Lifetime measurements of 0^+ states in ^{168}Er with the Doppler-shift attenuation method

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Background: The lowest-lying shape oscillations of deformed nuclei have been described as quadrupole in nature ($\lambda = 2$), resulting in two types of vibrations or oscillations: β vibrations with oscillations along the symmetry axis ($K^\pi = 0^+$) and γ vibrations breaking axial symmetry with a projection of $K^\pi = 2^+$ on the symmetry axis. The γ vibration seems to be well characterized as the first $K^\pi = 2^+_1$ (or 2^+_γ) band in deformed nuclei and exhibits a systematic behavior across the region. The nature of the $K^\pi = 0^+$ excitations, however, has remained poorly understood and has been open to debate for some decades.
Purpose: The goal of this work is to understand the nature of 0^+ states observed in ^{168}Er through measurements of the lifetimes of these states and to determine if they are consistent with oscillations built on a deformed ground state, the minima of other coexisting shapes, single-particle states, or a mixture of effects.
Method: Lifetimes of excited states in the ^{168}Er nucleus were measured with the Doppler shift attenuation method (DSAM) and the inelastic neutron scattering reaction, $(n, n'\gamma)$, at the University of Kentucky Accelerator Laboratory.
Results: Numerous 0^+ states had been observed by the (p, t) reaction [D. Bucurescu *et al.*, Phys. Rev. C **73**, 064309 (2006).]. We confirm the 0^+ states at 1217.2, 1421.5, 1833.6, 2364.9, 2392.1, and 2643.0 keV in ^{168}Er. We could not, however, support the previous assignments of 0^+ levels at 2114.1, 2200.6, 2572.5, and 2617.4 keV. We report measured lifetimes for six confirmed 0^+ excitations and additional members of 0^+ bands.
Conclusions: The results for ^{168}Er show that it is the third excited $K^\pi = 0^+$ (0^+_4) excitation that carries the collective strength and, therefore, the potential to be an oscillation on the ground state. This result is similar to the case in ^{166}Er, where it was also the 0^+_4 state that exhibited greater collectivity than the first excited $K^\pi = 0^+$ band. The Delaroche *et al.* [J.-P Delaroche *et al.*, Phys. Rev. C **81**, 014303 (2010).] prediction for a collective $K^\pi = 0^+$ band is at $E_T = 1.818$ MeV, which corresponds the third excited $K^\pi = 0^+$ band.

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I. INTRODUCTION

In 1975, Bohr and Mottelson provided a description of emergent collective motion in nuclei based on geometrical shapes with superimposed oscillations around that shape [1]. The lowest lying shape oscillations are quadrupole in nature ($\lambda = 2$), resulting in two types of vibrations built on a deformed ground state: β vibration with oscillations along the symmetry axis ($K^\pi = 0^+$) and γ vibrations breaking axial symmetry with a projection of $K^\pi = 2^+$ on the symmetry axis. The γ vibration seems to be well characterized as the first $K^\pi = 2^+_1$ (or 2^+_γ) band and exhibits a systematic behavior across the region of deformed nuclei with typical $B(E2 : 2^+_\gamma \to 0^+_g)$ values of a few Weisskopf units (W.u.) [2]. The nature of the $K^\pi = 0^+$ excitations, however, has remained poorly understood and open to debate for decades. In measurements with the high-precision Q3D spectrograph in Munich many 0^+ states were identified in various deformed rare-earth nuclei. For example, the discovery of thirteen 0^+ states in the ^{158}Gd nucleus [3] pioneered searches in many deformed rare-earth nuclei. This discovery itself led to a huge investment of theoretical and experimental effort and an onslaught of results pointing to large numbers of 0^+ states in nuclei spanning the entire deformed rare-earth region [4–6]. Today, in spite of the advances and developments in nuclear theory, we still do not have a universal description of nuclear structure that can explain the nature of the lowest lying $K^\pi = 0^+$ excitations. A review of 0^+ states by Heyde and Wood [7] summarizes the difficulties that have emerged in understanding these states from both the experimental and theoretical viewpoints.

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In this work, we report lifetimes of levels in the ^{168}Er nucleus, which has one of the most developed level schemes. The recent expansion of information for this well deformed nucleus included the reported observation of fifteen 0^+ states below 3 MeV [6]. The goal of the current work is to understand the nature of these excited states by measurements of level lifetimes and, therefore, the matrix elements [$B(E\ell)$] values to determine if they are oscillations built on a deformed ground state, the minima of other coexisting shapes, single-particle states, or a combination of several effects. Measured lifetimes for several $K = 0^+$ bands are known in deformed nuclei such as ^{156}Gd [8], ^{158,160}Gd [9,10], and ^{166}Er [11,12]. In the ^{156}Gd case, the first excited $K^\pi = 0^+$ was shown to be collective and has been described as a β vibration built on the ground state [13], while lifetimes in ^{166}Er indicate enhanced decays from the third excited $K^\pi = 0^+$ band [12] to the ground state. Studies of the ^{162}Er nucleus also indicate that the first excited 0^+ excitation is most likely a β vibration [14]. Here we report new measurements of lifetimes of 0^+ states in ^{168}Er using the Doppler shift attenuation method (DSAM). Lifetimes of $K^\pi = 0^+$ excitations in ^{168}Er have until now been limited only to the 2^+ state of the first excited $K^\pi = 0^+$ excitation.

In this study of ^{168}Er, we confirm the 0^+ states observed with the (p, t) reaction at 1217.2, 1421.5, 1833.6, 2364.9, 2392.1, and 2643.0 keV, but we could not support the assignments of 0^+ levels at 2114.1, 2200.6, 2572.5, and 2617.4 keV. We report lifetimes for the six 0^+ excitations and several additional band members of these states. The new results are presented along with data for the even $^{162–170}$Er isotopes. We show a global picture of the Er isotopes as a function of the neutron and proton pairing gaps and the predicted energies of the collective 0^+ excitations as calculated by Delaroche *et al.* [15] using the Hartree Fock-Bogoliubov theory extended by the generator coordinate method and mapped onto a five-dimensional collective quadrupole Hamiltonian. This theory predicts the collective $K^\pi = 0^+$ oscillation to lie at $E_T = 1.818$ MeV in excitation energy for this ^{168}Er nucleus.

II. EXPERIMENT

The ^{168}Er nucleus was probed using the $(n, n'\gamma)$ reaction at the University of Kentucky Accelerator Laboratory. Neutrons were produced by the ^{3}H(p, n) reaction. The target sample was 34.30 g of 95.47% enriched $^{168}Er_2O_3$ contained in a thin-walled polyethylene cylinder 4.0 cm in height and 2.2 cm in diameter. A ≈50% high-purity germanium(HPGe) detector with time-of-flight gating for background reduction and an annular bismuth germanate (BGO) shield for active Compton suppression [16] were used to detect the emitted γ rays.

