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K-mixing in the doubly mid-shell nuclide ^{170}Dy and the role of vibrational degeneracy

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ABSTRACT

A detailed study of the structure of the doubly mid-shell nucleus $^{170}_{66}\mathrm{Dy}_{104}$ has been carried out, following isomeric and β decay. We have measured the yrast band up to the spin-parity $J^\pi = 6^+$ state, the $K = 2$ γ-vibration band up to the 5^+ state, a low-lying negative-parity band based on a 2^- state that could be a candidate for the lowest energy octupole vibration state within this nucleus, and a candidate for the $K^\pi = 6^+$ two quasi-particle isomer. This state was determined to have an excitation energy of 1643.91(23) keV and a half life of 0.99(4) μs, with a reduced hindrance for its decay to the ground-state band an order of magnitude lower than predicted by $N_\mathrm{p}N_\mathrm{n}$ systematics. This is interpreted as being due to γ-vibrational mixing from a near degeneracy of the isomer and the 6^+ state of the γ band. Furthermore, the parent nucleus ^{170}Tb has been determined to have a half-life of $0.91(^{+18}_{-13})$ s with a possible spin-parity of 2^-.
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1. Introduction

One of the most successful descriptions of the structure of atomic nuclei is the spherical shell model. However, despite being a powerful model for certain regions of the nuclear chart, it becomes impractical when moving away from closed-shell nuclei. Instead, it is the interplay between the macroscopic shape degrees of freedom and the microscopic nature of the underlying single-particle structure of shell-model orbitals in a deformed basis that offers an explanation for the observed nuclear structure. Lying precisely in the middle of the closed proton $Z = 50, 82$ and neutron $N = 82, 126$ shells, with $Z = 66$ and $N = 104$, ^{170}Dy has become a central calibration point for tests of collective as well as single-particle models far from closed shells [1–4]. What speaks against this simplistic picture are possible deformed and spherical sub-shell closures and other deviations from the smooth systematics that are observed in, for example, ^{190}W [5–7] and along the $N = 100$ isotone chain [8–13]. Indeed, some theoretical studies predict that the quadrupole deformation maximum occurs below the $N = 104$ mid-shell neutron number within an isotope chain [4,3,14], while some experimental data indicate that the deformation increases as Z decreases below mid-shell [11–13].

One predicted property of ^{170}Dy is the long-lived $K^\pi = 6^+$ two quasi-particle isomer [15,3,4], where K is the total angular momentum projection on the prolate symmetry axis. The structural and decay properties of this predicted isomer also serve as a sensitive test of the structural evolution in the quadrupole deformed $150 \le A \le 180$ region. In the present work, we focus on the interpretation of the reduced hindrance, $f_\nu = F_\mathrm{W}^{1/\nu}$, which is defined as the reduced ratio of the experimental and Weisskopf estimated partial half-life of the $K^\pi = 6^+$ decay pathway, $F_\mathrm{W} = t_{1/2}/t_{1/2,\mathrm{W}}$, where the forbiddenness of the decay, $\nu = |\lambda - \Delta K|$, is the difference between the multipolarity, λ, and the change in K between the initial and final state [16]. This quantity, in particular, is very sensitive to nuclear structure effects and depends strongly on the product, $N_\mathrm{p}N_\mathrm{n}$, of valence protons, N_p, and neutrons, N_n. For a comprehensive discussion on this topic, see the recent reviews in Ref. [17,18].

The structure of ^{170}Dy is challenging to study experimentally. Attempts have been made using projectile fragmentation of a lead beam [19]; multi-nucleon transfer reactions between ^{82}Se and ^{170}Er, where a $4^+ \to 2^+$ ground-state band transition candidate at 163 keV was reported [20], and more recently in-flight fission from where an isomeric state was observed [21]. In fact, even with the power of the current high-intensity fragmentation facilities, the frontier of observed dysprosium ground states does not reach beyond the $N = 108$–110 isotopes $^{174–176}$Dy [22,21,23], illustrating that this region is particularly difficult to access for experimental measurements. In this letter we present, for the first time, a detailed study of the low-lying excited-state structure of the doubly mid-shell nucleus $^{170}_{66}\mathrm{Dy}_{104}$. This is the highest-$Z$ element that has so far yielded new structure information at the Japanese Radioactive Isotope Beam Factory (RIBF).

