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Transitional nature of the level structure of ^{217}Rn

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The level structure and configurations of ^{217}Rn have been studied following the α decay of mass separated ^{221}Ra (30 s). A number of new levels and γ-ray transitions have been observed. A group of low-energy states populated with low α decay hindrance factors is interpreted as intermediate between the $g_{9/2}$ shell model configuration and the 5/2(0.2;0.2) quadrupole-octupole deformed configuration. A second group of states populated with high hindrance factors is interpreted as intermediate between the $i_{11/2}$ shell model configuration and the mixed 1/2(−0.1;0.5;−2)+3/2(−0.1;0.6) quadrupole-octupole configuration. [S0556-2813(97)01106-0]

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I. INTRODUCTION

The nucleus ^{217}Rn lies in an intermediate region, nine nucleons beyond the double closed shell at ^{208}Pb with shell model applications and four nucleons below ^{221}Ra [1] where a reflection asymmetric model has been shown to apply. While ^{219}Fr and ^{219}Ra have been treated successfully with the reflection asymmetric model [2,3], already at $A=219$ major distortions in the parity doublet bands are observed.

It would therefore be of considerable interest to observe a more detailed level stucture in ^{217}Rn in order to attempt an interpretation in terms of one or more nuclear models. In this way we can better define the region of applicability of various nuclear models and study the experimental observables which occur with transitions between models.

Very little previous experimental work on ^{217}Rn has been reported. In part this is because heavy-ion reactions such as ^{210}Pb(^{9}Be,2n)^{217}Rn, require exotic targets, beams, or both. Two ^{221}Ra α decay studies [4,5] have given some information on ^{217}Rn. The thesis study of Ruiz [4] suggested a number of levels in ^{217}Rn. The recent study of Ackermann [5] confirmed the ground state and three lowest excited states of Ruiz giving more accurate energies for the levels and assigned specific spins to two of the levels. However, the higher levels of Ruiz appear to be questionable.

In this experiment we have used a mass separated source of ^{221}Ra in secular equilibrium with its daughters to study the levels in ^{217}Rn. The result is a much more complete level scheme together with a large number of γ transitions which depopulate most of the levels in ^{217}Rn.

II. EXPERIMENTAL METHODS AND RESULTS

10 g of a Th-Ce alloy (40–60% by weight) were bombarded by a 280-MeV 2 μA beam of ^{3}He at the Orsay Synchrocyclotron. The target constituted the anode of an ion-source arc chamber [6] and was continuously fluorinated by introducing CF_4 vapor. Under these conditions one of the main activities produced is 8 m ^{225}Th with ^{221}Ra (30 s), ^{217}Rn (0.5 ms), and ^{213}Po (4 μs) in secular equilibrium. Using the ISOCELE separator and the selective fluorination method [6] ^{221}Ra was separated as (RaF^+) at mass number 240 (221+19).

The collected activities were moved by a tape transport system to a position between a 2-cm^2 Si surface barrier α detector and a Ge γ-ray detector. The resolution of the α detector was 21 keV with only 5 mm between the source and α detector. The Ge detector was an ''N''-type coaxial (20%) with a Be window. The distance betwen the Be window and the source was approximately 1 cm. Collection-measurement cycles were 1 m. A total of ~ 600 cycles were collected. Simple α and γ spectra and 4000×4000 α-γ coincidence measurements were recorded simultaneously.

The resulting α spectrum of ^{221}Ra and its daughters in secular equilibrium is shown in Fig. 1. Major peaks in the ^{221}Ra α spectrum are labeled in keV. α peaks of ^{217}Rn and ^{213}Po daughters, and ^{222}Ra and ^{218}Rn impurities are indicated.

