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Semidecoupled band structure in odd-odd ^{134}La and ^{136}Pr

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The level schemes of the isotones ^{134}La and ^{136}Pr were obtained with in-beam gamma spectroscopy techniques using fusion evaporation reactions with ^{10}B, ^{14}N, and ^{16}O beams and enriched targets of ^{126,128}Te and ^{123}Sb. Rotational bands assigned to the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration were seen in both nuclei. Another band seen in ^{136}Pr was tentatively assigned to the $\pi[413]\frac{5}{2} \otimes \nu h_{11/2}$ configuration. A beginning of a backbend seems to show up in this band.

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I. INTRODUCTION

In recent years many articles have appeared on the study of odd-odd nuclei in the γ-soft, $A \sim 130$ mass region [1–4]. The doubly-odd nuclei in this region are particularly interesting in that they permit investigation of the competition between the relatively strong shape driving forces caused, on the one hand, by the neutron quasiparticle situated in the upper part of the $h_{11/2}$ shell and, on the other hand, by the proton quasiparticle at the lower part of the same high-j shell, which may result in triaxial equilibrium shapes. For small values of γ, the signature splitting of the $\pi h_{11/2}$ orbital is very large, in contrast to nearly zero splitting for a neutron in a high-Ω orbital. Thus, a semidecoupled band structure, with the proton in the favored signature orbital, showing a small signature splitting due to the neutron is expected for this configuration. Indeed, yrast bands with these characteristics have been found in several odd-odd nuclei in this region.

We present here the results of an investigation of in-beam gamma spectroscopy of the $N = 77$ isotones, ^{134}La and ^{136}Pr, using fusion-evaporation reactions with beams provided by the Pelletron Tandem Accelerator of the University of São Paulo. Prior to our investigation the available information on the level structure of ^{136}Pr came from the beta decay of ^{136}Nd [5]. The ground state and a 9.4 ns isomeric state at 40.1 keV of ^{136}Pr are both known to have spin $J^{\pi} = 2^{+}$. During the present work a paper on the high-spin spectroscopy of Pr nuclei was published by Dragulescu *et al.* [6]. The ^{134}La nucleus has been previously studied with the ^{133}Cs$(\alpha, 3n)$ and ^{136}Ba$(p, 3n)$ reactions [7], but no bands were identified.

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II. EXPERIMENTAL PROCEDURES AND RESULTS

Crossed-beam reactions, ^{123}Sb$(^{16}$O$, 3n)$ and ^{126}Te$(^{14}$N$, 4n)$, and excitation functions were used to identify the gamma rays belonging to ^{136}Pr. The targets, about 10 mg/cm^2 thick, were made of enriched ^{123}Sb (99%) and ^{126}Te (98.7%) powder compressed onto a lead foil. In the case of the ^{134}La nucleus, the gamma rays from the ^{128}Te$(^{10}$B$, 4n)$ reaction were identified through comparison with the $(\alpha, 3n)$ reaction [7]. The target was of enriched ^{128}Te (99.2%) 0.93 mg/cm^2 thick, evaporated onto a 1 mg/cm^2 gold foil. Two HPGe detectors were used for the γ-γ-t coincidences. The data were sorted on-line into a 1024×1024 channel, $E_\gamma \times E_\gamma$ array. A symmetrized background-subtracted matrix was generated using the technique described in Ref. [8]. The angular distributions were measured for the ^{123}Sb$(^{16}$O$, 3n)^{136}$Pr and ^{128}Te$(^{10}$B$, 4n)^{134}$La reactions at beam energies of 64 and 44 MeV, respectively. In most of the cases the A_4/A_0 values were ≈ 0 within errors. Due to the complexity of the singles spectra the quality of the angular distributions only permitted determination of the predominant multipole character of the transitions. The gamma intensities, taken from the singles spectra and corrected for detector efficiency together with the angular distribution results, are given in Tables I and II. Figure 1 shows typical gated spectra for ^{136}Pr and ^{134}La, respectively.

A. ^{136}Pr level scheme

The level scheme of ^{136}Pr, based on the present work, is shown in Fig. 2. The principal features are two bands showing small staggering, strong $M1$ transitions, and much weaker $E2$ crossovers. Both bands depopulate to an isomeric level of 92 ± 1 ns, the more intense band through two strong-dipole transitions (245 and 209 keV), while the weaker one through a 314 keV gamma ray. The latter band shows an indication of a backbend. The half-life of the isomeric state was determined by the deconvolution of the time spectrum.

