

$\pi h_{11/2}$ rotational structure in the neutron-deficient rare-earth nucleus ^{131}Pm

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High-spin states in the neutron-deficient nucleus $^{131}\text{Pm}_{70}$ have been investigated using the JUROGAM 3 γ -ray spectrometer. This is the lightest promethium isotope with known excited states. The proton intruder $h_{11/2}$ rotational structure has been extended to both higher and lower spin, and its unfavored-signature partner identified. This rotational structure is established down to a presumed $I^\pi = 5/2^-$ bandhead of the $\pi h_{11/2}$ [532]5/2⁻ Nilsson orbital, which is also expected to form the ground state of this deformed nucleus. Systematic comparisons are made with cranked shell-model calculations.

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Introduction. Experimental studies of odd-mass rare-earth nuclei provide an excellent opportunity to deduce the

interplay between collective excitations and their underlying single-particle configurations. For deformed odd-proton, even-neutron nuclei in the mass-130 region, yrast γ -ray spectra are frequently dominated by rotational bands based on proton $h_{11/2}$ configurations. Driven by the spin-orbit interaction, the $h_{11/2}$ orbitals descend from the $N_{\text{osc}} = 5$ shell to intrude into the positive-parity $N_{\text{osc}} = 4$ states. These

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negative-parity, high- j states are further lowered by increasing prolate deformation and collective rotation.

The active proton orbitals in promethium nuclei lie midway within the $h_{11/2}$ subshell. Their spin vectors are aligned neither parallel nor perpendicular to the intrinsic nuclear deformation axis, but somewhere in between. This has led to the concept of tilted-axis rotation and Fermi-aligned coupling, where the quantization axis for the motion is tilted away from the intrinsic principal axes defining the nuclear shape [1]. These so-called Fermi-aligned (FAL) orbitals add an additional layer of complexity to the structural interpretation of these nuclei, since their coupling behavior is influenced by the specific nuclear deformation and rotational frequency. For instance, a multiquasiparticle band based on the interplay of FAL orbitals at high spin was recently identified in ^{130}Ba [2].

The spectroscopy of ^{131}Pm is of particular interest in this regard. Its structural characterization is essential for the interpretation of neighboring odd-odd nuclei, where isolating the neutron-driven components of their level schemes requires a firm understanding of the odd proton's behavior. In addition, the proximity of ^{131}Pm to the proton drip line makes its spectroscopy directly relevant to proton-decay research, since calculations of half-lives, Q values, and fine-structure branching ratios are highly sensitive to the spins, parities, and relative excitation energies of the decaying states [3–5]. In particular, ^{131}Pm is the closest odd- Z , even- N nucleus with measured excited states to the deformed proton emitter ^{131}Eu , and therefore provides an essential reference system for a nucleus which has garnered much experimental and theoretical interest [5–9].

New results are presented for the $h_{11/2}$ states of ^{131}Pm , which is currently the lightest promethium isotope with known excited states. Through extensions of the known band at high and low spin along with identification of its unfavored signature partner, systematic comparisons with neighboring nuclei and comparison with cranked shell-model (CSM) calculations are made.

Experimental details. Excited states in ^{131}Pm were populated using the $^{58}\text{Ni}(^{78}\text{Kr}, 3p2n)$ fusion-evaporation reaction. A 390-MeV beam of ^{78}Kr ions, provided by the K130 cyclotron of the University of Jyväskylä, Finland, was directed at a self-supporting ^{58}Ni target foil of thickness 0.75 mg/cm². γ rays emitted at the target position were detected by the JUROGAM 3 spectrometer [10,11], comprising twenty-four Clover [12] and fifteen single-crystal [13] escape-suppressed HPGe detectors.

All detector signals were passed to the triggerless total data readout data-acquisition system [14], where they were time-stamped with a precision of 10 ns to facilitate temporal correlations between γ rays. Coincident γ -ray events were constructed requiring three or more γ rays within a 100 ns time window. Scattered events between two of the four Ge crystals in the Clover detectors were summed and included—the so-called add-back mode [12]. Data were then analyzed using the GRAIN [15] and RADWARE [16] software analysis packages. Coincident γ -ray events with a measured fold $N_\gamma \geq 3$ were unfolded into combinations of $N_\gamma = 3$ events and incremented into a symmetric triple-coincidence cube.

