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Lifetimes of 0^+ states in ^{162}Dy

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Abstract Transfer reactions at the high-precision Q3D spectrometer at the University of Munich have shown that there are many low-lying excited $K^\pi = 0^+$ states in well-deformed nuclei. A recent study of ^{162}Dy shows eleven 0^+ states below an energy of 3 MeV. While this nucleus is studied extensively, the lifetimes of the new states were not known. We report on lifetime measurements of the newly observed states in order to determine their properties and allow the characterization of these states. Level lifetimes of 0^+ states in ^{162}Dy were measured by the $(n, n'\gamma)$ reaction and the Doppler-shift attenuation method at the University of Kentucky. This work allow us to report the transition probabilities from six of the eleven 0^+ states. We suggest that the first excited $K^\pi = 0^+$ excitation at 1400.2 keV in ^{162}Dy may be the β vibrational excitation and not the $\gamma\gamma$ excitation indicated in the past or a shape coexistence minimum.

1 Introduction and motivation

One of the main challenges in nuclear structure today is the understanding of the emergent regularities in structure patterns, collectivity, or shape coexistence and the information that they can divulge about the nature of nuclear forces. The Q3D high-precision spectrometer at the University of Munich nearly two decades ago, revolutionized nuclear structure by introducing the capacity to observe a large number of 0^+ states in the low-lying spectra of nuclei. Historically, 0^+ states were difficult to measure and hindered testing and verification of numerous nuclear models due to the absence of the predicted and essential 0^+ states. In 2002, one of the first Q3D measurements showed 13 0^+ states [1] in one nucleus below 3.1 MeV. This work was followed by many others [2–15] to reveal that in some cases, tens of 0^+ states exist in the low lying structure of deformed nuclei. The lifetimes of several 0^+ states in ^{158}Gd were measured [16] but no distinct conclusions could be made since the full level scheme depopulation was incomplete.

In this ^{162}Dy nucleus, there are eleven 0^+ states reported [3] below an excitation energy of 2.8 MeV. What is the nature of these 0^+ states? Our goal was to measure the level lifetimes in an attempt to answer the question about the nature of these states. The ^{162}Dy nucleus remains one of the best studied rare-earth nuclei [17,18] in nuclear physics in terms of reactions and completeness. The focus of this work was not to expand the already well developed level scheme but to measure the lifetimes of the 0^+ levels in ^{162}Dy using the DSAM (Doppler-shift attenuation method). An earlier measurement of lifetimes in ^{162}Dy, used the GRID (Gamma Ray Induced Doppler Broadening) technique of lifetime measurements at the ILL facility in Grenoble, France [18]. The results showed one relatively collective $E2$ transition from the $K^\pi = 0_3^+$ band's 2^+ state to the $K^\pi = 2^+$ band and suggested that perhaps the $K^\pi = 0_3^+$ band has two-phonon $\gamma\gamma$ components. The $K^\pi = 0_2^+$ band at 1400 keV, contained several band members depopulating to the $K^\pi = 2^+$ band but no conclusions could be made about this band since the transition probabilities disagreed with the Alaga rules [19]. In this work, we show that the $K^\pi = 0_2^+$ band may indeed be the β vibration. Our conclusion is consistent with global calculations that indicate that the transition probabilities connecting this band to the ground state are not only expected to be weaker than the transition probabilities depopulating the $K^\pi = 2^+$ but they also exclude the characterization of this low lying band as a shape coexistence minimum. The $K^\pi = 0_2^+$ band at 1400.2 keV seems to be an oscillation built

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on the ground state of ^{162}Dy and indications are that it is the β vibration.

2 Experiment

Levels in ^{162}Dy were populated with the $(n, n'\gamma)$ reaction at the University of Kentucky Accelerator Laboratory (UKAL) using quasi-monoenergetic neutrons from the ^{3}H(p, n) reaction. Measurements included γ-ray excitation functions and angular distributions. The scattering sample was 24.0 g of 96.17% enriched ^{162}Dy oxide powder contained in a thin-walled polyethylene cylinder, 7.62 cm high and 3.81 cm in diameter. The emitted γ rays were detected with a $\leq$ 50% efficient HPGe detector with time-of-flight gating for background suppression and a BGO shield for active Compton suppression [20].

An excitation function was performed in 75 keV steps from E_n = 1.4–3.1 MeV with the detector placed at 90° to the beam axis and was used to confirm the established level scheme by checking the thresholds of γ rays which had already been placed. These excitation functions provide γ-ray yields as a function of neutron energy. Angular distribution measurements were performed at incident neutron energies of 1.6, 2.2, and 3.1 MeV over an angular range of 40° to 150°. These energies were chosen to reduce the effects of feeding to the levels of interest and facilitate accurate level lifetime measurements.

The angular distributions of the γ-ray intensities, W(θ), were fitted with even-order Legendre polynomials:

$$W(\theta) \approx a_o \left[1 + a_2 P_2(\cos\theta_\gamma) + a_4 P_4(\cos\theta_\gamma)\right] \qquad (1)$$

where the parameters a_2 and a_4 depend on the multipolarities and mixing amplitudes of the transitions.

Lifetimes of excited states shorter than about 2 ps [21] were determined by the Doppler-shift attenuation method (DSAM), a technique that exploits the shifting of gamma-ray transition energies emitted from a recoiling nucleus as a function of the angle of observation. The γ ray energies are therefore angular dependent, $E_\gamma(\theta) = E_\gamma^o[1 + \mathrm{v/c}F(\tau)\cos(\theta)]$, where de-exciting γ rays will be Doppler shifted linearly as a function of cos(θ), the un-shifted γ-ray energy E_γ^o, the recoil velocity of the decaying nucleus v/c, and a lifetime-dependent attenuation factor F(τ), depends primarily on the after nuclear stopping powers. Examples of which are shown in Fig. 1. Uncertainty in lifetime measurements is primarily due to the lack of knowledge of the stopping powers of the recoiling residual nuclei [21]. These techniques and methods are described in detail elsewhere [20,22–25].

3 Results

In this paper, the lifetimes of the low-lying 0^+ states in ^{162}Dy were measured and lifetimes were extracted for six of the reported eleven 0^+ states. In cases where lifetimes existed previously [18,26] there is agreement within experimental uncertainties as shown in Table 1.

Meyer et al. [3] reported eleven excited 0^+ states below 2.8 MeV. Two of those states were identified as tentative, and one as a likely contaminant [3]. In this work, we confirm the spin assignments of the identified 0^+ states, and obtain the level lifetimes where possible. Throughout this work, we have maintained the labeling or numbering of the 0^+ states in accordance with the (p, t) measurement results in order to avoid any further confusion between what was observed by Ref. [3] and our work with $(n, n'\gamma)$ where the ground state 0^+ is noted as 0_g^+.