An excitation function was performed using neutrons from $E_n = 1.2$ to 3.0 MeV in 0.1-MeV steps with the detector at 90° with respect to the incident beam. This provided γ ray yields as a function of neutron energy and allowed the placement of γ rays to energy levels based on thresholds (an example is shown in Fig. 1). γ-ray angular distribution measurements were performed at incident neutron energies of 1.3, 1.6, 2.0, and 2.7 MeV and at ten angles over a range of 40° to 150° at each neutron energy. These energies were chosen to minimize the effect of feeding of the desired levels and yield accurate level lifetimes. The yields of the γ rays, $W(\theta)$, were fitted with even-order Legendre polynomials,

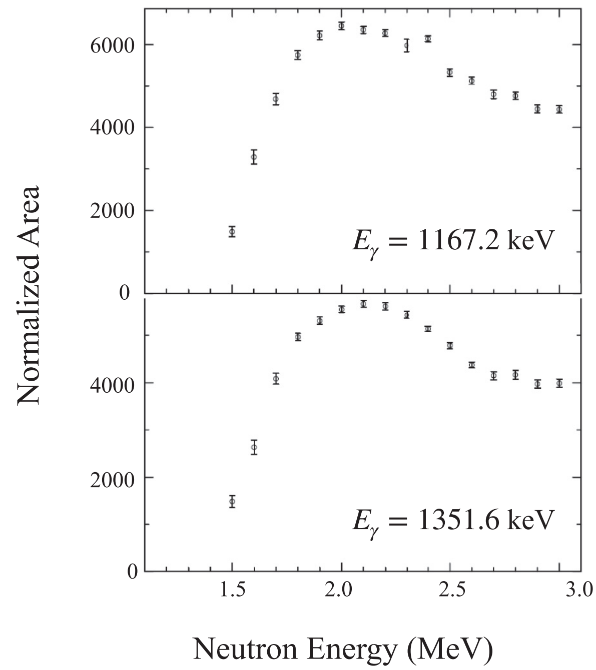

FIG. 1. Excitation functions for the 1431.4 keV level in ^{168}Er: plots of γ ray yields as a function of neutron energy. These plots show that two γ rays from the same level will demonstrate the same shape and energy threshold in the excitation function.

$$W(\theta) = A_o[1 + a_2P_2(\cos\theta_\gamma) + a_4P_4(\cos\theta_\gamma)], \quad (1)$$

where a_2 and a_4 depend on the multipolarities and mixing amplitudes of the transition. These results can also be compared with a statistical model calculation [17] to deduce the multipole mixing ratio (δ values) for some levels. Examples of angular distributions are found in Fig. 2. Lifetimes of excited states in the fs to ps range were also extracted from the angular distribution measurements using the Doppler-shift attenuation method (DSAM) [18]. The γ-ray peaks have angular dependent energies,

$$E_\gamma(\theta_\gamma) = E_{\gamma 0}\left[1 + \frac{v_0}{c}F(\tau)\cos\theta_\gamma\right], \quad (2)$$

where $E_{\gamma 0}$ is the unshifted γ-ray energy, v_0 is the recoil velocity in the laboratory frame, θ_γ is the angle of observation, and $F(\tau)$ is the experimental attenuation factor [18]. A theoretical $F(\tau)$ curve is calculated using the Winterbon formalism [19] and compared to the extracted $F(\tau)$ value determined by examining the energy of the γ ray as a function of angle. The lifetimes determined from each γ ray depopulating a level must agree within experimental uncertainties, aiding in the assignment of γ rays to specific levels.

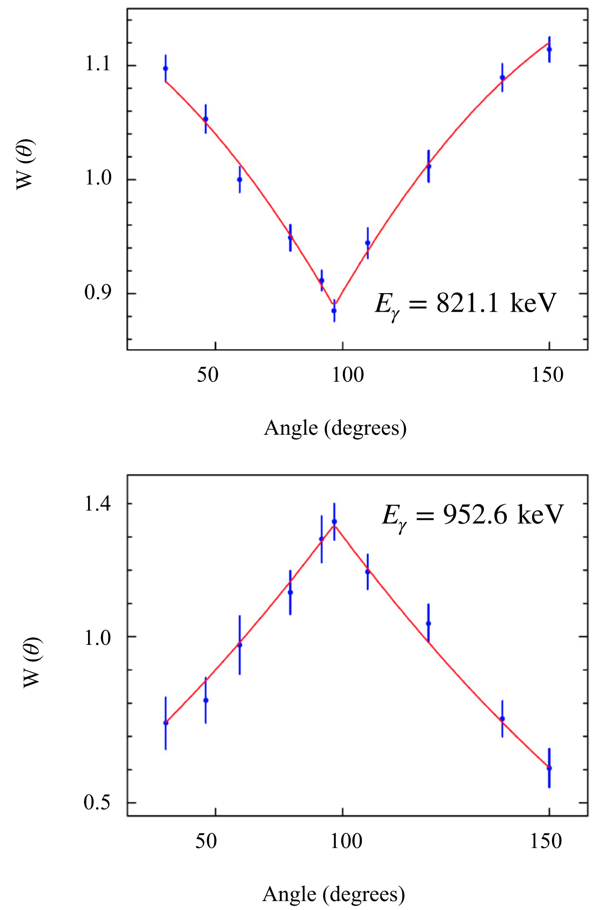

FIG. 2. Angular distribution examples: two different types of decay for ^{168}Er$(n, n'\gamma)$ with a neutron energy of 2.0 MeV. The top figure is an $E2$ from $E_{\mathrm{level}} = 821.0$ keV, $2^+_\gamma \rightarrow 0^+_g$. The bottom figure is a different distribution corresponding to a possible $M1$ transition from $E_{\mathrm{level}} = 1848.2$ keV, $2^+ \rightarrow 2^+$.

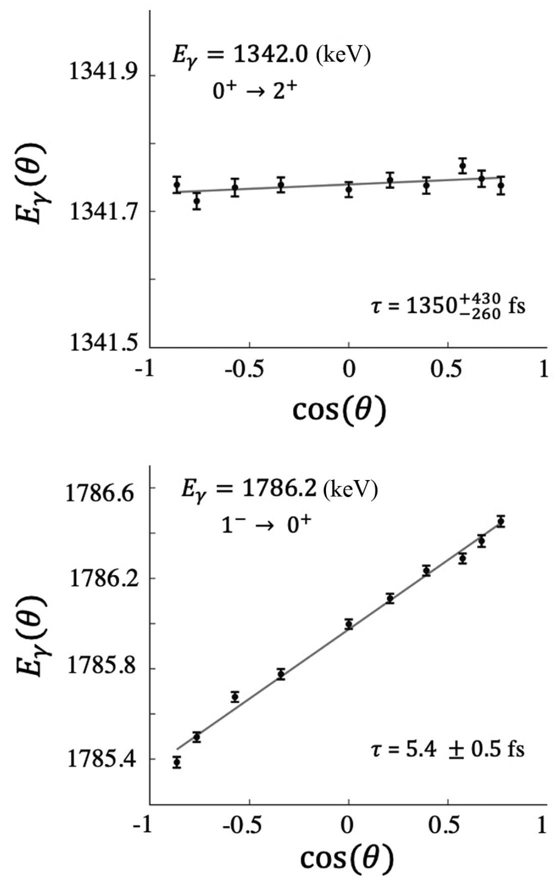

FIG. 3. Lifetime examples for ^{168}Er$(n, n'\gamma)$ with a neutron energy of 2.0 MeV. The top figure is an example of the $E_{\mathrm{level}} = 1421.5$ keV, 0^+_3 decay to 2^+_g, giving a new lifetime in this work. The bottom figure shows the lifetime of $E_{\mathrm{level}} = 1786.2$ keV, 1^- decay to the ground state, which is in good agreement to the literature value of 5 ± 1 fs.

In all measurements, ^{226}Ra and ^{152}Eu standard sources were used out-of-beam for energy and efficiency calibrations. To check for gain shifts during angular distribution measurements, standard sources of ^{60}Co, ^{137}Cs, or ^{207}Bi were placed near the detector. At higher neutron energies, an additional ^{24}Na source, produced by placing NaCl rings near a ^{252}Cf source and irradiating with neutrons, was placed in beam to provide accurate energy identification at high γ-ray energies. ^{24}Na emits 1368.63- and 2764.03 keV γ rays. Previous publications describe these methods and techniques in greater detail [16,20,21].