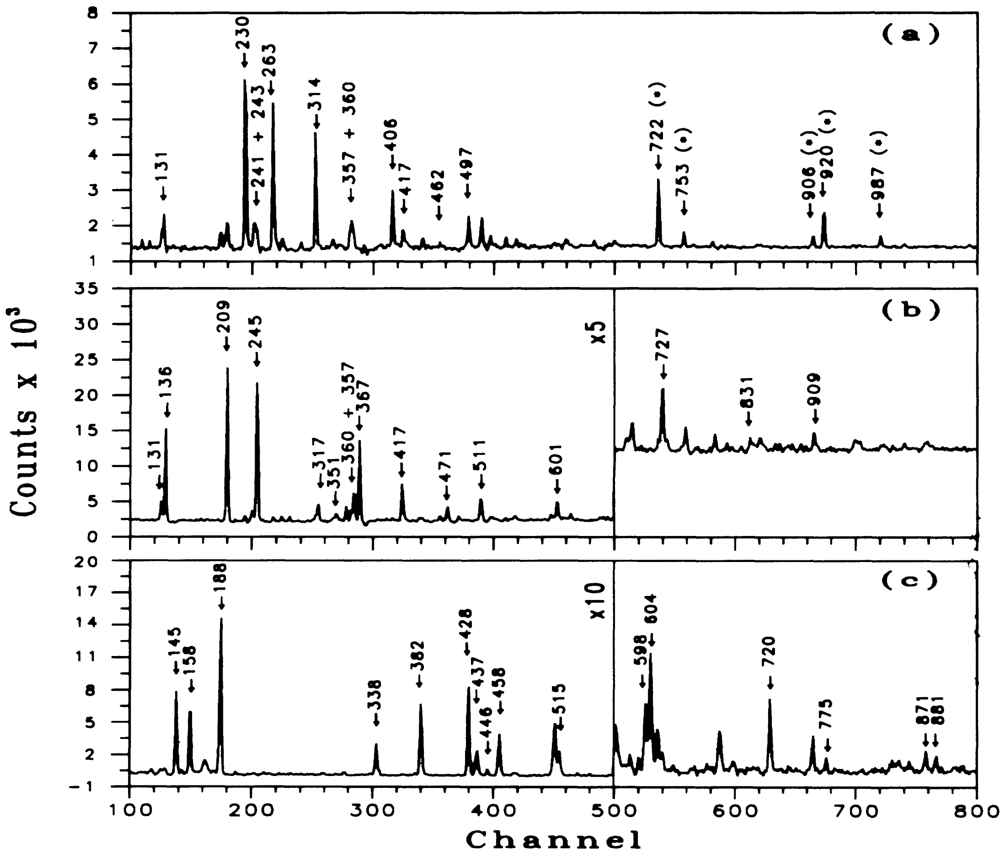

FIG. 1. Typical gamma-gamma coincidence spectra. (a) ^{136}Pr: sum of 314, 230, 405, and 497 keV gates; (b) ^{136}Pr: sum of 209, 245, 136, and 367 keV gates; (c) ^{134}La: sum of 145, 381, 338, and 437 keV gates; (*): gammas of ^{136}Pr which could not be placed consistently in the level scheme.

