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Single-particle and collective excitations in ⁶⁶Zn

A. D. Ayangeakaa,^{1, 2, *} N. Sensharma,^{1, 2, †} M. Fulghieri,^{1, 2} R. V. F. Janssens,^{1, 2} Q. B. Chen,³

S. Zhu,^{4,‡} M. Alcorta,⁵ M. P. Carpenter,⁶ P. Chowdhury,⁷ A. Gade,^{8,9} C. R. Hoffman,⁶

F. G. Kondev,⁶ T. Lauritsen,⁶ E. A. McCutchan,⁴ A. M. Rogers,⁷ and D. Seweryniak⁶

¹Department of Physics and Astronomy, University of North Carolina Chapel Hill, NC 27599

²Triangle Universities Nuclear Laboratory, Duke University, Durham, NC 27708, USA

³Department of Physics, East China Normal University, Shanghai 200241, China

⁴National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY 11973, USA

⁵TRIUMF, Vancouver, BC, V6T 2A3, Canada

⁶Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA

⁷Department of Physics, University of Massachusetts, Lowell, Massachusetts 01854, USA

⁸National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA

⁹Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA

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Single-particle and collective excitations in 66 Zn have been investigated via the multinucleon transfer reaction, 26 Mg(48 Ca, $\alpha 4n\gamma$) using the Gammasphere multidetector array and the Fragment Mass Analyzer. In addition to confirming and complementing the previously known low-spin structure, a new quasi-rotational band comprising several stretched E2 transitions has been established to high spins. However, due to fragmentary nature of its decay, it was not possible to link this sequence to the low-lying states and, thus, determine the absolute excitation energies, spins and parities unambiguously. Large-scale shell-model calculations employing the JUN45 and jj44b effective interactions are able to successfully describe the low-spin structure and herewith confirm that it is dominated by single-particle excitations. The newly-established rotational cascade is compared with known superdeformed bands in the $A \approx 60-70$ mass region, and with results of calculations performed within the frameworks of the cranked shell model and the adiabatic and configuration-fixed constrained covariant density functional theory and the quantum particle-rotor model.

I. INTRODUCTION

The underlying structure of nuclei in the $A \approx 60 - 70$ mass region provides opportunities to investigate the complex interplay between single-particle and collective degrees of freedom as a function of spin, N and Z. These nuclei are characterized by valence configurations in which the active orbitals correspond to the $\mathcal{N} = 3$ low-j pf, and the high-j $f_{7/2}$ subshells as well as the $\mathcal{N} = 4$ high-*j*, unique-parity $g_{9/2}$ orbital. The opposite deformation-driving effects of these orbitals play a major role in determining the structure and shape of these nuclei. On the one hand, the structure at low spin is dominated by single-particle and collective excitations generated primarily by valence nucleon excitations within the pf shell. On the other, collective excitations induced by multi-quasiparticle excitations across the Z = 28 shell gap into the $1g_{9/2}$ intruder orbital dominate at high angular momenta. These excitations have been linked, for example, to the appearance of highly-deformed [1-8] and terminating bands [9-12] as well as to the presence of strong magnetic dipole excitations [13, 14] in the region. Indeed, due to the limited number of orbitals available near the Fermi level and the proximity to the N = Z line,

the observation of rotational bands with superdeformed characteristics in the $A \approx 60-70$ region remains of much interest for both experimental and theoretical studies.

In the present work, results of the investigation of the structure of 66 Zn, following a complex multinucleon transfer reaction ${}^{26}Mg({}^{48}Ca, \alpha 4n\gamma)$, are presented. Previous spectroscopic studies of ⁶⁶Zn were undertaken in Refs. [15-19] and, very recently, by Bala *et al.* [20] and Rai et al. [21]. In the latter, a collective structure was observed up to termination accompanied by a crossing with the ground-state band around spin $6\hbar$. These observations have been confirmed and complemented with largescale shell-model calculations carried out in the present work. In addition, by combining the experimental sensitivities of Gammaphere and the Fragment Mass Analyzer (FMA) with a novel experimental multinucleon transfer technique, a high-spin rotational cascade comprising of $\Delta I = 2$ transitions has been observed in coincidence with the low-spin structure. This sequence is observed to share characteristics similar to those of bands associated with superdeformation seen in neighboring nuclei of the $A \approx 60 - 70$ region. Comparisons with calculations performed within the framework of the adiabatic and configuration-fixed constrained covariant density functional theory and the quantum particle rotor model suggest a configuration for the new band involving excitation of two protons from the $f_{7/2}$ into the $g_{9/2}$ sub-shells. Details of the present measurements and of the data analysis are given in Sec. II, while the discussion of the experimental results, and the description of the-

^{*}Electronic address: ayangeak@unc.edu

[†]Electronic address: nsensharma@unc.edu

[‡]Deceased

oretical calculations with shell-model and the combination of covariant density functional theory (CDFT) and particle-rotor model (PRM), are presented in Secs. III and IV, respectively.

II. EXPERIMENTAL DETAILS AND ANALYSIS

Medium and high-spin states in ⁶⁶Zn were populated via the ${}^{26}Mg({}^{48}Ca, \alpha 4n\gamma){}^{66}Zn$ multinucleon transfer reaction. A self-supporting 0.973-mg/cm² target of highlyenriched ²⁶Mg was bombarded by ⁴⁸Ca ions at incident beam energies of 275-, 290-, and 320-MeV. These energies were provided by the ATLAS accelerator facility at the Argonne National Laboratory, and were chosen to be roughly 200% above the Coulomb barrier in order to favor multinucleon transfer and, in turn, enhance the population of high-spin yrast and near-yrast states. Gamma rays emitted in the de-excitation process were detected with Gammasphere [22, 23], a 4π array of 101 Compton-suppressed high-purity germanium (HPGe) detectors. The reaction residues were transported to the focal plane of the Fragment Mass Analyzer (FMA), where they were dispersed according to their mass-to-charge ratios, M/q. For this experiment, the FMA was tuned for the optimum transport of ions with an average charge state of 19⁺. The recoils were identified on an event-byevent basis from the position and time-of-flight measured in a micro-channel plate detector (MCP) placed at the focal plane, and the energy loss measured with a threefold segmented ionization chamber positioned behind the focal plane. The events were accumulated and recorded under the condition that recoil products be detected in kinematic coincidence with two or more γ rays within a 50-ns time window. More detailed information regarding the isotopic selection techniques, and the overall experimental procedure can be found in Ref. [24]. Gammaray events associated with ⁶⁶Zn recoils were sorted into fully-symmetrized, two-dimensional $(E_{\gamma}-E_{\gamma})$ coincidence matrices while those arising from all Zn ions populated in the reaction were sorted into three-dimensional $(E_{\gamma}-E_{\gamma} E_{\gamma}$) histograms. The latter were used mostly to confirm placements made using the former. The analysis was performed using the RADWARE suite of spectrum analyses packages [25].