Lifetime and angular distribution measurements were compared with published values [22]. Many of the lower excitation energy lifetime values are outside the range of our technique but, for example, the literature lifetime of 5 ± 1 fs [22] for the 1^- level at 1786.2 keV was measured as 5.4 ± 0.5 fs in the current measurements and the 2022.5 keV $(3)^-$ level's literature lifetime of 150^{+50}_{-40} fs is within range of our measured lifetime of 110 ± 10 fs. An example of our lifetime measurements are shown in Fig. 3 for the 1342.0 and 1786.2 keV transitions which depopulate levels at 1421.5 and 1786.2 keV, respectively.

III. RESULTS

The lifetime results for levels observed in ^{168}Er are summarized in Table I and are compared to previous literature and the Nuclear Data Sheets (NDS) compilations [22]. In this experiment we did not attempt to identify new levels but to confirm previously reported states, to identify γ rays from the levels of interest, and to obtain level lifetimes. The excitation functions were used to support γ-ray placement. Additional γ-ray decays were identified or confirmed by matching energy and excitation shapes and/or thresholds. Angular distributions were used to extract lifetimes and multipole mixing ratios.

In the most recent high-resolution (p, t) study of ^{168}Er [6], twelve 0^+ states under 2.7 MeV were identified. This experiment set out to study the nature of these levels. Since the $(n, n'\gamma)$ reaction takes place via the compound nuclear reaction, it leads to an alignment of the excited nuclei, and the decay from the excited levels are anisotropic. To confirm the 0^+ assignment of a level, the angular distribution of the γ decay is measured and shown to be isotropic, i.e., $a_2 = 0$ in Eq. (1). The distributions for transitions depopulating a 0^+ to 2^+ state is due to the single angular magnetic substate of the

TABLE I. Levels in ^{168}Er as observed in this $(n, n'\gamma)$ experiment. Level lifetimes from previous literature values are denoted τ_{lit} and adopted from Ref. [22]; if levels do not match within 2σ, these discrepancies are discussed in the text. Lifetimes are determined by DSAM. Multipole mixing ratios (δ values) are noted when deduced. If there are two solutions for the mixing ratio of the χ^2 vs δ plot, both values are presented. Parentheses are used to denote tentative assignments and unresolved multiplets are noted and not used in calculating the level lifetime. Band assignments are taken from Ref. [22] and denoted by a numeric subscript when needed to distinguish them for reference in either the table or discussions.

E_L (keV)	K_i^π	J^π	E_γ (keV)	E_f (keV)	K_f^π	J^π	I_γ (%)	δ	$F(\tau)$	τ (fs)	$B(E2)$ (W.u.)	$B(E1)$ (mW.u.)	Notes
79.75(10)	0_g^+	2^+	79.80	0	0_g^+	0^+	100						
263.93(10)	0_g^+	4^+	184.24(5)	80	0_g^+	2^+	100		0.029(64)	>400			
										$\tau_{\mathrm{lit}} = 1.60(4) \times 10^5$			
548.66(11)	0_g^+	6^+	284.66(5)	264	0_g^+	4^+	100			$\tau_{\mathrm{lit}} = 1.7(7) \times 10^4$			
821.01(10)	2_γ^+	2^+	741.36(9)	80	0_g^+	2^+	100(2)			$\tau_{\mathrm{lit}} = 4000 \pm 130$	8.4 ± 0.3		
			821.14(5)	0	0_g^+	0^+	95(2)				4.7 ± 0.2		
895.73(10)	2_γ^+	3^+	631.72(5)	264	0_g^+	4^+	18(1)		0.031(22)	1200^{+2700}_{-500}	$4.6^{+0.3}_{-1.4}$		
			815.95(5)	80	0_g^+	2^+	100(1)			$\tau_{\mathrm{lit}} = 4600^{+1300}_{-300}$	$7.4^{+0.5}_{-2.1}$		
994.62(10)	2_γ^+	4^+	730.65(9)	264	0_g^+	4^+	100(2)		0.016(6)	2500^{+1500}_{-700}	8.6 ± 1.8		
			914.92(5)	80	0_g^+	2^+	61(2)			$\tau_{\mathrm{lit}} = 5000 \pm 1000$	1.7 ± 0.4		
1217.17(14)	0_2^+	0^+	1137.41(5)	80	0_g^+	2^+	100		0.011(8)	>2000	<3.9		
1276.20(10)	0_2^+	2^+	380.45(6)	896	2_γ^+	3^+	2.4(2)			$\tau_{\mathrm{lit}} = 2900^{+3100}_{-1000}$	7^{+3}_{-7}		
			455.10(5)	821	2_γ^+	2^+	4.8(2)	$-0.16^{+0.08}_{-0.10}$			$0.14^{+0.18}_{-0.14}$		
			1012.16(5)	264	0_g^+	4^+	100(2)				$2.2^{+0.8}_{-2.2}$		
			1196.56(5)	80	0_g^+	2^+	52(2)	$-6.2^{+1.0}_{-1.7}$			$0.49^{+0.17}_{-0.49}$		a
								-0.61 ± 0.04			$0.14^{+0.05}_{-0.14}$		
			1276.27(5)	0	0_g^+	0^+	58(2)				$0.40^{+0.14}_{-0.40}$		
1358.88(10)	1_1^-	1^-	1279.05(5)	80	0_g^+	2^+	100(1)		0.034(7)	1060^{+280}_{-190}		$0.11^{+0.02}_{-0.03}$	
			1358.89(5)	0	0_g^+	0^+	27(1)					0.02 ± 0.01	
1403.52(10)	1_1^-	$(2)^-$	582.60(5)	821	2_γ^+	2^+	30(1)						
			1323.92(5)	80	0_g^+	2^+	100(1)						
1411.07(10)	0_2^+	4^+	862.24(5)	549	0_g^+	6^+	82(2)			$\tau_{\mathrm{lit}} > 1200$	<8.5		
			1146.98(6)	264	0_g^+	4^+	69(2)				<1.7		
			1331.26(5)	80	0_g^+	2^+	100(2)				<1.2		
1421.49(14)	0_3^+	0^+	1341.96(5)	80	0_g^+	2^+	100		0.027(6)	1350^{+430}_{-260}	$2.5^{+0.5}_{-0.8}$		
1431.41(11)	1^-	3^-	1167.43(5)	264	0_g^+	4^+	100(1)		0.160(12)	200 ± 20		0.52 ± 0.05	b
			1351.69(5)	80	0_g^+	2^+	93(2)			$\tau_{\mathrm{lit}} = 6.0 \times 10^4$		0.31 ± 0.03	
1493.07(10)	0_3^+	2^+	1229.07(5)	264	0_g^+	4^+	96(1)		0.069(18)	490^{+190}_{-110}	$4.8^{+1.1}_{-1.9}$		
			1413.31(5)	80	0_g^+	2^+	100(1)	1.48 ± 0.10			$0.17^{+0.04}_{-0.07}$		
			1493.12(5)	0	0_g^+	0^+	19(1)				$0.36^{+0.08}_{-0.14}$		
1569.32(12)	2_1^-	$(2)^-$	673.58(6)	896	2_γ^+	3^+	42(1)		0.122(8)	310^{+30}_{-20}		1.0 ± 0.1	c
			748.31(5)	821	2_γ^+	2^+	100(1)			$\tau_{\mathrm{lit}} = 620^{+160}_{-120}$		$1.7^{+0.1}_{-0.2}$	
1633.43(12)	2_1^-	3^-	638.77(5)	995	2_γ^+	4^+	73(2)		0.064(18)	$\tau_{\mathrm{lit}} = 500^{+160}_{-120}$		$0.69^{+0.16}_{-0.22}$	
			737.74(5)	896	2_γ^+	3^+	88(2)			$0.54^{+0.13}_{-0.17}$			
			811.48(50)	821	2_γ^+	2^+	<100					<0.46	f
1656.23(12)	0_3^+	4^+	1107.66(5)	549	0_g^+	6^+	35(1)		0.031(9)	1200^{+500}_{-270}	$1.9^{+0.4}_{-0.8}$		
			1392.19(5)	264	0_g^+	4^+	100(1)	$0.52^{+0.18}_{-0.33}$			$0.37^{+0.38}_{-0.26}$		
1786.15(10)	0_1^-	1^-	1706.35(5)	80	0_g^+	2^+	100(1)		0.886(9)	5.4 ± 0.5		7.4 ± 0.7	
			1786.18(5)	0	0_g^+	0^+	62(1)			$\tau_{\mathrm{lit}} = 5 \pm 1$		4.0 ± 0.4	
1833.59(16)	0_4^+	0^+	1753.83(6)	80	0_g^+	2^+	100		0.179(38)	190^{+60}_{-40}	$4.7^{+1.0}_{-1.5}$		
1848.24(10)	2_2^+	2^+	952.56(5)	896	2_γ^+	3^+	19(1)	$-1.24^{+0.21}_{-0.18}$	0.019(10)	1900^{+1800}_{-640}	$0.53^{+0.19}_{-0.51}$		
			1768.10(6)	80	0_g^+	2^+	100(2)				$0.2^{+0.1}_{-0.2}$		
			1848.44(5)	0	0_g^+	0^+	96(2)				$0.20^{+0.06}_{-0.15}$		
1892.80(19)	3_2^-	$(4)^-$	798.86(5)	1094	4^-	4^-	100		0.168(24)	190^{+40}_{-30}			
										$\tau_{\mathrm{lit}} = 260^{+30}_{-20}$			
1892.95(11)	0_4^+	2^+	616.62(6)	1276	0_2^+	2^+	23(1)	$-0.01^{+0.06}_{-0.05}$	0.039(9)	1000^{+310}_{-190}	0.01 ± 0.01		
			1813.28(5)	80	0_g^+	2^+	100(1)	$-0.06^{+0.03}_{-0.04}$			0.01 ± 0.01		
1913.73(12)	0_1^-	3^-	1649.96(6)	264	0_g^+	4^+	80(3)		0.900(31)	$4.6^{+4.6}_{-1.5}$		$6.9^{+2.2}_{-6.9}$	e
			1833.80(6)	80	0_g^+	2^+	100(3)			$\tau_{\mathrm{lit}} < 16$		$6.3^{+2.0}_{-6.3}$	
1930.40(10)	2_3^+	2^+	1850.68(5)	80	0_g^+	2^+	100(2)	$-0.92^{+0.22}_{-3.6}$	0.044(17)	820^{+560}_{-240}	$0.23^{+0.96}_{-0.16}$		

