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Wobbling excitations in strongly deformed Hf nuclei?

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Abstract

Two Gammasphere experiments have been performed in order to establish the possible triaxial nature of strongly deformed (SD) bands in ^{174}Hf. A lifetime measurement, using the Doppler-shift attenuation method, confirmed the large deformation of the four previously observed bands in this nucleus with transition quadrupole moments ranging from 12.6 to 13.8 b. These values are significantly larger than those predicted for triaxial minima by ultimate cranker (UC) calculations. A thin-target, high-statistics experiment was also carried out to search for linking transitions between the SD bands. No such transitions, which represent an experimental signature for wobbling modes, were observed. Four additional SD bands were found in ^{174}Hf

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together with a single SD band in ^{173}Hf. These results indicate that the strongly deformed sequences of $N \approx 102$ Hf isotopes behave differently than the triaxial strongly deformed (TSD) bands found in Lu nuclei near $N = 92$. The interpretation of these bands in terms of possible stable triaxial deformation is confronted with the experimental findings and UC predictions.

The vast majority of known nuclei possess shapes with axial symmetry, where the moments of inertia about two principal axes are equal. Rotation about the third axis (often denoted as the symmetry axis) is not permitted quantum mechanically for axially deformed isotopes. These objects can rotate about the other two axes, and because of the identical moments of inertia, the rotation about either axis is equivalent. If a nucleus exhibits a stable triaxial shape, where different moments of inertia are associated with each axis, rotation about all three axes is possible. Although rotation about the axis with the largest moment of inertia is favored, the contributions from rotations about the other two axes can force the rotation angular momentum vector (R) off the principal axis to create a precession or wobbling mode of which the classical analog is the rotation of an asymmetric top. The degree to which R lies off axis can vary without changing the configuration associated with the rotational sequence, but it is quantized. This quantization is expressed in terms of wobbling quanta n_w and a stable triaxially deformed nucleus will exhibit a family of rotational bands (with identical moments of inertia and alignment) based on the same configuration, but with different wobbling phonon numbers ($n_w = 0, 1, 2, \ldots$) [1].

Such a family of three bands was recently observed in ^{163}Lu [2–4]. It was suggested that all three were based on the same $\pi i_{13/2}$ configuration, an orbital which increases the deformation in comparison with that of other observed structures in this nucleus. Because of their properties, the bands have been labeled as triaxial strongly deformed (TSD). In addition, linking transitions were observed from the two excited sequences to the yrast ($n_w = 0$) TSD band in ^{163}Lu. Analysis of the linking transitions from the yrare ($n_w = 1$) TSD band revealed that the $\Delta I = 1$ transitions have a dominant $E2$ component, consistent with the wobbling behavior predicted by the particle-rotor model [2]. These experimental findings constitute the best evidence to date for the rotation of a stable triaxial nucleus. Evidence of wobbling has also been presented in ^{161}Lu [5], ^{165}Lu [6] and ^{167}Lu [7], as well as candidate TSD bands have been reported in ^{168}Hf [8] and ^{170}Hf [9].

Ultimate cranker (UC) [10] calculations correctly predict a TSD minimum in the total energy surface (TES) of the Lu nuclei. However, they also suggest deep TSD minima for the neighboring ^{164,166}Hf nuclei, and no TSD band has been observed so far [11]. Recently, four candidate TSD bands were observed in ^{174}Hf [12], and UC calculations suggest that TSD minima exist for this nucleus as well. The data were not extensive enough to quantify the large deformation, nor to observe the critical linking transitions between the bands.

In order to investigate further the possibility of stable triaxiality in ^{174}Hf, two new experiments were performed utilizing the Gammasphere spectrometer [13]. The quadrupole moments of the bands were determined through a backed target experiment, using the Doppler-shift attenuation method (DSAM). Due to the relative weakness of the bands ($\sim 1\%$ of the total population for ^{174}Hf in the original measurement), a new, high-statistics experiment with a thin target was carried out to search for linking transitions between the strongly deformed sequences. From these two experiments, large deformation was indeed confirmed for the four bands, but no linking transitions could be established. The ramifications of these results on the issue of the possible triaxial nature of these bands will be addressed. The identification of four additional bands in ^{174}Hf, of a single sequence in ^{173}Hf, and another in ^{175}Hf [14] is discussed as well. Due to the uncertainty about whether these bands are indeed triaxial, the sequences in the Hf nuclei will be referred to as strongly deformed (SD), rather than TSD, in the remainder of this Letter.