Multipolarities for newly-identified and previously known transitions were assigned on the basis of angular distribution measurements and, in the case of weak transitions, a two-point angular-correlation ratio, $R_{\rm ac}$. The angular-distribution analysis was performed using coincidence matrices sorted such that energies of γ rays detected at specific Gammasphere angles (measured with respect to the beam direction) $E_{\gamma}(\theta)$, were incremented on one axis, while the energies of coincident γ rays detected at any angle, $E_{\gamma}(any)$, were placed on the other. To improve statistics, adjacent rings of Gammasphere, and those corresponding to angles symmetric with respect to 90° in the forward and backward hemispheres,



FIG. 1: (Color online) Angular distributions for some of the γ transitions shown in the ⁶⁶Zn level scheme. Experimental data is shown as black circles while the angular distribution fit is given as a red curve.

were combined. A total of seven matrices, with the angles 17.3°, 34.6°, 50.1°, 58.3°, 69.8°, 80.0°, and 90.0° [26] were created. By gating on the $E_{\gamma}(any)$ axis and projecting on the $E_{\gamma}(\theta)$ axis, background-subtracted and efficiency-corrected spectra were generated. From these, the intensities of transitions of interest were extracted and fitted to the angular distribution function $W(\theta) = a_o[1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)]$, where P_2 and P_4 are Legendre polynomials. The coefficients, a_2 and a_4 , containing information about the multipolarity of the transitions were extracted using an angular distribution code which uses the Markov Chain Monte Carlo (MCMC) high-dimensional probability sampling technique [27]. Representative fits of angular distributions for some transitions of interest are displayed in Fig. 1.

Transitions for which an angular-distribution analysis was not possible, due mainly to limited statistics, a normalized ratio, $R_{\rm ac}$, of γ -ray intensities observed in detectors in the forward (f)/backward (b) angles to the intensities in detectors centered around 90° was determined. For this purpose, two coincident matrices were incremented: In the first, $E_{\gamma}(f/b)$ -vs- $E_{\gamma}(any)$, detectors in the forward and backward angles were combined and the matrix incremented such that γ rays detected at the 31.7° , 37.4° , 142.6° , 148.3° , and 162.7° angles were placed on one axis, with γ rays observed at any angle grouped along the other. The second matrix, $E_{\gamma}(\sim 90^{\circ})$ vs- $E_{\gamma}(any)$, was incremented in a similar fashion, but with transitions observed in detectors at 79.2° , 80.7° , 90.0° , 99.3° , and 100.8° degrees placed on one axis. The two-dimensional angular correlation ratio, defined by $R_{\rm ac}$ $= I_{\gamma}(\theta_{f/b}, any)/I_{\gamma}(\theta_{\sim 90^{\circ}}, any),$ where $I_{\gamma}(\theta_x, any)$ is the γ -ray intensity obtained by placing gates on the corresponding $E_{\gamma}(any)$ axis. This ratio, which is independent of the multipolarity of the gating transition, was established to be greater than 1.0 for stretched-quadrupole transitions and less than 0.8 for stretched-dipole ones.

Table I presents the energies, relative intensities, associated angular-distribution coefficients and $R_{\rm ac}$ ratios as well as the multipolarity assignments for the observed transitions.

III. RESULTS

The level scheme resulting from the coincidence analysis of γ rays associated with 66 Zn recoils is displayed in Fig. 2. It was constructed primarily based on coincidence relationships and relative intensity balances using the γ - γ matrix gated on ⁶⁶Zn recoils and cross-checked, for intense transitions, using a γ - γ - γ cube constructed from all Zn events produced in the reaction. The level scheme features two primary structures; a low-to-medium spin one (shown on the right) and a newly-established high-spin rotational sequence composed of stretched-E2transitions, displayed on the left. As noted above, the low-to-medium spin structure, up to the 12^+_1 level at 7514.9(10) keV, was previously established in Refs. [15-19. The observations are confirmed here. While the present work was in preparation, Rai *et al.* [21] and Bala et al. [20] independently reported the observation of additional new excited states in ⁶⁶Zn. Using a heavy-ion induced reaction, Rai et al. [21] added positive-parity levels connected by the 519-, 1089-, 1367-, 1399-, 1576-, and 1786-keV transitions above the 12^+_1 state, and two new transitions (1408 and 1801 keV) in the negative-parity part, as well as the 644- and 828-keV transitions linking the two sequences. This established the structure up to an excitation energy of ≈ 12.3 MeV and a spin of $\approx 17\hbar$. These transitions, some of which are highlighted with red squares in the total projection spectrum displayed in Fig. 3, and their placements are also confirmed in the present work. Indeed, this work validates almost all placements within this structure and agrees with the multipolarity assignments for the newly-identified transitions associated with the positive-parity levels reported by Rai et al. [21]. It, however, differs somewhat in the placement and multipolarity assignments for the 738-, 1264-, and 1537-keV transitions linking the negative-parity states. For example, the 738-keV transition, of dipole character, is placed in Ref. [21] as feeding directly the 6_1^- level at 4074 keV, by passing the 4250-keV 7^-_1 state and thus, in anti-coincidence with the 176-keV γ ray. In the present work, the 738-keV transition is found to directly populate the 8^{-} level at 5338 keV, which is in turn depopulated by two transitions; a 1264-keV quadrupole one (reported as dipole in Ref. [21]) to the 4074-keV 6_1^- level, and a 1088keV one (not seen in Ref. [21]) to the 7_1^- state at 4250 keV. A γ - γ coincidence spectrum, obtained by gating on the 738-keV γ ray (see Fig. 4) exhibits a coincidence relationship between the 738- and 176-keV transitions. This, along with the presence of a 1088-keV γ ray in the 176keV gate, and the absence of coincidence relationships between the 1264- and 176-keV lines, supports the assignment of the 738-keV γ ray as the link between the 6076(2)



FIG. 2: Level scheme of ⁶⁶Zn as observed in the present study. The placement of Band 1 is schematic since the absolute excitation energy, spin and parity are unknown; see text for further details.