TABLE I. (*Continued.*)

E_L (keV)	K_i^π	J^π	E_γ (keV)	E_f (keV)	K_f^π	J^π	I_γ (%)	δ	$F(\tau)$	τ (fs)	$B(E2)$ (W.u.)	$B(E1)$ (mW.u.)	Notes
								$-2.8^{+2.1}_{-2.0}$			$0.44^{+0.15}_{-0.08}$		
			1930.35(5)	0	0_g^+	0^+	69(2)				$0.28^{+0.08}_{-0.19}$		
1936.53(13)	1_2^-	1^-	1936.52(5)	0	0_g^+	0^+	100		0.093(13)	370^{+60}_{-50}		0.12 ± 0.02	
										$\tau_{\text{lit}} = 350 \pm 40$			
1972.34(10)	1_2^-	$(2)^-$	1076.60(5)	896	2_γ^+	3^+	43(1)		0.068(9)	560^{+90}_{-70}		0.12 ± 0.02	d
			1151.24(5)	821	2_γ^+	2^+	25(1)			$\tau_{\text{lit}} = 190^{+120}_{-60}$		0.06 ± 0.01	
			1892.65(5)	80	0_g^+	2^+	100(1)					0.05 ± 0.01	
2002.10(11)	2_2^+	4^+	1738.35(6)	264	0_g^+	4^+		2.1 ± 0.2	0.029(18)	1350^{+2400}_{-540}	$0.31^{+0.13}_{-0.56}$		e
			1922.20(50)	80	0_g^+	2^+					$0.19^{+0.08}_{-0.34}$		f
2022.49(17)	1_2^-	$(3)^-$	1758.55(6)	264	0_g^+	4^+	100		0.278(22)	110 ± 10		0.54 ± 0.05	
			480.62	1541	3^-	3^-				$\tau_{\text{lit}} = 150^{+50}_{-40}$			g
2031.58(13)	0_4^+	$(4)^+$	620.05(6)	1411	0_2^+	4^+	23(1)	$0.21^{+0.82}_{-0.21}$	0.102(72)	340^{+900}_{-160}	$3.8^{+8.4}_{-3.8}$		
			1768.10(6)	264	0_g^+	4^+	100(3)	-0.22 ± 0.14			$0.10^{+0.12}_{-0.10}$		
			1950.97(6)	80	0_g^+	2^+							g
2055.74(12)	4_1^+	$(4)^+$	962.05	1094	4^-	4^-			0.207(21)	160^{+30}_{-20}		$0.86^{+0.12}_{-0.17}$	e h
			1159.96(6)	896	2_γ^+	3^+	51(2)			$\tau_{\text{lit}} = 460 \pm 230$	$7.7^{+1.7}_{-2.0}$		
			1234.76(5)	821	2_γ^+	2^+	100(4)				11 ± 2		
2080.44(17)	2_3^+	$(4)^+$	1259.27	821	2_γ^+	2^+			0.138(20)	250^{+50}_{-40}			g
			1816.50(6)	264	0_g^+	4^+	100	$-4.8^{+3.6}_{-7.9}$			2.9 ± 0.6		
2114.1		(0_5^+)	620.05	1492	0_3^+	2^+							i
2129.21(17)			1865.27(6)	264	0_g^+	4^+	100		0.753(27)	14 ± 2			
2136.90(10)		$(2)^+$	2057.20(6)	80	0_g^+	2^+	62(2)		0.313(11)	90^{+5}_{-4}			
			2136.84(5)	0	0_g^+	0^+	100(2)				0.22 ± 0.1		
2193.13(12)	2^+	2^+	789.98(6)	1404	1^-	$(2)^-$	27(1)		0.308(19)	90 ± 10	1.5 ± 0.2		
			1371.86(5)	821	2_γ^+	2^+	100(3)	2.3 ± 0.3			22 ± 3		
2200.6		(0_6^+)											j
2230.26(17)	2_2^-	$(2)^-$	1409.24(6)	821	2_γ^+	2^+	100		0.426(53)	56^{+14}_{-11}		$2.0^{+0.4}_{-0.5}$	
2243.37(11)	1_1^+	$(3)^+$	1979.49(5)	264	0_g^+	4^+	52(1)	$-0.50^{+0.10}_{-0.14}$	0.356(10)	75 ± 3	$0.44^{+0.2}_{-0.1}$		
								-1.5 ± 0.3			1.5 ± 0.2		
			2163.54(5)	80	0_g^+	2^+	100(2)	0.18 ± 0.03			0.09 ± 0.03		
2254.50(14)		$(2^+), (3)^+$	1259.95(5)	995	2_γ^+	4^+	87(5)		0.146(29)	240^{+70}_{-45}			
			1433.23(9)	821	2_γ^+	2^+	100(6)						
2263.5		(0^+)											b
2311.06(15)		$(4)^+$	2047.11(5)	264	0_g^+	4^+	100	$-0.07^{+0.05}_{-0.04}$	0.428(12)	56 ± 3	$0.04^{+0.04}_{-0.05}$		
2321.84(10)		2^+	1045.62(6)	1276	0_2^+	2^+	62(3)		0.032(14)	1200^{+1000}_{-390}	$2.7^{+0.9}_{-2.3}$		
			2242.31(5)	80	0_g^+	2^+	100(4)	$4.3^{+3.6}_{-1.4}$			$0.09^{+0.03}_{-0.08}$		
			2321.50(6)	0	0_g^+	0^+	63(3)				$0.05^{+0.02}_{-0.04}$		
2323.04(10)	3_5^-	3^-	1328.57	994	2_γ^+	4^+			0.204(14)	160^{+20}_{-10}			g
			1426.80(6)	896	2_γ^+	3^+	62(2)					0.19 ± 0.02	
			1502.43(6)	821	2_γ^+	2^+	73(2)				0.20 ± 0.02		
			2059.20(6)	264	0_g^+	4^+	100(4)				0.10 ± 0.01		
2336.88(10)	3_6^-	3^-	1441.39(6)	896	2_γ^+	3^+	29(1)		0.256(10)	120 ± 5		0.15 ± 0.01	
			1515.84(6)	821	2_γ^+	2^+	41(1)					0.18 ± 0.01	
			2256.95(5)	80	0_g^+	2^+	100(2)					0.14 ± 0.01	
2341.86(11)		1	2262.00(6)	80	0_g^+	2^+	82(2)		0.318(15)	90 ± 10			
			2341.93(6)	0	0_g^+	0^+	100(3)			$\tau_{\text{lit}} = 160 \pm 40$			
2345.25(17)			1524.23(6)	821	2_γ^+	2^+	100(2)		0.774(14)	12 ± 1			
2350.15(10)			(991.12(9))	1359	1^-	1^-	11(3)		0.319(13)	90 ± 5			
			1074.02(6)	1276	0_2^+	0^+	13(1)						
			2270.37(5)	80	0_g^+	2^+	100(4)						
2361.48(13)		1	2361.46(5)	0	0_g^+	0^+	100		0.255(15)	120 ± 10			
										$\tau_{\text{lit}} = 160 \pm 30$			
2364.89(14)	0_7^+	0^+	2285.12(5)	80	0_g^+	2^+	100(1)		0.103(17)	350^{+80}_{-60}	$0.68^{+0.12}_{-0.16}$		
2373.29(17)		2,3	1552.27(6)	821	2_γ^+	2^+	100		0.448(16)	50 ± 3			
2392.07(17)	0_8^+	0^+	2312.30(6)	80	0_g^+	2^+	100		0.149(18)	230^{+40}_{-30}	$0.60^{+0.08}_{-0.11}$		