We searched for γ ray decay from each of the identified 0^+ states expecting the $0_i^+ \rightarrow 2_g^+$ transition to be the dominant decay; transitions to low-lying 2^+, 1^+, and 1^- states were also sought. In each case, we required that the level-energy threshold from γ-ray excitation functions were consistent with level energy assignments. Furthermore, it was required that the angular distributions of γ rays from these states be isotropic, i.e., $a_2 = 0$ in Eq. 1.

The 0^+ state assigned at 774.2 keV [3] was identified as a probable contaminant although the source of that contaminant was not identified, and no attribution of the source of the contaminant was made by the authors. We did not observe $(0_1^+)\rightarrow 2_g^+$ decay from this level in our current experiment.

The 0^+ state at 1400.2 keV is well established and has been observed in (t, p) [27], (p, t) [3], and through $E0$ decay from β decay of ^{162}Ho [28]. We also support the identification of this level and observe a γ ray to the 2_g^+ level which provides a lower limit on the level lifetime of $\tau > 2100$ fs corresponding to a B($E2$) < 2 W.u. As this level is well established, the 1319.6 keV γ ray was used to calibrate the angular distributions. Additional members of this band were observed at 1453.4 keV (2_2^+) and at 1574.3 keV (4_2^+). We have determined a new level lifetime of 3400^{+5600}_{-1300} fs for the 2_2^+ level, and our measured lifetime is in agreement with the previously reported level lifetime [18] for the 4_2^+ level (see Table 1). Considerable theoretical and experimental focus [3,29–31] has been placed on the assessment of this 0_2^+ band as a $\gamma\gamma$ vibration, and its confirmation was contingent on the measurement of level lifetimes and the $0^+ \rightarrow \gamma$ vibration interband transitions: a weak 565.3 keV γ ray decaying from the 2_2^+, a 686.1 keV γ ray from the 4_2^+, and the elusive 512.0 keV γ ray from the 0_2^+ bandhead, to name a few. The broad annihilation peak in our spectra prevents detection of this latter γ ray in our γ-singles-based experiments, and the weak intensities

Table 1 Level energies (keV), γ-ray energies (keV), level F(τ) values, and mean lifetimes (fs) observed in the current ^{162}Dy($n, n'\gamma$) experiment for 0^+ states and band members. The literature lifetimes, τ_{lit}, are reported from Ref. [18] since they were published after the most recent compilation [26]. The ground-state band members are noted using "g". Parentheses around the 0^+ state indicate a tentative assignment

E$_{lev}$ (keV)	E$_\gamma$ (keV)	$J_i^\pi \rightarrow J_f^\pi$	I$_\gamma$ (rel)	F(τ)	τ (fs)	B($E2$) (W.u.)
774.2(3)[a]		(0_1^+)				
1400.21(6)	1319.60(5)	$0_2^+ \rightarrow 2_g^+$	100	0.031(38)	> 2100	< 2
1453.41(5)	1187.80(5)	$2_2^+ \rightarrow 4_g^+$	74(2)	0.042(26)	3400^{+5600}_{-1300}	$0.82^{+0.58}_{-0.53}$
	1372.80(5)	$2_2^+ \rightarrow 2_g^+$	100(2)			$0.54^{+0.37}_{-0.34}$
1574.27(6)	1308.64(5)	$4_2^+ \rightarrow 4_g^+$	100	0.043(31)	>2000	< 2
					τ_{lit} = 1080–3100	
1666.00(8)	1585.35(5)	$0_3^+ \rightarrow 2_g^+$	100	0.051(33)	3000^{+4800}_{-1300}	$0.52^{+0.40}_{-0.32}$
1728.28(5)	1462.69(5)	$2_3^+ \rightarrow 4_g^+$	82(2)	0.105(21)	1350^{+350}_{-170}	$0.57^{+0.12}_{-0.14}$
	1647.64(5)	$2_3^+ \rightarrow 2_g^+$	100(2)		τ_{lit} = 250–1000	$0.39^{+0.08}_{-0.09}$
	1728.29(5)	$2_3^+ \rightarrow 0_g^+$	64(2)			$0.19^{+0.04}_{-0.05}$
1814.6(5)[a]		(0_4^+)				
1820.3(5)[a]		(0_5^+)				
1886.48(6)	1805.86(5)	$4_3^+ \rightarrow 2_g^+$	100	0.086(34)	1600^{+1300}_{-390}	$0.51^{+0.16}_{-0.23}$
2127.96(6)	2047.34(6)	$0_6^+ \rightarrow 2_g^+$	100	0.071(31)	2200^{+1500}_{-770}	$0.20^{+0.11}_{-0.08}$
2189.72(7)	2109.10(6)	$(2)_6^+ \rightarrow 2_g^+$	100	0.267(58)	530^{+220}_{-160}	$0.70^{+0.30}_{-0.21}$
2497.85(10)	2417.22(9)	$0_7^+ \rightarrow 2_g^+$	100	0.376(55)	270^{+110}_{-60}	0.7±0.2
2505.68(12)	2505.68(12)	$\rightarrow 0_g^+$				
2588.8(7)[a]		(0_8^+)				
2655.91(20)	2575.28(20)	$0_9^+ \rightarrow 2_g^+$	100	0.436(164)	200^{+290}_{-100}	$0.69^{+0.69}_{-0.41}$
2663.0(7)[a]		(0_{10}^+)				
2800.92(24)	2720.28(24)	$0_{11}^+ \rightarrow 2_g^+$	100	0.653(200)	90^{+110}_{-60}	$1.2^{+2.3}_{-0.6}$

[a]Level identified in Ref. [3] but no γ-ray decay was observed in this work

(previously reported in the literature [17]) of the other two make detection unlikely. In this work, we have measured the lifetimes or lifetime limits of the 0_2^+ and 2_2^+ in addition to the previously measured 4_2^+ state of the band. B($E2$) values are shown in Table 1 with the measured lifetimes, γ-ray intensities, and associated B($E2$) value assuming 100% $E2$ yielding upper limits for the B($E2$) values. Given the additional level lifetimes, the transition probabilities for γ-rays connecting this band to the ground state ground state are stronger for this band than any of the other 0^+ states.

The spin and parity of the *0^+ level at 1666.0 keV* were reported by Meyer et al. [3] and supported by Aprahamian et al. [18]. The energy threshold of the excitation function and $a_2 = 0.02 \pm 0.03$ from the angular distribution support this placement. Our lifetime value 3000^{+4800}_{-1300} fs relies on the decay to the 2_g^+ state. The lifetime of the 2_3^+ level of this band at 1728.3 keV was previously reported [18] with a level lifetime of $250 - 1000$ fs. The current experimental value is 1350^{+350}_{-170} fs. In addition, we have measured the lifetime of the 4_3^+ at 1886.5 keV as 1600^{+1300}_{-390} fs corresponding to a B($E2 : 4_3^+ \rightarrow 2_g^+$)=$0.51^{+0.16}_{-0.23}$ W.u. As calculated in Table 2. These values imply strong transition probabilities connecting members of this band to the K$^\pi = 2^+$ band.