2. Experiment

Nuclei in the ^{170}Dy region were produced by in-flight fission of a 345 MeV/u ^{238}U beam with 10 pnA intensity, incident on a Be target. The beam was delivered by the accelerator complex at the RIBF in RIKEN [24]. The fragments were separated and identified in the BigRIPS separator and the ZeroDegree spectrometer [25,26] event-by-event, based on their mass-to-charge ratio (A/q) and atomic number (Z). At the final focal plane of the beam line they were implanted in the WAS3ABi active stopper [27,28], which in this experiment consisted of two 40×60 mm^2 double-sided silicon-strip detectors with strip widths of 1 mm in both horizontal and vertical directions.

The γ rays emitted following isomer and β decay of the implanted nuclei were detected using EURICA (Euroball-RIKEN Cluster Array) which consists of 84 HPGe crystals arranged in twelve clusters with a nominal distance of 22 cm from the center of the array [27,29]. However, during the experiment some detectors were moved closer to the center to increase the total full-energy peak detection efficiency to about 9% at a γ-ray energy of 1 MeV. Implanted ions were correlated to β-decay events when occurring within 2 mm of each other. Due to the high contamination of lighter fragments, a large plastic scintillator was placed behind WAS3ABi and used as a veto detector for fragments passing through the silicon detector. The experiment was carried out with two BigRIPS separator settings: 13.5 hours focusing on ^{170}Dy (~ 10000 implantations); and 45 hours focusing on ^{172}Dy, during which ~ 2500 ^{170}Tb nuclei were implanted.

3. Results

The γ-ray spectrum obtained during a time window of 0.3–6 μs after ^{170}Dy implantation is shown in Fig. 1. Peaks belonging to fully ionized ^{170}Dy are labeled, while unlabeled peaks have been identified to originate from H-like charge states of ^{165}Tb nuclei.

The level scheme obtained in the current work is shown in Fig. 2. The three lowest-lying excited states can be assigned as the 2^+, 4^+ and 6^+ members of the ground-state rotational band with energies closely following the expected $I(I+1)$ rotational dependence. Note that the $4^+ \to 2^+$ transition confirms the observed

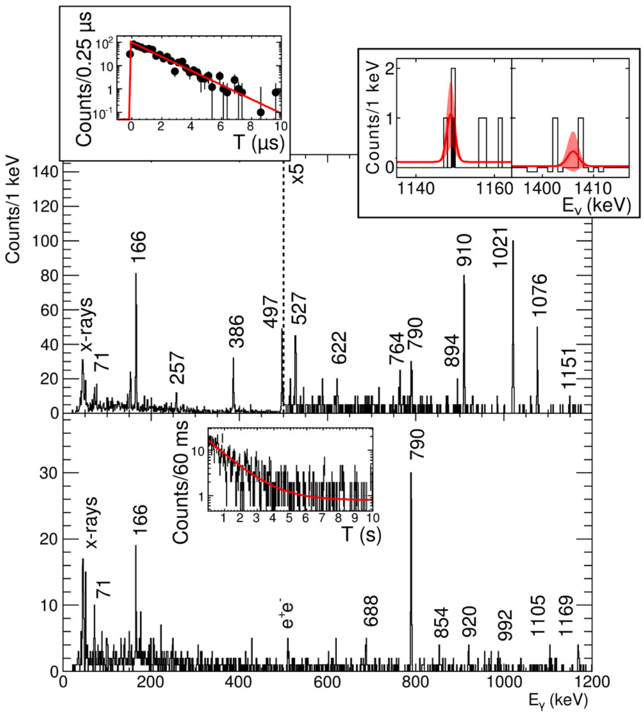

Fig. 1. Spectra of γ rays following the decay of the proposed 6^+ isomer of ^{170}Dy (top) and β decay of ^{170}Tb (bottom). Transitions identified as belonging to ^{170}Dy have been labeled. The time distribution associated with the sum of all transitions except the 71 keV is shown in the left inset of the top panel. The right insets show the close-up spectra of the single (white) and $\gamma\gamma$ coincidence gated on 257 keV (black) γ rays in the region of the expected M1 transition at 1149 keV (center) and E2 transition at 1406 keV (right) between the 6^+ isomer and the 6^+ and 4^+ states of the yrast band, respectively. The solid red line shows a Gaussian fit with a width fixed to the detector resolution (FWHM ≈ 2.5 keV) and the shaded red areas show the 1σ upper and lower limits of that fit. The inset of the lower panel shows the time distribution of the ^{170}Tb β decay with a fit consisting of an exponential, the daughter and granddaughter decays on top of a constant background. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