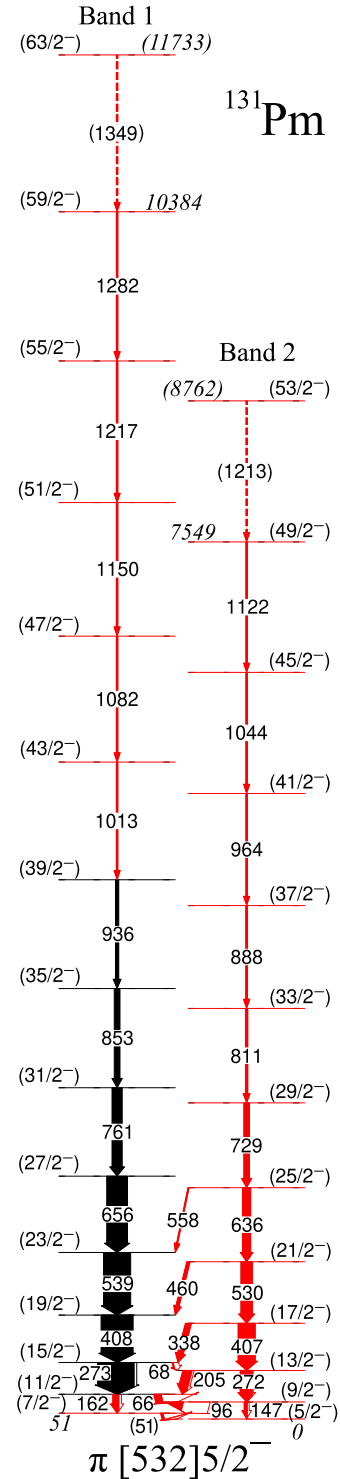


FIG. 1. Energy-level scheme for ^{131}Pm . Newly assigned transitions and states are in red. Arrow widths are proportional to the measured intensity except for the tentatively assigned 51-keV γ -ray transition. Solid segments of the arrow represent intensity by γ decay and open segments by internal conversion.

Following this procedure, a total of 1.3×10^{11} γ^3 -coincidence events were obtained. In the present work, the built-in background subtraction in RADWARE was modified

TABLE I. Excitation energies E_x , transition energies E_γ , angular-intensity ratios R , linear polarizations P , multipolarity, spin-parity assignments, and band number in ^{131}Pm . Uncertainties in brackets denote statistical error in the last quoted significant digit. The relative intensities are normalized to the 273-keV transition. Errors on the relative intensities are estimated to be $\leq 5\%$ for transitions of intensity ≥ 5 , and up to approximately 20% for weaker transitions.