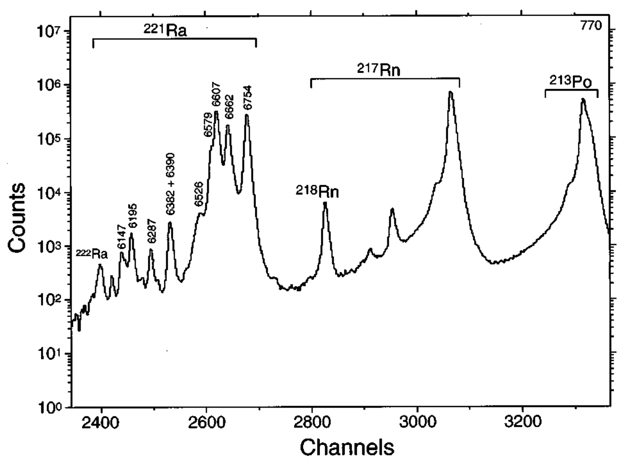

FIG. 1. The α spectrum of ^{221}Ra and its daughter and granddaughter ^{217}Rn and ^{213}Po. The region of each isotope is bracketed and the ^{221}Ra α energies are given in keV. ^{222}Ra and ^{218}Rn impurities are also indicated. They result from a slight contamination from the tail of the large ^{222}Ra peak in the isotope separation.

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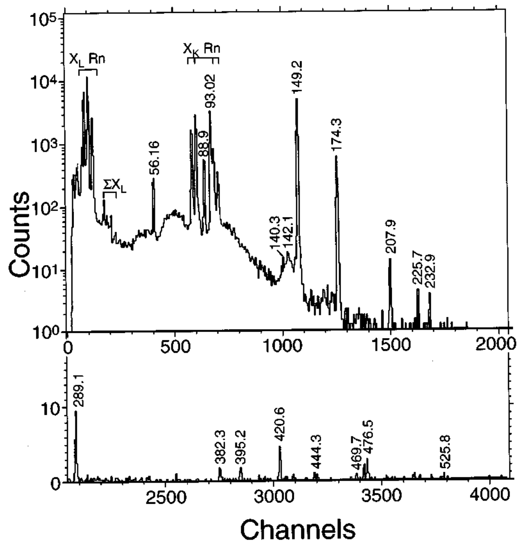

FIG. 2. The γ spectrum of ^{217}Rn in coincidence with all ^{221}Ra α's in Fig. 1. Energies of the γ's are given in keV and Rn x rays are indicated. Note that the lower energy part of the spectrum (upper panel) uses a logarithmic scale where the higher energy (lower panel) has a linear scale.

The γ spectrum coincident with all ^{221}Ra α's in Fig. 1 is presented in Fig. 2. Gamma rays are labeled in keV, and K and L x rays of Rn indicated. Figure 3 is a composite of γ spectra coincident with various lines or groups of lines labeled in Fig. 1. Energies in keV of the various γ rays are given.

Finally, Table I lists all γ rays of ^{217}Rn observed in these experiments, their energies, intensities, multipolarities (when available) deduced from intensity balances between α and γ, also by the $X_{k/\gamma}$ ratios for the 149.2 and 174.3 keV γ's, in good agreement with electron measurements [5] and assignment in the level scheme. All γ rays (representing >99.9% of the intensity) have been assigned except the weak 142.1 keV γ.

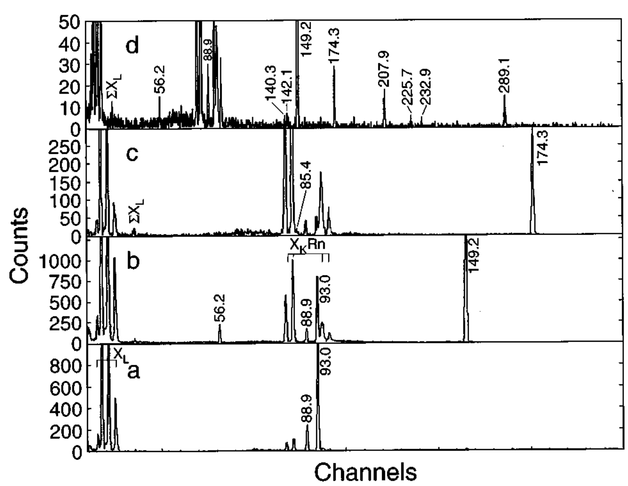

FIG. 3. Γ-ray spectra of ^{217}Rn in coincidence with various α groups of ^{221}Ra. (a) Coincidences with the 6662 keV α group; (b) with the 6607 keV α group; (c) with the 6579 keV α group; (d) with the 6526 to 6147 keV α region. γ ray energies are in keV.

TABLE I. γ-ray and K x-ray transitions in ^{217}Rn following the α decay of ^{221}Ra.