TABLE I. (*Continued.*)

E_L (keV)	K_i^π	J^π	E_γ (keV)	E_f (keV)	K_f^π	J^π	I_γ (%)	δ	$F(\tau)$	τ (fs)	$B(E2)$ (W.u.)	$B(E1)$ (mW.u.)	Notes
2402.16(17)		(1^-)	1581.14(6)	821	2_γ^+	2^+	100		0.766(25)	13 ± 2			
2416.88(14)		$1^{(-)}$	2337.11(5)	80	0_g^+	2^+	100		0.569(18)	30 ± 2			
										$\tau_{\rm lit} = 30 \pm 10$			
2423.35(22)		(4^+)	2159.40(8)	264	0_g^+	4^+	100	$0.86^{+0.39}_{-0.50}$	0.413(51)	58^{+14}_{-11}			
2424.97(15)		$(2)^+$	2424.95(6)	0	0_g^+	0^+	100		0.097(26)	360^{+140}_{-80}			
2461.71(10)		2^+	1185.60(6)	1276	0_2^+	2^+	64(3)	$0.09^{+0.15}_{-0.12}$	0.227(19)	140^{+16}_{-14}	0.10 ± 0.03		
								$-1.9^{+0.8}_{-0.6}$			9 ± 2		
			2197.66(6)	264	0_g^+	4^+	79(3)				$0.67^{+0.07}_{-0.08}$		
			2381.96(6)	80	0_g^+	2^+	100(3)	$-1.2^{+0.3}_{-1.0}$			$0.34^{+0.23}_{-0.08}$		
2493.77(11)		1^+	1673.17(6)	821	2_γ^+	2^+	85(19)		0.505(17)	40 ± 3			
			2493.33(6)	0	0_g^+	0^+	100(19)			$\tau_{\rm lit} = 50 \pm 6$			
2510.52(16)		$1^{(-)}$	2430.75(6)	80	0_g^+	2^+	100		0.526(22)	40 ± 3			b
										$\tau_{\rm lit} = 80 \pm 30$			
2572.5		(0_9^+)	2493.02(8)	80	0_g^+	2^+	100						k
2617.4		(0_{10}^+)	2536.44(7)	80	0_g^+	2^+	100						l
2643.04(21)		$1^{(+)}$	2643.02(8)	0	0_g^+	0^+	100		0.406(44)	60 ± 10			b
										$\tau_{\rm lit} = 100 \pm 20$			
2643.91(29)	0_{11}^+	0^+	2564.14(11)	80	0_g^+	2^+	100		0.377(68)	70 ± 20	1.9 ± 0.5		

[a]This δ value is consistent with that reported in Ref. [25].

[b]Refer to text for a discussion about this level.

[c]The known lifetime is from GRID [39] measurements which uses models to account for level feeding. Our lifetime is assigned near level threshold, where we obtain $F(\tau) = 0.122 \pm 0.008$. If we instead calculate our lifetime at the highest measured neutron energy we obtain $F(\tau) = 0.067 \pm 0.07$, which corresponds to a level lifetime of 580^{+80}_{-60} fs, in agreement with the previously reported lifetime.

[d]This lifetime does not agree with the lifetime reported in Ref. [22], which assumed extreme feeding assumptions and simulations of γ-ray cascades from Ref. [39]. Also included in Ref. [39] is a lifetime range using simulations for unknown feeding. When these additional parameters are considered, a lifetime range of 95–570 fs is determined which agrees with our reported value.

[e]The intensities of all the γ rays used to calculate the transition probabilities for this level are adopted from Ref. [22].

[f]This γ ray is part of an unresolved multiplet in the current work.

[g]The placement of this γ-ray decay is unsupported in our work.

[h]This γ ray is mixed with the 962.06 keV ^{63}Cu background line. The peak is observed but it cannot be separated from the background.

[i]A 0^+ assignment is unsupported in this work from the Legendre polynomial fit of $a_2 = 0.42 \pm 0.11$.

[j]A γ-ray decay was not observed from this level, therefore a level at this energy is unsupported in this work.

[k]A 0^+ assignment is unsupported in this work from the Legendre polynomial fit of $a_2 = -0.24 \pm 0.05$.

[l]A 0^+ assignment is unsupported in this work from the Legendre polynomial fit of $a_2 = 0.33 \pm 0.09$.

0^+ state. Identification of in-band transitions in the observed $K^\pi = 0^+$ bands was not possible due to the absorption in the thick scattering sample and internal conversion which generally renders it difficult to observe < 100 keV γ rays.

Table I lists the levels observed in this experiment including their γ ray decays and lifetimes. The $B(E2)$ and $B(E1)$ values of interest were also calculated and are reported. In this experiment, we did not observe internal conversion electrons and, therefore, the $E0$ decays to the ground states are not taken into account. For consistency, we adopted the 0^+ state numbering convention used in Ref. [6]. A detailed discussion of each proposed 0^+ assignment is highlighted below along with selected additional levels in Table I.

A. $K^\pi = 0_2^+$ band at 1217.2 keV

A 1137.3 keV γ ray deexciting this level was identified in an ^{167}Er(n,γ) reaction [23] then labeled as a 0^+ state in transfer reactions [6,24]. Our work confirms the placement of the γ ray but does not allow the placement of any additional γ rays. The $F(\tau)$ value allows only a lifetime limit of $\tau > 2000$ fs and a transition probability $B(E2: 0_2^+ \rightarrow 2_g^+) < 3.9$ W.u.