E_x (keV)	E_γ (keV)	I_γ	R	P	I_i^π	I_f^π	Band
0					(5/2 ⁻)		2
51.0(5)	51(2) ^a				(7/2 ⁻)	(5/2 ⁻)	1
147.0(4)	96.1(4)	56	0.6(1)		(9/2 ⁻)	(7/2 ⁻)	2 → 1
	147.0(6)	9	0.8(1)		(9/2 ⁻)	(5/2 ⁻)	2
213.3(4)	66.2(2)	22			(11/2 ⁻)	(9/2 ⁻)	1 → 2
	162.1(6)	17	1.1(1)		(11/2 ⁻)	(7/2 ⁻)	1
418.8(4)	204.6(8)	25	1.2(1) ^b		(13/2 ⁻)	(11/2 ⁻)	2 → 1
	271.8(1)	33	1.1(1)		(13/2 ⁻)	(9/2 ⁻)	2
487.5(4)	68.1(2)	3			(15/2 ⁻)	(13/2 ⁻)	1 → 2
	272.8(7)	$\equiv 100$	0.9(1)	0.2(1)	(15/2 ⁻)	(11/2 ⁻)	1
826.4(4)	337.9(3)	16	0.7(1)	-1.0(4)	(17/2 ⁻)	(15/2 ⁻)	2 → 1
	406.7(1)	46	1.2(2)	0.2(2)	(17/2 ⁻)	(13/2 ⁻)	2
895.4(4)	407.8(1)	84	1.1(1)	0.2(2)	(19/2 ⁻)	(15/2 ⁻)	1
1355.9(5)	459.6(4)	9	0.7(1)		(21/2 ⁻)	(19/2 ⁻)	2 → 1
	529.8(2)	31	0.8(1)	0.4(3)	(21/2 ⁻)	(17/2 ⁻)	2
1434.0(5)	538.6(1)	73	0.9(1)	0.9(3)	(23/2 ⁻)	(19/2 ⁻)	1
1991.6(5)	557.6(1)	3	1.0(3)		(25/2 ⁻)	(23/2 ⁻)	2 → 1
	635.8(2)	22	0.9(3)		(25/2 ⁻)	(21/2 ⁻)	2
2090.2(5)	656.2(2)	56	1.1(1)	0.1(1)	(27/2 ⁻)	(23/2 ⁻)	1
2720.2(5)	728.6(4)	15			(29/2 ⁻)	(25/2 ⁻)	2
2850.7(5)	760.5(2)	28	1.1(1)	0.6(3)	(31/2 ⁻)	(27/2 ⁻)	1
3531.0(6)	810.8(1)	6			(33/2 ⁻)	(29/2 ⁻)	2
3703.9(5)	853.2(1)	16	1.1(1)		(35/2 ⁻)	(31/2 ⁻)	1
4418.6(6)	887.6(1)	4			(37/2 ⁻)	(33/2 ⁻)	2
4640(1)	936(1)	9			(39/2 ⁻)	(35/2 ⁻)	1
5383(1)	964(1)	2			(41/2 ⁻)	(37/2 ⁻)	2
5653(2)	1013(1)	4			(43/2 ⁻)	(39/2 ⁻)	1
6427(2)	1044(2)	<1			(45/2 ⁻)	(41/2 ⁻)	2
6735(2)	1082(1)	2			(47/2 ⁻)	(43/2 ⁻)	1
7549(3)	1122(2)	<1			(49/2 ⁻)	(45/2 ⁻)	2
7885(3)	1150(2)	2			(51/2 ⁻)	(47/2 ⁻)	1
8762(3) ^a	1213(2) ^a	<1			(53/2 ⁻)	(49/2 ⁻)	2
9102(3)	1217(2)	<1			(55/2 ⁻)	(51/2 ⁻)	1
10384(4)	1282(2)	<1			(59/2 ⁻)	(55/2 ⁻)	1
11733(4) ^a	1349(2) ^a	<1			(63/2 ⁻)	(59/2 ⁻)	1

^aThe assignment of this γ ray per energy level is tentative.

^bDipole gate used, so the ratio is inverted.

[17] to incorporate the background-subtraction technique of Ref. [18].

An analysis of angular-intensity ratios, based on the method of directional correlations from oriented states [19,20], together with linear-polarization measurements, was performed to determine the relative spin and parity of many of the states. The angular-correlation ratios were measured by sorting the γ -coincidence data into an asymmetric cube ($E_{\gamma 1}$ - $E_{\gamma 2}$ - $E_{\gamma 3}$), where $E_{\gamma 1}$ is a selected γ ray measured in any detector, $E_{\gamma 2}$ is measured with detectors in the “forward” direction (polar angles relative to the beam direction $\theta = 157.6^\circ, 133.6^\circ$), and $E_{\gamma 3}$ is measured with detectors in the “90°” direction ($\theta = 104.5^\circ, 75.5^\circ$). The angular-correlation

ratio, R , is then defined as

$$R = \frac{I_{\gamma 2} \text{ (measured forward, gated } 90^\circ)}{I_{\gamma 3} \text{ (measured } 90^\circ, \text{ gated forward)}}. \quad (1)$$

When the gating γ rays are of stretched-quadrupole character, an R value of approximately 1.0 is obtained for subsequent γ rays with stretched-quadrupole character and approximately 0.65 for those of stretched-dipole character. If the gating γ rays have stretched-dipole character, the ratios are “inverted,” i.e., approximately 1.5 for subsequent γ rays with stretched-quadrupole character and approximately 1.0 for those with stretched-dipole character.