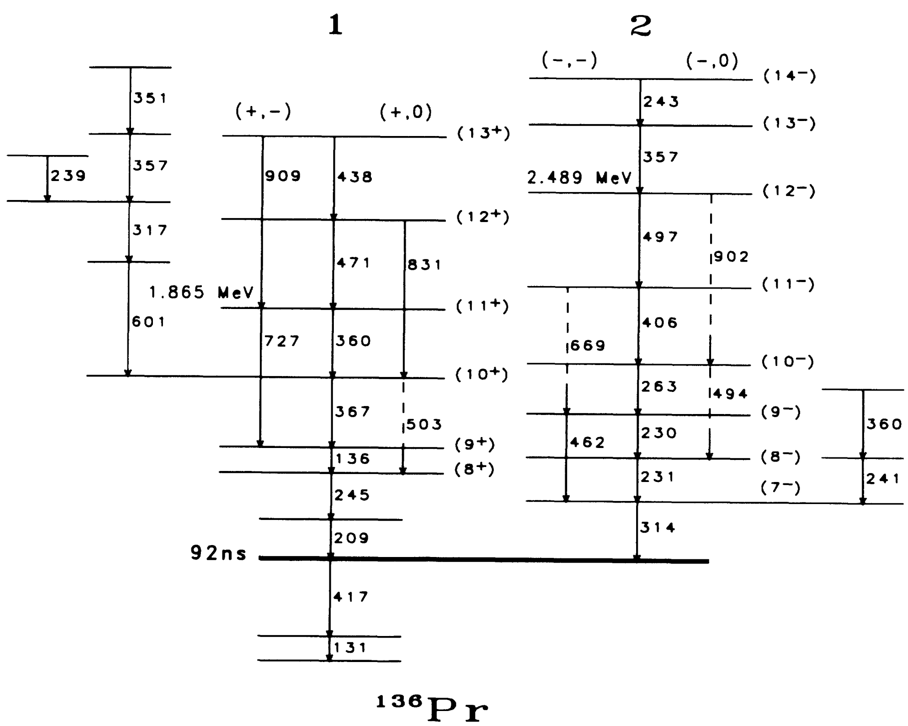

FIG. 2. The level scheme of ^{136}Pr based on the present work.

The present level scheme and that proposed by Dragulescu *et al.* [6] are essentially in agreement up to a relative excitation energy of 1.865 MeV for the stronger band and up to 2.489 MeV for the weaker one. On the basis of the observed crossover transitions of 831 and 909 keV, we have been able to extend the first band to a higher excitation energy. However we differ in the configurations and the spin assignments for both bands, as will be discussed below.

B. ^{134}La level scheme

The level scheme of ^{134}La (Fig. 3) shows a band with striking similarity to the yrast band in ^{136}Pr. The present level scheme agrees well with the relevant part of that proposed by Morek *et al.* [7] based on the $(\alpha, 3n)$ reaction, up to a relative excitation energy of 1.97 MeV, except for the 775 and 604 keV transitions which were not observed in the $(\alpha, 3n)$ work. In addition our placement of the crossover 871 keV line differs from that of Ref. [7]. There are also quite a few lines seen in both investigations, which although correlated, could not be placed consistently in the present level scheme. No isomeric state was observed in the range of 50 to 500 ns in this nucleus.

TABLE I. Gamma-ray energies, relative intensities, and spin assignments for ^{136}Pr.

E_γ (keV)[a]	I_R (%)	A_2/A_0	$I_i \rightarrow I_f$
131.2	132.5(1.6)	−0.16(1)	
136.7	44.6(8.0)	−0.29(2)	$(9^+) \rightarrow (8^+)$
209.7	117.6(1.2)	−0.47(1)	
230.8[c]	29.3(1.0)	−0.53(3)	$(8^-) \rightarrow (7^-)$
238.8	20.2(1.0)	−0.07(5)	
240.5	9.1(2.0)	−0.37(6)	
243[b]	3.3(0.2)		$(14^-) \rightarrow (13^-)$
245.0	100.0(1.2)	−0.31(1)	
263.1	8.9(0.9)	−0.43(19)	$(10^-) \rightarrow (9^-)$
313.9	31.8(1.1)	−0.33(3)	
317.4	8.8(1.4)	−0.42(11)	
351.1	9.2(1.5)	−0.26(13)	
357.7[c]	4.9(0.9)		
360.2[c]	16.6(1.0)	−0.74(16)	$(11^+) \rightarrow (10^+)$
367.0	39.5(1.1)	−0.65(6)	$(10^+) \rightarrow (9^+)$
405.4	6.5(1.4)	−0.39(7)	$(11^-) \rightarrow (10^-)$
417.8	192.2(13.0)	−0.11(17)	
438[b]	1.4(0.1)	−0.65(6)	$(13^-) \rightarrow (12^-)$
462[b]	3.0(0.1)		$(9^-) \rightarrow (7^-)$
471.7	5.5(1.0)	−0.57(14)	$(12^+) \rightarrow (11^+)$
494[b]	1.6(0.1)		$(10^-) \rightarrow (8^-)$
497[b]	3.5(0.1)		$(12^-) \rightarrow (11^-)$
501.9	6.1(1.0)		$(10^+) \rightarrow (8^+)$
601.7	17.7(2.0)	−0.82(14)	
669[b]	2.0(0.2)		$(11^-) \rightarrow (9^-)$
727.0	18.4(2.0)		$(11^+) \rightarrow (9^+)$
830.0	5.6(1.3)		$(12^+) \rightarrow (10^+)$
903	< 1		$(12^-) \rightarrow (10^-)$
909	< 2		$(13^+) \rightarrow (11^+)$