The *0^+ states at 2128.0 (0_6^+), 2497.8 (0_7^+), and 2655.9 (0_9^+) keV* decay to the 2_g^+, via 2047.3 ($a_2 = 0.04 \pm 0.06$), 2417.2 ($a_2 = 0.12 \pm 0.11$) and 2575.3 keV ($a_2 = 0.24 \pm 0.32$), respectively. No additional decay branches were observed. The lifetimes extracted are 2200^{+1500}_{-770} fs for the level at 2128.0 keV, 270^{+110}_{-60} fs for the level at 2497.8 keV, and 200^{+290}_{-100} fs for the level at 2655.9 keV as shown in Fig. 1. We note that the 2127.96 keV level is not within 2σ of the 2126.5 keV reported in Ref. [3]. A search for other γ rays near this energy was conducted without success.

The isotropic radiation observed for the 2720.3 keV γ ray that depopulates the 0_{11}^+ *state at 2801.0 keV*, leads us to support the assignment of this previously assigned "tentative" state as a 0^+ excitation. The 2720.3 keV decay has an angular distribution $a_2 = -0.16 \pm 0.21$ and provides the shortest 0^+ lifetime of 90^{+110}_{-60} fs with a B($E2$)=$1.2^{+2.3}_{-0.6}$ W.u.

In the work we did not observe γ rays depopulating the reported 0^+ states at 1814.6 (0_4^+), 1820.3 (0_5^+), 2588.8 (0_8^+), or 2663.0 keV (0_{10}^+) identified in (p, t) experiments [3]. There

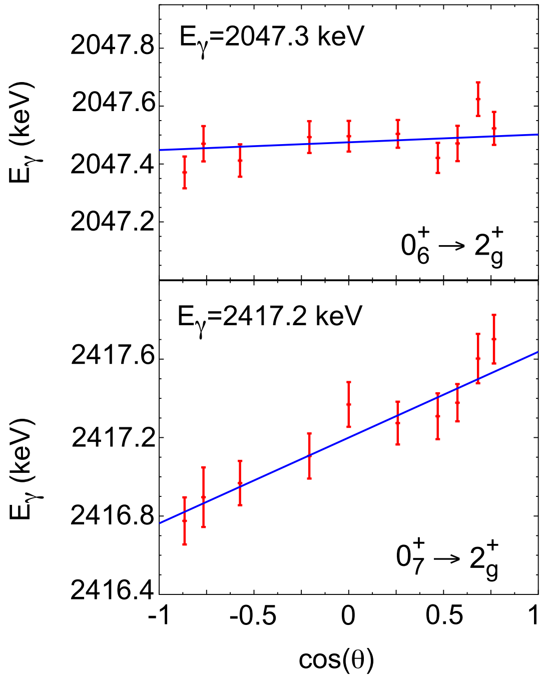

Fig. 1 Examples of Doppler energy shifts observed for selected transitions following the ^{162}Dy$(n, n'\gamma)$ reaction. In each case, the γ ray shown is the $0_i^+ \rightarrow 2_g^+$ transition

are no obvious peaks above our background with the exception of the expected γ ray from the 2588.8 keV state as shown in Fig. 2. The angular distribution of the 2505.7-keV γ ray produces an $a_2 = 0.46 \pm 0.10$ precluding it from being a 0^+ level decay. Through excitation functions and angular distributions, this γ ray was placed to a level at 2505.7 keV.

In this work, eleven 0^+ states were studied and six level lifetimes were possible to measure. An additional five 2^+ and 4^+ band member state lifetimes were measured in agreement with previous measured.

4 Discussion

This study reports on the measured lifetimes of $K^\pi = 0^+$ states in ^{162}Dy using DSAM. The extracted lifetimes are used to calculate transition probabilities in an attempt to identify the properties of these states. The lifetime of the 0^+ states de-exciting to the ground state band members are compiled in Table 1 along with the deduced $B(E2)$ transition probabilities. A partial level scheme including the observed 0^+ states in ^{162}Dy is shown in Fig. 3 along with the excitation energies of the two-neutron and two-proton pairing gaps.

The main focus of nuclear structure discussions has revolved around the viability of observing low-lying collective oscillations versus the existence of a shape coexisting minimum. The ^{162}Dy nucleus is well deformed with a $4^+/2^+$ ratio ($R_{4/2}$) of 3.28. Rotational motion is expected in deformed nuclei; the question is whether the "granularity" [32] of nuclei allows single or multiple quanta of vibrational oscillations superimposed on the deformed ground state shape of the nucleus. The observation of so many $K^\pi = 0^+$ states below 3.0 MeV has not only revitalized but also led to spirited discussions about the viability of vibrational excitations built on a deformed ground state. The lifetime measurements of numerous 0^+ states in ^{162}Dy is a significant addition.

Quadrupole oscillations ($\lambda = 2$) of a deformed shape are expected to be the lowest shape affecting oscillations. That would result in two types of vibrations: β with no projection on the symmetry axis and γ with a projection of $K^\pi = 2^+$. Discussions in recent years have focused on a debate about the absence, or the lack of, a ($K^\pi = 0^+$) β vibration with a multitude of possible interpretations that vary broadly between claims of "no collective excitations" built on the deformed ground state to the impossibility of having one of the quadrupole shape oscillations, that is the $K^\pi = 2^+$ γ-oscillations to the exclusion of the other type

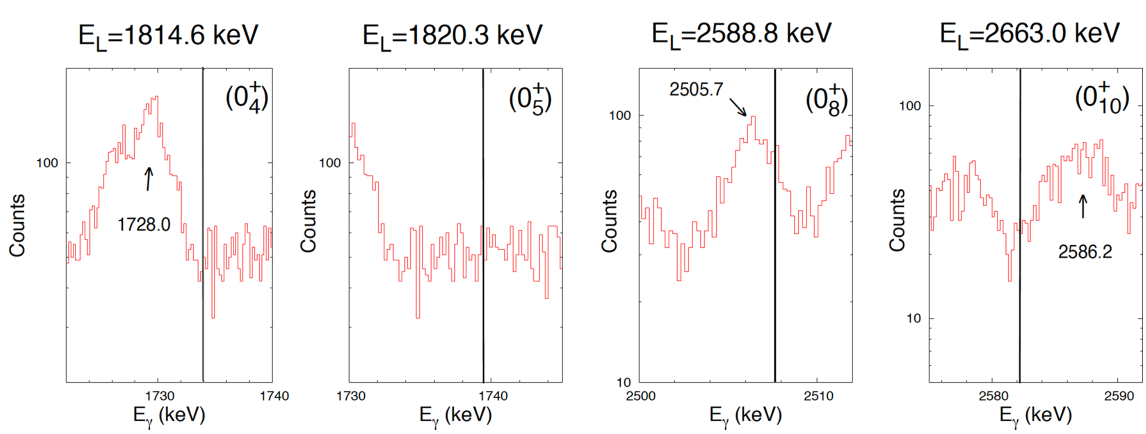

Fig. 2 Solid lines represent the areas of the ^{162}Dy spectrum where the $0_i^+ \rightarrow 2_g^+$ gamma rays are expected to appear

