Coexistence of Low-*K* Prolate and High-*K* Oblate $\pi h_{11/2}$ Orbitals

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Following theoretical predictions of competing prolate and oblate potential-energy minima, we present experimental evidence for the coexistence of prolate and oblate nuclear shapes which are associated in a given nucleus with the same single-quasiproton orbital. Prolate $\Delta I = 2$ and oblate $\Delta I = 1$ bands observed in the ^{119}I nucleus are proposed as built on an $h_{11/2}$ proton with low K and high K, respectively.

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In a number of odd-proton nuclei for $Z > 50$, the $h_{11/2}$ proton orbital is observed as a low-K ($K = \frac{1}{2}$) decoupled $\Delta I = 2$ rotational band with a prolate quadrupole deformation[1–4] of $\beta \sim 0.2$, where K is the angular momentum projection on the axis of deformation. Theoretical calculations for the $\pi h_{11/2}$ orbital, using the Nilsson-Strutinsky procedure,[5] reveal, however, specific (Z,N) regions where the high-K ($K = \frac{11}{2}$) oblate energy minimum is competitive with that of the usually observed $K = \frac{1}{2}$ prolate bandhead. The Nilsson diagram already suggests this general tendency provided the potential-energy surfaces allow significant deformations. Despite these theoretical expectations, high-K oblate $h_{11/2}$ proton orbitals have not been observed. The purpose of this study is to search experimentally for the coexistence of this theoretically predicted low-lying $h_{11/2}$ oblate proton orbital.

In the theoretical calculations, the coexistence of an oblate minimum in the potential-energy surface (PES) along with the normal prolate minimum results from the delicate competition between the proton and neutron shape-driving forces. The orbitals near the Fermi surface as influenced by the pairing correlations play the dominant role in this competition.[6,7] Thus, by selecting nuclei with different (Z,N) values, which determine the proton and neutron Fermi levels, adjustments in this shape-driving competition can be made. For odd-proton nuclei in the region ($52 < Z < 56$, $60 < N < 68$), the average proton and neutron γ-driving forces are calculated to be of the opposite sign. This fact leads to the prediction of both oblate and prolate minima of similar depths in the PES. The theoretical result showing these two minima for ^{119}I with ($Z = 53$, $N = 66$) from the above defined region is presented in Fig. 1, where newly fitted[8] (κ,μ) Nilsson parameters have been used. The ^{119}I nucleus was thus selected for this experimental search.

In order to search for the existence of the predicted low-lying high-K oblate orbital for the $h_{11/2}$ proton, a knowledge of the characteristics expected for the associated rotational band is necessary. Cranked shell-model (CSM) calculations show that a strongly coupled $\Delta I = 1$ rotational band with evenly spaced levels, namely no signature splitting, would be built on a high-K oblate $h_{11/2}$ orbital having only a small rotational alignment. The $M1$-to-$E2$ crossover intensity ratios must be consistent with the $h_{11/2}$ proton configuration and the $E2$ collectivity expected for these deformations.[9] Also, the $E2/M1$ mixing ratios for the $\Delta I = 1$ transitions would be negative because of the oblate deformation,[9,10] which would result in larger negative A_2/A_0 angular-distribution coefficients than for a pure diple ($M1$) transition.

Because of the lack of wave-function overlap between the high-K oblate $h_{11/2}$ band and the low-K prolate $h_{11/2}$ band, transitions out of the oblate band are theoretically expected to favor other high-K final states following the K-forbiddenness rule. It is known from systematic studies[1,2,11] of Sb, I, and Cs isotopes that high-K bands

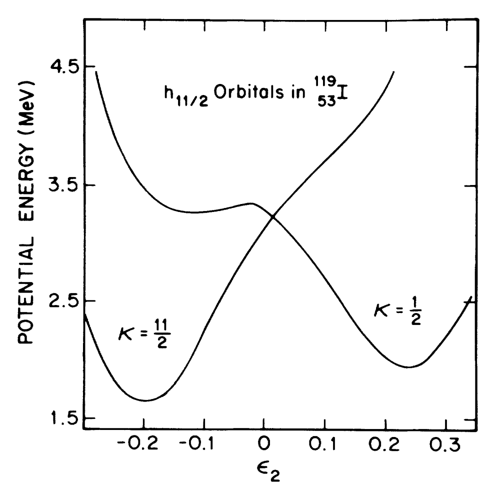

FIG. 1. PES calculations for ^{119}I showing competing low-K prolate and high-K oblate energy minima. Newly fitted (Ref. 8) (κ,μ) parameters were used in the calculations, and only axial shapes were considered.

($K=\frac{9}{2}$) associated with the $g_{9/2}$ proton-hole intruder exist at low energies in this region. Thus, preferential decay to the strongly coupled $g_{9/2}$ proton-hole band would be another characteristic of the high-K oblate $h_{11/2}$ band.