[a]Energy uncertainties of 0.5 keV except for very weak transitions.
[b]Intensities obtained from coincidence spectra.
[c]Doublets.

TABLE II. Gamma-ray energies, relative intensities, and multipolar characters for ^{134}La .

E_γ (keV)	I_R (%)	A_2/A_0	$I_i \rightarrow I_f$
145.0	100.(8)	−0.310(40)	$(9^+) \rightarrow (8^+)$
158.4	116.(7)	−0.340(29)	
187.8		−0.232(49)	
229.4	30.(3)		
257.9	26.(3)	−0.31(10)	
277[a]			
307.2	61.(5)	−0.441(75)	
338.0	53.(3)	−0.21(25)	$(11^+) \rightarrow (10^+)$
381.6	83.(4)	−0.380(53)	$(10^+) \rightarrow (9^+)$
407[a]			
427.9	114.(6)	−0.228(46)	
434.1 }	31.7(7)		$(13^+) \rightarrow (12^+)$
436.5 }			$(12^+) \rightarrow (11^+)$
445.9[b]	35.(4)		$(14^+) \rightarrow (13^+)$
458.1	75.(5)	−0.052(56)	
719.			
774.7	4.(2)		$(12^+) \rightarrow (10^+)$
870.8	20.(2)	+0.39(27)	$(13^+) \rightarrow (11^+)$
880.5	6.(2)		$(14^+) \rightarrow (12^+)$

[a]Contaminated with 444 keV from ^{133}La.
[b]Doublet.

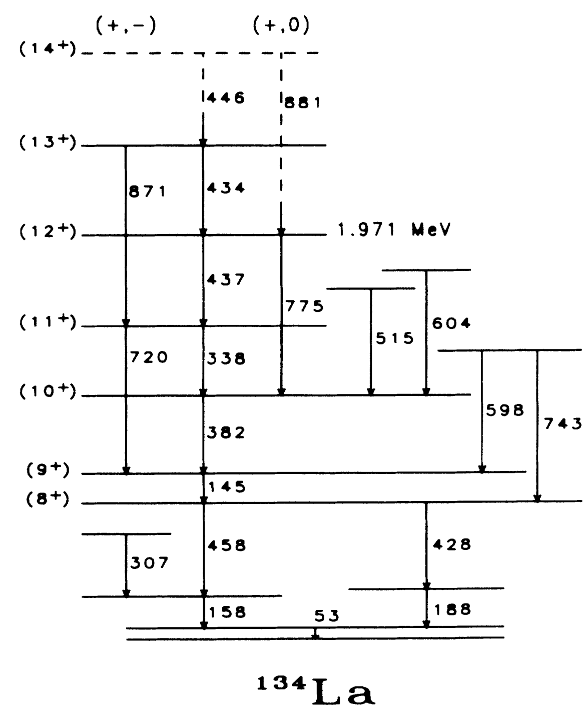

FIG. 3. The level scheme of ^{134}La based on the present work.

III. THEORETICAL CALCULATIONS

Theoretical calculations were made within the framework of the triaxial cranking shell model [9]. The total single particle Hamiltonian includes a cranking term together with a pairing term given by

