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Spin-parity assignments and extension of the 0_2^+ band in ^{158}Er

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Abstract. Low and medium spin collective structures in ^{158}Er have been studied using the ^{150}Sm(^{12}C,4n$\gamma\gamma$) fusion-evaporation reaction at a beam energy of E_{lab} = 65 MeV. A band built on the 0_2^+ excitation has been established and extended to $J^\pi = 18^+$ from the analysis of γ-γ coincidence relationships, intensity arguments and *DCO* ratios. The 0_2^+ band in ^{158}Er presents a similar trend to the 0_2^+ bands in the lighter N = 90 isotones but lies about 125 keV higher. This systematic trend supports a similar configuration for the 0_2^+ bands in the N = 90 isotones.

1 Motivation

The interpretation of excited 0^+ bands built well below the pairing gap remains a fundamental open question in nuclear-structure physics. The lowest-lying 0_2^+ bands occur in the $N = 90$ isotones and have long been associated with the text-book picture of a β vibration, i.e. a quadrupole vibration about the nuclear surface while maintaining axial symmetry [1]. The nuclides $^{152}_{62}$Sm$_{90}$ and $^{154}_{64}$Gd$_{90}$ may be the best examples of a β vibration [2]. Nevertheless, two-phonon quadrupole vibrations have not been found in ^{152}Sm [3], which questions the origin of the 0_2^+ bands [3, 4] and any critical-point interpretation [5–7].

Shape coexistence has been suggested in ^{152}Sm [8] and ^{154}Gd [9] as a result of proton pairs excited across the Z = 64 midshell. The resulting proton-neutron interaction may then lower the energy of the excited 0^+ bands [10, 11]. The large $E0$ strengths between the two $K = 0$ bands in ^{152}Sm, ^{154}Gd and $^{156}_{66}$Dy$_{90}$ support the strong mixing between coexisting bands [10, 12, 13]. This interpretation is, however, not consistent with the negligible population of the 0_2^+ state in ^{152}Sm observed in the *(^{3}He,n)* reaction study of Alford and co-workers [14].

An alternative interpretation arises from the interpretation of the 0_2^+ state as a second vacuum [4]; where these 0_2^+ excitations are explained as a two-neutron two-hole seniority zero state placed into the pairing gap by the configuration-dependent pairing interaction and the low density of the oblate states near the Fermi surface [4, 15]. This is the "pairing isomer" concept of Ragnarsson and Broglia [16] and the two-neutron character of the 0_2^+ states in ^{152}Sm and ^{154}Gd is supported by the available (t, p) transfer data [17, 18]. Evidence for weakly-deformed pairing isomeric bands has been found in ^{152}Sm [8] and ^{154}Gd [9], but associated with the 0_3^+ excitation. Experimentally, the second-vacuum picture is based on the congruence of similar level schemes built on the 0_1^+ and 0_2^+ vacuum states [4]. The lack of experimental matrix elements prevents, however, additional support. Theoretical calculations that would accomodate such extreme lowering in the energy of the 0^+ excitations into the pairing gap are lacking for either the shape-coexistence or second-vacuum pictures.

The 0_2^+ bands have undoubtly been found in the stable $N = 90$ isotones lighter than $^{158}_{68}$Er$_{90}$ [8, 19–21] and in $^{160}_{70}$Yb$_{90}$ [22]. The nucleus ^{158}Er has been studied through electron-capture decay [23] and heavy-ion fusion-evaporation reactions [24–27]. The 0_2^+ band has only been proposed up to the 4^+ level [28]. In this work, we present the firm assignment of previously proposed members of the 0_2^+ band in ^{158}Er and its extension from $\gamma - \gamma$ coincidence techniques and discuss the available energy systematics in the N = 90 isotones.