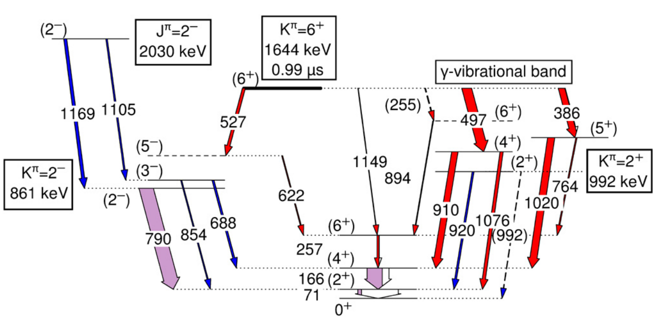

Fig. 2. Partial level scheme of ^{170}Dy obtained in the current work. The thick $K^\pi = 6^+$ level at 1644 keV represents the isomeric state and dashed levels and γ rays represent tentative states and transitions. Red and blue arrows are transitions observed from the isomer and β decay channels, respectively, while purple arrows are transitions observed in both. Unfilled parts of the arrows correspond to estimated transition strengths associated with electron conversion. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

candidate in Ref. [20]. From $\gamma\gamma$ energy coincidences it was determined that the isomeric state mainly decays via the 497 and 386 keV transitions to two intermediate states, the lower of which feeds the 4^+ and 2^+ states of the yrast band via the 910 and 1076 keV transitions, respectively. The higher-lying state feeds the proposed 6^+ and 4^+ states of the yrast band through transitions with energies of 1021 and 764 keV. Based on the systematics of the even-even $N = 104$ isotones the isomer was assigned to 6^+ and from the decay pattern these two intermediate states were assigned to spin and parity 4^+ and 5^+, respectively. This would suggest that the $6^+ \to 6^+$ transition has an energy of 1149 keV. There are three counts with that energy, one of which is coincident with the 257 keV γ ray assigned as the $6^+ \to 4^+$ yrast transition. Besides these transitions, three other γ-rays are notable in the spectrum at energies of 527, 622 and 894 keV. As the latter is in coincidence with the 257 keV γ-ray it has been tentatively assigned to originate from a 6^+ state. Such a state could be populated via a 255 keV transition from the isomer state. However, since this is very similar in energy to the 257 keV γ-ray and both are expected to be in coincidence with the 894 keV γ-ray, it is not possible to directly observe this transition in the current experiment. The other two transitions, 527 and 622 keV add up to 1149 keV which suggests that they are in cascade via an intermediate state. Since the relative intensity is significantly different between these states, we propose that the decay of the intermediate state is fragmented into more than one path. This proposition is strengthened by the observation of a 790 keV γ-ray that together with the 622 keV transition adds up to the 527 keV intensity within error bars. We tentatively assign the intermediate state as being a 5^- state. The negative parity assignment of this state is discussed in more detail below. See Fig. 2 and Table 1 for details of these assignments.

From the β-delayed γ-ray spectrum we observe a strong transition at 790 keV that has been assigned to populate the 2^+ state. This γ ray is in coincidence with a 1169 keV γ-ray that would originate from a high-energy state that is well matched in energy with a 1105 keV decay to an intermediate state, in turn decaying into the 4^+ and 2^+ states of the yrast band. Based on the relative intensities of the 790, 854 and 688 keV γ-rays, these states have been assigned to spins 2 and 3, as shown in Fig. 2. We, furthermore, note that approximately 75% of the ground state band $2^+ \to 0^+$ transition strength originates from the 861 keV $J = 2$ level and is, thus, only weakly populated directly from β decay. This means that these two $J = 2$ levels must be different in nature and, thus, we assign the 861 keV level to be the band head of a negative-parity band. We, furthermore, tentatively assign the other new states obtained from the β-decay data to share this negative-parity property. The $\log ft$ values obtained after these assignments are found to be consistent with our interpretation, see Table 1. For the $\log ft$ calculations an estimated value of $Q_\beta = 6940(446)$ keV was used [30] and the β-decay half-life of ^{170}Tb, used to calculate the $\log ft$ values, was measured to be $0.91(^{+18}_{-13})$ s. Furthermore, a weak 920 keV transition is observed, believed to be originating from a 2^+ state decaying into the 2^+ state of the yrast band. There is a small excess of events in the spectrum at 992 keV, which would correspond to the $2^+ \to 0^+$ transition. However, due to the large background in this part of the spectrum, we have marked this transition as tentative.