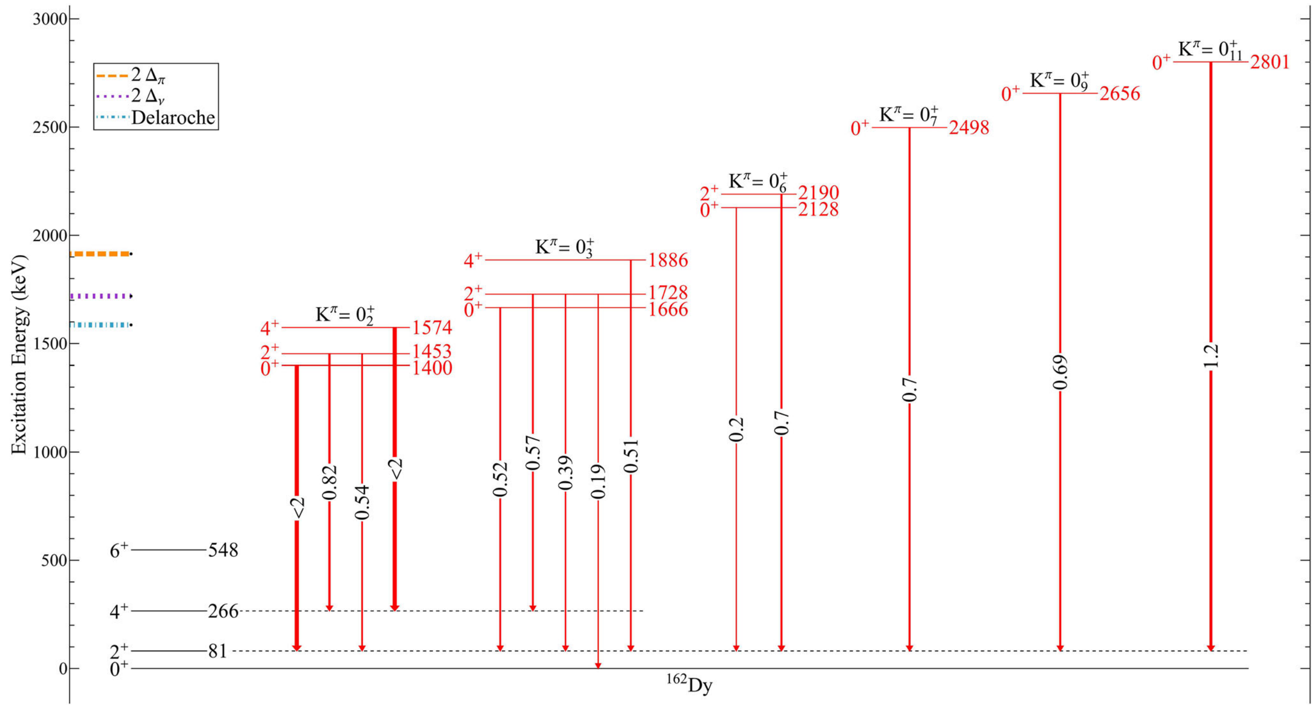

Fig. 3 The energies of the excited 0^+ states, the first excited 2^+ bandhead, and low-lying ground-state band for ^{162}Dy. The new transition probabilities resulting from our measurements are presented with relative widths of all transitions proportional to known literature B($E2$) values (in W.u.). The proton and neutron pairing gap values ($2\Delta_\pi$ and $2\Delta_\nu$) are indicated on the left vertical scale as well as the Ref. [33] predicted value for the 0^+ that shows the greatest collective strength to the ground state

$K^\pi = 0^+$ β-oscillations. Presently, the towering point in the discussions is the claim of shape coexistence for the low lying $K^\pi = 0^+$ bands. There are several comprehensive, theoretical studies [33–35] in support of our conclusion that this nucleus does not exhibit shape coexistence.

Delaroche et al. [33] have studied the entire chart of nuclides from Z = 10 to Z = 110 with neutron numbers N < 200 and have mapped the structure of even-even nuclei using a collective Hamiltonian and the DIS Gogny interaction. In various parts of the table, they interpret the character of the first excited 0^+ state as either shape coexistence or β-vibration based on the relative quadrupole transition strengths. This theory shows shape coexistence is found to be more prevalent across the entire chart of nuclides but many deformed nuclei exhibit strong rotational spectra when the $4^+/2^+$ ratios ($R_{4/2}$) correspond to axial rotors. This is the case for ^{162}Dy. They find, that in many cases, deformed nuclei exhibiting strong rotational spectra ($4^+/2^+$) ratios that correspond to axial rotors have a β-vibration for the first excited 0^+ state, although shape coexistence is found to be more prevalent across the entire chart of nuclides.

Bonatsos et al. [34] explore the signatures of shape coexistence for the ground state band and the first excited $K^\pi = 0^+$ bands. They publish a practical guide for the experimental findings of coexistence and these exclude well deformed rotors. Their studies specifically exclude the ^{162}Dy nucleus from the coexistence picture with $R_{0/2} = 17$ and $R_{4/2} = 3.27$.

The IBM [36–38] model also has a viewpoint. The first excited 0^+ and 2^+ bands are members of the same representation, and in a pure SU(3) limit, would not decay to the ground state. Most deformed nuclei, are not pure SU(3) in nature and the breaking of that symmetry gives rise to interband transitions from both of the low-lying $K^\pi = 2^+$ and $K^\pi = 0^+$ ("γ" and "β") bands of significant strengths. An investigation [35] exploring the B($E2$) dominance of $\beta \rightarrow \gamma$ and $\gamma \rightarrow g$ transitions over the $\beta \rightarrow g$ resulted in a prediction of weaker $\beta \rightarrow g$ values by 1/6 where "g" denotes the ground state band. This result was found to stand independently of the deformation or the proximity/distance to SU(3).