$$H = H_0 - \omega J_x + H_{\mathrm{pair}}. \tag{1}$$

A modified oscillator potential was used in the intrinsic Hamiltonian H_0 as in Ref. [10]. The deformation parameters used were $\beta = 0.165$, $\varepsilon_4 = 0$. The value of β was extracted from the relation $\beta = \sqrt{1224/E_\gamma(15/2^- \to 11/2^-)}$ applied to the first $E2$ transition of the $\pi h_{11/2}$ bands of the nearby odd-proton nuclei, which are expected to be axially symmetric (Fig. 4, $\gamma = 0°$). Although this formula was deduced for the energy of the first 2^+ states of even-even nuclei [11], it is also valid if complete decoupling of the rotation aligned $h_{11/2}$ proton is assumed. This is nearly the case, since the level spacing of the $\pi h_{11/2}$ bands closely follows the spacing of the ground-state bands of the even-even neighbors in this mass region. The pairing strengths used were $\Delta_p = 1.28$ MeV and $\Delta_n = 1.12$ MeV, typical values for this region. The Fermi levels were adjusted to give the correct mean value of the number of protons and neutrons (Z=57, 59 and N=77) at a deformation of $\gamma = 0°$. The calculated Routhians corresponding to the first excited quasiparticle states as a function of γ (in the Lund

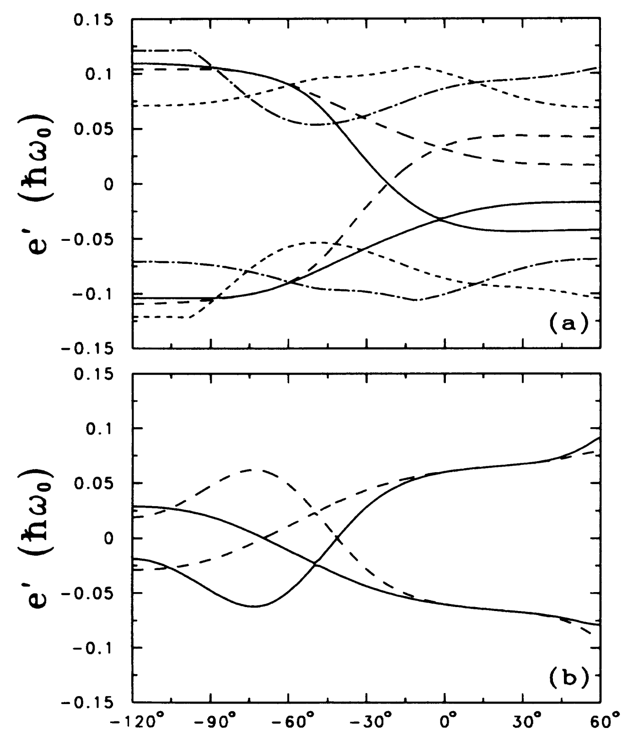

FIG. 4. Calculated Routhians for (a) the quasiproton levels at $\hbar\omega = 0.038\hbar\omega_0$, $\beta = 0.165$, $\Delta_n = 0.16\hbar\omega_0$, $\Delta_p = 0.14\hbar\omega_0$. The solid and dashed lines are for $\pi h_{11/2}$ favored ($\alpha = -\frac{1}{2}$) and unfavored ($\alpha = +\frac{1}{2}$) components, respectively. The dash-dotted and dotted lines represent the $\pi[413]\frac{5}{2}$ levels. (b) The same as (a) for the first $h_{11/2}$ quasineutron.

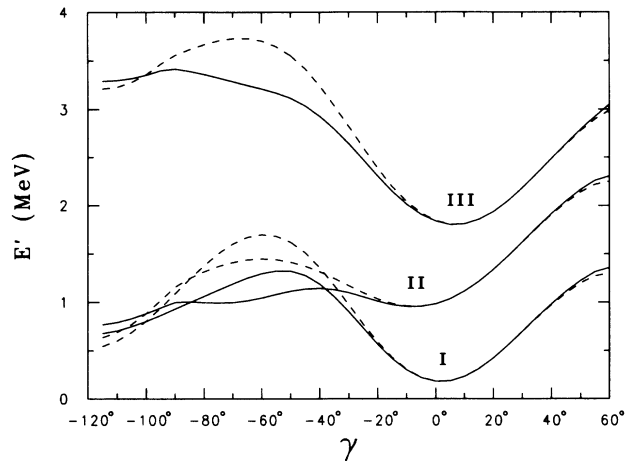

FIG. 5. The total Routhians as a function of the gamma deformation. The dashed line is for the signature $\alpha = 0$ and the solid line for the signature $\alpha = -1$. I, the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration at $\hbar\omega = 0.03\hbar\omega_0$; II, the $\pi[413]\frac{5}{2} \otimes \nu h_{11/2}$ two-quasiparticle configuration at $\hbar\omega = 0.03\hbar\omega_0$; and III, the $\pi[413]\frac{5}{2} \otimes \pi h^2_{11/2} \otimes \nu h_{11/2}$ four-quasiparticle configuration at $\hbar\omega = 0.038\hbar\omega_0$.