States in ^{119}I were populated via the ^{110}Cd(^{12}C, $p2n$)^{119}I reaction with beams produced at the Stony Brook Nuclear Structure Laboratory. Following excitation-function measurements, a ^{12}C beam of 60 MeV was chosen for γ-γ coincidence and γ-ray angular distribution experiments. A thick target of separated ^{110}Cd was used, backed with natural Pb, which served to stop the recoiling nuclei. An array of six bismuth-germanate- (BGO-) suppressed Ge detectors was used to record γ-γ coincidences. The detectors were located at angles $\pm 27°$, $\pm 145°$, $+94°$, and $-78°$ with respect to the beam direction. Multiplicity information was also recorded with fourteen closely packed hexagonal BGO crystals to optimize the appropriate reaction channel. Angular-correlation[12] results for the γ transitions were extracted from the coincidence data for multipolarity and spin information. In addition, angular-distribution data were recorded to obtain mixing-ratio and further multiplicity information.

The present experimental investigation focuses on three rotational bands extracted from the data for ^{119}I. These results are shown in Fig. 2. The yrast $\Delta I=2$ decoupled band based on the Nilsson $h_{11/2}[550]$ $K=\frac{1}{2}$ proton and a $\Delta I=1$ strongly coupled $g_{9/2}[404]$ $K=\frac{9}{2}$ band are prominent structures in the observed γ-ray spectra. The systematics of these two prolate bands are well established[1-4] for the $Z>50$ nuclei; the band associated with the other signature of the decoupled band is usually not seen in these reactions because of the expected large signature splitting, in excess of 500 keV. These bands have been extended to higher spin states in the present experiment.

The third band observed in ^{119}I shows the properties that were defined as characteristic of the theoretically predicted oblate $h_{11/2}[505]$ $K=\frac{11}{2}$ band. These detailed properties will now be presented and discussed in terms of this interpretation. Although the precise experimental energy of this high-K band relative to the low-K $h_{11/2}$ band is different from the theoretical energy minima shown in Fig. 1, the existence of the high-K band is consistent with the calculated double PES minima. This new band, which is shown in Fig. 2, is a $\Delta I=1$ strongly coupled, negative-parity band with $E2$ crossover transitions. The intensity of this band is about 10% of the yrast $\Delta I=2$ band. The band levels, which are evenly spaced, show no signature splitting; this already indicates a high K.

The extracted $B(M1;I\rightarrow I-1)/B(E2;I\rightarrow I-2)$ ratios for this band are shown in Table I. The values average ~ 12 $(\mu_N/e\mathrm{b})^2$, which is consistent with the proposed configuration. These ratios are in agreement with the estimates provided by the semiclassical model[9] of Dönau and Frauendorf for the $K=\frac{11}{2}$ $\pi h_{11/2}$ orbital. On the assumption of this K value and a variable moment-of-inertia reference extracted for the new band, a small constant alignment of $i_x \sim 0.3\hbar$ is extracted as expected for this high-K single quasiproton state. Because of the complexity of the γ-ray singles spectrum, it was not possible to determine angular distributions for all of the γ-ray transitions. Therefore the coincidence data were used to create a two-dimensional angular-correlation ar-

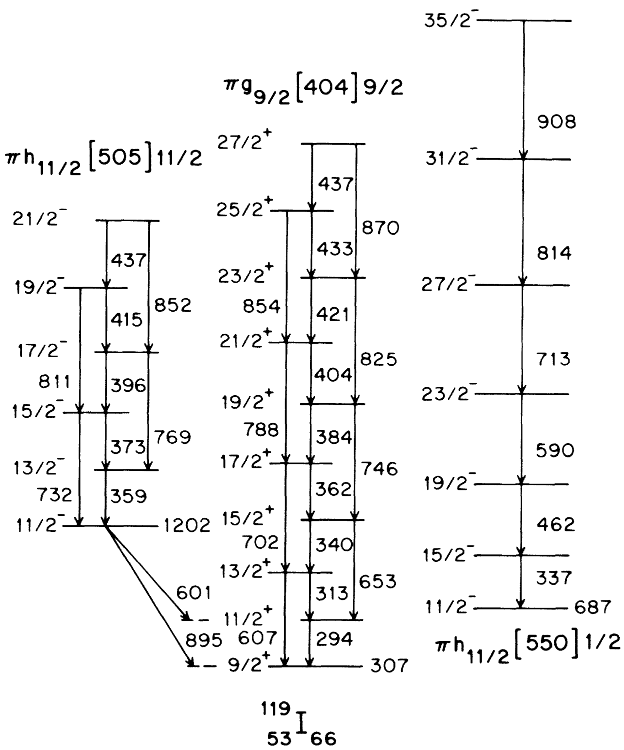

FIG. 2. Partial level scheme for ^{119}I deduced from this work. The transition energies are given in keV. In addition, the bandhead energies (keV) of the three bands are given relative to the $\frac{5}{2}^+$ ground state. The 307-keV $\frac{9}{2}^+$ bandhead, which is isomeric with $t_{1/2}=28.8\pm 1.0$ ns, decays directly to the $\frac{5}{2}^+$ ground state and to the nearly degenerate $\frac{7}{2}^+$ state, while the 687-keV prolate $\frac{11}{2}^-$ bandhead decays, following two parallel low-energy $E1$ transitions, to the same two states (Ref. 1).

