Collective Oblate Rotation at High Spins in Neutron-Rich ^{180}Hf

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(Received 13 May 2008; revised manuscript received 13 August 2008; published 30 October 2008)

We report on experimental evidence for collective oblate rotation becoming favored at high spins in a rigid, well-deformed, axially symmetric nucleus. Excited states established up to spin $20\hbar$ in ^{180}Hf are consistent with predictions that nucleon alignments would favor oblate over prolate shapes at high spins in neutron-rich Hf isotopes. The results highlight the influence of valence orbitals on the interplay between nucleon alignments and nuclear shapes and provide a rare example of independent particle dynamics in competing potential wells.

DOI: 10.1103/PhysRevLett.101.182503 PACS numbers: 21.10.Re, 21.60.Ev, 23.20.Lv, 27.70.+q

The shape of an atomic nucleus embodies the strong and complex correlations between its constituent fermions. Most nuclei that exhibit quadrupole deformation in their ground state are found to be prolate, with oblate shapes occurring primarily in a small subset of nuclei near the end of a shell. Oblate deformed nuclei exhibit coexisting and competing prolate states at low angular momenta (spins), e.g., around the proton-rich Pb [1,2], and $A \approx 70$ [3,4] regions. The Hg isotopes [5,6] are characterized by weak oblate deformation near the ground state evolving to noncollective prolate shapes at high spin in several instances. Regular magnetic dipole bands in the $A \approx 130$ region, with varying collective contributions, have been interpreted as arising from either oblate rotation [7] or the shears mechanism [8]. Low potential energy barriers in the triaxial (γ) degree of freedom lead to considerable overlap of wave functions between the prolate and oblate states in these nuclei. With increasing spin, prolate rotation is usually energetically favored over oblate rotation. This is a consequence of the higher moment of inertia (MOI) for prolate shapes, for rotation perpendicular to the symmetry axis at similar quadrupole deformations [9]. A transition from prolate to oblate collective rotation at high spins has not been observed to date in rigid, well-deformed, axially symmetric nuclei. The observation of oblate shapes at high spin would offer a rare insight into independent particle dynamics in competing potential wells and the interplay between nucleon alignments and nuclear shapes.

Neutron-rich nuclei with $A \approx 180$, around the Hf ($Z = 72$) region, exhibit distinctive characteristics which should enable a transition from prolate to oblate collective rotation at high spins [10,11]. These nuclei are well-deformed, axially symmetric, and prolate in their ground states. Both valence protons and neutrons occupy high-j orbitals. For prolate deformation, the orbitals near the Fermi surface have large values of Ω, the projection of the intrinsic angular momentum along the symmetry axis. For oblate shapes, on the other hand, valence nucleons occupy low-Ω orbitals. As the nuclei rotate collectively, individual nucleon pairs align at sufficiently high rotational frequencies. The aligned nuclear states are energetically favored by virtue of their larger effective MOI. Since valence nucleons in low-Ω orbitals align at lower rotational frequencies, both proton and neutron alignments are conducive to oblate shapes being preferred over prolate ones at high spins. This unusual combination of features in the $A \approx 180$ region has led to long-standing predictions of a prolate to oblate shape transition at high spins [11,12]. The lack of experimental evidence to date can be attributed to the difficulty of populating highly excited states in these neutron-rich nuclei. Recent experimental advances have allowed these nuclei to be studied through deep-inelastic and transfer reactions using heavy projectiles [13], with the coincident detection of binary reaction fragments and γ rays emitted in their deexcitation [14]. A very small number of nuclei predicted to exhibit oblate shapes at high spins are accessible through these experimental techniques. The neutron-rich Hf isotopes are particularly suitable since they are characterized by axially symmetric, γ-rigid shapes. The heaviest stable isotope, ^{180}Hf, is an excellent candidate since it can be studied via inelastic excitation with a relatively large cross section.

