Collective Oblate Band in ^{131}La Due to the Rotational Alignment of $h_{11/2}$ Neutrons

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Several rotational bands have been populated to high spin in the γ-soft nucleus ^{131}La. We present experimental evidence for a collective oblate rotational band based on a $\pi h_{11/2} \otimes (\nu h_{11/2})^2$ three-quasiparticle configuration. It is the rotational alignment of the pair of neutrons from the upper $h_{11/2}$ midshell which drives the nucleus from a prolate ($\gamma=0°$) shape to a collectively rotating oblate ($\gamma=-60°$) shape. This band coexists with a prolate band that contains a pair of aligned protons from the lower $h_{11/2}$ midshell.

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Shapes of rotation-aligned quasiparticle orbitals for high-j shells in deformed nuclei are predicted to change significantly as a function of the Fermi surface. In the cranked shell model (CSM) the corresponding quasiparticle energies are minimized for optimally overlapping nuclear shapes, and calculations[1,2] show that this occurs for very specific values of γ, the triaxiality coordinate in the polar representation of rotating quadrupole shapes. The polarization of the nuclear shape due to these energy minima can influence the degree of triaxiality and lead to the coexistence of quadrupole structures of different spectroscopic character. Verification of these shape-driving effects for different orbitals is best made in nuclei with γ-soft potential-energy surfaces. Nuclei in the γ-soft[3] $A=130$ mass region are thus appropriate[4] for these experimental tests. In this region the neutron Fermi surface lies in the upper $h_{11/2}$ midshell where the predicted deformation driving force is towards a collectively rotating oblate shape. Conversely, the proton Fermi surface is in the lower $h_{11/2}$ midshell where the orbitals favor prolate axial symmetry. Thus the alignment of a pair of $h_{11/2}$ protons tends to drive the nuclear shape towards $\gamma \geq 0°$, while the alignment of a pair of $h_{11/2}$ neutrons tends to drive the nucleus towards $\gamma=-60°$ (Lund convention[5]; see the schematic illustrations at the top of Fig. 2, below). Odd-mass nuclei are of particular interest in this regard because the occurrence of both $\Delta J=1$ and $\Delta J=2$ intraband transitions provides specific experimental sensitivities to the value of γ and to the unpaired configurations involved. The present paper focuses on experimental results for the odd-proton nucleus ^{131}La which show the alignment of a pair of neutrons from the upper $h_{11/2}$ midshell driving the nucleus from a prolate shape ($\gamma=0°$) to a collective oblate shape ($\gamma=-60°$). Although small shape changes have been observed in this and other transition regions for the usual lower-midshell alignments, this is the first experimental evidence for an upper-midshell alignment that drives a γ-soft prolate nucleus to an oblate, but still collectively rotating, nuclear shape. This band coexists with a prolate ($\gamma \sim 0°$) three-quasiparticle rotational band containing a pair of aligned protons from the lower $h_{11/2}$ midshell.

States in ^{131}La were populated through the reaction ^{116}Cd(^{19}F,4$n\gamma$)^{131}La at a beam energy of 76 MeV, the heavy-ion beams being delivered by the Stony Brook superconducting LINAC facility. The γ-γ coincidence data were recorded by use of four n-type Ge detectors, each with a bismuth germanate anti-Compton shield of the transverse type.[6] The partial level scheme of ^{131}La deduced from this work is shown in Fig. 1.

Most of the bands can be given configuration assignments in line with the systematics of other nuclei in this region. The negative-parity band built on the $\frac{11}{2}^-$ state is a prolate decoupled $h_{11/2}$ proton band. CSM calculations appropriate for ^{131}La are shown in Fig. 2, where the lowest-energy $h_{11/2}$ proton and neutron single-quasiparticle states are shown as functions of the γ deformation at a fixed rotational frequency of $\hbar\omega=250$ keV. The proton levels are derived from the [550]$\frac{1}{2}^-$ Nilsson orbital at $\gamma=0°$, while the neutron levels are derived from the [514]$\frac{9}{2}^-$ orbital at $\gamma=0°$. The nuclear shape and the sense of rotation of the nucleus are shown at the top of the figure for specific values of γ that correspond to axially symmetric shapes. A proton occupying the lowest $h_{11/2}$ level, in this case the signature $\alpha=-\frac{1}{2}$ component of the [550]$\frac{1}{2}^-$ orbital, will tend to keep the nucleus prolate with $\gamma \sim 0°$. It will also block the first allowed decoupling of $h_{11/2}$ protons. The aligned angular