The static moments of inertia deduced from the excited states in the yrast band are shown in Table 2. For the $2^+ \to 0^+$ transition a value of 41.98(9) $\hbar^2$ MeV^{-1} was obtained, compared to a value of 43.24 $\hbar^2$ MeV^{-1} that was calculated for the ground state in Ref. [31]. For the proposed γ band the moments of inertia values agrees well with the grounds state band, supporting the assignment of these states. Note that, although the 6^+ member of the γ band is not firmly identified, rotational energy spacings imply the 6^+ state would anyway be within a few keV of the tentatively assigned state. Finally, for the negative parity states the similar values suggest that these states also form a rotational band. For a more detailed discussion about the yrast states, see Ref. [32].

Table 1
Initial level energy, E_i, and spin-parity, J_i^π, of the levels in ^{170}Dy. For each γ ray the energy E_γ, γ-ray branching ratio B_γ, total intensity from isomer decay, I_γ(iso) (relative to the total number of isomer implantations), and β decay, $I_\gamma(\beta)$ (relative to the total number of transitions to the ground state), and final level spin-parity J_f^π, reduced isomer-hindrance, f_ν, and β-decay hindrance, $\log ft$, are listed. For the 0^+ and 4^+ states the $\log ft$ with uniqueness one are shown. The bold f_ν is the value used for the systematics in Fig. 3. The italic transitions are not observed directly in this experiment, but the deduced upper (lower) limit on the intensity (hindrance) is given.

E_i (keV)	J_i^π	E_γ (keV)	B_γ	I_γ(iso) (%)	$I_\gamma(\beta)$ (%)	J_f^π	f_ν	$\log ft$
0	0^+							>7.2 (1U)
71.46(15)	(2^+)	71.45(15)	100	9.2(24)	9.2(27)	0^+		>5.85
237.32(18)	(4^+)	165.84(11)	100	58(5)	15.1(33)	(2^+)		8.00(31) (1U)
494.29(28)	(6^+)	256.9(29)	100	9.0(28)		(4^+)		
861.35(21)	(2^-)	789.93(15)	100	6.1(21)	74(9)	(2^+)		5.09(31)
925.23(30)	(3^-)	687.72(33)	64(28)		10.4(35)	(4^+)		5.9(4)
		853.7(5)	36(20)		5.9(29)	(2^+)		
991.8(4)	(2^+)	920.2(4)	80(40)		9.7(35)	(2^+)		5.72(22)
		992.1(7)	22(18)		2.8(21)	0^+		
1116.53(29)	(5^-)	621.8(4)	100	4.4(19)		(6^+)		
1147.21(21)	(4^+)	909.79(18)	66(14)	29(5)		(4^+)		
		1075.68(30)	34(9)	2.9(15)		(2^+)		
1257.77(20)	(5^+)	764(4)	14(6)	5.3(21)		(6^+)		
		1020.5(10)	86(8)	33.2(19)		(4^+)		
1388.8(5)	(6^+)	894.5(5)	100	3.3(17)		(6^+)		
1643.92(22)	(6^+)	*255*	*<3.6*	*<3.2*		(6^+)	*>160*	
		386.33(15)	33(5)	30(4)		(5^+)	196(11)	
		496.64(14)	49(7)	44(5)		(4^+)	79(6)	
		527.28(22)	15.2(35)	13.7(30)		(5^-)	1660(130)	
		1148.9(7)	2.3(16)	2.0(15)		(6^+)	**80(12)**	
		1406	*<2.4*	*<2.1*		(4^+)	*>57*	
2030.4(4)	(2^-)	1104.5(6)	32(17)		8(4)	(3^-)		5.08(22)
		1169.31(35)	68(26)		16(5)	(2^-)		

Table 2
Rotational frequencies, $\hbar\omega$, and static moments of inertia, $\mathcal{J}^0$, for sequential combinations of spin and parity J_2^π and J_1^π.