The accepted band structure includes the 1276.2 keV $J^\pi = 2^+$ state. Our experiment did not yield any additional lifetime information but can contribute information on the $E2/M1$ mixing ratio δ for the $2^+ \rightarrow 2_\gamma^+$ transition, which indicates a strong $M1$ component. In general, when two δ values are possible, the one with the smaller χ^2 is reported. In the case of the 1196.6 keV transition, another delta value within 2σ is possible and is in agreement with the adopted value [22]. Therefore, both values are reported.

The 4^+ member of the band at 1411.1 keV was observed but no new information was obtained.

B. $K^\pi = 0_3^+$ band at 1421.5 keV

The 1421.5 keV 0_3^+ level was identified in (p,t) and (t,p) reactions in Ref. [24]. Using the $(n,n'\gamma)$ reaction, Berendakov *et al.* [25] observe an isotropic $E_\gamma = 1342.0$ keV γ ray, which our data confirms with $a_2 = 0.01 \pm 0.03$. From this γ ray we found a level lifetime of $\tau = 1350^{+430}_{-260}$ fs and calculate a $B(E2: 0_3^+ \rightarrow 2_g^+) = 2.5^{+0.5}_{-0.8}$ W.u.

Our data support three deexciting γ rays of 1229.1, 1413.3, and 1493.1 keV from the 2^+ level in this band (E_L = 1493.1 keV). The level lifetime is found to be 490^{+190}_{-110} fs with calculated transition probabilities. The 4^+ member of this band was found to have $\tau = 1200^{+500}_{-270}$ fs and $B(E2) < 2$ W.u. for all transitions.

C. $K^\pi = 0_4^+$ band at 1833.6 keV

First reported in (p,t) and (t,p) experiments [24] and verified with high-precision (p,t) measurements [6], the 1833.6 keV level is a spin-0 excitation with a lifetime of $\tau = 190^{+60}_{-40}$ fs as determined in this work. The excitation function, lifetime measurement, and angular distributions confirm the placement of the 1753.8 keV γ ray as depopulating the $0_4^+ \rightarrow 2_g^+$ excitation with a calculated value for the $B(E2: 0_4^+ \rightarrow 2_g^+) = 4.7$ W.u.

Our data also support the 2^+ and 4^+ level assignments to this $K^\pi = 0_4^+$ band at 1893.0 and 2031.6 keV, respectively. The 2^+ member of this band shows weak decays to the 2^+ states of the 0_2^+ band and the ground-state band (2_g^+), while the 4^+ member of this band shows strong decay to the 4^+ member (E_L = 1411.1 keV) of the $K^\pi = 0_2^+$ band.

D. $K^\pi = (0_5^+)$ band at 2114.1 keV

Identified in (p,t) [6] with a small cross section and low relative strength, our work was unable to confirm this 0^+ level with γ-ray decay. There was no decay to the 2_g^+ state observed and the only possible deexciting γ ray was identified at 620.0 keV which had been previously assigned to the 2031.6 keV 4^+ level [26]. Using the excitation function threshold and the nonisotropic angular distribution of the 620.0 keV γ ray, our work supports the 2031.6 $\rightarrow$ 1411.1 keV placement.

E. $K^\pi = (0_6^+)$ band at 2200.6 keV

Bucurescu *et al.* [6] identified this level with a small cross section and low relative strength. The γ-ray decay to the ground-state band is not observed and the decay to the 2_γ^+ state is on a laboratory background line. Another analysis of the (p,t) data was unable to find the peak in the 5° spectrum where it should be the largest for the $L = 0$ states [4]. For these reasons, we regard this level as questionable; additional experiments are needed to investigate the nature of this level.

F. $K^\pi = (0^+)$ band at 2263.5 keV

This level is identified as a (0^+) in the NDS [22] as assigned in Burke *et al.* via the (t,p) experiment. In reviewing this publication, a level at 2265(4) keV is observed but is not marked as a 0^+ state, instead it is listed as corresponding to the 2262.7 keV $J, K^\pi = 3, 3^-$ level. An additional literature search does not reveal the source of the 0^+ identification. In the most recent (p,t) experiment using a high resolution spectrograph [6] this level was not observed. For these reasons, this state is removed from 0^+ consideration.

G. $K^\pi = 0_7^+$ band at 2364.9 keV

Identified with a large cross section in Ref. [6] we support the placement of this state with the observation of a 2285.1 keV γ ray to the 2_g^+ level and assign a lifetime of 350^{+80}_{-60} fs for the level. We are able to confirm that this is not the previously identified (1^+) level at 2365.3 keV as we do not observe the ground state γ ray, 2364.7 keV, used to calculate the lifetime [27]. The angular distribution of the decaying γ ray at 2285.1 keV is also isotropic as shown by $a_2 = -0.06 \pm 0.05$.

H. $K^\pi = 0_8^+$ band at 2392.1 keV

This level was identified in Ref. [6] where the authors note the angular distribution could be affected by the known 2^+ state at 2393.6 keV; however, γ rays from this 2^+ state were not observed in our data. Nor is this level the 2392.9 keV $(3^-, 4^+)$ level in the NDS [22] as the known γ-ray decay is not observed. We did detect a γ ray from the 0_8^+ level, $E_\gamma = 2312.3$ keV, which shows an isotropic angular distribution consistent with a spin-0 assignment ($a_2 = 0.03 \pm 0.03$). A lifetime of 230^{+40}_{-30} fs is found for this level.

An additional γ ray at 580.1 keV was observed as a possible decay to the 1812.2 keV (2^+) level. We are unable to confirm the 1812.2 keV level since the γ-ray decay energies are at the same energies as more intensive decays in our spectrum. For this reason, the 580.1 keV γ ray is not assigned to the 2392.1 keV level.

I. $K^\pi = (0_9^+)$ band at 2572.5 keV and $K^\pi = (0_{10}^+)$ band at 2617.4 keV

These two levels were identified in Ref. [6] with large cross-sections at the 5° spectrograph setting indicating $L = 0$. With the $(n, n'\gamma)$ data, we were able to identify γ-ray decays from each level to the 2_g^+ state; however, the angular distributions are not isotropic and the a_2 values are reported in Table I. No other γ rays were identified for these 0^+ states. Therefore, we consider them as tentative.

J. $K^\pi = 0_{11}^+$ band at 2643.0 keV

We were able to place a γ-ray decay to the 2_g^+ state, and confirm the 0^+ level at 2643.0 keV in Ref. [4], and assign a lifetime of 70 ± 20 fs. This translates into a $B(E2)$ value of 1.9 Wu. as shown for ^{168}Er in Fig. 4 and Table I.

K. Other levels

Collective excitations have been extensively studied in ^{168}Er including octupole [23,27–29] and two-phonon γ-vibrational states [30–34]. Our work has resulted in a lifetime of $4.6^{+4.6}_{-1.5}$ fs for the 1913.7 keV 3^- level where only an upper limit of 16 fs previously existed, and we have narrowed the uncertainty on the lifetime of the 2055.7 keV level.