The mean lifetimes of the SD states in ^{174}Hf were measured with the ^{130}Te(^{48}Ca, 4n) reaction at a beam energy of 200 MeV and beam current of 2 pnA. A self-supporting target was used consisting of a 50 μg/cm^2 Au flashing in front of 850 μg/cm^2 enriched ^{130}Te evaporated on a 25.6 mg/cm^2 Au backing. The ^{48}Ca beam was provided by the 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory. The γ radiation was detected with the Gammasphere array which consisted of 102 Compton suppressed HPGe detectors for this experiment. A requirement of at least five prompt coincident γ rays defined an event and a total of 3.5×10^9 of these was recorded. The γ-ray information was sorted into a Blue data base [15], where the γ-ray energies and the angles of detection for an event were stored, in order to facilitate a fast and efficient DSAM analysis. Gating requirements for both energy and angle of two γ rays could be performed and resulting coincidence transitions were then recorded into one-dimensional spectra following background subtraction with the method developed by Starosta et al. [16].

In order to search for linking transitions, a high-statistics experiment with a thin target was carried out. The ^{130}Te(^{48}Ca, 4n) reaction was again used, but at a beam energy of 205 MeV. The beam was delivered by the ATLAS facility at Argonne National Laboratory. Four targets, with ~ 500 $\mu g/cm^2$ of Au in front of the Te and ~ 80 $\mu g/cm^2$ Au on the back, were mounted onto a rotating target wheel. The thicknesses of the ^{130}Te ranged from 400 to 660 $\mu g/cm^2$. The maximum sustained beam current was 2.5 pnA. One hundred Ge detectors were operational in the Gammasphere array to collect $\sim 2.6 \times 10^9$ events with at least four γ rays detected in prompt coincidence. The data were analyzed using the Radware [17] suite of programs after sorting into coincidence cubes and hypercubes.

In the analysis of the lifetime data it became clear that fully stopped transitions were not present in the SD sequences. The time scale for stopping the recoils is larger than the lifetime of the states and, thus, a given decay in a strongly deformed sequence will always occur at a non-zero velocity β of the recoil. In order to observe the bands, angle-dependent gating conditions taking into account the so-called fractional Doppler shift; i.e., the fraction of the full Doppler shift $F(\tau) = \beta/\beta_0$, were used [18], where β_0 is the average recoil velocity at mid-target. Since the fractional Doppler shifts for the transitions in the new sequences were not known a priori, initial $F(\tau)$ values were computed assuming a transition quadrupole moment similar to that measured for the candidate yrast TSD band in ^{168}Hf [8]. Angle dependent double coincidence gates using the computed $F(\tau)$ values were applied to produce first spectra where the lines of the SD bands were visible. The procedure was then repeated by varying $F(\tau)$ until the best enhancement of the transitions closest in energy to the gating γ rays was achieved. These spectra provided the location of the gates for the next transitions in the sequence, and the final spectra at each angle were obtained by summing all such optimized double-gated coincidence spectra. Representative spectra for band 1 are shown in Fig. 1 for forward and backward rings of Gammasphere at $\theta = 50°$ and 130°, respectively.