This Letter reports on new states observed in a study of prompt rotational structures in ^{180}Hf using ^{232}Th as a reaction partner. The onset of the first nucleon alignment in the prolate yrast structure of ^{180}Hf is observed and a band associated with collective oblate rotation identified. Our earlier attempt, using a lighter ^{136}Xe beam [10], fell short of achieving these objectives and, therefore, the heavier ^{232}Th was used as the reaction partner in an effort to reach higher spins. Excited states in ^{180}Hf were populated with a 1300 MeV ^{180}Hf beam from the ATLAS accelerator at Argonne National Laboratory, incident on a 700 μg/cm^2 ^{232}Th target. The heavier projectile and higher beam energy ($\approx$25% above the Coulomb barrier), compared to our previous experiment, favored the population of higher spins [15]. The binary reaction partners were detected by the position-sensitive, parallel-plate avalanche counter CHICO [14], while γ rays emitted in their deexcitation were recorded in 100 Compton-suppressed germanium detectors of the Gammasphere array [16,17]. Mass identification was obtained with CHICO through measurements of position and time-of-flight difference of the recoiling nuclei, and Q-value conditions were placed on the particle spectra for selecting quasielastic events [18,19].

New transitions and collective states up to spin $I = 20\hbar$ (Fig. 1), crucial for realizing the objectives of the experiment, were identified in this work. The previously identified yrast $I = 18\hbar$ state in band 1 [10,20] is observed to be fed by parallel branches (bands 1 and 1a), with the 872 and 984 keV transitions being newly established. Band 2 was extended from $I = 16\hbar$ to $I = 20\hbar$, and several new interband transitions between bands 1 and 2 are observed. Bands 3 and 4 were known from the earlier work [10], except for the $I = 15\hbar$ state in band 3. Band 1 up to $I = 18\hbar$ and band 1a beyond this spin are identified with the prolate g (or ground state) band, while band 1 beyond $18\hbar$ is associated with the prolate s band (rotation-aligned band with two quasiparticles). A sharp upbend in the kinematic MOI [Fig. 2(b)] at $\hbar\omega \approx 0.43$ MeV suggests the onset of the first nucleon alignment in the yrast structure, although a precise experimental value of the crossing frequency will require the alignment to be mapped out fully. Bands 2 (up to $10\hbar$) and 3 are the even- and odd-spin signature partners of the γ-vibrational band. As discussed in our earlier work [10], this is supported by the parallel trajectory of their excitation energies with the g band [Fig. 2(a)], as well as by the agreement of the experimental branching ratios of the transitions from these bands to the g band [Fig. 2(c)] with Alaga intensity rules [21]. Above $10\hbar$, the energies and branching ratios for band 2 deviate rapidly from those expected for a vibrational band, while the energies of states in band 3 continue to follow the expected pattern. This is due to the interaction between bands 2 and 4 around $I = 10\hbar$, as evident from the deviations in their energy trajectories, and underscored by the observed interband transitions (Fig. 1). The energy trajectories of states in band 4 [Fig. 2(a)] and the strong out-of-band transitions to the g band suggest a vibrationlike character for band 4 at low

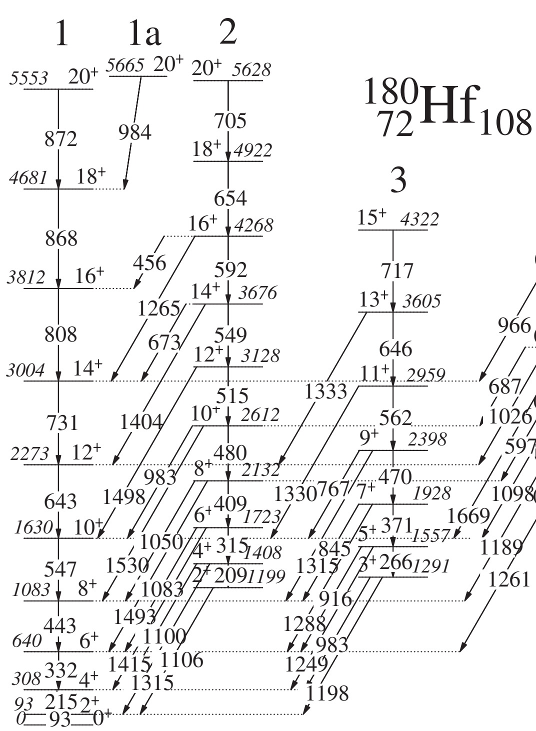

FIG. 1. Partial level scheme for ^{180}Hf, showing the relevant collective structures.