Our direct lifetime measurement for the 3^- level at 1431.2 keV is in conflict with the 59 ps reported in Ref. [29] and adopted in the NDS [22]. Upon further inspection, Meyer *et al.* did not observe γ-ray decay from this level but determined the lifetime through a reevaluation of existing data

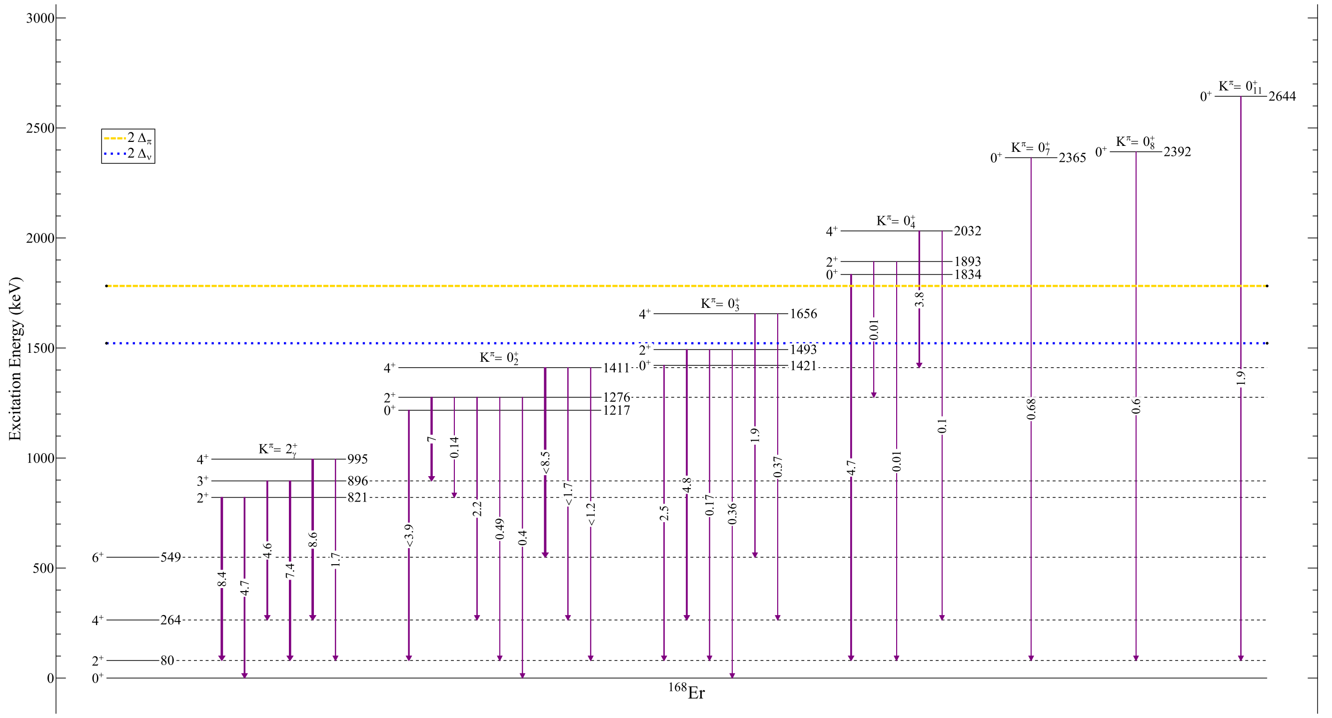

FIG. 4. Partial level scheme for the 0^+ bands identified and discussed in this work. The solid arrows represent $E2$ transitions. The upper limits of the transition probabilities are given in Table I. The band labels are according to the (p, t) experiment labels [6]. The dotted horizontal lines are the two-neutron and two-proton pairing gaps for ^{168}Er calculated using the formulas in Ref. [40] and masses from Ref. [41].

and private communications, which subsequently were never published and, therefore, cannot be reproduced. In our measurement, two γ rays are observed depopulating this level, 1167.4 and 1351.7 keV with excitation functions shown in Fig. 1. The extracted $F(\tau) = 0.160 \pm 0.012$ corresponding to a $\tau = 200 \pm 20$ fs.

IV. DISCUSSION

The erbium nuclei have been a testing ground for nuclear structure models, including the β, γ, and octupole vibrational states, as well as higher lying vibrations such as γ-γ structures [11,14,30,32–39]. Despite extensive studies, questions regarding the nature of the 0_2^+ bands as oscillations on the ground state or states of a completely different nature have persisted. The new level lifetimes and transition rates observed in our work for the levels in ^{168}Er contribute to this discussion.

Figure 4 shows the measured $B(E2)$ values. The $B(E2 : 0^+ \rightarrow 2_g^+)$ values are <3.9, 2.5, 4.7, 0.68, 0.60, 1.9 W.u. for the decays to the 2^+ member of the ground state band from the levels at 1217.2, 1421.5, 1833.6, 2364.9, 2392.1, and 2643.0 keV, respectively. The largest $B(E2)$ value of 4.7 W.u. corresponds to $0_4^+ \rightarrow 0_g^+$ or $1833.6 \rightarrow 80$ keV. Two other states (0_3^+ and 0_{11}^+) also exhibit possible collective behavior with <3.9 and 2.5 W.u.

To understand how these values compare with the deexcitations of the first excited $K^\pi = 2^+$ and the known $K^\pi = 0^+$ bands in the nearby Er isotopes, even $^{162-170}$Er isotopes were plotted along with the evolution of the two-neutron and two-proton pairing gaps using the formulas in Ref. [40] and masses from Ref. [41] and shown in Fig. 5. In the ^{168}Er nucleus, two of the six excited $K^\pi = 0^+$ excitations observed are below the pairing gaps. Higher excitation energy pairing gaps have the impact of pushing down wave function components that can contribute to the observed collectivity to the ground state while the lower pairing gap allows closer mixing of single-particle states and can have the potential impact of reducing the $B(E2)$ transition values connecting to the low lying bands. The 0^+ state combinations are easier or more likely to form from the various combinations of single-particle states. This reason may be justification for the variability of the collective strength of the first excited $K^\pi = 0^+$ excitations in the entire deformed rare-earth region of nuclei. In the case of the $^{168-170}$Er nuclei which have a relatively lower two-neutron and two-proton pairing gaps, we can expect that single-particle states can form the dominating components mixing with the states below.

In addition, Table II summarizes the $B(E2)$ values normalized to the Clebsch-Gordon coefficients (CG^2) for the decay of the 2^+ state of the first excited $K^\pi = 0^+$ band for the various isotopes of Er. If the excitation is built on the ground state, the matrix elements should be the same except for angular momentum aspects. The ^{162}Er case is in fairly good agreement as is ^{164}Er, although the $B(E2)$ values represent upper limits. The ^{166,170}Er cases do not support assigning the first excited $K^\pi = 0^+$ band as a collective excitation. The $K^\pi = 0^+$ results for ^{168}Er are not clearly conclusive. The extracted lifetime of >2000 fs leading to a $B(E2 : 0_2^+ \rightarrow 2_g^+) < 3.9$ W.u., is at