convention [10]) are presented in Fig. 4 for both protons and neutrons. The results show a preference of $\gamma = -60°$ for the first favored $h_{11/2}$ quasineutron and $\gamma > 0°$ for the first favored $h_{11/2}$ quasiproton.

The total Routhian (E'_{tot}), Fig. 5, was calculated using the method of Frauendorf and May [12], in which a phenomenological contribution from the core is added to the quasiparticle Routhians.

IV. DISCUSSION

The experimental alignment i_x and the Routhian e' were extracted from the data, using the procedure described in Refs. [13, 2]. The Harris parameters $\mathcal{J}_0$ and $\mathcal{J}_1$ are obtained from the least squares fit of the angular momentum alignment to the experimental data in the frequency range below the first crossing.

A. The $\pi h_{11/2} \otimes \nu h_{11/2}$ bands

In the neighboring odd-neutron nucleus ^{133}Ce, the observed yrast band with a bandhead spin of $9/2^-$ [14] is built on a $h_{11/2}$ neutron strongly coupled to the core ($\Omega_n = 9/2$), while the yrast bands in the odd-proton nuclei, ^{133}La [15] and ^{135}Pr [16], with bandhead spins of $11/2^-$ are due to a decoupled $h_{11/2}$ proton ($\Omega_p = 1/2$). This suggests a $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration for the yrast band in ^{134}La and ^{136}Pr. The assignment of (8^+) to the spin and parity of the bandheads is based on a perpendicular coupling between neutron and proton as discussed by Kreiner [17]. The observed bandheads, $I = (8^+)$, belong to the unfavored component of the band, which for the above configuration corresponds to the signature $\alpha = 0$ [$I = \alpha$ mod(2)]. We point out here that Dragulescu *et al.* [6] explain the structure of the odd-odd Pr nuclei as due to the $2d_{3/2}$, $3s_{1/2}$, and $1h_{11/2}$ neutron coupled to the $2d_{5/2}$, $1g_{7/2}$, and $1h_{11/2}$ proton. In particular they assign for the $\Delta J = 1$ bands seen in ^{136}Pr a $[\pi d_{5/2} \otimes \nu h_{11/2}^{-1}]$ configuration, giving rise to a negative-parity band. Unfortunately the section which refers to the ^{136}Pr nucleus in their article is very sketchy.

In this mass region the Fermi level for the neutron is around $\Omega_n = 9/2$, while that for the proton is around $\Omega_p = 1/2$ or $3/2$ of the $h_{11/2}$ shell. However, cranking shell model calculations predict that $\Omega_p = 1/2$ is by far the nearest to the Fermi level, resulting in $K = \Omega_p + \Omega_n = 5$ according to the Gallagher-Moszkowski rule [18]. The assignment of the angular momentum projection $< K >$ is usually corroborated by comparing the experimental $B(M1)/B(E2)$ values with the predictions of the semiclassical formalism of Dönau and Frauendorf [19]. The experimental $B(M1)/B(E2)$ ratios are obtained from the measured $M1/E2$ branching ratios as

$$\frac{B(M1; I \rightarrow I-1)}{B(E2; I \rightarrow I-2)} = 0.693 \frac{E_\gamma^5(E2)}{E_\gamma^3(M1)} \frac{I_\gamma(M1)}{I_\gamma(E2)}, \qquad (2)$$

where the $E2/M1$ mixing ratio δ for the dipole transition is assumed negligible. A reasonable agreement between the experimental and calculated $B(M1)/B(E2)$ ratios is obtained using $< K >= 5$ for both ^{134}La and ^{136}Pr. The calculated alignments and Routhians are shown in Figs. 6 and 7.