TABLE I: Transition energies E_{γ} , relative intensities I_{γ} , angular distribution and correlation information for all transitions in ⁶⁶Zn. The intensities are corrected for detector efficiency and normalized to the 1038.5(4)-keV ground-state transition. $R_{\rm ac}$ is the normalized ratio of γ -ray intensities in the detectors at forward/backward angles to the intensities in the detectors at angles centered around 90°. The spin and excitation energy of Band 1 are based on $x \ge 10$ MeV and $J \ge 12$, as discussed in the text. All reported uncertainties are purely statistical in nature. Transitions marked with asterisk (*) are those for which the electric or magnetic character could not be confirmed in the present work. The assignments are taken from Refs. [20, 21].)

$E_{\rm (keV)}$	I	$E_{\rm c}~(\rm keV)$	$L^{\pi} \rightarrow L^{\pi}$	<i>a</i> ₀	<i>a</i> .	B	Mult
$\frac{D_{\gamma}(\text{ReV})}{175.0(2)}$	$\frac{1\gamma}{76.6(2)}$	$\frac{D_i (\text{keV})}{4240.6(7)}$	7^{-} 6^{-}	0.24(2)	0.10(2)	0.84(1)	M1
175.9(3)	70.0(3)	4249.0(7)	$i \rightarrow 0$	-0.24(2)	-0.10(3)	0.64(1)	
312.0(1)	2.8(5)	3075.7(7)	$4 \rightarrow 4$	—	—	—	(M1/E2)
315.3(6)	3.4(9)	2763.8(6)	$4^+ \rightarrow 4^+$	_	—	—	(M1/E2)
327.7(1)	29.8(2)	4180.3(7)	$6^+ \rightarrow 6^+$	-	-	0.86(1)	M1
328.6(2)	83.2(4)	4073.5(6)	$6^- \rightarrow 5^-$	-0.22(1)	-0.06(2)	0.86(1)	M1
400.8(4)	2.4(6)	7915.7(1)	$12^+ \rightarrow 12^+$	_ ` `	_ ` `	0.9(1)	M1/E2
462.8(2)	4.2(9)	2773(2)	$(4^+) \rightarrow (3^+)$	_	_	0.8(5)	M1/E2
504.7(2)	99.4(2)	4240.6(7)	7- 5-			1.00(1)	E9
504.7(3)	00.4(3)	4249.0(7)	$7 \rightarrow 3$	-	-	1.09(1)	
518.9(10)	24.1(1)	9820(2)	$15' \rightarrow 14'$	-0.59(5)	0.26(8)	0.77(5)	M1/E2
577.0(4)	4.0(6)	2448.5(6)	$4^+ \rightarrow 2^+$	_	—	1.26(2)	E2
627.3(10)	24.1(2)	3075.7(7)	$4^+ \rightarrow 4^+$	-0.28(6)	-0.57(9)	1.11(4)	M1/E2
643.2(5)	3.1(6)	5204.9(7)	$8^+ \rightarrow 6^+$	0.54(14)	0.07(21)	1.54(4)	E2
644.3(5)	1.43(6)	7514.9(10)	$12^+ \rightarrow 11^-$	()	· · /	0.91(13)	$E1^*$
669 3(8)	27.5(14)	3744 7(6)	$5^- \rightarrow 4^+$	-0.37(4)	-0.06(5)	0.85(4)	$E1^*$
728.4(9)	$\frac{21.3(14)}{10.2(10)}$	6076(9)	$0^ 0^-$	-0.37(4)	-0.00(3)	0.00(4)	M1/E9
738.4(2)	10.3(10)	0070(2)	$9 \rightarrow 0$	—	—	0.91(1)	M1/E2
755.8(3)	6.5(12)	3066(2)	$(5^{+}) \rightarrow (3^{+})$	—	—	1.16(5)	E2
758.0(8)	0.16(10)	3521.8(1)	$\rightarrow 4^+$	—	—	—	_
828.1(1)	19(1)	6290.2(8)	$10^+ \rightarrow 9^-$	-0.45(7)	0.09(11)	0.89(6)	$E1^*$
830.7(8)	7(1)	2702.3(1)	$3^+ \rightarrow 2^+$	_	_	0.78(5)	M1/E2
833.2(4)	23.2(4)	1871.6(6)	$2^+ \rightarrow 2^+$	_	_	0.79(5)	$\dot{M1}$
855 5(10)	31(0)	71457(1)	$12^+ \rightarrow 10^+$			1.46(34)	F2
800.9(10)	0.1(3)	F100 C(7)	$12 \rightarrow 10$			1.40(34)	M1/E0
860.8(8)	2.4(10)	5109.6(7)	$8 \rightarrow 7$			0.86(14)	M1/E2
863.2(3)	4.7(8)	3929(2)	$(7^+) \rightarrow (5^+)$	-	-	1.21(4)	E2
892.3(3)	11(1)	2763.8(6)	$4^+ \rightarrow 2^+$	-	-	1.35(18)	E2
919.9(3)	6.6(8)	3744.7(6)	$5^- \rightarrow 3^-$	_	_	1.17(14)	E2
943.8(4)	1(1)	3707.6(1)	$\rightarrow 4^+$	_	_		_
953.7(1)	1.2(9)	2824.7(6)	$3^- \rightarrow 2^+$	_	_	_	$(E1^{*})$
054.2(5)	45.0(2)	5204.0(7)	9 / 2 9+ , 7-	0.28(2)	0.04(2)	0.80(2)	(L1) E1*
954.2(5)	43.9(2)	5204.9(7)	$0 \rightarrow 1$	-0.58(2)	-0.04(3)	0.80(2)	E1 D1*
981.3(2)	7.8(8)	3744.7(6)	$5 \rightarrow 4$	_	—	0.76(11)	E1
1025.8(5)	30.2(3)	5204.9(7)	$8^+ \rightarrow 6^+$	_	—	1.16(3)	E2
1036.0(3)	56.4(3)	5109.6(7)	$8^- \rightarrow 6^-$	_	_	1.21(5)	E2