2 Experimental Details

The nucleus ^{158}Er has been studied at the iThemba Laboratory for Accelerator Based Sciences using the ^{150}Sm(^{12}C,4n$\gamma\gamma$)^{158}Er fusion-evaporation reaction at a bombarding energy of E_{lab} = 65 MeV. The ^{12}C beam was

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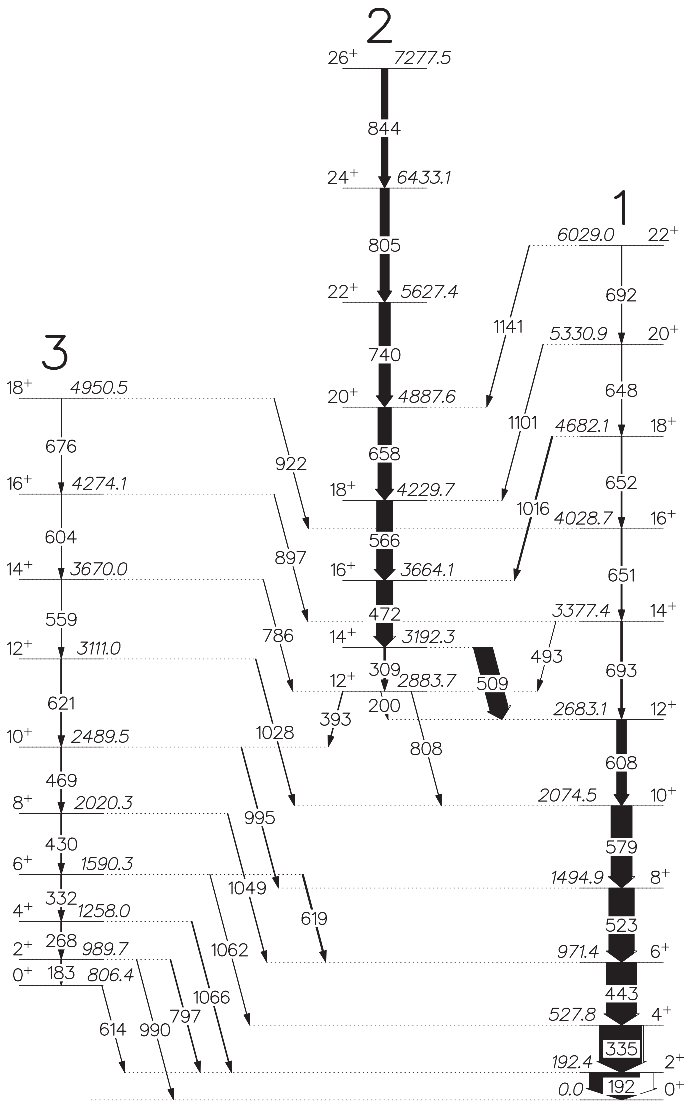

Figure 1: Partial decay scheme of ^{158}Er showing the ground-state, S and 0_2^+ bands, which are labelled 1, 2 and 3, respectively.

delivered by the $K = 200$ Separated Sector Cyclotron and bombarded a 1 mg/cm^2 ^{150}Sm target, backed on a thick 12 mg/cm^2 Au foil. The ^{12}C ions are the lightest beams utilised to study ^{158}Er in fusion-evaporation reactions. The γ decays from the reaction products have been detected using the AFRODITE γ-ray spectrometer [29] equipped with nine escape-suppressed clover detectors; five positioned at 90° and four positioned at 135°. A time window of 110 ns between two γ-rays being detected by two separate clovers in the AFRODITE array characterised the γ-γ coincidence events. An average beam current of 15 enA was used and a total of about 4.2×10^8 coincidence events were accumulated during approximately fifty hours of beam time.

In the offline analysis, γ-γ coincident events were unfolded from the raw data and replayed into Radware-format [30] for subsequent analysis. The total projection of the ^{150}Sm(^{12}C,4n$\gamma\gamma$)^{158}Er γ-γ coincidence matrix confirms that ^{158}Er is the main channel in the reaction. In addition, there were open reaction channels from 5n and 3n neutron evaporations, the break-up of the carbon beam and from reactions with the Au backing.