Our data show that the largest B($E2$) values to the ground state band in ^{162}Dy are associated with the $K^\pi = 0^+$ band at 1400.2 keV. This band that had been claimed as a two-quanta oscillation built on the $K^\pi = 2^+$ band [29] with one strong gamma ray measurement. There are strong B($E2$) values to the $K^\pi = 2^+$ band. This is expected in the IBA since the two bands ($K^\pi = 2^+$ and $K^\pi = 0^+$) are members of the same representation. The character of the first $K^\pi = 0^+$ band is that of a β vibration. The nature of the $K^\pi = 0^+$ at 1666.0 keV and others remain open to future experiments. Many of

Table 2 Transition probabilities are calculated for bands of interest in ^{162}Dy. Level energies (keV), γ-ray energies (keV), level lifetimes (fs), $E2/M1$ mixing ratios (δ), and relative intensities are from this $(n, n'\gamma)$ work and reported in Table 1 unless noted. If γ rays from previous measurements are added to the level, the relative intensities are adopted from that reference and normalized with the intensities of the observed transitions. Conversion coefficients (α_T) are theoretically calculated from Ref. [26] and the assigned multipolarities are deduced given the transitions and reported in parentheses. The B($E2$) values are reported in W.u. where 1 W.u. = 5.2461×10^{-3} e^{2}b^2. For transitions with mixed $E2/M1$ assignments, the B($E2$) value is reported as an upper limit. The B($E1$) transition probabilities are reported in mW.u. where 1 mW.u. = 1.9155×10^{-5} e^{2}b. Gamma rays with low intensities were not observed in our work and the relative intensities were adopted from Refs. [17] or [29] and noted. When our lifetime measurement provided a limit, the literature lifetime [17,26] was used and denoted with a †

E_L (keV)	J_i^π	E_γ (keV)	K_f	J^π	E_f (keV)	I_γ (rel.)	α_T	τ (fs)	$\pi\ell$ or δ	B($E1$) or B($E2$) mW.u or W.u.	Notes
$K^\pi = 2^+_\gamma$											
888.16	2^+	622.49	0	4^+_g	266	1.94(5)	0.00875	2840 ± 130 †	$E2$	$0.59^{+0.06}_{-0.05}$	a
		807.54	0	2^+_g	81	100(3)	0.00481		$-0.45^{+0.05}_{-0.06}$	1.4 ± 0.4	
		888.18	0	0^+_g	0	91(2)	0.00391		$E2$	4.7 ± 0.4	
962.86	3^+	697.30	0	4^+_g	266	19(1)	0.00670	> 3200	0.20 ± 0.06	< 0.3	
		882.31	0	2^+_g	81	100(1)	0.00397		99.3%$E2$	< 8	
1060.92	4^+	98.05	2	3^+_γ	963	0.08(1)	2.53	3200^{+4800}_{-1300}	$M1$	–	a
		172.84	2	2^+_γ	888	0.71(3)	0.387		$E2$	140^{+110}_{-87}	a
		512.46	0	6^+_g	548	1.58(6)	0.01422		$E2$	$1.4^{+1.0}_{-0.8}$	a
		795.35	0	4^+_g	266	100(2)	0.00500		$-0.92^{+0.04}_{-0.05}$	$4.4^{+3.6}_{-2.8}$	
		980.36	0	2^+_g	81	57(1)	0.00317		$E2$	$1.9^{+1.4}_{-1.2}$	
1182.69	5^+	121.77	2	4^+_γ	1061	0.17(1)	1.325	> 2500	75%$E2$	< 260	a
		219.82	2	3^+_γ	963	2.5(1)	0.1729		$E2$	< 260	a
		634.24	0	6^+_g	548	20(1)	0.00853		$E2$	< 10	
		917.10	0	4^+_g	266	100(2)	0.00365		96.2%$E2$	< 8	
$K^\pi = 0^+_2$											
1400.20	0^+	512.0	2	2^+_γ	888	8.3(38)	0.01425	> 2100	$E2$	< 24	b
		1319.60	0	2^+_g	81	100(2)	1.77×10^{-3}		$E2$	< 2	
1453.40	2^+	177.70	0	1^-	1276	0.94(11)	0.0664	3400^{+5600}_{-1300}	$E1$	$0.09^{+0.07}_{-0.06}$	a
		392.48	2	4^+_γ	1061	0.99(11)	0.0292		E2	$2.7^{+2.3}_{-1.8}$	a
		490.51	2	3^+_γ	963	3.26(17)	0.0164		$\geq$ 94.5%$E2$	> 1	a
		565.32	2	2^+_γ	888	2.04(33)	0.016		$E2/M1$	$0.89^{+0.83}_{-0.61}$	a
		1187.80	0	4^+_g	266	74(2)	0.00215		$E2$	$0.79^{+0.56}_{-0.51}$	
		1372.80	0	2^+_g	81	100(2)	0.00241		$M1$	–	
1574.26	4^+	120.82	0_2	2^+	1453	0.21(4)	1.357	$1080 - 3100$†	$E2$	330–940	a
		216.36	0	3^-	1358	0.25(3)	0.0396		$E1$	0.02-–0.06	a
		277.28	2_1	4^-	1297	0.20(3)	0.021		$E1$	0.01-–0.02	a
		364.21	2_1	3^-	1210	0.48(3)	0.01070		$E1$	0.01-–0.02	a
		391.541	2	5^+_γ	1183	0.92(8)	0.044		$E2/M1$	4–12	a
		513.314	2	4^+_γ	1061	2.1(1)	0.021		$E2/M1$	2.4-–6.8	a
		611.228	2	3^+_γ	963	0.50(8)	0.013		$E2/M1$	0.24-–0.68	a
		686.146	2	2^+_γ	888	1.2(3)	0.00695		$E2$	0.32-–0.91	a
		1025.84	0	6^+_g	548	18(1)	0.0028		$E2$	0.6-–1.8	
		1308.64	0	4^+_g	266	100(2)	0.002181		$0.93^{+0.14}_{-0.15}$	0.5-–1.4	
$K^\pi = 4^+$											
1535.80	4^+	238.67	2_1	4^-	1297	0.12(2)	0.0310	1200^{+2100}_{-450}	$E1$	$0.014^{+0.012}_{-0.010}$	a
		352.90	2	5^+_γ	1183	0.90(16)	0.046		$>$ 62%$E2$	> 2.2	a
		475.27	2	4^+_γ	1061	9.0(6)	0.0219		73%$E2$	20^{+15}_{-13}	c