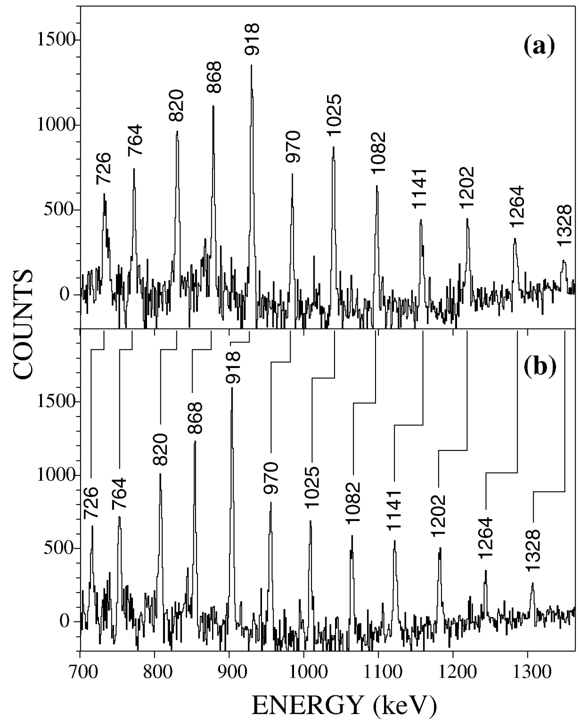

Fig. 1. Summed coincidence γ-ray spectra for SD 1 in ^{174}Hf in the (a) "forward" 50° and (b) "backward" 130° groups of detectors. The peaks are labeled by their unshifted γ-ray energies.

The experimental fractional Doppler shift $F(\tau)$ was extracted by fitting the Doppler-shifted peaks at all the angles and performing a linear regression for both E_0 and $F(\tau)$ with the expression

$$E(\theta) = E_0\big(1 + \beta_0 F(\tau)\cos(\theta)\big), \qquad (1)$$

where E_0 is the centroid of the peak at 90° and $E(\theta)$ is the measured centroid at angle θ. The mid-target recoil

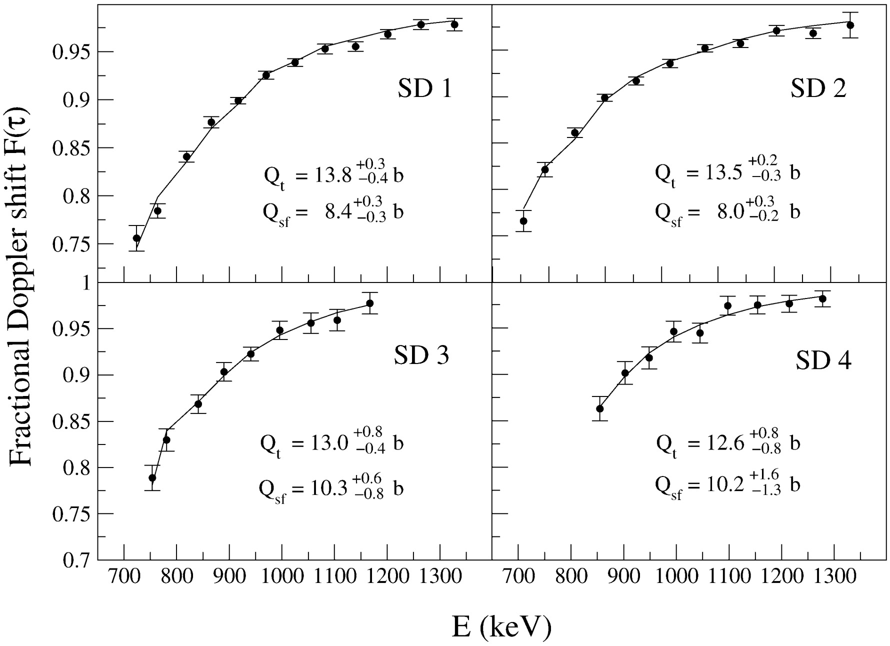

Fig. 2. The data points represent the measured fractional Doppler shift of transitions in the four previously known SD bands in ^{174}Hf [12]. Results from the FITFTAU code (described in the text) are shown as solid lines, and the transition quadrupole Q_t and sidefeeding Q_{sf} moments from the fitting routine are given for each band.

velocity β_0 was calculated based on the target thickness, beam energy, as well as the Z and A of the recoil using the code SRIM 2003 [19]. Corrections for multiple scattering were introduced using the prescription by Blaugrund [20]. The extracted $F(\tau)$ values for the four SD bands in ^{174}Hf [12] are displayed in Fig. 2. To determine the intrinsic quadrupole moments Q_t, computer simulations of the actual decay of the levels within the bands and their sidefeeding were performed with the code FITFTAU [21]. In the code, the following assumptions are implicit:

(1) the Q_t moment is constant within a given band;
(2) the sidefeeding cascades have a common, constant quadrupole moment Q_{sf};
(3) the number of transitions feeding levels of the main cascade is proportional to the number of transitions above the state of interest.