1038.5(4)	207.4(9)	1038.5(4)	$2^+ \rightarrow 0^+$	0.10(2)	-0.08(2)	1.07(1)	E2
1085.3(4)	66.0(3)	6290.2(8)	$10^+ \rightarrow 8^+$			1.22(2)	E2
1087.8(5)	31(0)	53373(10)	$8^- \rightarrow 7^-$	_	_	(_)	(M1/F2)
1087.8(3)	1.7(1)	19976(9)	$3 \rightarrow 1$ $17^{+} \rightarrow 16^{+}$			0.70(10)	(M1/D2) M1/D2
1089.3(10)	1.7(1)	12270(2)	$17^{\circ} \rightarrow 10^{\circ}$	—	—	0.70(19)	M1/E2
1204.2(5)	8.9(10)	3075.7(7)	$4^{+} \rightarrow 2^{+}$	-	-	1.09(7)	E2
1212.5(4)	57.8(3)	5462.1(8)	$9^- \rightarrow 7^-$	0.25(3)	-0.09(4)	1.20(1)	E2
1224.7(7)	48.3(2)	7514.9(10)	$12^+ \rightarrow 10^+$	0.15(3)	-0.13(4)	1.13(3)	E2
1263.9(3)	5.1(1)	5337.3(10)	$8^- \rightarrow 6^-$	0.16(9)	-0.13(12)	1.35(12)	E2
1271.0(10)	7.9(5)	9820(2)	$15^+ \rightarrow (14^+)$				_
1271.9(2)	35(3)	2310.4(1)	$(3^+) \rightarrow 2^+$	_	_	_	_
1271.0(2) 1004.0(2)	5.0(0)	2010.4(1)	(3^{+}) (4^{+})			1.04(10)	EO
1284.8(3)	5.9(9)	4058.0(1.9)	$(0^+) \rightarrow (4^+)$	-	-	1.24(10) 1.07(1)	E 2
1286.0(5)	5.3(3)	x + 1280.0	$J+2 \rightarrow J$	0.22(10)	0.14(12)	1.27(1)	EZ
1295.6(4)	90.9(4)	3744.7(6)	$5^- \rightarrow 4^+$	-0.32(2)	-0.05(2)	0.75(2)	$E1^*$
1307.1(7)	9.5(4)	6416.7(1)	$\rightarrow 8^{-}$	_	-	-	-
1366.6(2)	6.3(8)	11186.5(2)	$16^+ \rightarrow 15^+$	_	_	0.77(17)	M1/E2
1385.3(5)	2.6(5)	9301.0(1)	$14^+ \rightarrow 12^+$	_	_	1.21(22)	E2
1399.4(3)	57(7)	$12275 \ 8(2)$	$17^+ \rightarrow 16^+$	_	_	_ /	(M1/E2)
1404.9(1)	226(2)	2852.6(1)	6^+ 4^+			1.91(54)	(IN 1/ 12) F9
1404.2(1)	22.0(3)	3852.0(1)	$0 \rightarrow 4$	_	—	1.21(34)	E2
1408.5(2)	30.2(2)	6870.6(1)	$11 \rightarrow 9$	—	—	1.14(4)	E2
1410.3(8)	132.0(8)	2448.5(6)	$4^+ \rightarrow 2^+$	0.22(4)	0.01(6)	1.14(1)	E2
1432.4(4)	4.2(2)	x + 2718.4	$J+4 \rightarrow J+2$	_	—	1.17(12)	E2
1457.6(5)	2.2(6)	5515.6(2)	$(8^+) \to (6^+)$	-	-	1.33(11)	E2
1484.2(2)	0.5(4)	12670.8(2)	$17^+ \rightarrow 16^+$	_	_	0.78(14)	M1/E2
1486.2(5)	2.9(12)	4561.8(1)	$6^+ \rightarrow 4^+$	_	_	1.29(15)	$\dot{E2}$
1508.0(8)	2(1)	9022 9(2)	$14^+ \rightarrow 12^+$	_	_	1.22(43)	E2
1500.0(0) 1527.0(6)	2(1) 2.2(6)	7612.7(2)	14 / 12 $11^{-} > 0^{-}$			1.22(40) 1.17(41)	<u> </u>
1557.0(0)	2.2(0)	1012.7(2)	$11 \rightarrow 9$	-	-	1.17(41)	E2
1575.5(2)	6.7(9)	10876.4(2)	$16^+ \rightarrow 14^+$	0.19(14)	0.02(18)	1.20(11)	E2
1625.2(2)	11.2(11)	7915.7(1)	$12^+ \rightarrow 10^+$	0.21(10)	-0.10(15)	1.16(9)	E2
1628.7(5)	3.9(1)	x + 4347.1	$J+6 \rightarrow J+4$	_	-	1.27(15)	E2
1656.1(2)	0.7(5)	9268.8(2)	$13^- \rightarrow 11^-$	_	_	1.28(20)	E2
1725.4(4)	25.8(3)	2763.8(6)	$4^+ \rightarrow 2^+$	_	_	1.26(4)	E2
17329(5)	343(2)	4180.3(7)	$6^+ \rightarrow 4^+$	_	_	1.25(4)	E2
1785 9(7)	10.6(4)	2824 7(6)	3^{-} , 3^{+}	_		1.20(1)	([1 *)
1796 1 (9)	10.0(4)	2024.7(0)	$3 \rightarrow 2$	_	_	1.09(0)	
1/80.1(2)	19.4(2)	9301.0(1)	$14 \rightarrow 12$	_	—	1.23(8)	E2
1801.0(5)	4.1(8)	8671.6(2)	$13^- \rightarrow 11^-$	_	—	1.20(31)	E2
1832.1(4)	4.4(9)	x + 6179.2	$J+8 \rightarrow J+6$	_	—	1.30(16)	E2
1925.5(1)	1(1)	11226.5(2)	$(16^+) \to 14^+$	_	_	_	(E2)
2040.3(7)	2.1(7)	x + 8219.5	$J + 10 \rightarrow J + 8$	_	_	1.23(19)	E2
2215.3(4)	0.7(4)	x + 10434.8	$J + 12 \rightarrow J + 10$	_	_		E2
2423.4(7)	1.0(4)	x + 12858.2	$J + 14 \rightarrow J + 12$	_	_	_	E2
2679.4(4)	0.19(3)	x + 15537.6	$J + 16 \rightarrow J + 14$	_	_	_	E2
2933.1(4)	0.1(9)	x + 18470.7	$(J+18) \rightarrow J+16$	_	_	_	_
	- (-)						



FIG. 3: (Color online) Total background corrected projection spectrum obtained for $^{66}{\rm Zn}.$



FIG. 4: (Color online) Coincidence gate on the 738-keV transition.