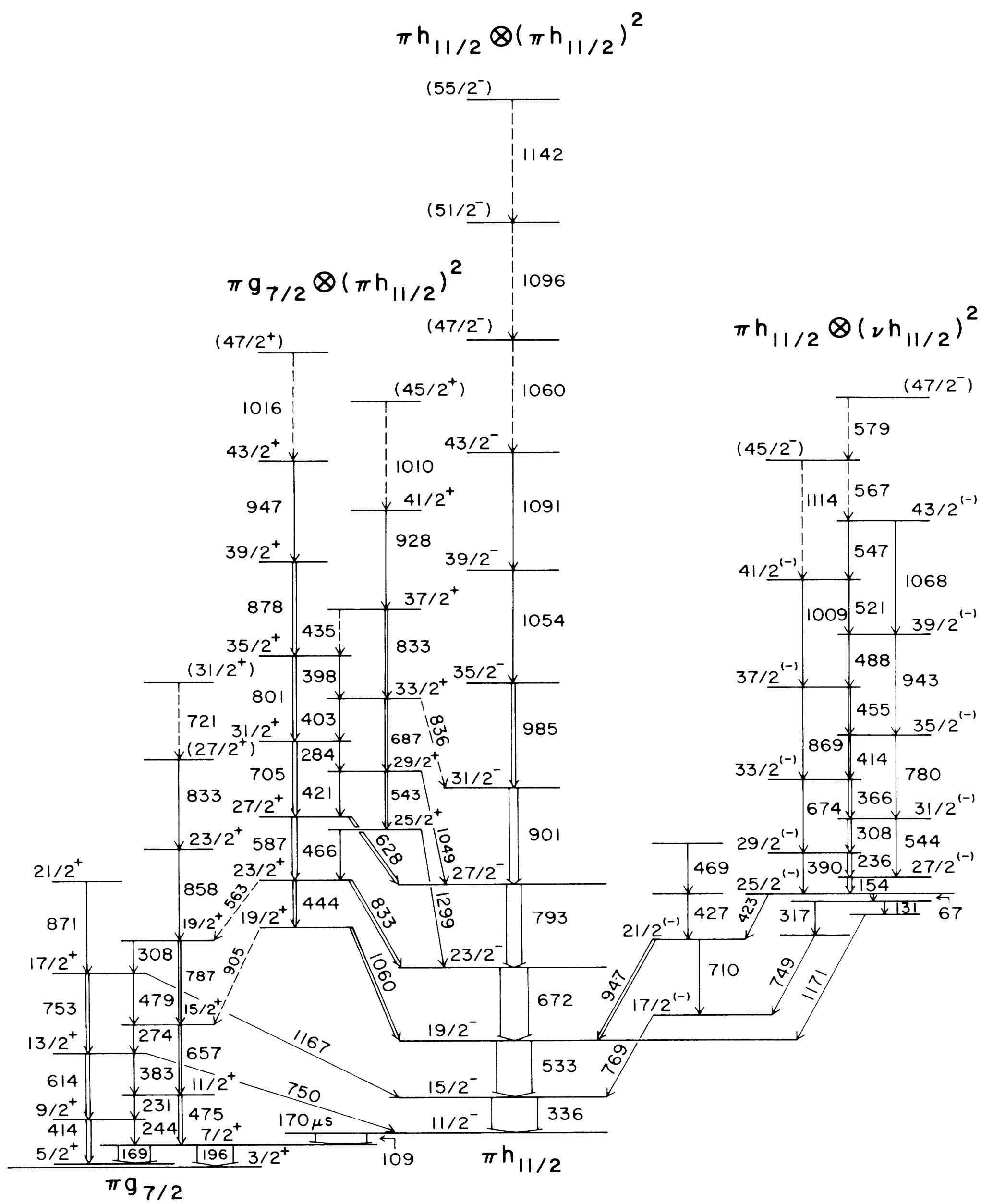

FIG. 1. A partial level scheme of [131]La deduced from this work. The γ-ray energies are given in kiloelectronvolts, and their intensities are indicated by the widths of the arrows.