Linear-polarization measurements are possible using the Clover detectors [21] and were used to differentiate between the electric and magnetic nature of γ rays. The four crystals in each Clover, mounted together in a common cryostat, can be used as a Compton polarimeter; each crystal acts as a scatterer, and those adjacent to it—in the perpendicular and parallel directions (with respect to the reaction plane)—act as absorbers [12].

The γ -ray linear polarization, P , is given by

$$P = \frac{1}{Q(E_\gamma)} \left[\frac{a(E_\gamma)N_\perp - N_\parallel}{a(E_\gamma)N_\perp + N_\parallel} \right], \quad (2)$$

where $Q(E_\gamma)$ is the energy-dependent polarization sensitivity of the detector, and $a(E_\gamma)$ is a correction factor (≈ 1.0) based on the ratio of the perpendicular- versus parallel-scattering count rates in the individual Ge crystals and measured independently of the effects of linear polarization. These quantities were measured for the JUROGAM 3 Clover detectors in Ref. [21].

Results. The level scheme deduced for ^{131}Pm is shown in Fig. 1 and comprises two parallel rotational structures, which are linked by $\Delta I = 1$ $M1/E2$ transitions at low spin. The excitation and γ -ray energies, R values, linear-polarization (P) measurements, and spin-parity assignments for these levels are given in Table I. Band 1 has been extended to higher spin compared with previous work [22], from $(39/2^-)$ to $(63/2^-)$, to an excitation energy of approximately 12 MeV. The 1082-keV transition ($47/2^- \rightarrow 43/2^-$) replaces the tentative 1099-keV transition reported in Ref. [22]. Several new low-energy transitions, of energies 66, 96, 147, and 162 keV, have been established below the $(11/2^-)$ level, which was previously the lowest energy level measured in this band [22]. The 162-keV transition continues the favored odd-signature ($\alpha = -1/2$) band 1 down to a $(7/2^-)$ state, while the 66- and 96-keV transitions interlink with the newly observed band 2, which is established to a $(5/2^-)$ state via the 147-keV transition.

Figure 2(a) presents a summed spectrum combining a set of double gates in the γ -triples cube, applied to all combinations from the gatelist comprising the 273-, 408-, 539-, 656-, 761-, 853-, 936-, 1013-, and 1082-keV transitions in band 1. Figure 2(b) shows the new band 2 obtained from summed coincidences between the 96-, 205-, 272-, or 407-keV γ rays and the gatelist including the 636-, 729-, 811-, 888-, 964-, and 1044-keV transitions. The ordering of the 96-, 147-, and 162-keV transitions is central to the reinterpretation of this band as based on the $h_{11/2}$ $[532]5/2^-$ Nilsson orbital, as discussed in the following section.

Discussion. The previous study on the excited states of ^{131}Pm by Parry *et al.* [22] assigned band 1 to the $h_{11/2}$ $[541]3/2^-$ Nilsson orbital. However, in the present work, band 1 and the newly observed band 2 are assigned as signature partners based on the $h_{11/2}$ $[532]5/2^-$ orbital that is observed down to a $I^\pi = \Omega^\pi = 5/2^-$ bandhead. This assignment is based on experimental $B[M1]/B[E2]$ values, rotational alignment and Routhian properties of the bands, and theoretical predictions.