3 Data Analysis

Figure 1 shows a partial decay scheme built in this work from the γ-γ coincidence data. Band 1 is the ground-state band, which continues above the S band crossing near spin 12_1^+ and band 2 is the yrast (π,α)=(+,0) S band, a sequence of 8 rotational states up to the 26_1^+ level at 7278 keV. Band 3 is the band built on the 0_2^+ excitation, which was previously known up to spin 4_2^+ [23], but has been assigned and extended in this work. The confirmation of in-band transitions for the 0_2^+ band is supported by the two γ-γ coincidence spectra shown in Fig. 2, where gates set on the 430 and 469 keV γ-ray transitions allow an arrangement of the band, which has been extended to spin 18_3^+. The ordering of the γ-rays is also supported by the agreement of the in-band and out-of-band decays. The 1066 keV γ-ray

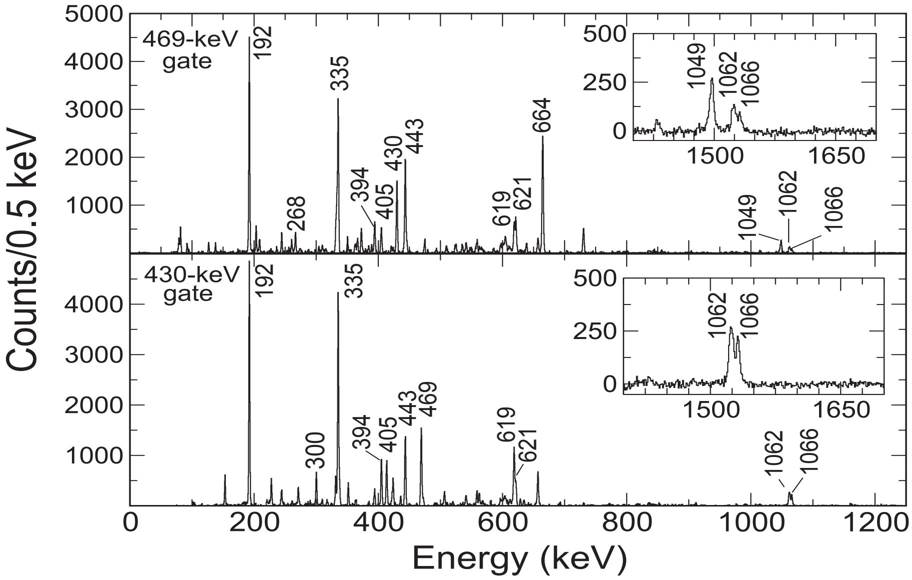

Figure 2: Background-subtracted coincidence γ-ray spectra gated by the 469 keV (top) and 430 keV (bottom) γ-rays showing transitions depopulating the 0_2^+ band in ^{158}Er.

transition was previously observed but placed in a different band. The spins and parities of the states above the 4_2^+ level in band 3 have been firmly assigned in this work (as discussed below) and the transitions linking states between 18_2^+ and 10_2^+ are new.

In this work, spin and parity values were determined using the method of directional correlations from oriented states (*DCO*) [31, 32]. The R_{DCO} values have been obtained by gating only on stretched quadrupole transitions below the transitions of interest. $\Delta J = 2$ and pure ($\delta = 0$) $\Delta J = 1$ transitions are expected to have R_{DCO} values of ≈ 1 and ≈ 0.6, respectively. For all transitions in Band 1, including the triplet of 648, 651 and 652 keV γ-ray transitions, values of $R_{DCO} \approx 1$ have been determined in agreement with available experimental data. Gamma-ray spectra gated on the 430 keV $8_2^+ \rightarrow 6_2^+$ transition depopulating the 0_2^+ band present similar intensities at $\theta_{lab} = 90°$ and 135° clover detection angles and suggest a predominant $E2$ character for the in-band transitions. The R_{DCO} values for these in-band transitions are listed in Table 1.

Table 1: R_{DCO} ratios and multipolarities for in-band γ-ray transitions depopulating the 0_2^+ band in ^{158}Er.