 9^- and 5337.3(10)-keV 8^- states. As depicted in Fig. 2, energy sums and intensity balances suggest the population and depopulation of the 8^- , 5337.3(10)-keV level by the 738- and 1264-keV γ rays, respectively, in contrast with the reverse order suggested in Ref. [21]. It should be noted that none of the new transitions reported in Ref. [20] following the ${}^{56}\text{Fe}({}^{12}\text{C}, 2p\gamma)$ fusion-evaporation reaction is observed in the present work.

The rotational sequence identified as Band 1 in Fig. 2 is newly established. It consists of nine transitions; i.e., the 1286-, 1432-, 1629-, 1832-, 2040-, 2215-, 2423-, 2679and (2933-) keV γ rays. A summed coincidence spectrum obtained by individually gating on all the in-band transitions is presented in Fig. 5. This spectrum highlights an almost constant energy spacing, ΔE_{γ} , between these γ rays, which suggests the onset of collectivity. While it was not possible to connect it directly to the



FIG. 5: (Color online) Sum of single coincidence gates placed on γ -ray transitions in band 1. Pertinent γ rays are highlighted in red.



FIG. 6: (Color online) Coincidence spectra obtained by single gating on transitions at (a) 1432 keV and (b) 1832 keV. Members of the rotational band are marked in red.

low-to-medium spin structure of Fig. 2, presumably because of the low intensities and possible fragmented decay paths, Band 1 is assigned to ⁶⁶Zn based on the FMA focal plane information, and the observed coincidence relationships with lower-lying states. The quadrupole character of the in-band transitions was inferred from the measured angular-distribution coefficients and the twopoint angular correlation ratios. In particular, as seen in Fig. 1, the angular distribution of the 1286-keV γ ray and correlation ratios for the 1432-, 1629-, 1832-, 2040-, and 2215-keV transitions (Table I) are all consistent with a stretched-E2 nature. Due to limited intensities, no angular correlation ratios could be determined for the transitions between the higher-spin states within the band. However, because of the regularity of the band pointing towards a rotational behavior. E2 multipolarity was assumed for these γ rays, and the information available on Band 1 transitions is also summarized in Table I. Furthermore, given the lack of decay-out transitions (the intensity is most likely transferred out of the band before reaching the bandhead), the absolute excitation energies and spins of the levels in the band are not established. However, the coincidence pattern shown in Figs. 6 (a) and (b), obtained by gating on the 1432- and 1832-keV transitions, suggests a feeding to the lower-lying states through the 12^+_1 level at 7515 keV in the yrast sequence. As a result, a tentative excitation energy and spin-parity of the bandhead greater or equal to $\sim 10 \text{ MeV}$ and 12^+ , respectively, is proposed. This is consistent with the established bandhead spin-parity for similar bands observed in $^{60-65,68}$ Zn [3-6, 8, 10], as discussed further below.

IV. DISCUSSION

The presence of high-i intruder orbitals in the vicinity of the Fermi level plays a significant role in determining the structure and equilibrium shape of the nucleus. In neutron-rich Zn isotopes, the rotational alignment of $\pi g_{9/2}$ and/or $\nu g_{9/2}$ intruder orbitals, which come progressively closer to the Fermi level with increasing neutron excess, give rise to a significant increase in aligned angular momentum, resulting in the appearance of a large variety of deformed, collective excitations as observed in several nuclei of the $A \approx 60 - 70$ mass region [3-6, 8, 10]. At low spins, however, the structure is dominated by singleparticle type excitations involving a few nucleons as a result of their proximity to the Z = 28 shell closure. In this section, the low-spin structure of ⁶⁶Zn nucleus, with two protons and eight neutrons outside the doubly-magic core, 56 Ni, is investigated by comparing the data with results of large-scale shell-model calculations. The rotational characteristics of the high-spin structure, on the other hand, are compared with similar bands observed in the region and discussed within the framework of the combination of constrained covariant density functional theory (CDFT) and particle-rotor model (PRM) as well as the cranked shell model (CSM).

A. Low-spin excitations

Several theoretical approaches, such as the shell model [28, 29] and its deformed configuration mixing variant [30], the cluster vibration model [31, 32] and a microscopic description within the framework of the Hartree-Fock-Bogoliubov approximation [33] have been previously employed to investigate the structure of lowlying states in 66 Zn. In Ref. [30], the yrast structure is calculated to be composed of two parts; the groundstate sequence with $J^{\pi} = 0^+, 2^+, 4^+, 6^+$ described as resulting predominantly from the $\pi\nu(p_{3/2}, f_{5/2}, p_{1/2})^{10}$ configuration, and a series of excited states with J^{π} = 8⁺, 10⁺, 12⁺, 14⁺, belonging mainly to the 2p-2h $\pi(p_{3/2}, f_{5/2}, p_{1/2})^8 \otimes \nu(g_{9/2})^2$ configuration, which is associated with a small deformation. These two modes of excitation are found to cross (see Fig. 8) as a result of the two particle-hole excitation involving the neutron $1g_{9/2}$ orbital. Thus, in the total Routhian surface (TRS) calculations of Ref. [21], the crossing is attributed to the alignment of a pair of neutrons which drives the 66 Zn nucleus from an oblate shape in the ground state via the triaxial shape at the intermediate spin to a collective prolate shape at high spin.

In the present study, the nature of the 66 Zn low-lying states has been investigated by means of a configuration interaction calculations in the jj44 model space which comprises the $0f_{7/2}$, $1p_{3/2}$, $1p_{1/2}$, and $0g_{9/2}$ orbitals for both protons and neutrons and assumes a 56 Ni inert core. The calculations were performed using the shell-model code NUSHELLX [34] with an isoscalar effective charge of $e_{\pi} + e_{\nu} = 2.6$ and two effective interactions tuned for the $f_{5/2}pg_{9/2}$ model space – the jj44b and JUN45 Hamiltonians. These interactions have been extensively used to study low-lying structures in nuclei of the $A \approx$ 60 - 70 region, and were able to reproduce the general features exhibited by the data quite well.