Table 2 continued

E_L (keV)	J_i^π	E_γ (keV)	K_f	J^π	E_f (keV)	I_γ (rel.)	α_T	τ (fs)	$\pi\ell$ or δ	B($E1$) or B($E2$) mW.u or W.u.	Notes
		572.96	2	3^+_γ	963	63(1)	0.0113		89%$E2$	67^{+45}_{-44}	
		647.61	2	2^+_γ	888	100(2)	0.00794		$E2$	65^{+44}_{-42}	
		987.15	0	6^+_g	548	1.0(4)	0.0022		$E2$	$0.08^{+0.10}_{-0.06}$	a
$K^\pi = 0^+_3$											
1666.00	0^+	1585.35	0	2^+_g	81	100		3000^{+4800}_{-1300}	$E2$	$0.52^{+0.40}_{-0.32}$	
1728.27	2^+	154.026	0_2	4^+	1574	0.57(7)	0.575	1800^{+880}_{-430}	$E2$	270^{+160}_{-120}	a
		370.39	0	3^-	1358	3.54(16)	0.01028		$E1$	$0.06^{+0.03}_{-0.02}$	a
		452.54	0	1^-	1276	3.23(55)	0.00643		$E1$	$0.03^{+0.02}_{-0.01}$	a
		840.204	2	2^+_γ	888	3.9(16)	0.0063		$E2/M1$	$0.39^{+0.38}_{-0.24}$	a
		1462.69	0	4^+_g	266	32(6)	1.49×10^{-3}		$E2$	$0.20^{+0.13}_{-0.10}$	c
		1647.64	0	2^+_g	81	100(2)	1.78×10^{-3}		$M1$	–	
		1728.29	0	0^+_g	0	64(2)			$E2$	$0.17^{+0.08}_{-0.07}$	d
1886.45	4^+	1805.86	0	2^+_g	81	100		1600^{+1300}_{-390}	$E2$	$0.51^{+0.16}_{-0.23}$	
2180.58	4^+	1217.72	2	3^+_γ	963	100(21)		240^{+200}_{-80}	$0.24^{+0.07}_{-0.05}$	$0.7^{+1.6}_{-0.5}$	
		1292.44	2	2^+_γ	888	88			$E2$	$8.4^{+5.8}_{-4.3}$	e
2230.97	2^+	955.75	0	1^-	1276	73(2)		360^{+70}_{-60}	$E1$	$0.44^{+0.12}_{-0.09}$	
		1342.57	2	2^+_γ	888	100(3)			89%$E2$	$5.1^{+1.4}_{-1.1}$	

[a] This γ-ray was not observed in this work. Energy and intensity information adopted from Ref. [17]
[b] This γ-ray was not observed in this work. Energy and intensity information adopted from Ref. [29]
[c] Since this is a multiplet in our work, the intensity of the γ ray was adopted from Ref. [17]
[d] This γ ray was not observed in Ref. [17], and, therefore, the intensities were scaled between the two measurements
[e] This γ ray was not observed in this work. Energy and intensity information adopted from Ref. [41]. An error was not reported for the intensity of this γ ray

them are above the pairing gaps. The 2^+_3 and 4^+_3 members of the $K^\pi = 0^+_3$ at 1666.0 keV form the band structure on top of this state. Transitions from this band however are only weakly connected to the ground state. Further experiments with conversion electrons should help determine the nature of the remaining $K^\pi = 0^+$ bands.

5 Conclusion

We have measured the lifetimes of nine new levels in ^{162}Dy including six of the eleven reported 0^+ states. We assert that the 1400.2 keV 0^+ excitation may be the β vibration and it is connected to the ground state band with stronger transition probabilities than any of the other $K^\pi = 0^+$ bands. Reduced transition probabilities to the ground state band are not in the order of tens or several Weisskopf units [24], they are however in line with other observations of 0^+ state decays to the ground state band for Er, Yb, and other Dy isotopes [39, 40]. Further, the transition probabilities agree with the Alaga rules.

The measurement of the 1666.0 keV 0^+ band show weaker connections to the ground state band than the 1400.2 keV band. The 2^+ state of this band seems to show a strong connection to the $K^\pi = 2^+$ band in agreement with previous measurements [18] although that is not shown in Fig. 3. The $K^\pi = 0^+$ bands at 2497.8 keV, 2655.7 keV, and 2800.9 keV show fairly collective E2 transitions connecting to the ground state in the order of approximately 1 W.u. The state at 2800.9 keV shows a depopulating transition B($E2$) value between 0.6 to 1.2 W.u. The $K^\pi = 0^+$ band at 2497.8 keV also shows a fairly collective connection to the ground state 2^+ with a B($E2$) value of 0.7 W.u. In a deformed nucleus, B(E2) values in the order of 1 W.u. can only result from collective effects.

The nature of the $K^\pi = 0^+$ at 1666.0 keV remains open. The 2^+ and 4^+ members of strongly connected and form the band structure on top of this state. Previous measurements had seen a strong connection to the γ-band. Transitions from this band are only weakly connected to the ground state. Further experiments are needed to determine if this band is a potential candidate for a coexisting shape. All of the 0^+ states except the first two are above the two-neutron and two-proton pairing gaps as indicated in Fig. 3.

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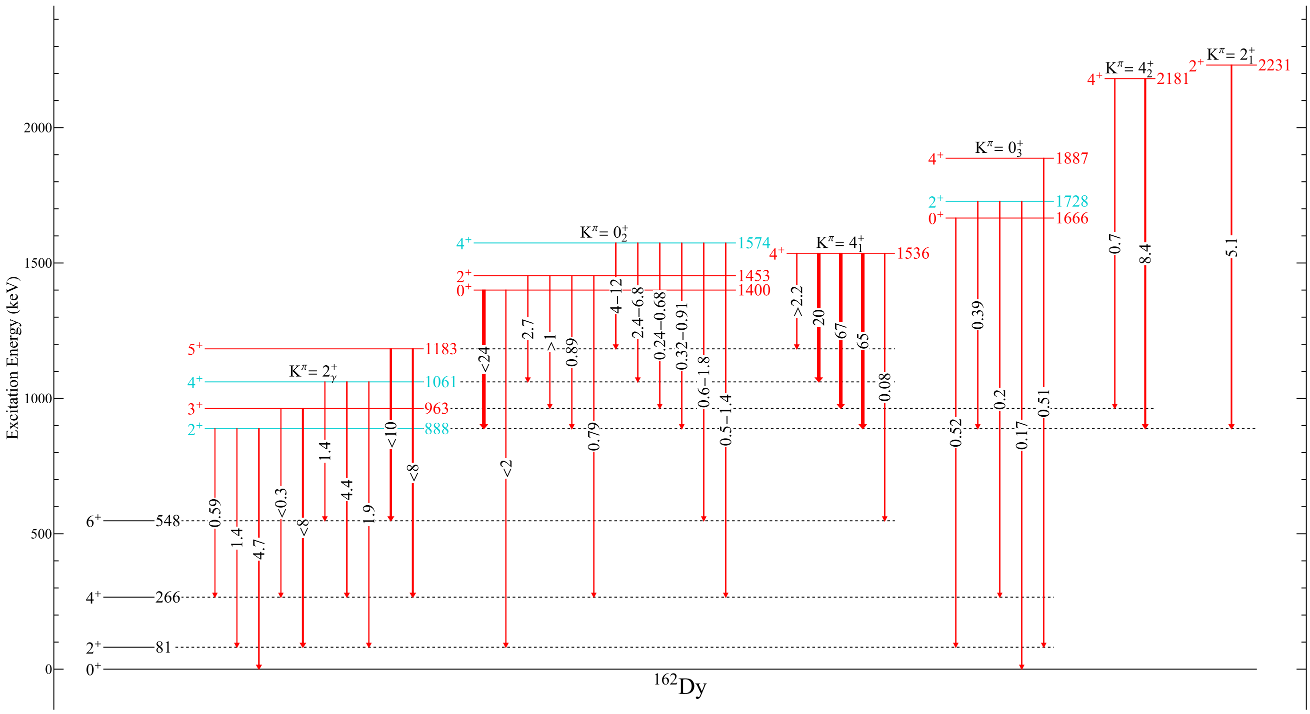