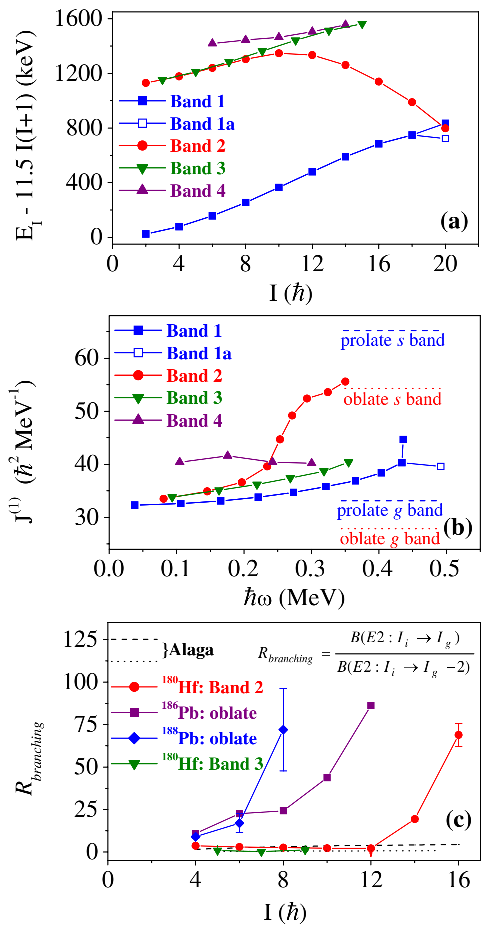

FIG. 2 (color online). (a) Level energies as a function of spin in ^{180}Hf, with a rigid rotor reference subtracted. (b) Kinematic MOI for the bands in ^{180}Hf. Dashed lines and dotted lines indicate expected MOI for different situations. (c) Ratios of the reduced transition probabilities for interband transitions between the indicated bands and the prolate g band. Data for ^{186}Pb [2] and ^{188}Pb [25] are compared with band 2. For the odd-spin band 3 in ^{180}Hf, the ratio for the $I \to (I+1)$ to $I \to (I-1)$ transitions is shown.

spin. Above $10\hbar$, band 4 evolves into the even-spin γ-vibrational band.

The energy difference between bands 2 and 1 gradually decreases above $10\hbar$ and band 2 lies below the prolate g band at $20\hbar$ [Fig. 2(a)]. The MOI of band 2 at the highest rotational frequency, after it changes character, is approximately $53\hbar^2\ \mathrm{MeV}^{-1}$ [Fig. 2(b)]. This is considerably higher than any of the other collective or two-quasiparticle high-K bands in ^{180}Hf, but is less than that expected for the prolate s band ($\approx$60–$65\hbar^2\ \mathrm{MeV}^{-1}$, from a survey of nuclei in this region wherein states well above the g- and s-band crossing are known) [22–24]. The MOI of band 2 beyond $I = 14\hbar$ is, however, consistent with that expected for an oblate s band, assuming the same quadrupole deformation (β) for the prolate and oblate g bands (in accordance with predictions described below), and a proportionate increase in the MOI from the g- to s-band structure, similar to the prolate states. This is illustrated in Fig. 2(b), in terms of the expected MOI for the oblate g and s and prolate s bands. These have been calculated using the measured $J_{\mathrm{prolate}} \approx 33\hbar^2\ \mathrm{MeV}^{-1}$ for the prolate g band and $\beta = 0.26$ for the ground state, with the MOI of the oblate g band obtained using $J_{\mathrm{oblate}} = [(1 - 0.3\beta)/(1 + 0.3\beta)]J_{\mathrm{prolate}}$, assuming rigid rotation [9]. The MOI of the s bands are indicated at twice the respective values for the g bands [Fig. 2(b)] in accordance with observed trends for prolate g and s bands in this region [22–24]. The agreement between the expected MOI for the oblate s band and that of band 2 at the highest spins is striking. Above $10\hbar$, the transitions from band 2 to the prolate g band become progressively weaker with increasing spin. No interband transitions are observed above $16\hbar$, despite the proximity in excitation energy of corresponding states in the two bands (Fig. 1). The ratio of the reduced transition probabilities for the intraband (within band 2) to interband (between bands 2 and 1) transitions increases rapidly above $I = 10\hbar$, from a value of ≈ 80 at $I = 10$ to ≈ 170 at $I = 16\hbar$. For the interband transitions, the ratio of the reduced transition probabilities for the $I \rightarrow I$ to $I \rightarrow (I - 2)$ transitions is markedly higher for transitions from the states at $I = 14\hbar$ and $16\hbar$, compared to states at lower spin. Intensity limits on unobserved transitions from higher spin states in band 2 point to a further increase beyond $16\hbar$. Such behavior is symptomatic of mixing between different shapes, as in ^{186}Pb [2] and ^{188}Pb [25] [Fig. 2(c)]. Furthermore, there is no evidence of an odd-spin signature partner for band 2 at higher spins.