The results of shell-model calculations using both sets of interactions are compared with the ⁶⁶Zn experimental excitation energies for the vrast and near-vrast states in Fig. 7. For clarity, the positive- and negative-parity states have been separated into two groups and, in the calculated spectra, only the lowest-energy levels for each spin with corresponding experimental states are presented. The yrast levels are indicated by red lines. As can be seen, the yrast structure is reproduced well by both interactions for excitation energies below ~ 6 MeV, thus indicating a predominately spherical or nearly-spherical character at low spin. The limited number of valence particles available outside the spherical ⁵⁶Ni core implies that the low-lying structure will be dominated by spherical shell-model states. This is particularly evident in the calculations, as the 2^+_1 level energy is predicted to within 13 and 20 keV of the experimental value of 1039 keV by the ji44b and JUN45 interactions, respectively. Likewise, the experimental 4_1^+ state at 2449 keV is reproduced by the calculations, with the JUN45 interaction performing slightly better (2451 keV) than the ji44b (2272 keV) one. Overall, the yrast sequence of states comprising the 2^+_1 , $4_1^+, 6_1^+, 8_1^+$, and 10_1^+ at 1039, 2449, 4180, 5205, and 6290 keV is reproduced better by the JUN45 interaction as illustrated in Fig. 8, although the jj44b predictions remain within 200 keV of the experimental values. This is not surprising since ⁶⁶Zn is one of the nuclei to which the effective single-particle energies (ESPE) and two-body matrix elements (TBME) for both the JUN45 and jj44b Hamiltonians were empirically adjusted in order to fit the experimental binding and excitation energies. For the yrast and near-yrast states, the two interactions predict a predominantly mixed $\pi(f_{5/2})^2 \otimes \nu(p_{1/2}, f_{5/2}, p_{3/2})^8$ configuration with minimal contribution (~ 4% probability) from the $\pi(f_{5/2}, p_{3/2})^2 \otimes \nu(p_{1/2}, f_{5/2}, p_{3/2}, g_{9/2})^8$ component. The contribution of the latter increases in amplitude towards higher spins. The average neutron occupation of the $\nu q_{9/2}$ orbital increases from 0.8 for the 0_1^+ state (in agreement with single-neutron pickup data indicating a particle occupation number in the ground state of at least 0.7 for this $g_{9/2}$ state [35, 36]) to about 1.29 while that for the proton decreases from 0.10 (0_1^+ state) to $0.06 (10^+_1 \text{ level})$ in the JUN45 calculations. A similar trend is observed in the jj44b computations. Beyond the 10^+_1 state, the divergence between the calculated and experimental yrast states becomes significant, with both interactions systematically under-predicting the experimental observations (see Fig. 8). As discussed below, this could be due to the increasing role of collective excitations at high angular momenta. Theoretical predictions for the non-yrast states, indicated by black lines in Fig. 7, follow a pattern similar to those for the yrast



FIG. 7: (Color online) Experimental level energies in 66 Zn compared with spherical shell-model calculations using the jj44b and JUN45 effective interactions. The yrast levels are indicated by the red lines while the negative structure is colored dark-blue.

states; i.e., the calculations predict the energies of the low-lying states well, but underestimate (overestimate in the case of jj44b) the experimental energies at high spin. This is apparent in Fig. 7 as both interactions predict the excitation energy of the 2^+_2 and 4^+_2 states well, but fail at higher energies. For the 2^+_2 state, a predominantly $\pi(f_{5/2}, p_{3/2})^2 \otimes \nu(p_{1/2}, f_{5/2}, p_{3/2}, g_{9/2})^8$ configuration (46%) is predicted while the $\pi(f_{5/2}, p_{3/2})^2 \otimes$ $\nu(p_{1/2}, f_{5/2}, p_{3/2}, g_{9/2})^8$ component is about 2%. The latter configuration is calculated to become the leading component with 18% probability in the 4^+_2 state. Similarly, the 2825-keV excitation energy of the $I^{\pi} = 3^{-}$ state is reproduced well by the jj44b interaction which is calculated to within ~ 100 keV of the experimental value. The overall good agreement between calculations and experimental levels demonstrates that the low-spin structure is predominantly of single-particle character and is, thus, consistent with the expectation that the limited

number of valence particles outside of doubly-magic 56 Ni allows for a low angular momentum structure dominated by spherical shell-model states.

B. High-spin structure

The results of the previous section indicate that, as is the case for most nuclei in the $A \approx 60 - 70$ mass region, the ⁶⁶Zn low-spin structure is determined primarily by excitations involving the $1f_{5/2}$, $2p_{3/2}$, and $2p_{1/2}$ single-particle levels with minimal contributions from the intruder $1g_{9/2}$ orbital. With increasing spin, contributions from both neutron and proton occupation of this shape-driving $1g_{9/2}$ intruder orbital become significant, thereby enhancing the possibility of observing deformed shapes as well as the onset of specific collective rotational behavior such as that manifested through rota-



FIG. 8: (Color online) Comparison of the yrast level energies in ⁶⁶Zn with spherical shell-model states calculated using the jj44b and JUN45 effective interactions (see text for details).

tional sequences such as smoothly terminating, highlydeformed, and superdeformed (SD) bands. Microscopically, the emergence of SD bands in this mass region is understood as a result of multiple excitations of $\pi f_{7/2}$ and $\nu f_{7/2}$ particles/holes into the shape driving $\pi g_{9/2}$ and $\nu g_{9/2}$ intruder orbitals. In a manner consistent with theoretical predictions of SD shell gaps at particle numbers N, Z = 30, 32 [37], rotational bands associated with superdeformation have been reported in several isotopes of Zn and Ge, thus enabling a systematic study of highly-deformed shapes in nuclei with $N \approx Z$. In the case of the Zn isotopes, bands with SD properties have been observed in $^{60-63,65,68}$ Zn [3-6], with the exception of ^{64,66,67}Zn. Lifetime measurements in several of these nuclei support the interpretation that these bands are characterized by unusually large deformations. For instance, an average transition quadrupole moment, Q_t , of $3.0^{+0.5}_{-0.4}$ eb has been reported in ⁶¹Zn [5]. This corresponds to a quadrupole deformation of $0.50^{+0.07}_{-0.06}$, when assuming an axially symmetric shape. Calculations within the Hartree-Fock formalism suggest that this band most likely has the $(\nu g_{9/2})^3 (\pi g_{9/2})^2$ configuration. For the SD band in 62 Zn, a quadrupole moment of $2.7^{+0.7}_{-0.5}$ eb, corresponding to a deformation $\beta_2 = 0.45^{+0.10}_{-0.07}$ [8], has been measured. Similar deformation parameters have been found in 60,68 Zn [3, 6]. While the SD bands observed in ^{60,61}Zn have been linked to the states of lower spin, those reported in ^{63,65,68}Zn have not, potentially due to the fragmentation of strength associated with the decay out of the SD band.