In order to model the sidefeeding contribution, the intensity profile for each band was determined by summing the peak intensities of the transitions from all angles. The sidefeeding cascade was assumed to have a similar energy spacing to that of the known band. In addition, it was determined that the best fits to the data occur when four sidefeeding levels are assumed to be located above the highest state observed.

A summary of the results for the four SD bands in ^{174}Hf is presented in Fig. 2. Large deformation has been established as the bands quadrupole moments range between $Q_t = 12.6$–13.8 b, where normal deformation in this nucleus corresponds to $Q_t = 7$ b [22]. The quoted errors are based solely on the uncertainty in determining the centroid energy of the peaks. An additional systematic error of 15–20% should be added to account for uncertainties in the stopping powers. However, this does not affect the relative Q_t values as these bands were produced in the same experiment. A quadrupole moment of $14.5^{+0.8}_{-0.8}$ b was also measured [23] for the SD sequence in ^{173}Hf, discussed below. One may note that these moments are not as high as those seen in the "classic" superdeformed $A = 150$ and 190 regions ($Q_t = 16$–20 b). In fact, the $A = 170$ region of strong deformation may well be similar to that defined by the $A = 130$ highly deformed nuclei and could possibly be viewed as "transitional"

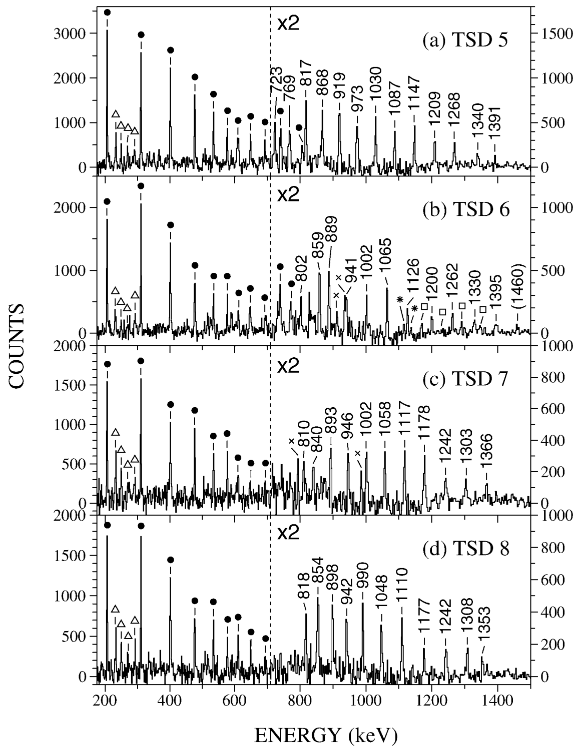

Fig. 3. Representative spectra of four new, presumably SD, bands in ^{174}Hf. The spectra were generated with all possible inband triple-gate combinations within the hypercube. To the right of the dashed line the scale has been reduced by a factor of two. Transitions denoted with filled circles and open triangles result from the known ground-state and $K^{\pi} = 14^{+}$ bands, respectively. Peaks denoted with a cross are possible feed-out transitions from the band. In panel (b), transitions from SD 3 are marked with an open square and asterisks denote linking transitions from SD 3.