All the observations are consistent with a collective, oblate rotational character for band 2 at high spins. Alternate interpretations have been considered. The crossing of energy trajectories of band 2 and the prolate g band, and the large deviation (above $I = 12\hbar$) of the branching ratios from Alaga intensity rules, obviously preclude a γ-vibrational character at high spins. The decay characteristics of band 2 (above $I = 10\hbar$), with transitions from states up to $I = 16\hbar$ to levels in band 1, and the absence of an odd-spin signature partner rule out a high-K character, especially since expected low-lying high-K states have already been determined from our earlier work on K isomers in ^{180}Hf [26,27]. A prolate s band, or alternatively, a Fermi-aligned (t-band) character, as seen in the W and Os isotopes [28,29], would be inconsistent with the absence of interband transitions in the region of crossing with the prolate g band. Thus, an oblate collective band appears most probable.

We have performed cranking calculations using both the universal Woods-Saxon (WS) potential [30] as described in our earlier work [10] and standard Nilsson parameters in the ULTIMATE CRANKER (UC) code [31]. The predictions of both calculations are in qualitative agreement and consistent with the appearance of an oblate structure at the observed rotational frequency and spin. The calculations predict an axially symmetric, prolate shape with $\beta_2 \approx 0.26$ for the ground state in ^{180}Hf [Fig. 3(a)], which persists beyond $I = 20\hbar$. An oblate energy minimum, also with $\beta_2 \approx 0.26$, appears around $\hbar\omega \approx 0.2$ MeV and $I = 8\hbar$. This is in good agreement with the observation of oblate states above $I = 10\hbar$ and $\hbar\omega \approx 0.25$ MeV. The energy difference between the predicted prolate and oblate minima decreases with increasing spin, and oblate shapes are favored above $I = 24\hbar$ [Fig. 3(b)]. The experimental oblate state is found to be lower in energy than the prolate g band at $I = 20\hbar$, and just 75 keV higher than the prolate s-band state at the same spin [Figs. 1 and 2(a)]. The predicted prolate-oblate energy difference at this spin is,

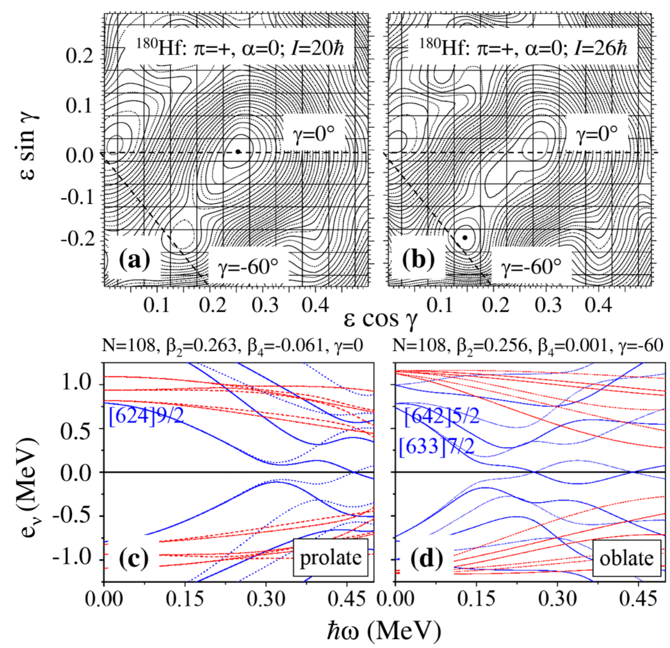

FIG. 3 (color online). (a),(b) Shape evolution in ^{180}Hf from UC calculations. The lowest energy minimum is indicated by a dot. Quasineutron levels in ^{180}Hf from WS calculations for (c) prolate and (d) oblate deformations (see text).