The fitting of the three parameter function

$$I_x(\omega) = i_x + \omega \mathcal{J}_o + \omega^3 \mathcal{J}_1, \qquad (3)$$

to the experimental values of I_x led to very small values of $\mathcal{J}_o$ with uncertainties greater than the value itself for both ^{134}La and ^{136}Pr. In fact, the inclusion of this parameter did not improve the quality of the fit. Thus we simply assumed $\mathcal{J}_o = 0$. The values of $\mathcal{J}_1$ and i_x from the

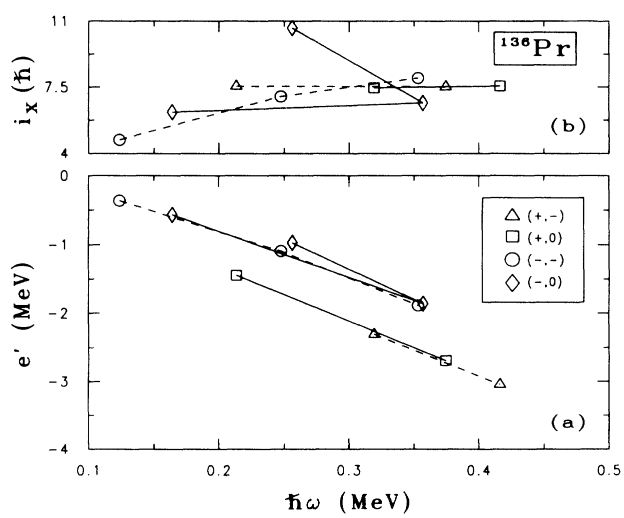

FIG. 6. (a) The experimental alignments and (b) Routhians for the $\pi h_{11/2} \otimes \nu h_{11/2}$ and $\pi[413]\frac{5}{2} \otimes \nu h_{11/2}$ bands in ^{136}Pr. The dashed and solid lines are the favored ($\alpha = -1$) and unfavored ($\alpha = 0$) components of the band, respectively. The Harris parameters used were $\mathcal{J}_0 = 0.0\hbar^2$ MeV^{-1} and $\mathcal{J}_1 = 64.4\hbar^4$ MeV^{-3}.

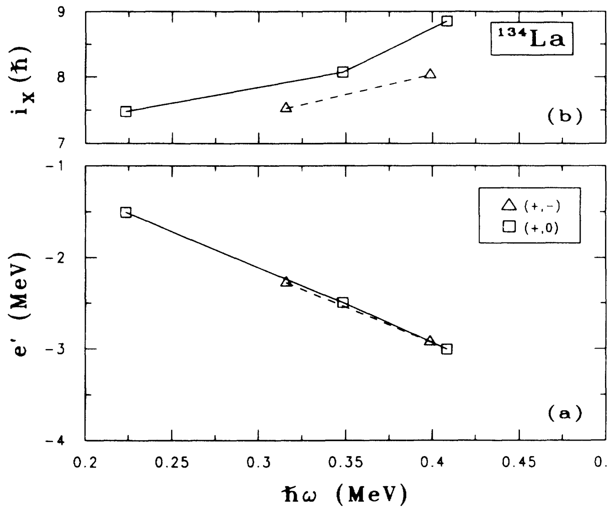

FIG. 7. (a) The experimental alignments and (b) Routhians for the $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{134}La. The same Harris parameters were used as in Fig. 6.

fitting of the remaining two parameter curve were very similar for both nuclei: $\mathcal{J}_1 = 65.9\hbar^{-4}$ MeV^{-3}, $i_x = 7.35\hbar$ for ^{134}La and $\mathcal{J}_1 = 54.6\hbar^{-4}$ MeV^{-3}, $i_x = 7.50\hbar$ for ^{136}Pr. In both nuclei, the alignment i_x is constant up to a frequency of 0.4 MeV, as would be expected for the $\pi h_{11/2} \otimes \nu h_{11/2}$ band since the first neutron and proton orbitals are blocked. A moderate signature splitting is extracted from the data, 40 keV for ^{136}Pr and about 50 keV for ^{134}La. The observed signature splitting is found to correspond to the splitting of the two neutron signatures at $\gamma = -15°$ to $-25°$, Fig. 4, depending on the rotational frequency, for both ^{134}La and ^{136}Pr. The bands based on the unfavored signature of the proton are not seen since they lie high above the yrast line due to the large splitting. The results of the total Routhian calculations for these bands show minima at $\gamma \sim 0°$, where the calculated splitting is about 2 to 5 keV, much smaller than the experimental values. A similar situation was also reported in the articles about ^{132}La [2] and ^{138}Pm [1].