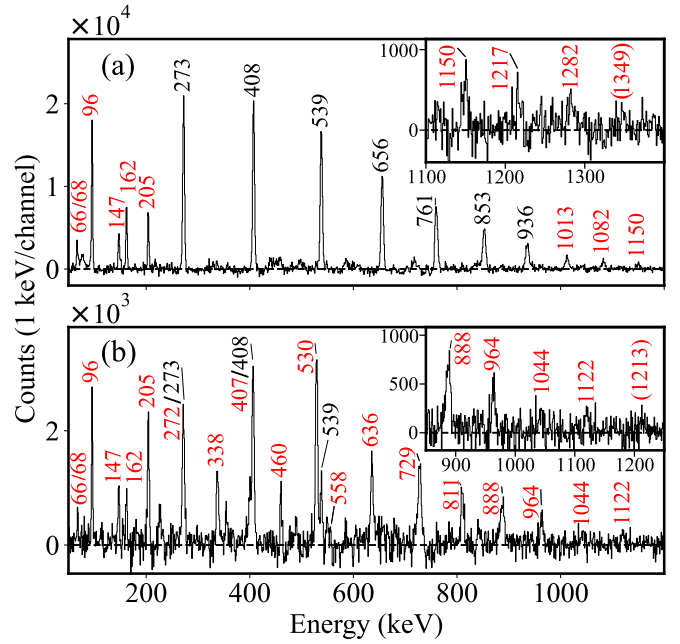


FIG. 2. γ -ray spectra obtained from triple-gamma (γ^3) coincidence data. (a) Sum of double gates, comprising all combinations from the gatelist (273, 408, 539, 656, 761, 853, 936, 1013, and 1082 keV) of band 1. (b) γ rays observed in coincidence with the 96-, 205-, 272-, or 407-keV γ rays and the gatelist including the 636-, 729-, 811-, 888-, 964-, and 1044-keV transitions of band 2. Unlabeled peaks are contaminants originating from other reaction products which are not part of the proton $h_{11/2}$ band in ^{131}Pm .

The proton Fermi surface of ^{131}Pm can be initially characterized using the Nilsson diagram (Fig. 3), calculated using a Woods-Saxon potential as described in Ref. [23]. For a predicted ground-state deformation of $\beta_2 = 0.32$ [25],

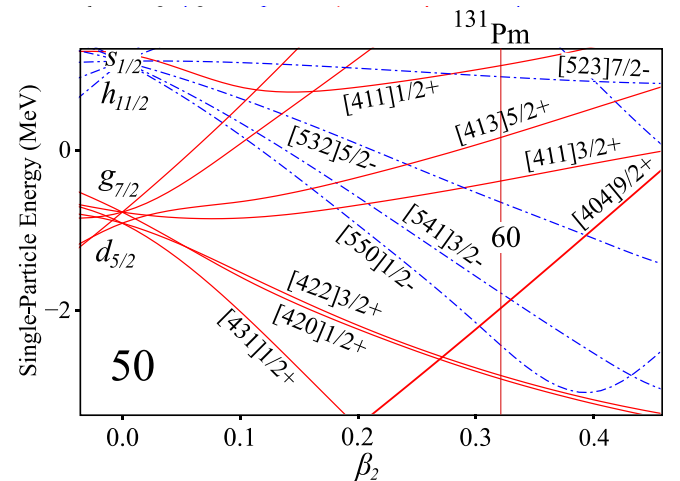


FIG. 3. Nilsson diagram for protons, based on a Woods-Saxon potential [23]. Positive-parity orbitals are in red and negative-parity orbitals are in blue. The predicted (Ref. [24]) ground-state deformation for $^{131}_{61}\text{Pm}$ ($\beta_2 = 0.32$) is displayed as a vertical line.