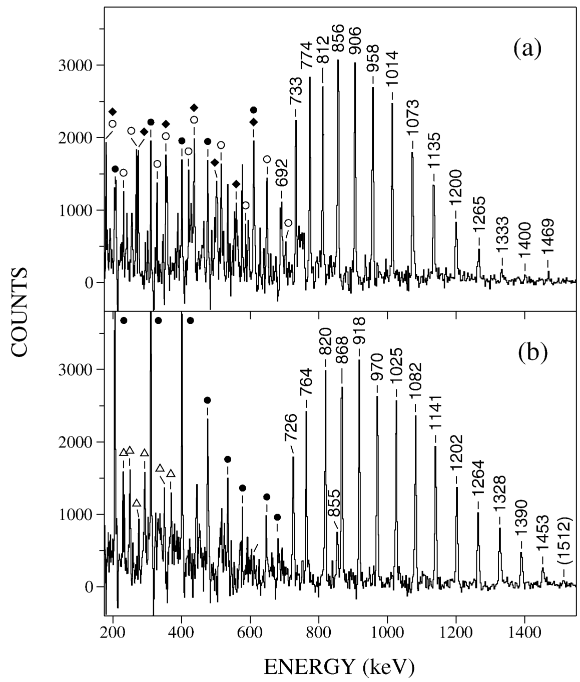

Fig. 4. Spectra of (a) the new strongly deformed band in ^{173}Hf and (b) SD 1 in ^{174}Hf. Both spectra were generated by summing all possible combinations of triple gates consisting of all inband transitions. In panel (a), transitions denoted with an open circle (filled diamond) are associated with the $\nu i_{13/2}$ ($\nu 5/2[512]$) band in ^{173}Hf. Peaks marked with a solid circle are contaminants from ^{174}Hf. The solid circles in panel (b) represent transitions from the ground-state band in ^{174}Hf, whereas the open triangles are from known sidebands in ^{174}Hf. The 855-keV γ ray in panel (b) appears to be a possible decay-out transition.

between the $A = 150$ and $A = 190$ superdeformed regions. The implication of the large Q_t moments for the interpretation of the nature of these bands is discussed below.

The search for linking transitions between SD bands was conducted using coincidence cubes and hypercubes from the thin-target data. Four new bands with moments of inertia similar to those of the other strongly deformed bands have been observed as a result of this search: sample spectra for these are given in Fig. 3. As was the case for the four SD bands reported in Ref. [12], the structures are assigned to ^{174}Hf on the basis of observed coincidences with transitions in the ground-state band, denoted in the figure by filled circles. The intensities of the new bands were determined to be only one third, or less that observed for SD 1. It should be noted that SD 5 is nearly identical to SD 1 (shown in Fig. 4(b)), as the transition energies differ by less than 7 keV throughout most of the band. The four previously known SD bands were extended to higher spin with the following transition energies (in keV); SD 1: 1390, 1453, (1512); SD 2: 1400, 1466, 1530; SD 3: 1226, 1287, 1349, 1412, (1475); SD 4: 1216, 1278, 1344, 1411, (1478). The spectrum shown in Fig. 4(a) illustrates the candidate SD band observed in ^{173}Hf. Assignment to ^{173}Hf is again based on coincidence relationships with known lower-lying states in this nucleus.

Unfortunately, no linking transitions nor coincidence relationships consistent with wobbling excitations were observed between any of the eight SD bands in ^{174}Hf.[1] In ^{163,165,167}Lu [4,6,7], the strength of linking transitions from wobbling excitations to the $n_w = 0$ band was found to be comparable to that of the inband transitions: branching ratios ($I_{\mathrm{inband}}/I_{\mathrm{out}}$) near the bottom of the wobbling bands were determined to be $\sim$ 1–3 in these nuclei. As linking transitions between bands could not be observed in ^{174}Hf, only limits for these branching ratios at the bottom of the bands could be determined. These limits were obtained by assuming that I_{out} was equal to the intensity of the weakest observable peak in the spectrum from which I_{inband} was measured. The limiting branching ratios were found to be 21, 13, 11, 7, 18, 15, and 5 for SD 2–8, respectively.