It is within this context that a closer examination of the behavior of the rotational band observed in the present work becomes important. Figure 9 presents a plot of the angular momentum as a function of transition energy for the SD bands in 60,68 Zn [3, 6] and 68 Ge [12], the N = 36 isotone of 66 Zn, compared with the band established in this work. Due to lack of knowledge of the



FIG. 9: (Color online) Angular momentum as a function of transition energy for the superdeformed bands in 60 Zn, 68 Zn, and 68 Ge compared with the newly established band in 66 Zn. The data for 68 Ge and 66 Zn are plotted for bandhead spins of $I_0 = 14$ and $I_0 = 16$, and $I_0 = 12$ and $I_0 = 14$, respectively (see text for details).

absolute excitation energies and spins, the data for 68 Ge and ⁶⁶Zn are plotted for two bandhead spins, $I_0 = 14$ and $I_0 = 16$, and $I_0 = 12$ and $I_0 = 14$, respectively. Furthermore, following the approach of Ref. [12], the transition energies for the band in ⁶⁰Zn have been scaled by $(60/66)^{5/3}$ to account for the expected mass dependence of the moments of inertia. As can been seen from Fig. 9, the slope, which characterizes the moment of inertia, is similar for all the bands. In particular, the variation in the angular momentum as a function of γ -ray energy for band 1 (in 66 Zn) and the SD band in 68 Ge follow the same trend, especially if the bandhead spins are taken as 12 \hbar and 16 \hbar , respectively. This likely suggests a similar intrinsic configuration. To highlight this similarity further, the SD band in ⁶⁸Ge is plotted alongside the ⁶⁶Zn rotational sequence in Fig. 10. Note that the striking similarities between the levels of 66 Zn and 68 Ge has been extensively discussed in Ref. [21], albeit for lower spin states. Theoretical calculations for all the cases presented in Fig. 9, as well as for the known SD bands in 63,65 Zn [5], indicate that the band configurations involve at least two proton holes in the $f_{7/2}$ subshell and it is, thus, reasonable to expect that the band in 66 Zn is based on a similar configuration as well.

Since no direct linking to the low-energy levels is observed, only the dynamic moment of inertia $\mathcal{J}^{(2)}$, which is strongly influenced by the alignment of high-j configurations, can be extracted from the experimental data with certainty. This moment is plotted for the newlyestablished band in ⁶⁶Zn as a function of the rotational frequency, $\hbar\omega$, alongside those of ^{60,68}Zn and ⁶⁸Ge in Fig. 11. In contrast to the SD band in ⁶⁸Zn, which displays a regular, smooth decrease with increasing rotational frequency, the $\mathcal{J}^{(2)}$ moments for ^{60,66}Zn and ⁶⁸Ge



FIG. 10: Comparison of the rotational band in 66 Zn with the SD sequence in 68 Ge. The data for 68 Ge are taken from Ref. [12].

exhibit a more staggering behavior, with pronounced peaks at certain frequencies. For ⁶⁰Zn, the rise in the $\mathcal{J}^{(2)}$ moment of inertia at ~ 0.9 $\hbar\omega$ has been interpreted as the simultaneous alignment of the $g_{9/2}$ protons and neutrons [3], mediated by various components of the nucleon-nucleon interaction. A detailed systematic analysis of the $\mathcal{J}^{(2)}$ moments of inertia for bands in ⁶⁰⁻⁶⁵Zn [5] indicates that the rise cannot only be attributed to changes in *nn* or *pp* pairing, but rather involves a significant *np* component as the main cause for the enhancement. These studies further suggest that the



FIG. 11: (Color online) Variation of the experimentally deduced dynamic moment of inertia as a function of the rotational frequency ($\hbar\omega$) for Band 1 in ⁶⁶Zn (present work), compared with known SD bands in the neighboring ⁶⁸Ge [12] and ^{60,68}Zn [3, 6].



FIG. 12: (Color online) The calculated quasiproton routhian (e') as a function of rotational frequency $(\hbar\omega)$. The following convention is adopted for the parity and signature (π, α) of the Routhians: (+, 0) solid lines, (+, 1) dotted lines, (-, 0) dash-dotted lines, and (-, 1) dashed lines.

rise appears only when the occupation of the $g_{9/2}$ intruder states is identical for valence protons and neutrons. It is, thus, conceivable that the enhancements observed in 66 Zn and 68 Ge at about the same frequency (~ 0.9 $\hbar\omega$), but reduced strength, can be attributed to similar configurations undergoing such interactions.

To understand these interactions, the alignment properties of the rotational sequence observed in 66 Zn were investigated within the framework of the cranked shell model (CSM). The calculations were performed for both quasiprotons and quasineutrons with the associated single-particle level energies determined using a deformed Wood-Saxon potential with universal parameters. For the present calculation, the deformation parameter set $(\beta_2 = 0.4, \beta_4 = 0.0, \text{ and } \gamma = 23^\circ)$ was chosen to correspond with those of the highly-deformed bands in the region [12]. The pairing energies at zero frequency $\Delta_n(\omega=0) = 1.4542$ MeV and $\Delta_p(\omega=0) = 0.6473$ MeV were determined using the BCS formalism and kept constant as a function of frequency. The resulting quasiproton routhian is presented in Fig. 12 with the relevant quasiparticle orbitals (i.e., those near the Fermi surface) labeled according to the convention of Ref. [38]. The calculation predicts an AB crossing, corresponding to the alignment of a pair of $g_{9/2}$ protons, at a frequency (~ 0.63 MeV/\hbar) lower than the point to which the available data for Band 1 extend and hence, is unlikely to be observed in the present measurement.

