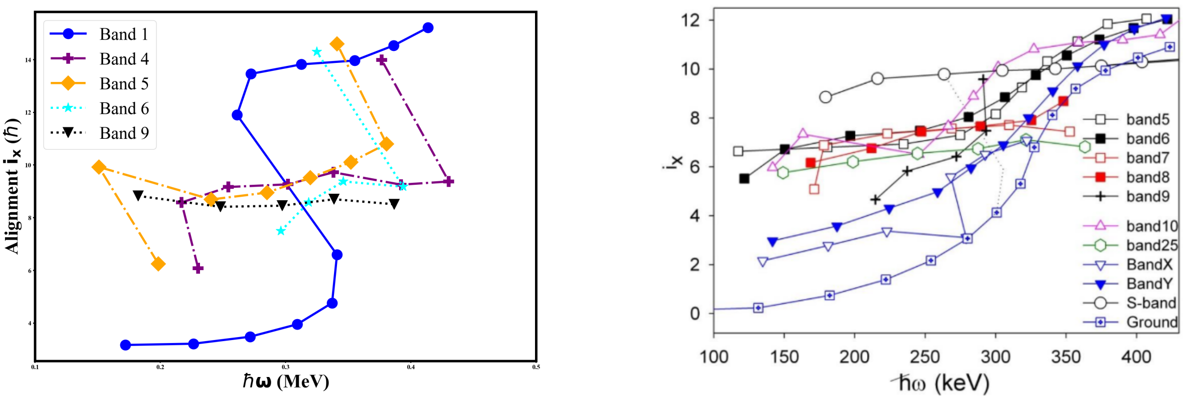
The observed spin limit of 24^+ in this experiment is lower than the 46^+ states reported by Rees *et al.* [5], who used a heavier ^{48}Ca beam at 215 MeV, compared to the ^{12}C beam at 65 MeV used in this work. The lower energy and lighter ion in our experiment favour the population of low to medium spin states, while the higher energy, heavier ion used by Rees *et al.* contributes more angular momentum, allowing access to higher-spin levels.

Further support for this revised assignment comes from the alignment data. Band 9 shows an alignment of approximately 7.5 $\hbar$, which is lower than that observed in Band 1 and is typical of negative-parity two-quasiparticle bands. In contrast, Band 1 displays higher alignment values consistent with the alignment of $i_{13/2}$ neutrons.

This alignment behaviour is also seen in other negative-parity bands within ^{156}Er, as illustrated in Figure **??**. These bands exhibit similar rotational properties and alignment values in the range of 6–7.5 $\hbar$, indicating that they likely share a comparable two-quasiparticle configuration. The consistency across bands strengthens the interpretation that Band 9 follows the same structural trends typical of negative-parity configurations in the $A \sim 160$ mass region.

Similar alignment trends have also been reported in neighbouring nuclei such as ^{156}Dy, where negative-parity bands typically align between 6 and 7 $\hbar$ [9]. This reinforces the argument that Band 9 in ^{156}Er likely has negative parity.

These coincidence relationships support a revised configuration of Band 9. The 365 keV gamma-ray, previously believed to connect the 2998 keV level in Band 9 to the yrast 10^+ state in Band 1, is now interpreted to feed a newly identified band head. The presence of strong coincidence between the 365 keV, 495.8 keV, and 604.2 keV transitions, and the absence of coincidence with the 603.7 keV and 674.2 keV transitions, suggests that the 365 keV transition feeds Band 9 via the 674.7 keV transition, not Band 1. This is supported by the gated spectra shown in Figures 2 and 3, where the 365 keV transition appears in both the 604.2 keV- and 674.7 keV-gated spectra.



(a) Measured alignments, i_x, plotted as a function of rotational frequency, ω, for the negative parity bands in ^{156}Er.

(b) Measured alignments i_x as a function of rotational frequency $\hbar\omega = 0.2$ for different bands observed in ^{156}Dy [9].

Figure 4: (a) Alignment of Band 9 (black) in ^{156}Er, originally assigned positive parity based on $(vh_{9/2}, f_{7/2})$ orbitals, showing lower alignment ($\sim 7.5\hbar$) than typical $i_{13/2}$ alignments. (b) Multiple band alignments for negative-parity bands at around $7.5\hbar$ in neighboring nuclei, supporting the idea that Band 9's parity was likely misassigned.

The reassignment of the 365 keV gamma-ray transition in Band 9 significantly impacts the interpretation of its structure. This, together with strong stretched $E2$ cross-band transitions at 591 keV and 386 keV between Bands 8 and 9, suggests strong mixing between the 2999.2 keV level in Band 9 and the 2904.3 keV level in Band 8.

Such mixing is only allowed between states with the same spin and parity, which implies that the 2999.2 keV level must have spin-parity 10^-, supporting a negative-parity assignment for Band 9. This contrasts with the earlier interpretation by Rees *et al.* [5], who assigned positive parity based on a proposed $(f_{7/2}, h_{9/2})$ configuration.

To confirm the revised spin-parity assignments, further work is needed. Planned steps include Directional Correlation from Oriented states (DCO) ratio measurements and theoretical modelling using approaches such as configuration-constrained or cranked shell model calculations. These studies will help clarify the nature of the rotational bands in ^{156}Er and may contribute to broader applications in gamma-ray detection.

Conclusion

This study investigated low- to medium-spin states in ^{156}Er using a γ-γ coincidence analysis of data from the ^{147}Sm(^{12}C,3n)^{156}Er reaction at 65 MeV. The experiment, conducted at iThemba LABS using the AFRODITE spectrometer, yielded approximately 1.4×10^9 coincidence events. A key outcome of this secondary analysis was the reassignment of the 365 keV transition in Band 9. Rather than linking to the 10^+ state in Band 1 as previously proposed, this transition appears to feed a newly identified band head.

These findings challenge the earlier positive-parity interpretation by Rees *et al.* [5] and align well with observed trends in negative-parity bands across the rare-earth region, including neighbouring nuclei such as ^{156}Dy.

In order to confirm the validity of our interpretation, future work should focus on performing DCO ratio measurements to confirm multipolarities and refine spin-parity assignments. Theoretical modelling will also be essential to validate the proposed band structures and further elucidate the role of quasiparticle configurations of band in question (band 9) in ^{156}Er. If confirmed to be true these findings contribute to a deeper understanding of quasiparticle alignments and structural evolution in even-even nuclei within the $A \sim 160$ mass range.

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