Fig. 4 Level scheme showing all observed transitions from the lowest-lying 2^+_γ, 0^+_2, 0^+_3, and 4^+_1 band with all interband ($K^\pi = J^+_i \rightarrow K^\pi = 2^+_\gamma$) decays. Levels with new lifetime measurements are drawn in red while those with an associated literature lifetime are drawn in turquoise (color online). The B(E2) calculations are expressed in Weisskopf units (W.u.) and drawn in red. Intensities for transitions to the γ band are taken from [17]. Also shown is a tentative (2^+) state at 2231.0 keV with a strong decay to the 2^+_γ band

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Data Availability Statement Mymanuscript has no associated data. [Authors' comment: Data will be made available from the corresponding author on reasonable request.]

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References

1. S.R. Lesher, A. Aprahamian, L. Trache, A. Oros-Peusquens, S. Deyliz, A. Gollwitzer et al., New $K^\pi = 0^+$ bands in ^{158}Gd. Phys. Rev. C **66**, 051305(R) (2002). https://doi.org/10.1103/PhysRevC.66.051305
2. H.F. Wirth, G. Graw, S. Christen, D. Cutoiu, Y. Eisermann, C. Günther et al., 0^+ states in deformed actinide nuclei by the (p, t) reaction. Phys. Rev. C **69**, 044310 (2004). https://doi.org/10.1103/PhysRevC.69.044310
3. D.A. Meyer, V. Wood, R.F. Casten, C.R. Fitzpatrick, G. Graw, D. Bucurescu et al., Extensive investigation of 0^+ states in rare earth region nuclei. Phys. Rev. C **74**, 044309 (2006). https://doi.org/10.1103/PhysRevC.74.044309
4. D. Bucurescu, G. Graw, R. Hertenberger, H.F. Wirth, N.L. Iudice, A.V. Sushkov et al., High-resolution study of 0^+ and 2^+ excitations in ^{168}Er with the (p, t) reaction. Phys. Rev. C. **73**, 064309 (2006). https://link.aps.org/doi/10.1103/PhysRevC.73.064309
5. G. Suliman, D. Bucurescu, R. Hertenberger, H.F. Wirth, T. Faestermann, R. Krücken et al., Study of the ^{130}Ba nucleus with the (p, t) reaction. Eur. Phys. J. A **36**, 243 (2008). https://doi.org/10.1140/epja/i2008-10589-2
6. L. Bettermann, S. Heinze, J. Jolie, D. Mücher, O. Möller, C. Scholl et al., High-resolution study of 0^+ states in ^{170}Yb. Phys. Rev. C **80**, 044333 (2009). https://doi.org/10.1103/PhysRevC.80.044333
7. C. Bernards, R.F. Casten, V. Werner, P. von Brentano, D. Bucurescu, G. Graw et al., High-resolution study of excited 0^+ states in ^{200}Hg and ^{202}Hg. Phys. Rev. C **87**, 064321 (2013). https://doi.org/10.1103/PhysRevC.87.064321
8. C. Bernards, R.F. Casten, V. Werner, P. von Brentano, D. Bucurescu, G. Graw et al., Investigation of 0^+ states in ^{198}Hg after two-neutron pickup. Phys. Rev. C **87**, 024318 (2013). https://doi.org/10.1103/PhysRevC.87.024318
9. A.I. Levon, G. Graw, R. Hertenberger, S. Pascu, P.G. Thirolf, H.F. Wirth et al., 0^+ states and collective bands in ^{228}Th studied by the (p, t) reaction. Phys. Rev. C **88**, 014310 (2013). https://doi.org/10.1103/PhysRevC.88.014310
10. A.I. Levon, P. Alexa, G. Graw, R. Hertenberger, S. Pascu, P.G. Thirolf et al., Spectroscopy of ^{232}U in the (p, t) reaction: More information on 0^+ excitations. Phys. Rev. C **92**, 064319 (2015). https://doi.org/10.1103/PhysRevC.92.064319
11. M. Spieker, S. Pascu, D. Bucurescu, T.M. Shneidman, T. Faestermann, R. Hertenberger et al., High-resolution (p, t) studies of low-spin states in ^{240}Pu: Octupole excitations, α clustering, and other structure features. Phys. Rev. C **97**, 064319 (2018). https://doi.org/10.1103/PhysRevC.97.064319