TABLE I. Experimental $B(M1;I\rightarrow I-1)/B(E2;I\rightarrow I-2)$ ratios of reduced transition probabilities for the new band in ^{119}I.

$I(\hbar)$	$B(M1)/B(E2)$ $[(\mu_N/e\mathrm{b})^2]$
$\frac{15}{2}$	9.4 ± 1.2
$\frac{17}{2}$	12.3 ± 1.2
$\frac{19}{2}$	16.0 ± 3.0
$\frac{21}{2}$	9.9 ± 2.0

ray. The array was formed by sorting the two detectors close to 90° (+94°, −78°) against the other four detectors. Gates were set on peaks along both axes of the array and the intensities of coincident peaks measured. In general, the ratio of the two intensities obtained by gating this way depends on the multipolarity of the transition. In this manner it is possible to distinguish between quadrupole and dipole transitions. The results of this analysis combined with angular-distribution data obtained for resolved γ rays indicate that several of the $\Delta I=1$ transitions in the new negative-parity band in ^{119}I have large negative A_2/A_0 values, while the A_2/A_0 values for the $\Delta I=1$ transitions in the $g_{9/2}$ proton-hole bands were near zero. The negative A_2/A_0 values for the strongly coupled $h_{11/2}$ proton are consistent within statistics with a negative mixing ratio $\delta_{E2/M1}$, while the much smaller values (A_2/A_0 near zero) for the $g_{9/2}$ proton-hole band require a positive $\delta_{E2/M1}$. For axial shapes,[10] $\mathrm{sgn}(\delta_{E2/M1})=\mathrm{sgn}[Q_0/(g_K-g_R)]$ and since large positive g factors are expected for the $\pi h_{11/2}$ and $\pi g_{9/2}$ orbitals, then $\mathrm{sgn}(\delta_{E2/M1})=\mathrm{sgn}(Q_0)$, i.e., the sign of the mixing ratio is directly related to the sign of the quadrupole moment. Thus, negative $\delta_{E2/M1}$ values for the new band would specifically indicate an oblate shape, while the positive values for the $g_{9/2}$ band[1–4] are a result of its prolate shape.

This third band is observed to decay into the high-K $g_{9/2}$ proton-hole band via two interband transitions rather than into the low-K $h_{11/2}$ yrast band. The $\frac{11}{2}^- \to \frac{9}{2}^+$ 895-keV transition has about one-third the intensity of the $\frac{11}{2}^- \to \frac{11}{2}^+$ 601-keV transition. The angular-correlation results are consistent with the assigned $E1$ multipolarities for these two interband transitions. The transitions from the high-K oblate $h_{11/2}$ band to the high-K prolate $g_{9/2}$ band should be hindered due to the different shapes. Calculations show that reasonable 3^- octupole-core admixtures would allow these interband $E1$ transitions to proceed in a manner which would enhance the $\Delta I=0$, $\frac{11}{2}^- \to \frac{11}{2}^+$ transition relative to the $\Delta I=1$ stretched $\frac{11}{2}^- \to \frac{9}{2}^+$ transitions as is observed experimentally.

In summary, the current experiment reveals a new band in ^{119}I with the following characteristics: (1) strong $\Delta I=1$ transitions with no signature splitting as expected for the high-K orbital; (2) $M1$-to-$E2$ crossover intensity ratios which are consistent with the $h_{11/2}$ proton configuration; (3) negative $E2/M1$ mixing ratios for the in-band $\Delta I=1$ transitions indicative of an oblate shape; (4) a small constant alignment $i_x \sim 0.3\hbar$ assuming $K=\frac{11}{2}$; and (5) calculable $E1$ deexcitation transitions from the $K=\frac{11}{2}$ bandhead into another known high-K ($K=\frac{9}{2}$) band. These experimental results are in agreement with the predicted theoretical double-minimum PES calculations and the CSM calculations for an oblate, high-K $h_{11/2}$ proton orbital coexisting with the previously observed prolate low-K $h_{11/2}$ proton orbital. Additional studies are planned to investigate this shape-driving competition and different regions of coexistence. The observed oblate stability of the high-K $h_{11/2}$ proton orbital will undoubtedly influence other configurations that contain this orbital.

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