however, significantly larger. A notable feature from both calculations is that rigid axial symmetry is preserved for both prolate and oblate energy minima in ^{180}Hf over the calculated range of spins. The weak or nonexistent interband transitions are consistent with a minimal overlap between prolate and oblate wave functions.

For prolate collective rotation, the calculations predict a frequency, $\hbar\omega = 0.33$ MeV (WS) [Fig. 3(c)] and 0.38 MeV (UC) for the alignment of $i_{13/2}$ neutrons, and $\hbar\omega = 0.45$ MeV (UC) and 0.50 MeV (WS) for $h_{11/2}$ protons. The observed upbend in the MOI of the prolate sequence [band 1 in Fig. 2(b)] is presumably due to the alignment of a pair of $i_{13/2}$ neutrons. The predicted small interaction strength at the crossing for $N = 108$ could lead to a sharp backbend in the experimental MOI plot at higher spins. The $i_{13/2}$ crossing frequency appears to be considerably higher than in lighter Hf isotopes, which is not unexpected given the subshell closure at $N = 108$ for prolate deformation [10].

A noteworthy result of the cranking calculations is the prediction of neutron and proton alignment frequencies in ^{180}Hf for collective oblate rotation. The first $i_{13/2}$ neutron alignment is predicted to occur at $\hbar\omega = 0.17$ MeV [Fig. 3(d)] from both calculations. For the $h_{11/2}$ proton alignment, UC predicts $\hbar\omega = 0.24$ MeV, with the WS prediction being $\hbar\omega = 0.30$ MeV. Thus, both neutron and proton alignments for oblate shapes are expected at lower frequencies than the first alignment for prolate shapes. This is a consequence of higher-Ω orbitals near the Fermi level for prolate as compared to oblate shapes. Oblate states with an aligned nucleon pair should have higher MOI than prolate states with no aligned nucleon pair and should, therefore, be energetically favored with increasing spin. The high MOI of band 2 above $\hbar\omega = 0.3$ MeV [Fig. 2(b)] can be associated with an oblate rotational band with one pair of aligned quasineutrons. The higher MOI for the oblate states, resulting from the nucleon alignment, leads to a progressive decrease in the prolate-oblate energy difference at high spins [Fig. 2(a)]. The oblate g band, expected to be considerably nonyrast, is not observed. The mixing of the oblate-aligned band with the even-spin members of the γ-vibrational band rather than the γ-rigid prolate band is not entirely unexpected, given the smaller difference in excitation energies (for states with identical spins), as well as a qualitatively better overlap of the shape wave functions through the γ degree of freedom. The trajectory of the bands above $I = 20\hbar$ would help to further clarify their respective structures.

In summary, we present evidence that collective oblate rotation becomes favored at high spins in a rigid, well-deformed, axially symmetric nucleus. The observations indicate that nucleon alignments favor oblate over prolate shapes at high spins in neutron-rich Hf isotopes, consistent with predictions. The results underscore the influence of valence orbitals on the interplay between nucleon alignments and nuclear shapes, and provide a rare example of independent particle dynamics in competing potential wells. Recently developed inelastic excitation techniques with heavy beams were crucial for populating the neutron-rich nucleus ^{180}Hf to high spins. Explorations of more neutron-rich nuclei in this mass region, where the phenomenon is predicted to occur at lower spins, will benefit from the rare isotope beams and more sensitive detectors that are on the horizon.

We would like to acknowledge useful discussions with P. M. Walker, and the ATLAS accelerator staff for developing the ^{180}Hf beam. This research is supported by the U.S. Department of Energy, Office of Nuclear Physics, under grants DE-FG02-94ER40848 and DE-AC02-06CH11357, and the National Science Foundation.

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