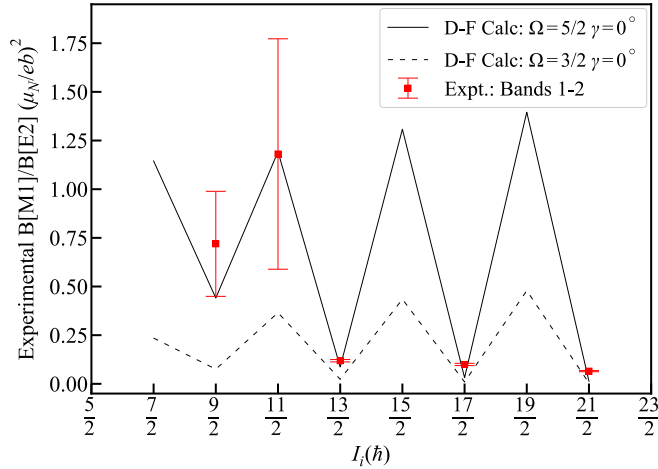


FIG. 4. Experimental (red points) and theoretical (solid and dashed lines) ratios of reduced transition probabilities $B[M1]/B[E2]$, plotted as a function of spin for bands 1 and 2 of ^{131}Pm . The theoretical quantities are calculated using the geometrical model of Dönau and Frauendorf [26] as described in the text. Calculations are displayed for Ω values of $5/2$ (solid line), representative of the $h_{11/2}$ [532] $5/2^-$ orbital, and $3/2$ (dashed line), representative of the $h_{11/2}$ [541] $3/2^-$ orbital.

the diagram suggests that the 61^{st} proton occupies the $h_{11/2}$ [532] $5/2^-$ orbital.

The observation of γ -ray transitions linking bands 1 and 2 allows the estimation of $B[M1; I \rightarrow I-1]/B[E2; I \rightarrow I-2]$ ratios of reduced transition probabilities. Experimental values are shown in Fig. 4 where they are compared with predictions using the geometrical model of Dönau and Frauendorf [26]. Experimental values of $\approx 0.1 (\mu_N/eb)^2$ are found for spins above $13/2$, but much larger values are observed below this spin. Theoretical values are shown assuming the odd $h_{11/2}$ proton resides in [532] $5/2^-$ or [541] $3/2^-$ Nilsson orbitals, respectively. The calculations used single-particle g -factors ($g_j = 1.214$), signature splitting $\Delta e' = 0.15$ MeV, and a predicted quadrupole deformation ($\beta_2 = 0.32$ [25], $\gamma = 0^\circ$ [24]). The experimental results are more compatible with the [532] $5/2^-$ assignment, especially at low spin.

The observation of band 2 enables a direct comparison between the experimentally observed and predicted signature splitting as a function of rotational frequency. Cranked shell-model (CSM) [27,28] calculations were carried out to characterize the high-spin behavior of the bands. The CSM Routhians, calculated using codes based on the universal Woods-Saxon single-particle potential detailed in Refs. [23,29], are displayed in Fig. 5. Table II summarizes the correspondence between these quasiparticle states and their dominant Nilsson configurations at zero rotational frequency.

Experimentally derived alignments (i_x) and Routhians (e') for the bands in ^{131}Pm are presented in Fig. 6, where they are compared with the even-even core nucleus ^{130}Nd . The alignments and Routhians require the removal of collective-rotational effects: this is conventionally achieved using a variable moment-of-inertia (VMI) rotational reference [31]. In this work, the reference was defined using Harris parameters

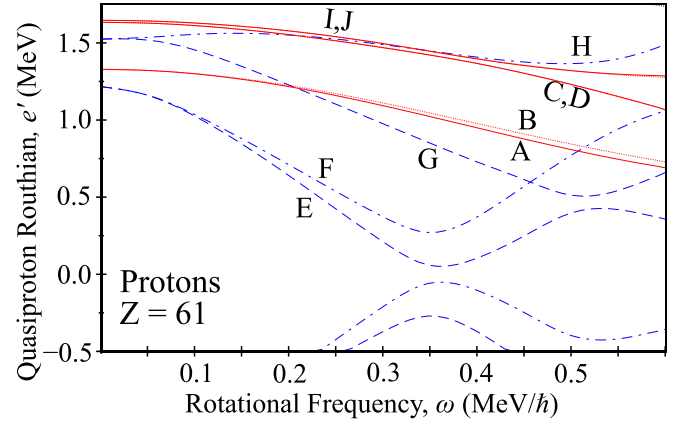


FIG. 5. Representative CSM single-quasiproton Routhians calculated for $Z = 61$, with deformation parameters: $\beta_2 = 0.32$, $\beta_4 = 0.00$ [25], and $\gamma = 0^\circ$ [24]. Red lines represent positive-parity Routhians with signature $\alpha = +1/2$ (solid) and $\alpha = -1/2$ (dotted). Blue lines represent negative-parity Routhians with $\alpha = +1/2$ (dot-dash) and $\alpha = -1/2$ (dashed). The Routhian labels are detailed in Table II.