J_2^π, J_1^π	$\hbar\omega$ (MeV)	$\mathcal{J}^0$ ($\hbar^2$ MeV^{-1})
Ground state band		
$6^+, 4^+$	0.128	42.82(5)
$4^+, 2^+$	0.0820	42.20(5)
$2^+, 0^+$	0.0292	41.98(9)
γ vibrational band		
$6^+, 5^+$	0.130	45.82(10)
$5^+, 4^+$	0.110	45.22(12)
$4^+, 2^+$	0.0768	45.05(13)
2^- band		
$5^-, 3^-$	0.0950	47.05(11)
$3^-, 2^-$	0.0630	46.963(29)

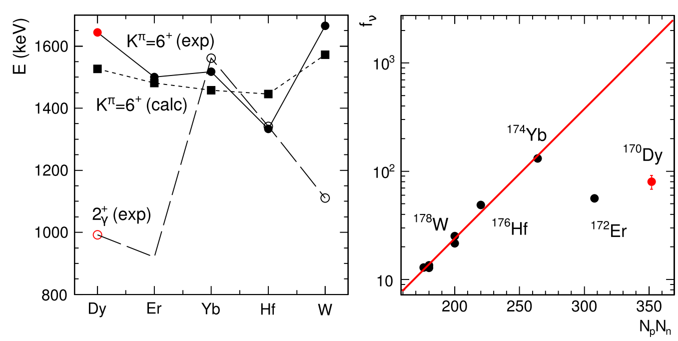

Fig. 3. In the left panel, experimental (filled circles) and theoretical (filled squares) energy systematics of the $K^\pi = 6^+$ isomeric, and experimental 2^+_γ states for $N = 104$ (open circles) from $Z = 66$ (Dy) to $Z = 74$ (W). Note that the lowest $K^\pi = 6^+$ state in ^{176}Hf is of a mixed two-neutron and two-proton configuration [17] whereas the calculations are for the pure two-neutron configuration. The right panel shows the reduced M1 hindrance (f_ν) against the product of valence protons and neutrons (N_pN_n) for known $K^\pi = 6^+$ to ground state band $J^\pi = 6^+$ M1 transitions in this region: ^{170}Dy, ^{172}Er, ^{174}Yb, $^{172-178}$Hf and ^{178}W (filled circles). The $N = 104$ isotones have been labeled and the solid line shows the extrapolated f_ν trend. Data points from the current work are marked in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

In the following discussion, we will assume that the 1149 keV decay is of pure M1 character. An E2 mixing, even as large as $\delta_{M1/E2} = -1.80^{+6}_{-7}$ as observed in the corresponding ^{174}Yb isomer [33], could influence the K-hindrance to the yrast band, but most likely not to the extent that it would change the conclusions. For the decay into the γ-vibrational band and the $K^\pi = 2^-$, however, such a mixing would strongly influence the hindrance and as it is not directly measured in the present work our discussion will focus on the ground-state band component. To obtain an estimate of the E2 strength to the yrast band, we have looked for the expected 1406 keV γ ray, but it was not observed. From the current data, an upper limit of 4×10^{-8} W.u. is obtained for this transition branch, which corresponds to a reduced hindrance of $f_\nu > 57$, compared to 6.8 (^{178}W), 42 (^{176}Hf), and 327 (^{174}Yb) across the heavier $N = 104$ isotones. Recent calculations using the triaxial projected shell model show a strong correlation between the isomer hindrance and the properties of the γ band [34].

In particular, we note the energy systematics of the γ bands, see Fig. 3. While the $K^\pi = 2^+$ band head of ^{172}Er was not observed in Ref. [35] it is expected to be at an energy close to 920 keV [35]. One interesting feature is the steady increase in the $K^\pi = 2^+$ band-head energies from W to Yb, with a sudden drop at Er. This also happens to be the point where the hindrance breaks out of the N_pN_n extrapolation. The hindrance of the $K^\pi = 6^+$ isomers could be influenced by members of the $K^\pi = 2^+$ γ band, both directly from the proximity of the two $J^\pi = 6^+$ states, as discussed in Ref. [34] and the general effect of low-lying γ vibrations being a signal of increased γ softness and, hence, more K mixing.