$E_\gamma(\Delta E_\gamma)$	I_γ rel	$I_\gamma / 10^3{}_\alpha$		Transition
56.16 (5)	2.5 (5)	3.2	$(M1)$	149.2 → 93.0
85.4 (3)	0.15 (5)	0.18		174.3 → 88.9
86.0 (5)	0.04 (2)	0.05		235.2 → 149.2
88.90 (5)	7.5 (10)	9.4	$(M1)$	88.9 → 0
93.02 (5)	33 (3)	41	$E2+M1$	93.0 → 0
140.3 (3)	0.04 (2)	0.05		375.0 → 235.2
142.1 (3)	0.05 (2)	0.07		
149.2 (1)	100	125	$E2$	149.2 → 0
174.3 (1)	17 (2)	18	$M1$	174.3 → 0
207.9 (2)	0.6 (2)	0.68		382.2 → 174.3
225.7 (2)	0.2 (1)	0.27		375.0 → 149.2
232.9 (3)	0.2 (1)	0.23		382.2 → 149.2
289.1 (3)	0.7 (2)	0.87		382.2 → 93.0
382.2 (3)	0.3 (1)	0.36		382.2 → 0
395.2 (3)	0.3 (1)	0.40		569.6 → 174.3
420.6 (2)	0.7 (2)	0.86		569.6 → 149.2
444.3 (5)	0.2 (1)	0.26		618.9 → 174.3
469.7 (5)	0.15 (6)	0.16		618.9 → 149.2
474.5 (4)	0.35 (12)	0.40		474.5 → 0
476.5 (4)	0.40 (15)	0.52		569.6 → 93.0
525.8 (5)	0.15 (5)	0.18		618.9 → 93.0
X_K(Rn)				
$K_\alpha + K_\beta$	62 (8)	78		

III. THE LEVEL SCHEME OF ^{217}Rn

The level scheme of ^{217}Rn is given in Fig. 4. The level structure itself, as distinct from spin-parity assignments, is clearly established (except for the tentative ~ 295 keV state) by the combination of α decay spectroscopy and by α-γ coincidences with α lines or groups of α lines as the energy of the α particles is decreased. This procedure corresponds to moving up systematically in excitation energy and observing the γ depopulation of individual ^{217}Rn levels. One observes specific γ rays growing into the spectrum or decaying out with decreasing α energy, thus connecting certain transitions with specific ^{217}Rn levels. This allows us to construct the level scheme and put the transitions with their multipolarities firmly in place in Fig. 4. Once the γ-ray transitions are assigned quite definitely between levels and some of the multipolarities determined, we proceed to the much more difficult task of assigning spins and parities.

Only three states can be assigned spins and parities unambiguously. They are the ground state ($9/2^+$), the 93.0 keV state ($7/2^+$), and the 149.2 kev state ($5/2^+$). The first and third of these states were previously assigned [5] and are confirmed by these measurements. The ground-state α decays to the ground state of ^{213}Po with known ground-state spin $9/2^+$ with hindrance factor (HF) 1.4 establishing spin $9/2^+$ for the ^{217}Rn ground state. The 149.2 keV state is populated by the $5/2^+$ ^{221}Ra ground state (measured by on-line collinear laser spectroscopy [7] with HF 3). Furthermore, it decays to the ground state with a very strong $E2$