To gain further insight, the rotational characteristics of Band 1 in ⁶⁶Zn was analyzed with the help of the adiabatic and configuration-fixed constrained covariant density functional theory (CDFT) [39-41] and the quantum particle rotor model (PRM) formalism [42–44]. First, the former approach was used to search for possible configurations and deformations associated with the band. In the calculations, the point-coupling effective interaction PC-PK1 [45], with a basis of 10 major oscillator shells, was employed, while the pairing correlations were neglected for simplicity. It was found that the ground state of ⁶⁶Zn is triaxial with deformation parameters $(\beta = 0.19, \gamma = 29^{\circ})$. Based on this state and by always keeping two aligned neutrons or protons in the first and second states of the $g_{9/2}$ shell while the other nucleons fill the orbitals according to their energies, the $\nu(1g_{9/2})^2$ and $\pi(1q_{9/2})^2$ configurations were obtained. Their excitation energies with respect to the ground state are about 2.0 and 11.8 MeV, respectively. As can be seen from the experimental level scheme (Fig. 2) and following arguments outlined in Sec. III, the bandhead energy of Band 1 is greater than 10 MeV at $I^{\pi} \geq 12^+$. Thus, within this framework, Band 1 is assigned the $\pi(1g_{9/2})^2$ configuration with deformation parameters of $\beta = 0.20$ and $\gamma = 45.9^{\circ}$.

With the configuration and deformation parameters obtained from the adiabatic and configuration-fixed constrained covariant density functional theory, single-*j* shell quantum particle rotor model [42–44] calculations were performed to further examine the energy spectra for band 1. For this purpose, the irrotational flow type of moment of inertia $\mathcal{J}_k = \mathcal{J}_0 \sin^2(\gamma - 2k\pi/3)$ with $\mathcal{J}_0 = 19.0 \ \hbar^2/\text{MeV}$ was adopted. The energy spectra obtained as function of spin are compared in Fig. 13 with the experimental data. Clearly, the theoretical calculations are able to reproduce the data and support the configuration assignment of $\pi(1g_{9/2})^2$ to Band 1.

In Fig. 14, the root mean square components along the medium (*m*-), short (*s*-), and long (*l*-) axes of the core $R_k = \langle \hat{R}_k^2 \rangle^{1/2}$, the active protons $J_{\pi k} = \langle \hat{j}_{pk}^2 \rangle^{1/2}$, and



FIG. 13: (Color online) Energy as a function of spin for the rotational band (Band 1) in 66 Zn calculated by particle rotor model in comparison with the experimental data.



FIG. 14: (Color online) The root mean square components along the medium (m-), short (s-), and long (l-) axis of the core $R_k = \langle \hat{R}_k^2 \rangle^{1/2}$, the active protons $J_{\pi k} = \langle \hat{j}_{pk}^2 \rangle^{1/2}$, and the total nuclear system $I_k = \langle \hat{I}_k^2 \rangle^{1/2}$ as function of spin calculated by means of particle rotor model for the Band 1 in ⁶⁶Zn.

the total nuclear system $I_k = \langle \hat{I}_k^2 \rangle^{1/2}$ are displayed as functions of spin when calculated for Band 1 by means of the particle rotor model. As can be seen, the angular momentum of the collective core is mainly aligned along the *m*-axis, which corresponds to the largest moment of inertia. It is noted that the *l*-axis component cannot be neglected in the low spin region. The angular momentum of the $g_{9/2}$ active proton particles mainly align along the *s*-axis with a value of about 7.5 \hbar at the bandhead, which corresponds to maximal overlap with the triaxial core [46]. With increasing spin, the protons tend to align gradually along the *m*-axis, which is attributed to the fact that the core induces a strong Coriolis force to the proton particles and tries to align them along the *m*-axis to minimize energy. As a result, the angular momentum of the total nuclear system has comparable components along the three principal axes in the low spin region. At high spin, however, the nucleus aligns along the *m*-axis, which is, in fact, the principal axis of rotation and leads naturally to the observed $\Delta I = 2$ quadrupole band struc-

ture. Within the present theoretical framework, the properties of Band 1 are accounted for without invoking the large deformation inferred on the basis of comparisons with bands in other Zn isotopes and the ⁶⁸Ge isotone. It should be noted, however, that just as in the present case, there is no lifetime information available for the SD bands in ⁶⁸Ge and ⁶⁵Zn. The interpretation in terms of extended shapes relies on striking similarities with bands in other Zn isotopes where lifetimes data are available as well as on theoretical approximations which differ from those discussed above. Hence, it is clear that further progress regarding the description of the 66 Zn band and the associated nuclear shape will have to await additional lifetime measurements. The latter will likely be challenging in view of the small intensity (less than 10% relative to the ground-state band) with which the band is fed, at least with the reaction used in the present measurements. Furthermore, a comparison of calculations within the CDFT/PRM framework presented in this study with the data on the other sequences observed in nuclei of the region, which were interpreted in earlier works as superdeformed bands, would be of considerable interest.

V. CONCLUSIONS

Medium and high-spin states in 66 Zn have been investigated by means of the complex multinucleon transfer reaction, 26 Mg(48 Ca, $\alpha 4n\gamma$), carried out at beam energies of 275, 290 and 320 MeV in inverse kinematics. The previously reported low-spin structure was essentially confirmed. Large-scale shell-model calculations carried out using the JUN45 and jj44b effective interactions have successfully described the observations and confirmed the view that the low-lying levels in this nucleus and in other neighboring nuclei of the region are mostly as-

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sociated with single particle-hole excitations. In addition, evidence for a new, high-spin rotational sequence of stretched-E2 transitions has been observed in coincidence with the known low-spin states. Due to difficulties in identifying linking transitions between the newlyestablished sequence and the low-spin levels, presumably because of the low in-band intensity and the fragmented decay paths, the excitation energies of the levels, the spins and parity could not be determined. The band is, however, observed to share striking similarities with rotational cascades associated with superdeformation in neighboring $A \approx 60-70$ nuclei. Calculations, carried out within the framework of the adiabatic and configurationfixed constrained covariant density functional theory and the quantum particle rotor model, suggest an associated configuration involving two proton particles occupying the $g_{9/2}$ intruder orbital. Within this theoretical framework, the band is associated with triaxial deformation. Further data will be required to firmly establish the associated nuclear shape. Nevertheless, it is clear that despite the limited number of orbitals present near the Fermi surface, nuclei of the $A \approx 60 - 70$ mass region display a rich diversity of phenomena similar to those seen in heavier mass systems and, in particular, exhibit strong collectivity at high spins.

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