Under the assumption that the $\langle 6^+_i | 6^+_\gamma \rangle$ mixing matrix elements are similar and small, the ratio between the hindrances, F_W, and square of the excitation energy differences, ΔE^2, should stay constant. For the closest neighbor, ^{172}Er, the 6^+_γ is, unfortunately, not known, but can be determined by extrapolation of the known energies to be close to 1390 keV [35]. Together with the tentative 6^+_γ state in ^{170}Dy, this gives a $\Delta E(^{170}\text{Dy})^2/\Delta E(^{172}\text{Er})^2 = 255^2/110^2 \approx$

5.4. Comparing this to the value of $F_W(^{170}\text{Dy})/F_W(^{172}\text{Er}) = 3.1 \cdot 10^9/0.55 \cdot 10^9 \approx 5.6$, we find that there is indeed a remarkable similarity in the band-mixing effects of these nuclei. On the other hand, comparing these values for ^{178}W, that has a similar level structure to ^{170}Dy and is known to be γ soft, we get the numbers $\Delta E(^{170}\text{Dy})^2/\Delta E(^{178}\text{W})^2 = 255^2/128^2 \approx 4.0$ and $F_W(^{170}\text{Dy})/F_W(^{178}\text{W}) = 3.1 \cdot 10^9/0.35 \cdot 10^6 \approx 9200$. From this we can conclude that although the large N_pN_n value should predict a very hindered decay in ^{170}Dy [15], the near degeneracy between the $K^\pi = 6^+$ state and the 6^+ state of the γ-vibrational band plays the key role in reducing the actual hindrance.

Potential energy surface calculations, similar to those reported in Ref. [15,11], were performed for the ground state and $K^\pi = 6^+$, $5/2^-[512] \otimes 7/2^-[514]$ two-neutron configurations, including β_6 deformation [11]. While the deformation parameters were chosen to minimize the potential energy, the neutron–neutron pairing strength was adjusted according to systematics of similar nuclei in this region. It is already known that a factor of 1.115 adjustment is needed for calculating the multi quasi-particle states in ^{178}W [36]. Using the same method as in Ref. [36], a factor of 1.05 and 1.06 was obtained for ^{172}Er and ^{166}Dy, respectively. However, due to the absence of experimental odd-even mass differences, this method can not be used for more neutron-rich nuclei. Furthermore, it has been pointed out [37] that the pairing strength to reproduce the measured excitation energies of the $K^\pi = 6^+$ states in the $N = 104$ chain is larger than that needed to reproduce the mass difference. Thus, in this work, we have adopted an adjustment factor of 1.1 for the entire chain, increasing the energies of the states with approximately 300 keV and giving a satisfactory reproduction of the experimental data, as shown in Fig. 3.

The interpretation of the low-K states is less straightforward than the high-K ones as they are created through an interplay of several different configurations and have a tendency to be collective. The $\log ft$ values in Table 1 suggest a $J^\pi = 2^-$ ground state in ^{170}Tb. In this case $\pi 7/2^-[523] \otimes \pi 3/2^+[411]$ is populated as a pure two-proton configuration, where the 2^- coupling is energetically favored. The excitation energy of 861 keV for the first $J^\pi = 2^-$ state is the lowest in all $N = 104$ isotones, which may be indicative of an octupole character. This is also consistent with the assignment of the $J^\pi = 2^-$ band head at 1148 keV in ^{162}Dy expected to be the dominant component of the $J^\pi = 2^-$ octupole vibration, [38,39].

5. Summary

In summary, a detailed study of the structure of the doubly mid-shell valence maximum nucleus $^{170}_{66}\text{Dy}_{104}$ has been carried out. From the γ-ray spectra following isomeric and β decay several states of this nucleus were observed. We have identified the yrast band up to the $J^\pi = 6^+$ state, the γ-vibration band up to the 5^+ state with a tentative 6^+ state, a low-lying negative-parity state that could be a candidate for the lowest energy octupole deformed state, and the $K^\pi = 6^+$ two quasi-particle isomer. The 6^+ isomer was observed with a reduced hindrance an order of magnitude smaller than originally predicted, which has been attributed to γ-vibrational mixing.

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