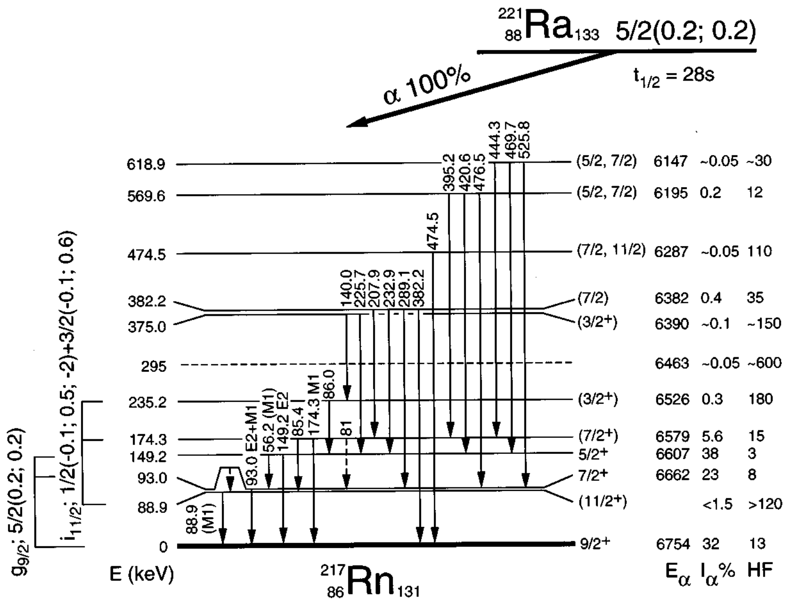

FIG. 4. Energy level scheme of ^{217}Rn resulting from the present study. α energies, their intensities, and hindrance factors populating the levels are shown to the right. γ transitons are shown as vertical lines together with their energies in keV and their multipolarities if known. The resulting spins, parities, and configurations are shown to the extreme left.

γ ray. The 93.0 keV state is populated by a 56.2 keV $M1$ transition from the $5/2^+$ state at 149.2 keV and depopulates by a 93.0 keV mixed $M1 + E2$ transition to the $9/2^+$ ground state, fixing its spin parity as $7/2^+$.

Of considerable interest is a new state, the first excited state in ^{217}Rn. This state is established at 88.9 keV by the observation of an 88.9 keV $M1$ transition in coincidence with the 6662 keV α group populating the 93.0 keV $7/2^+$ state and by an 85.4 keV transition depopulating the well established 174.3 keV state, establishing positive parity. As will be discussed in a later section of this paper, the 88.9 keV positive parity state is clearly of a different character than the other low lying states in view of its high HF. Its population and depopulation suggest the tentative assignment as $(11/2)^+$.

The previously known 174.3 keV state depopulates to the $9/2^+$ ground state, to the tentative $(11/2)^+$ 88.9 keV state, and with a tentative 81 keV transition (partially obscured by the K_α x ray), to the 93.0 keV $7/2^+$ state, suggesting spin parity $(9/2)^+$. For reasons which will become apparent in the Sec. IV of this paper, we have chosen instead to assign it tentatively as the $(7/2)^+$ member of the $i_{11/2}$ "band." The 235.2 keV state decays only to the $5/2^+$ 149.2 keV state. Since it does not decay to the $7/2^+$ state, we tentatively assign spin parity $(3/2^+)$. A similar statement can be made for the 375.0 keV state which decays to the 235.2 keV state and the $5/2^+$ 149.2 keV state.

The 382.2 keV state decays to $5/2^+$, $7/2^+$, and $9/2^+$ lower lying states and therefore is given tentative assignment as (7/2). The 569.6 and 618.9 keV states decay to $5/2^+$ and $7/2^+$ lower lying states and are given tentative assignments as (5/2, 7/2). The 474.5 keV state decays only to the ground state and is given the tentative assignment (7/2–11/2). In summary then, although the levels, their connecting transitions, and some of the parities in Fig. 4 are not in doubt, only three spins and parities have been determined with certainty in ^{217}Rn.

IV. DISCUSSION

Even a cursory glance at the α spectra of Fig. 1 indicates quite clearly that there are two very different groups of HF's populating states in ^{217}Rn. The high-energy group of α's from 6754 to 6579 keV populates with HF's from 3–15. Beginning with the state at 235.2 keV and on up in excitation or down in α energy, most of the states are populated with much higher HF's. In fact, only the 569.6 keV state in this region of higher excitation is populated in α decay with a HF as low as 12. We note also that the 88.9 keV state with HF > 120 belongs to the group of states with higher HF's.