momentum, i_x, of this band is plotted against rotational frequency in Fig. 3. A high-frequency upbend is evident at $\hbar\omega=0.53$ MeV, consistent with the alignment of the second and third $h_{11/2}$ protons.

Both signatures of a positive-parity band were also populated, as shown to the left in Fig. 1. These bands are built on the $\pi g_{7/2}$ ground state (the $\pi d_{5/2}$ orbital is nearly degenerate with the $\pi g_{7/2}$ orbital), and are crossed at $\hbar\omega=0.32$ MeV by three-quasiparticle bands containing a pair of aligned $h_{11/2}$ protons. This corresponds to the first $h_{11/2}$ proton crossing which is blocked in the negative-parity $h_{11/2}$ band. The unblocked proton-crossing frequency is somewhat higher than that observed[7] in the isotone [133]Pr, but can be reproduced in CSM calculations if the positive-parity bands are triaxial with $\gamma\sim-20°$ below the band crossing. Above the crossing the three-quasiparticle bands are prolate ($\gamma\sim0°$) because of the influence of the two aligned $h_{11/2}$

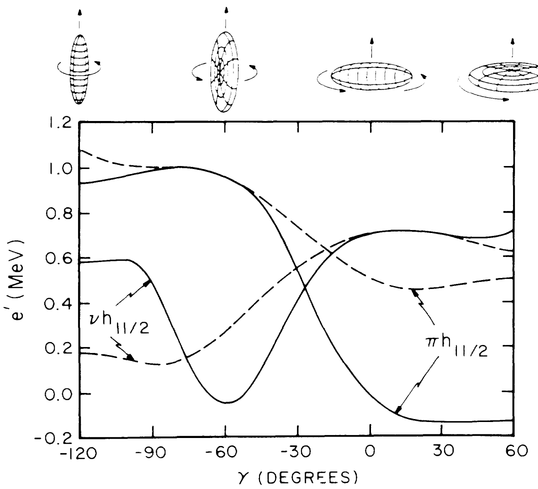

FIG. 2. Calculated $h_{11/2}$ neutron and proton single-quasiparticle levels in ^{131}La of signature $\alpha = -\frac{1}{2}$ (solid lines) and $\alpha = +\frac{1}{2}$ (dashed lines) shown as functions of the γ deformation. The shape and sense of rotation of the nucleus are indicated at the top of the figure for specific values of γ which correspond to axially symmetric shapes. The calculation was performed at a frequency $\hbar\omega = 250$ keV, with $\varepsilon_2 = 0.2$, $\varepsilon_4 = 0$, and $\Delta_n = \Delta_p = 1.2$ MeV.

proton orbits as shown in Fig. 2.

An additional band structure, shown to the right in Fig. 1, is observed which has several distinct properties. This band has (1) strong $\Delta J = 1$ transitions relative to the $E2$ crossovers, (2) negative $E2/M1$ mixing ratios (δ) for the $\Delta J = 1$ transitions, (3) no signature splitting, (4) a reduced moment of inertia, (5) a constant alignment, equal to $10.9\hbar$ for a large K value, (6) band members that are yrast above a frequency $\hbar\omega = 0.45$ MeV, and (7) an unusually weak interaction with the $\pi h_{11/2}$ one-quasiproton band. These experimental properties are markedly different from those of the prolate band involving the alignment of a pair of $h_{11/2}$ protons. We propose that this distinct structure is a collective oblate band ($\gamma \sim -60°$) based on a $\pi h_{11/2} \otimes (\nu h_{11/2})^2$ configuration. The CSM calculations of Fig. 2 show that while the proton orbitals favor a prolate shape ($\gamma \sim 0°$), the neutrons favor an oblate shape ($\gamma \sim -60°$). An alignment of a pair of $h_{11/2}$ neutrons would thus drive the nucleus to an oblate shape.