E_x (keV)	E_γ (keV)	R_{DCO}	Multip.	$J_i^\pi \rightarrow J_f^\pi$
989.7	183		($E2$)	$2^+ \rightarrow 0^+$
1258.0	268	0.99(0.02)	$E2$	$4^+ \rightarrow 2^+$
1590.3	332	1.02(0.06)	$E2$	$6^+ \rightarrow 4^+$
2020.3	430	1.07(0.04)	$E2$	$8^+ \rightarrow 6^+$
2489.5	469	1.03(0.04)	$E2$	$10^+ \rightarrow 8^+$
3111.0	621	1.20(0.08)	$E2$	$12^+ \rightarrow 10^+$
3670.0	559	1.09(0.04)	$E2$	$14^+ \rightarrow 12^+$
4274.1	604	1.20(0.10)	$E2$	$16^+ \rightarrow 14^+$
4950.5	676	1.20(0.04)	$E2$	$18^+ \rightarrow 16^+$

4 Discussion and Conclusions

Figure 3 shows the energy systematics of available 0_1^+ and 0_2^+ bands in the $N = 90$ isotones. The 0_2^+ excitation in ^{158}Er lies at 806.4 keV, about 125 keV higher than in the lighter $N = 90$ isotones. As shown in Fig. 3, the 0_2^+ band in ^{158}Er follows a similar trend to its counterparts in the lighter $N = 90$ isotones. The $E(J + 2)/E(J)$ energy ratios for the 0_2^+ bands in the $N = 90$ isotones are very similar, except for a slightly smaller $E(4_2^+)/E(2_2^+)$ ratio in ^{158}Er and ^{160}Yb. This systematic trend may suggest a similar structure for the 0_2^+ bands related to a two-particle ($2p$) two-hole ($2h$) neutron configuration [17, 18].

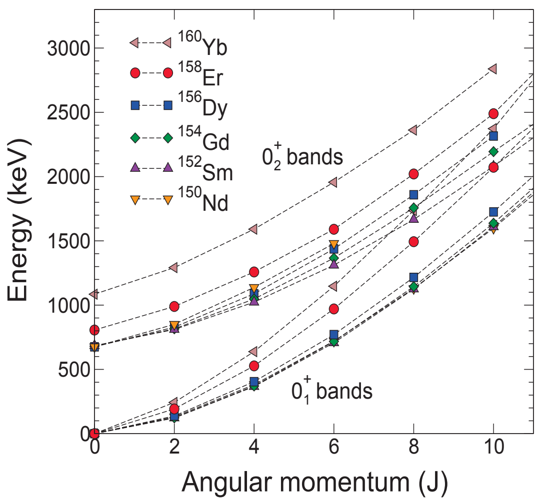

Figure 3: Excitation energy as a function of angular momentum for members of the 0_1^+ and 0_2^+ bands in the $N = 90$ isotones.

In ^{152}Sm, ^{154}Gd and ^{156}Dy, the similarity in energy spacing between the ground and 0_2^+ band, together with the large $E0$ strengths between the two $K = 0$ bands, has been associated with strong mixing of coexisting bands with different deformations [10]. In contrast, as shown in Fig. 3, the similarity in energy spacing does not continue in the heavier isotones, which indicates a reduction in deformation of the ground-state bands of ^{158}Er and ^{160}Yb, which is not mirrored in the 0_2^+ bands.

Summarizing, a detailed spectroscopic study at low and medium spins in ^{158}Er has been carried out using the ^{150}Sm(^{12}C,4n$\gamma\gamma$) reaction. The spin and parities of the band built on the first excited 0_2^+ state have been assigned and the band extended to 18_3^+ from the analysis of coincidence relationships, intensity arguments and the assignment of DCO ratios. A more detailed study of the positive- and negative-parity states as well as comparison with theoretical calculations using density-functional theory will be discussed in a separate paper. Beyond mean-field calculations of Bender and Heenen [33] consider multiple np-nh excitations and may be crucial to elucidate 0^+ excitations, in general. Further ($^3He, n\gamma$) coincidence measurements as well as multi-step Coulomb-excitation studies using stable $N = 90$ beams at iThemba LABS will shed light into the various interpretations argued in the $N = 90$ isotones. The authors acknowledge the staff of the accelerator group at iThemba LABS for their support and dedication. This work was supported by the South African National Research Foundation.

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