We can understand this division into two groups of HF's by comparing the level structures and the octupole-quadrupole levels and configurations [8,3] in the parent ^{221}Ra and in ^{217}Rn. Using these levels we anticipate that the ground state of the 133 neutron nucleus ^{221}Ra at $\epsilon \sim 0.09$ has spin parity $5/2^+$ and octupole-quadrupole configuration 5/2(0.2;0.2). It is clear then from the very low HF's that the ground state and other low lying states in ^{217}Rn are closely related to this $5/2^+$ rotational band with the same octupole-quadrupole configuration while the higher HF group involves another configuration. However, in ^{217}Rn with just one less α particle, the rotational structure has been seriously disturbed. Furthermore, the allowed unhindered α decays go from the ^{221}Ra ground state to the ^{217}Rn ground state band, whereas we might have anticipated a ground state to excited state α transition. This can be explained with the reasonable assumption that the quadrupole deformation ϵ in ^{217}Rn has decreased to ~ 0.07 as we go toward the 126 neutron closed shell, resulting in a level crossing so that the $5/2^+$ band remains the ground state in ^{217}Rn. We see a very similar disruption in the same $5/2^+$ band in ^{219}Ra, the isotone [3]. The fact that the $5/2^+$ band in ^{219}Ra is an excited band in contrast to ^{217}Rn implies that the quadrupole deformation in ^{219}Ra is slightly larger ($\epsilon \sim 0.09$) so that the band crossing has not occurred. If we now note that at the vanishing octupole and quadrupole deformation this 5/2(0.2;0.2) band goes over into the $g_{9/2}$ shell model state, the disruption in the band becomes more clear with the tendency of the lowest member of the band to become $9/2^+$.

In Fig. 5 a comparison of the $5/2^+(0.2;0.2)$ band in ^{221}Ra [1], with the level structure of ^{219}Ra [3] and ^{217}Rn, and with a schematic $g_{9/2}$ shell model weak-coupling inter-

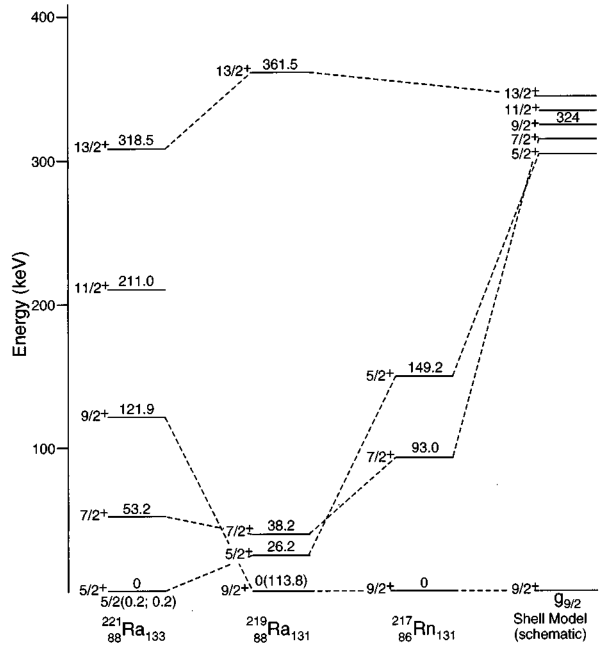

FIG. 5. Comparison of the $K=5/2^+$ band with configuration 5/2(0.2;0.2) in ^{221}Ra and related bands in ^{219}Ra, ^{217}Rn and a schematic weak-coupling model based on the $g_{9/2}$ shell model.

pretation, is given. The quadrupole spacing of 324 keV for weak coupling is taken from the energy of the first 2^+ state in ^{218}Rn.

The disruption of the rotational bands in ^{217}Rn and ^{219}Ra in Fig. 5 can be explained by the influence of the spherical symmetry of the shell model with the $9/2^+$ state sweeping down to become the ground state while the $5/2^+$ and $7/2^+$ states go up in excitation toward the shell model limit. Thus Fig. 5 suggests that the $5/2^+$ band of ^{217}Rn is intermediate between the $5/2^+$(0.2;0.2) quadrupole-octupole band of ^{221}Ra and the spherical shell model.

A somewhat parallel situation occurs between ^{221}Ra and its α decaying parent ^{225}Th. The first excited configuration in 133 neutron ^{221}Ra is the 3/2(-0.1;0.6) with, however, considerable admixture of the 1/2(-0.1;0.5;-2) configuration, giving rise to a quite disturbed $3/2^+$ band with the sequence $7/2^+$, $3/2^+$, $5/2^+$. However, in the ^{225}Th parent the sequence is a reasonably regular $K=3/2^+$ rotational band. It should be noted that this configuration at $\epsilon = \epsilon_3 = 0$ goes over into the $i_{11/2}$ shell model state. Therefore we suppose that the $(11/2)^+$ band head state at 88.9 keV in ^{217}Rn is clearly showing the nature of this band. In ^{221}Ra we have the more intermediate situation with $7/2^+$ as the lowest band member.