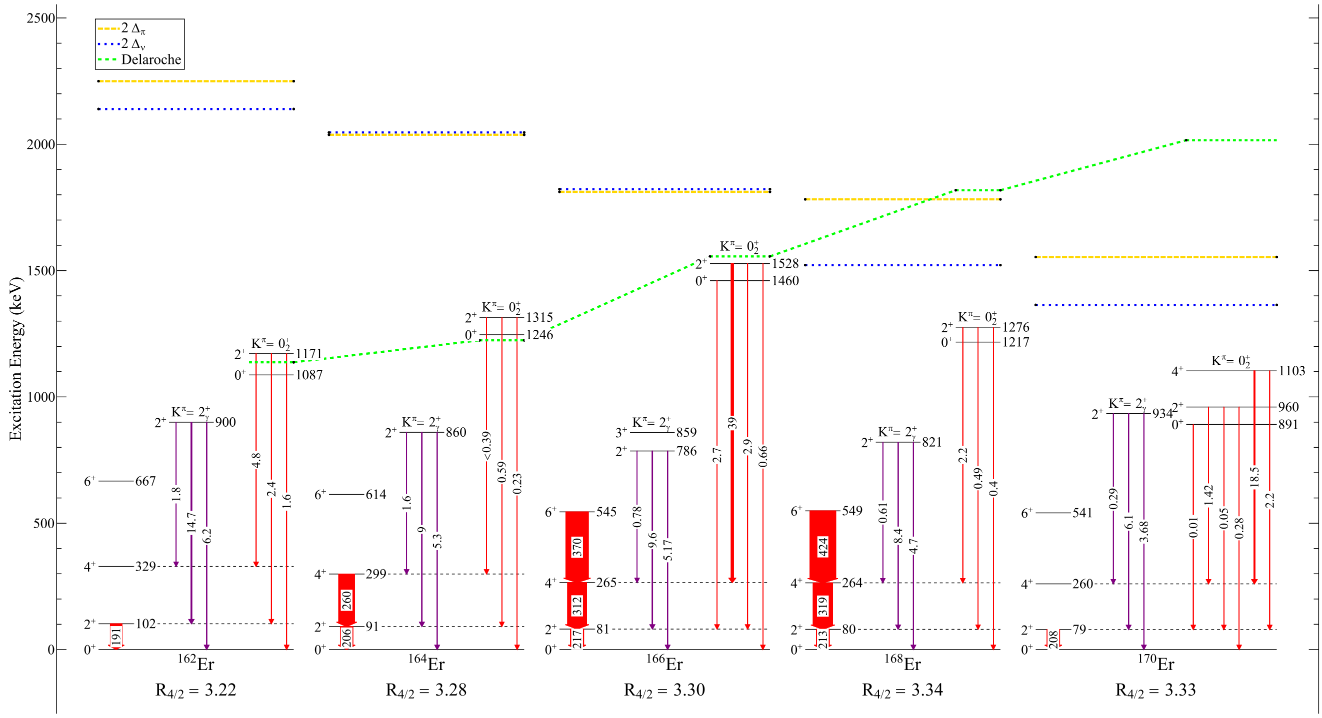

FIG. 5. Level schemes for $^{162-170}$Er nuclei showing the depopulation and $B(E2)$ values for the transitions from the first excited 0^+ and 2^+ bands. In green, we show the calculated energies [15] of the excited 0^+ state that is an oscillation on the ground state. In the dotted yellow and blue are the two-proton and two-neutron pairing gaps, respectively. The pairing gaps are calculated using the formulas in Ref. [40] and masses from Ref. [41].

the edge of the DSAM capability. The higher excited $K^\pi = 0_4^+$ state in the ^{168}Er nucleus at $E_{\rm ex} = 1833.59$ keV yields a $B(E2: 0_4^+ \to 2_g^+) = 4.7^{+1.0}_{-1.5}$ W.u. and is within uncertainties of the the 0_2^+ value.

Delaroche *et al.* [15] have developed a methodology that could explain the evolution of structure across the entire chart of nuclides. They use Hartree Fock-Bogoliubov theory extended by the generator coordinate method, and mapped onto a five-dimensional collective quadrupole Hamiltonian. This theory shows that, where explicit deformation is expected, a significant percentage of deformed nuclei should exhibit states with collective character for the first excited $K^\pi = 0^+$ excitation as an oscillation built on the ground-state band, while there are also entire regions of nuclei where the oscillations are predicted to occur at much higher excitation energies than the observed low-lying $K^\pi = 0^+$ excitations. This is the case for ^{168}Er. where the predicted collective 0^+ excitation is at $E_T = 1.818$ MeV and the experimentally collective 0_4^+ excitation is observed at $E_{\rm ex} = 1.833$ MeV. Figure 5 shows the theoretically calculated [15] collective excitations or oscillations of the ground state in green. For the ^{162,164,166}Er nuclei, the predicted, collective 0^+ level is at the excitation energy range of the first excited 0^+ state corresponding to an oscillation built on the ground state. This is in spite of our full awareness of the experimental results in the ^{166}Er nucleus.

The Delaroche theory predicts that the third excited $K^\pi = 0^+$ state in ^{168}Er should be a collective excitation build on the ground state. Experimentally, we show that the $K^\pi = 0^+$ state that shows somewhat greater collectivity to the ground state is the level at $E_{\rm ex} = 1833.59$ keV, acknowledging that the $B(E2)$ value upper limit is, within error bars, the same value.

TABLE II. A comparison of the $B(E2)$ values for the depopulation of the 2^+ of the first excited $K^\pi = 0_2^+$ band to the ground state band in $^{162-168}$Er isotopes in comparison to the Clebsch-Gordon values (CG^2) of the same transitions. All values are normalized to the $2^+_{K^\pi=0_2^+} \to 0_g^+$ transition. All data from ENSDF with the exception of the results presented here. The errors for ^{166}Er are large but still exclude agreement with CG^2. The ^{168}Er errors are too large to be conclusive in any way, although the ^{170}Er values are clear and in disagreement.

	CG^2	^{162}Er	^{164}Er	^{166}Er	^{168}Er	^{170}Er
$B(E2: 2^+_{K^\pi=0_2^+} \to 0_g^+)$	1.0	1.0 ± 0.4	<1.0	1.0 ± 0.2	$1.0^{+0.5}_{-1.0}$	1.0 ± 0.2
$B(E2: 2^+_{K^\pi=0_2^+} \to 2_g^+)$	1.4	1.5 ± 0.6	<2.6	4.3 ± 4.3	$1.2^{+0.6}_{-1.2}$	0.2 ± 0.2
$B(E2: 2^+_{K^\pi=0_2^+} \to 4_g^+)$	2.6	3.0 ± 1.2	<1.7	60 ± 12	$5.5^{+2.8}_{-5.5}$	5.1 ± 0.9

Influenced by the prediction of Delaroche *et al.*, we dare to conclude that is not the first excited $K^\pi = 0^+$ excitation that is an oscillation on the ground state. Instead, pointing to a higher excited 0^+ state as the collective oscillation in this nucleus supporting the higher $B(E2)$ value from the $E_T = 1818$ keV level. Most likely, it is this excited 0^+ state that is the β excitation, similar to the previous observation of a similarly highly excited 0^+ state in ^{166}Er [12].

V. CONCLUSION

In this work we have confirmed the existence of several excited 0^+ states reported in a (p, t) experiment [6]. We confirm that the levels at 1217.2, 1421.5, 1833.6, 2364.9, 2392.1, and 2643.0 keV are 0^+ states. We cannot confirm 0^+ assignments for the levels at 2114.1, 2200.6, 2572.5, and 2617.4 keV, reducing the number of confirmed 0^+ states in ^{168}Er to six below 3.0 MeV. In this work, we have measured level lifetimes for eleven 0^+ state bandhead states and members. The transition probability from the $K^\pi = 0^+_4$ state at $E_{\rm ex} = 1833.6$ keV to the ground-state band indicates somewhat larger collectivity than the first excited $K^\pi = 0^+$ excitation, although the upper limit and the measured value are within error bars. This implies that perhaps the first excited 0^+ band in ^{168}Er is not the oscillation built on the deformed ground state. The calculations of Delaroche *et al.* [15] predict the β vibration to be at $E_T = 1818.4$ keV, as shown in Fig. 5. The 0^+ state at $E_{\rm ex} = 1833.6$ keV shows the relatively larger collectivity to the ground state band. This nucleus is similar to ^{166}Er, where it is the third excited 0^+ state exhibiting the largest $B(E2)$ values in transitions to the ground-state band and not the first excited 0^+ band, while the theory predictions for ^{166}Er indicate that it should be the first excited $K^\pi = 0^+$ that is the oscillation on the ground state. In order to explore the structure of these 0^+ states further, additional information is required which includes experimental $E0$ and conversion coefficient measurements.

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