Based upon the present experimental facts, we will now address the possibility that these sequences in ^{174}Hf are associated with stable triaxial deformation. It is important to first note that SD 1 is nearly isospectral with one of the SD bands observed in ^{175}Hf [14]. The latter structure has been linked to the known levels, and thus the excitation energy (12.682 MeV) as well as the spin/parity ($79/2^-$) of the lowest state have been determined. A seven-quasiparticle configuration including two $i_{13/2}$ protons, two $i_{13/2}$ neutrons, and two $j_{15/2}$ neutrons has been proposed for this sequence [14]. Identical bands, especially those with large deformation, are often associated with closely related configurations. In particular, they often contain the same high-j orbitals [25]. Thus, the strongly deformed bands in ^{174}Hf may well be based on configurations with at least six quasiparticles and be located at high excitation energy ($>$ 10 MeV). Additionally, if this reasoning is correct, the spin assignments suggested for the four previously known bands in ^{174}Hf [12] should be raised by 12–14 $\hbar$, assuming spins similar to those of the identical SD band in ^{175}Hf. This assignment creates a large gap in both energy ($>$ 3.5 MeV) and spin ($\sim$ 14 $\hbar$) between the lowest level in the SD band and the normal deformed states fed by the band. Thus, no linking transitions to the known levels have been identified.

The complex configurations suggested for the Hf cases are in contrast to the relatively simple one-

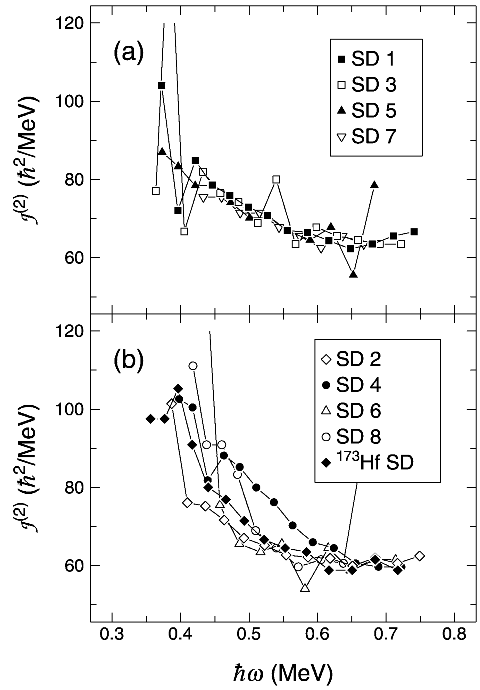

Fig. 5. The dynamic moments of inertia for the eight SD bands in ^{174}Hf and the one in ^{173}Hf. The ^{174}Hf bands were split into possible "families" of bands based on the similarity of their moments of inertia.

quasiparticle, $\pi i_{13/2}$ configurations of the lighter Lu isotopes. Evidence of this added complexity may be found in the quadrupole moments. Relatively small values of $Q_t =$ 6–10 b were measured for the Lu TSD bands [26,27] compared to those in ^{174}Hf reported here and even in ^{168}Hf ($Q_t = 11.4^{+1.1}_{-1.2}$ b [8]). The larger deformation in ^{174}Hf can be explained by the suggested presence of the intruder $j_{15/2}$ neutrons in the configuration of SD 1. The $j_{15/2}$ orbital, which originates above the $N = 126$ spherical shell gap, is known to drive nuclei to higher deformations, such as in the mass 150 and 190 regions of superdeformation [28]. The similarity of the quadrupole moments measured for bands 1–4 in ^{174}Hf suggests related configurations in all cases, and, thus the involvement of $i_{13/2}$ protons and $j_{15/2}$ neutrons in each band. Therefore, the Hf bands appear to be part of a different "class" of SD bands than the Lu TSD structures [14].