12. D. Bucurescu, S. Pascu, G. Suliman, H.F. Wirth, R. Hertenberger, T. Faestermann et al., High-resolution study of ^{166}Er with the (p, t) reaction. Phys. Rev. C. **100**, 044316 (2019). https://link.aps.org/doi/10.1103/PhysRevC.100.044316
13. A.I. Levon, D. Bucurescu, C. Costache, T. Faestermann, R. Hertenberger, A. Ionescu et al., New data on 0^+ states in ^{158}Gd. Phys Rev C. **100**, 034307 (2019). https://link.aps.org/doi/10.1103/PhysRevC.100.034307
14. J.C. Nzobadila Ondze, B.M. Rebeiro, S. Triambak, L. Atar, G.C. Ball, V. Bildstein et al., Investigation of pair-correlated 0^+ states in ^{134}Ba via the ^{136}Ba(p, t) reaction. Phys. Rev. C **103**, 034329 (2021). https://doi.org/10.1103/PhysRevC.103.034329
15. D. Bucurescu, S. Pascu, G. Graw, R. Hertenberger, H.F. Wirth, T. Faestermann et al., Updated analysis of the ^{170}Er$(p, t)^{168}$Er reaction data. Phys. Rev. C **108**, 014310 (2023). https://doi.org/10.1103/PhysRevC.108.014310
16. S.R. Lesher, J.N. Orce, Z. Ammar, C.D. Hannant, M. Merrick, N. Warr et al., Study of 0^+ excitations in ^{158}Gd with the $(n, n'\gamma)$ reaction. Phys. Rev. C **76**, 034318 (2007). https://doi.org/10.1103/PhysRevC.76.034318
17. A. Aprahamian, X. Wu, S.R. Lesher, D.D. Warner, W. Gelletly, H.G. Börner et al., Complete spectroscopy of the ^{162}Dy nucleus. Nucl. Phys. A **764**, 42 (2006). https://doi.org/10.1016/j.nuclphysa.2005.09.020
18. A. Aprahamian, S.R. Lesher, C. Casarella, H.G. Börner, M. Jentschel, Lifetime measurements in ^{162}Dy. Phys. Rev. C **95**, 024329 (2017). https://link.aps.org/doi/10.1103/PhysRevC.95.024329
19. G. Alaga, K. Alder, A. Bohr, B.R. Mottelson, Intensity rules for beta and gamma transitions to nuclear rotational states. Dan. Mat. Fys. Medd. **29**, 1 (1955)
20. P.E. Garrett, N. Warr, S.W. Yates, Nuclear structure studies with the inelastic neutron scattering reaction and gamma-ray detection. J. Res. Natl. Inst. Stand. Technol. **105**, 141 (2000). https://doi.org/10.6028/jres.105.019
21. T. Belgya, G. Molnár, S.W. Yates, Analysis of Doppler-shift attenuation measurements performed with accelerator-produced monoenergic neutrons. Nucl. Phys. A **607**, 43 (1996). https://doi.org/10.1016/0375-9474(96)00221-7
22. K.B. Winterbon, An analytic theory of Doppler-shift attenuation. Nucl. Phys. A **246**, 293 (1975). https://doi.org/10.1016/0375-9474(75)90647-8
23. C.A. McGrath, P.E. Garrett, M.F. Villani, S.W. Yates, Gamma-gamma coincidence measurements following inelastic neutron scattering. Nucl. Instrum. Methods Phys. Res. A **421**, 458 (1999). https://doi.org/10.1016/S0168-9002(98)01170-X
24. P.E. Garrett, H. Lehmann, J. Jolie, C.A. McGrath, M. Yeh, W. Younes et al., Properties of ^{112}Cd from the $(n, n'\gamma)$ reaction: levels and level densities. Phys. Rev. C **64**, 024316 (2001). https://doi.org/10.1103/PhysRevC.64.024316
25. E.E. Peters, A. Chakraborty, B.P. Crider, B.H. Davis, M.K. Gnanamani, M.T. McEllistrem et al., Level lifetimes in the stable Zr nuclei: effects of chemical properties in Doppler-shift measurements. Phys. Rev. C **88**, 024317 (2013). https://doi.org/10.1103/PhysRevC.88.024317
26. C.W. Reich, ^{162}Dy data sheets. Nucl. Data Sheets **108**, 1807 (2007). https://doi.org/10.1016/j.nds.2007.07.002
27. D.G. Burke, G. Løvhøiden, T.F. Thorsteinsen Studies of ^{158,160,162,164,166}Dy levels with the (t, p) reaction. Nucl. Phys. A **483**, 221 (1988). https://doi.org/10.1016/0375-9474(88)90533-7
28. L.O. Edvardson, L. Westerberg, GCh. Madueme, E0 transitions from a K=0^+ band in ^{162}Dy. Nucl. Phys. A **252**, 103 (1975). https://doi.org/10.1016/0375-9474(75)90604-1
29. N.V. Zamfir, R.F. Casten, B. Liu, D.S. Brenner, C.J. Barton, R. Krücken et al., Status of the $K^\pi = 0_2^+$ band in ^{162}Dy. Phys. Rev. C **60**, 054319 (1999). https://doi.org/10.1103/PhysRevC.60.054319
30. D. Tonev, A. Dewald, T. Klug, P. Petkov, J. Jolie, A. Fitzler et al., Transition probabilities in ^{154}Gd: Evidence for X(5) critical point symmetry. Phys. Rev. C **69**, 034334 (2004). https://doi.org/10.1103/PhysRevC.69.034334
31. J. Berzins, P. Prokofjevs, R. Georgii, R. Hucke, T. von Egidy, G. Hlawatsch et al., ^{162}Dy studied with (n, γ), $(n, n'\gamma)$, (d, p) and (d, t) reactions. Nucl. Phys. A **584**, 413 (1995). https://doi.org/10.1016/0375-9474(94)00522-O
32. S. Frauendorf, The low-energy quadrupole mode of nuclei. Int. J. Mod. Phys. E Nucl. Phys. **24**, 1 (2015). https://doi.org/10.1142/S0218301315410013
33. J.-P. Delaroche, M. Girod, J. Libert, H. Goutte, S. Hilaire, S. Péru et al., Structure of even–even nuclei using a mapped collective Hamiltonian and the D1S Gogny interaction. Phys. Rev. C **81**, 014303 (2010). https://doi.org/10.1103/PhysRevC.81.014303
34. D. Bonatsos, A. Martinou, S.K. Peroulis, T.J. Mertzimekis, N. Minkov, Shape coexistence in even–even nuclei: A theoretical overview. Atoms **11**, 34 (2023). https://doi.org/10.3390/atoms11090117
35. R. Bijker, A.E.L. Dieperink, Phys. Rev. C **26**, 2688 (1982). https://doi.org/10.1103/PhysRevC.81.014303
36. D.D. Warner, R.F. Casten, Interacting-Boson-Approximation E2 operator in deformed nuclei. Phys. Rev. C **25**, 2019 (1982). https://doi.org/10.1103/PhysRevC.25.2019
37. D.D. Warner, R.F. Casten, Revised formulation of the phenomenological interacting boson approximation. Phys. Rev. Lett. **48**, 1385 (1982). https://doi.org/10.1103/PhysRevLett.48.1385
38. R.F. Casten, D.D. Warner, The Interacting Boson Approximation. Rev. Mod. Phys. **60**, 389 (1988). https://doi.org/10.1103/RevModPhys.60.389
39. C. Fahlander, A. Axelsson, M. Heinebrodt, T. Härtlein, D. Schwalm, Two-phonon γ-vibrational states in ^{166}Er. Phys. Lett. B **388**, 475 (1996). https://doi.org/10.1016/S0370-2693(96)01203-8
40. P.E. Garrett, M. Kadi, C.A. McGrath, V. Sorokin, M. Li, M. Yeh et al., The nature of 0^+ excitations in ^{166}Er. Phys. Lett. B **400**, 250 (1997). https://doi.org/10.1016/S0370-2693(97)00373-0
41. C.Y. Wu, D. Cline, M.W. Simon, G.A. Davis, R. Teng, A.O. Macchiavelli et al., Electromagnetic properties of the rotationally aligned band in ^{162}Dy. Phys. Rev. C **64**, 064317 (2001). https://doi.org/10.1103/PhysRevLett.48.1385