We assume therefore that the $(11/2)^+$ state at 88.9 keV, the $(7/2)^+$ state at 174.3 keV, and the $(3/2^+)$ state at 235.2 keV in ^{217}Rn are all elements of a very distorted 1/2(-0.1;0.5; -2)+3/2(-0.1;0.6) band with the mixing and the $i_{11/2}$ shell model character producing the distortion.

In Fig. 6 the sequence of states for ^{225}Th [9], ^{221}Ra [1], ^{219}Ra [3], ^{217}Rn and a weak coupling interpretation of $^{218}\mathrm{Rn} \otimes i_{11/2}$ are compared. The trend from a near normal $3/2^+$ band to increasingly distorted bands with $11/2^+$ becoming the band head is obvious. There is, however, a difficulty with the configurational assignment to the $7/2^+$ state at 174.3 keV. It has an anomalously small HF (15) to be a member of the 3/2(-0.1;0.6) band. We assume this results from mixing with the $7/2^+$ 93.0 keV state which lies only 81.3 keV away and has a HF of 8.

Figures 5 and 6 depict the transitions in both the $3/2^+$ and $5/2^+$ bands from the normal rotational structures to shell model configurations. In this way they show the transitional nature of the ^{217}Rn levels, which is the primary focus of this research.

V. CONCLUSION

In this experimental study of ^{217}Rn following the α decay of ^{221}Ra we have observed seven new states and one tenta-

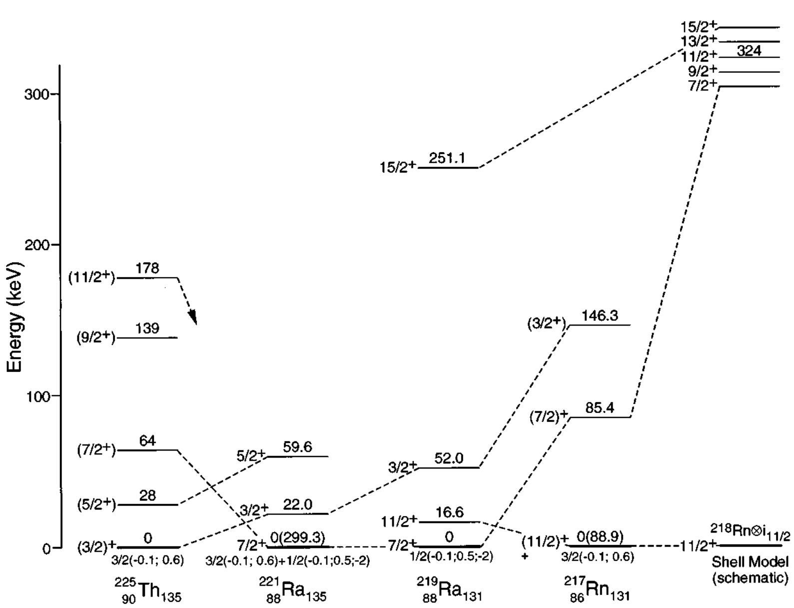

FIG. 6. Comparison of the $K=3/2^+$ band with configuration 3/2(-0.1;0.6) in ^{225}Th and related bands in ^{221}Ra, ^{219}Ra, ^{217}Rn and a schematic weak-coupling model based on the $i_{11/2}$ shell model. As we move to the right in the sequence ^{225}Th, ^{221}Ra, ^{219}Ra, and ^{217}Rn there are increasing amounts of the configurations 1/2(-0.1;0.5;-2) and $i_{11/2}$.

tive new state and connecting γ-ray transitions. In general, the spin parities were not determined with certainty. The HF's observed in the ^{221}Ra α decay indicate that there are two distinctly different types of states. We have interpreted the first of these sets of states with low α HF's as intermediate between the $g_{9/2}$ shell model configuration and the 5/2(0.2;0.2) quadrupole-octupole deformed configuration. The second set of states with high HF's are interpreted as intermediate between the $i_{11/2}$ shell model configuration and a mixed 1/2(−0.1;0.5;−2)+3/2(−0.1;0.6) quadrupole-octupole deformed configuration.

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