Each of the above experimental properties will be examined as evidence for this interpretation. The first three properties provide the basis for a strong argument in favor of this interpretation, while the remaining properties add considerable strength but with less rigor.

(1) The measured ratios of reduced transition rates, $B(M1;I \rightarrow I-1)/B(E2;I \rightarrow I-2)$, in this band, typically ~ 15 $(\mu_N/e\cdot\text{b})^2$, are more than an order of magnitude larger than those extracted from the positive-parity one- and three-quasiproton bands. Empirically and theoretically, this is indicative of neutron alignment in an odd-proton nucleus.[8] The measured $B(M1)/B(E2)$ ratios for this band are in quantitative agreement with calculations using the semiclassical formalism of Dönau and Frauendorf[9] for the proposed configuration. Calculations for other possible configurations containing either a pair of aligned $h_{11/2}$ neutrons or a pair of aligned $h_{11/2}$ protons yield $B(M1)/B(E2)$ ratios more than 10 times smaller. The larger value for the $\pi h_{11/2} \otimes (\nu h_{11/2})^2$ configuration results for two reasons. First, as opposed to a proton alignment, for a neutron alignment there is no cancellation in the $B(M1;I \rightarrow I-1)$ expression[9] because the g factor for the aligned $h_{11/2}$ neutron pair is opposite in sign. Second, for an oblate shape ($\gamma = -60°$) the proton Fermi surface lies nearest the $K = \frac{11}{2}$ member of the $h_{11/2}$ shell, namely the $[505]\frac{11}{2}^-$ Nilsson orbital. The reduced $M1$ transition probability $B(M1;I \rightarrow I-1)$ is proportional to the square of the component of $\mu_\perp$ of the magnetic dipole moment perpendicular to the total spin $\mathbf{I}$ of the nucleus, and such a large K value would indeed enhance the reduced $M1$ transition probability.

(2) Fits of the angular distributions measured for the $\Delta J = 1$ transition by

$$W(\theta) = A_0 + A_2 P_2(\theta) + A_4 P_4(\theta)$$

yielded A_2/A_0 values that are large and negative (~ -0.4) implying a negative $E2/M1$ mixing ratio δ. Since the calculated contribution[9] to the sign of δ from the $M1$ operator is positive for this three-quasiparticle configuration, a negative δ implies a negative quadrupole moment Q_0, namely an oblate shape ($\gamma = -60°$). The other $\Delta J = 1$ bands were observed to have positive mixing ratios.

(3) The observed absence of signature splitting in the band is consistent with the proposed structure with $\gamma \sim -60°$. It can be seen from Fig. 2 that the signature splitting of the $h_{11/2}$ proton orbital is strongly dependent on the value of γ. Although large for $\gamma \sim 0°$, the splitting of the proton orbital is seen to approach zero as γ approaches $-60°$. No other candidate valence-proton orbital shows zero signature splitting at any value of γ in the full range $-120° \leq \gamma \leq +60°$. Thus the proposed structure is the only possible configuration that would give rise to a band with zero signature splitting in this odd-proton nucleus.

(4) The dynamical moment of inertia ($\mathcal{J}^{(2)} = dI_x/d\omega$) extracted from the energy spacings of this band is found to be $\sim 65\%$ of that for the prolate, positive-parity, three-quasiproton band and also of that for the prolate one-quasiproton, negative-parity band. Such a difference is indicative of a different collective shape for the neutron-aligned band when compared to the other bands observed in ^{131}La.