$\mathcal{J}_0 = 17 \hbar^2/\text{MeV}$ and $\mathcal{J}_1 = 26 \hbar^4/\text{MeV}^3$, values commonly adopted for nuclei in this mass region (i.e., Refs. [22,30]).

The experimental alignments of bands 1 and 2, Fig. 6(a), display a smooth and gradual alignment gain, and are juxtaposed against the alignment of the yrast states in the even-even core nucleus ^{130}Nd [30]. The striking $(h_{11/2})^2$ proton alignment seen in ^{130}Nd at $\hbar\omega \approx 0.35$ MeV is not observed in bands 1 and 2 of ^{131}Pm . This is readily explained by considering this crossing to be Pauli blocked in ^{131}Pm , owing to the occupation of the (E/F) orbital by the odd quasiproton. As indicated in Table II, the (EF) quasiproton pair is based on the [532] $5/2^-$ orbital.

The CSM calculations are consistent with the observed data when comparing the theoretical [Fig. 5] and experimental [Fig. 6(b)] Routhians for this nucleus. At low spin, the experimental signature splitting is minimal but steadily in-

TABLE II. Quasiparticle labeling scheme for ^{131}Pm along with their predominant Nilsson configurations, valid at zero rotational frequency. The spin and parity quantum numbers (π, α) of each state are also given.

Label	(π, α)	Configuration
Quasiprotons		
A	$(+, +1/2)$	[411] $3/2^+$
B	$(+, -1/2)$	[411] $3/2^+$
C	$(+, +1/2)$	[413] $5/2^+$
D	$(+, -1/2)$	[413] $5/2^+$
I	$(+, +1/2)$	[404] $9/2^+$
J	$(+, -1/2)$	[404] $9/2^+$
E	$(-, -1/2)$	[532] $5/2^-$
F	$(-, +1/2)$	[532] $5/2^-$
G	$(-, -1/2)$	[541] $3/2^-$
H	$(-, +1/2)$	[541] $3/2^-$

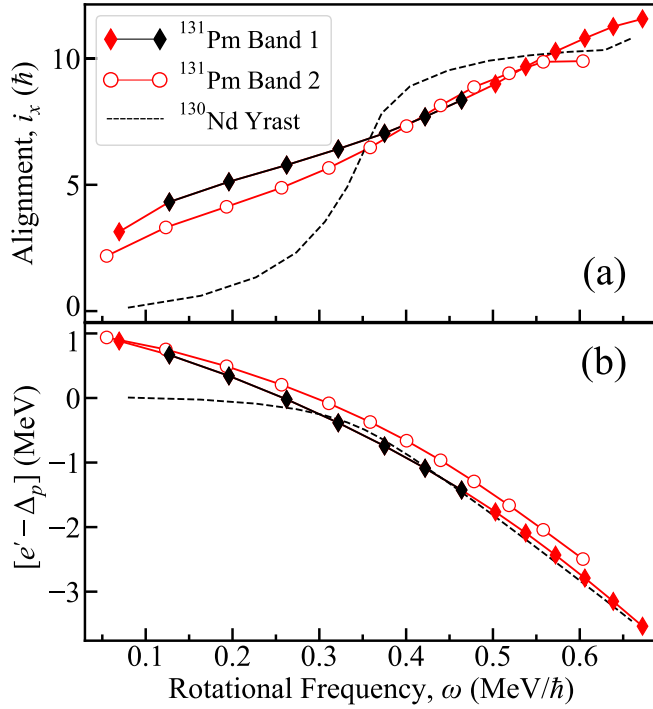


FIG. 6. (a) Experimental alignments i_x and (b) Routhians e' for bands 1 and 2 of ^{131}Pm . The Harris parameters of $\mathcal{J}_0 = 17 \hbar^2/\text{MeV}$ and $\mathcal{J}_1 = 26 \hbar^4/\text{MeV}^3$ were used to subtract the angular momentum of the collective core. A pairing energy of $\Delta_p = 1.2 \text{ MeV}$ has been included for odd- Z ^{131}Pm . The final point for band 2 on each panel is tentative. States newly discovered in this work are in red. For comparison, the alignment and Routhian for the ground-state band of the even-even core nucleus, ^{130}Nd , are included (Ref. [30]).