B. The $\pi[413]\frac{5}{2} \otimes \nu h_{11/2}$ band

In ^{136}Pr a second, near yrast band, was observed. Another Nilsson orbital for protons near the Fermi energy in this region is the $[413]\frac{5}{2}$. A possible configuration for this band is the $\pi[413]\frac{5}{2} \otimes \nu h_{11/2}$ with bandhead values of $K = 2$ or 7. The value of $< K >= 2$, although favored by the Gallagher-Moszkowski rule, is unlikely as it would not result in a near yrast configuration. A low K value could not explain the extremely weak $E2$ crossover transitions in this band. Thus a value $< K >= 7$ was used in the calculations. Using the same reference configuration parameters of the yrast band, the experimental alignment and Routhians were obtained. The curve of i_x as a function of ω (Fig. 6) indicates the beginning of a backbend. The experimental crossing frequency ω_c can be extracted from the mean value of the frequencies at which i_x starts to bend backward and again forward. Unfortunately, our observational limit is below the forward bend due to the relatively low angular momentum of the compound system. Thus we can only state an upper limit of 0.31 MeV for the crossing frequency which is close to the calculated value of 0.3 MeV for the crossing of the $h_{11/2}$ proton orbital, indicating that the $\pi h_{11/2}$ orbital is not blocked in contrast to the situation in the yrast band. In this context we point out that the band assigned to the $\pi[413]\frac{5}{2}^+$ configuration in ^{135}Pr [16] exhibits nearly collective prolate shape, with the first backbend occurring at 0.32 MeV.

The experimental signature splitting could not be determined precisely (see Fig. 7) but it is certainly not large. Total Routhian calculations performed with the V_{po} parameter [12] of -1 MeV for the $\pi[413]\frac{5}{2} \otimes \nu h_{11/2}$ configuration show two competing equilibrium deformations, one at $\gamma \sim -70°$ and another near $\gamma = 0°$. However an oblate shape ($\gamma \sim -70°$) is unlikely as it would mean decoupling of the neutron implying strong $E2$ transitions, not observed experimentally.

We note here that Beausang *et al.* [1] have assigned the $\pi[413]\frac{5}{2}^+ \otimes \nu h_{11/2}$ configuration to a band in ^{138}Pm, which backbends at a rotational frequency of $\hbar\omega = 0.37$ MeV. At low frequencies this band consists of two sequences of stretched $E2$ transitions of opposite signature, in complete contrast with the second band seen in ^{136}Pr in the present work (strong $M1$ and very weak $E2$ transitions). The calculated total Routhians in ^{138}Pm [1] lead to equilibrium shape for this configuration at $\gamma \sim -65°$, i.e., collective oblate rotation. According to these authors a value of $\gamma \sim -40°$ is required in order to reproduce the observed crossing frequency of $\hbar\omega_c \sim 0.37$ MeV in the $\pi[413]\frac{5}{2} \otimes \nu h_{11/2}$ band. Above the crossing frequency the calculations of the total Routhians for both ^{136}Pr and ^{138}Pm show minima much closer to $\gamma \sim 0°$. Thus the behavior of the $\pi[413]\frac{5}{2} \otimes \nu h_{11/2}$ band in ^{136}Pr on the one hand, and ^{138}Pm on the other hand, seems to indicate that the addition of two protons at a neutron number of $N=77$ leads to a tendency towards oblate deformations.

V. CONCLUSIONS

The isotones ^{134}La and ^{136}Pr were investigated via (HI,xn) reactions. The yrast bands were assigned the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration. Cranking shell model calculations predict equilibrium deformations at $\gamma \sim 0°$ with signature splitting much smaller than the experimental values. In ^{136}Pr a second band was observed, showing the beginning of a backbend. The $\pi[413]\frac{5}{2} \otimes \nu h_{11/2}$ configuration was assigned to this band. The experimental crossing frequency of $\hbar\omega_c \leq 0.31$ MeV is well reproduced by the calculations for a prolate ($\gamma \sim 0°$) shape.

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