(5) The $\Delta J = 2$ energy spacings in this band, which vary from 390 to 1146 keV, are fully consistent with the

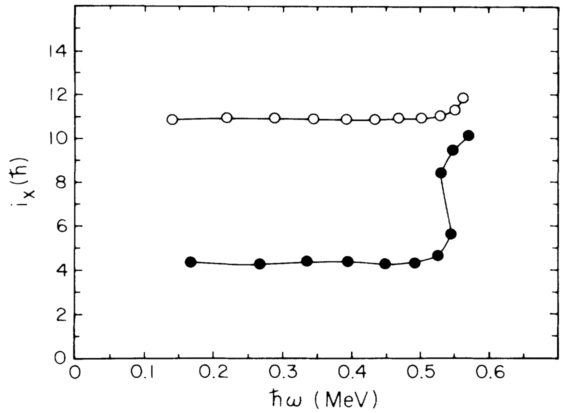

FIG. 3. Aligned angular momentum, i_x, of the $\pi h_{11/2}$ band (closed circles) and the $\pi h_{11/2} \otimes (\nu h_{11/2})^2$ band (open circles) as a function of frequency. A frequency-dependent reference moment of inertia, $\mathcal{J}_{\text{ref}} = \mathcal{J}_0 + \omega^2 \mathcal{J}_1$, has been subtracted. For the $\pi h_{11/2}$ band, $\mathcal{J}_0 = 14.7\hbar^2$ MeV^{-1}, $\mathcal{J}_1 = 45.8\hbar^4$ MeV^{-3}. For the $\pi h_{11/2} \otimes (\nu h_{11/2})^2$ band, $\mathcal{J}_0 = 9.9\hbar^2$ MeV^{-1}, $\mathcal{J}_1 = 30.7\hbar^4$ MeV^{-3}.

proposed configuration. On the assumption of $K = \frac{11}{2}$ and a variable moment of inertia reference based on the extracted $\mathcal{J}^{(2)}$ values for this band, a constant alignment is extracted in the frequency range 0.15 MeV $\leq \hbar\omega \leq$ 0.50 MeV, as shown in Fig. 3. The value for the alignment, $i_x = 10.9\hbar$, is in agreement with that calculated for a pair of rotationally aligned $h_{11/2}$ neutrons at $\gamma = -60°$ together with the strongly coupled $h_{11/2}$ proton.

(6) The fact that this band becomes yrast above a frequency of 0.45 MeV is consistent with CSM calculations of total Routhians by the methods of Refs. 1 and 4. A value for the oblate-prolate energy difference $\Delta E \sim 250$ keV is taken in accordance with the predictions of Ragnarsson *et al.*[3] The quantity ΔE is the energy required to change the shape of the nucleus from prolate ($\gamma = 0°$) to oblate ($\gamma = -60°$), and the smaller the value of ΔE, the more soft is the nucleus with respect to the γ deformation. The relatively small value of ΔE predicted for ^{131}La is needed in order that the alignment of the neutrons, with the associated shape change, can compete with the alignment of the protons.

(7) No transitions were observed between the $\pi h_{11/2} \otimes (\nu h_{11/2})^2$ band and the yrast portion of the $\pi h_{11/2}$ band, indicating a weak interaction between the two bands. The interaction must be considerably smaller than the energy difference between band members of the same spin and parity; for example, the $\frac{27}{2}^-$ states observed in the $h_{11/2}$ one-quasiparticle band and the oblate band are separated by only 60 keV. The implied unusually weak interaction is likely due to the large difference in shape between the two structures. Only at the band head are transitions observed feeding out of the oblate band, the number of which (only two are shown in Fig. 1) points to the reduced transition probabilities caused by the structural difference. The most intense of these (423 keV) feeds into the $\alpha = +\frac{1}{2}$ signature component of the $\pi h_{11/2}$ band with perhaps a less dissimilar shape.

In conclusion, it has been demonstrated that a collective oblate structure involving the alignment of a pair of $h_{11/2}$ neutrons coexists in ^{131}La with a prolate structure involving the alignment of a pair of $h_{11/2}$ protons. This is the first observation of the rotational alignment of a pair of particles from the upper middle part of a high-j shell driving a prolate nucleus to a collective oblate shape. Band structures with similar characteristic features have been observed[7] in the isotone ^{133}Pr but with less completeness. These may have a similar origin to the oblate band structure reported here.

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