creases to a stable value of approximately 0.22 MeV beyond $\omega = 0.35 \text{ MeV}/\hbar$. The CSM calculations for the E/F ($h_{11/2}$) quasiprotons closely replicate this behavior, with the signature splitting similarly increasing from zero to around 0.25 MeV at $\omega \approx 0.35 \text{ MeV}/\hbar$. Note that the $h_{11/2}$ [541] $3/2^-$ orbital (G/H) has a significantly larger predicted signature splitting.

This configuration assignment is in agreement with the measured $5/2^-$ ground state of the neighboring nucleus ^{129}Pm [32]. Indeed, a similarity is expected between ^{129}Pm and ^{131}Pm since theoretical models [25] predict ground-state quadrupole deformation parameters, β_2 , that are comparable (0.33 for ^{129}Pm and 0.32 for ^{131}Pm), implying the position of the proton Fermi surface should be similar for both nuclei. The predicted β_2 values are consistent with the quadrupole deformation observed via lifetime measurements in the $h_{11/2}$ band of the neighboring ^{133}Pm [$\beta_2 = 0.333(14)$ [33] and $\beta_2 = 0.29(3)$ [34]]. Moreover, predictions by Möller *et al.* [35,36] also advocate a ground-state spin-parity of $\Omega^\pi = 5/2^-$ for ^{131}Pm and its neighboring isotopes $^{129,133}\text{Pm}$.

The Routhian obtained for the yrast band of ^{130}Nd is also displayed in Fig. 6(b). To enable comparison between the Routhian of this nucleus and those for ^{131}Pm , the Routhian for ^{131}Pm has been offset by an energy representative of the proton pairing gap, $\Delta_p = 1.2 \text{ MeV}$, calculated following the methodology detailed in Ref. [37]. At low spin, the Routhians diverge as a result of the increased binding due to valence pairing in the even-even ^{130}Nd . However, with increasing rotational frequency, the rotation-induced alignment of the $h_{11/2}$ proton pair in ^{130}Nd causes its Routhian to converge with that of ^{131}Pm . At high spin, the Routhians are very similar; the particle-rotor coupling is weak, and the odd proton in ^{131}Pm is effectively decoupled. Consequently, the energetic evolution of both nuclei becomes dominated by the collective rotation of the underlying core.

Conclusions. The $h_{11/2}$ structure in ^{131}Pm has been extended to higher and lower spin ($\approx 30\hbar$) and its signature partner has also been identified. This structure has been observed down to a proposed bandhead spin-parity ($5/2^-$), as expected for the [532] $5/2^-$ Nilsson state. The experimental signature splitting and $B[M1]/B[E2]$ values support this assignment. Moreover, while the ground-state spin-parity of ^{131}Pm remains experimentally unconfirmed, the [532] $5/2^-$ configuration is predicted [36] to form the ground state for all odd-even promethium isotopes with $N \leq 72$. The proposed $5/2^-$ bandhead also has implications for the structural interpretation of nearby odd- Z , even- N nuclei. The $h_{11/2}$ bands of several neighboring nuclei with comparably large predicted quadrupole deformation (e.g., ^{133}Pm [34,38], ^{135}Pm [39,40], ^{137}Eu [41,42]) have previously been assigned $11/2^-$ bandheads—an interpretation that warrants reexamination in light of the present results. In addition, lowering the $h_{11/2}$ bandhead spin to $5/2^-$ diminishes both the spin and energy differences relative to neighboring positive-parity bandheads. This reduces the likelihood of spin-trap or K -isomers and reinforces that the structural interpretation of these nuclei must account for the dynamical coupling of FAL orbitals to the core with the evolution of quadrupole deformation.

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Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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