As stated above, if the strongly deformed sequences in ^{174}Hf are triaxial (as suggested by UC calculations), a family of bands (with nearly identical moments of

[1] Linking transitions between SD 3 and 6 were observed due to an accidental degeneracy, and will be discussed in a future publication [24].

inertia) is expected to be observed, and each band is then associated with a different wobbling quanta. It is indeed possible to group the bands in ^{174}Hf into two distinct families based on the behavior with frequency of their moments of inertia, as seen in Fig. 5. Bands 1, 3, 5, and 7 all have nearly the same moments over the observed frequency range (Fig. 5(a)), while bands 2, 6, and 8 (Fig. 5(b)) also have moments similar to each other, but approximately 10% less in magnitude. In the context of triaxiality, this could suggest two $n_w = 0$ configurations associated with bands 1 and 2 (the strongest of the SD sequences) with the weaker structures representing wobbling excitations built on each. The existence of two families in ^{174}Hf would imply two TSD minima, a possibility supported by the UC calculations. Indeed, TSD minima are predicted for all parity/signature combinations, thus SD 1 and 2 may result from two minima with different parity and/or signature. However, the presence of SD bands with similar moments of inertia is not unique to wobbling. Observing linking transitions between these bands is necessary to validate this picture. Since such transitions have not been observed, the presence of triaxiality cannot be asserted conclusively. Band 4 has a unique $\mathcal{J}^{(2)}$ profile in comparison with the other sequences, which may indicate that it is based on a yet another configuration.

As seen in Fig. 5(a), SD 1 and 3 do have similar moments, thus, SD 3 may be a wobbling excitation based on SD 1. The quadrupole moment of a wobbling excitation should be the same as that of the $n_w = 0$ band (associated with SD 1), as recently demonstrated in ^{163}Lu [27]. Although the measured moment of SD 3 ($13.0^{+0.8}_{-0.4}$ b) is somewhat smaller than that of SD 1 ($13.8^{+0.3}_{-0.4}$ b), the values agree within error, in support of this interpretation. However, this is once again not conclusive as many superdeformed bands have similar quadrupole moments. Unfortunately, the weakness of bands 5–8 did not allow for a reliable measurement of their quadrupole moments.

Not only do the present experimental data not prove stable triaxial deformation for ^{174}Hf, they also result in some inconsistencies with the theoretical predictions if triaxiality were present. For example, the measured quadrupole moments are significantly larger than those calculated by the ultimate cranker. The total energy surface (TES) of the $(\pi, \alpha) = (+, 0)$ configuration is shown in Fig. 6. It should be noted that this

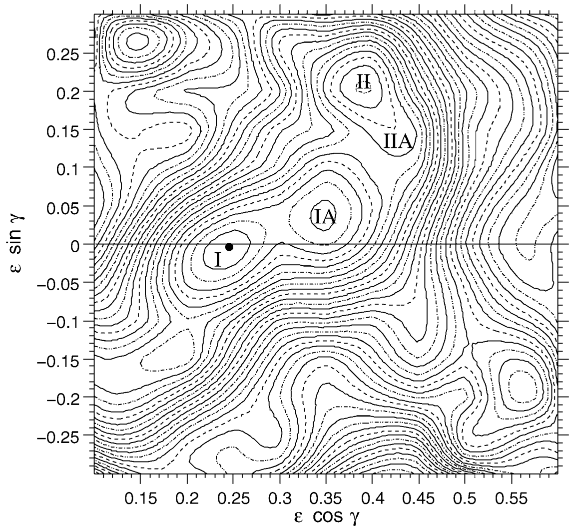

Fig. 6. Potential energy surface for ^{174}Hf for the lowest $(\pi, \alpha) = (+, 0)$ configuration at spin $I = 50$. Four minima are marked in the surface and are described in the text. The energy spacing between contour lines is 200 keV.

surface was calculated somewhat differently than that given in Ref. [12]. A spin projection has been applied in the latest calculations, and the various minima were tracked over a wide range of spin (0–58 $\hbar$). A representative surface at $I = 50\,\hbar$ is displayed in Fig. 6. Located near $\epsilon_2 = 0.25$ and $\gamma = 0°$, minimum I is representative of the normal deformed configurations. The lowest TSD minimum is labeled II in Fig. 6, with parameters of $\epsilon_2 \approx 0.45$ and $\gamma \approx 27°$. A similar minimum is found in each of the parity/signature combinations, and is also observed over a wide spin range ($> 25\,\hbar$). These deformations lead to a quadrupole moment of ~ 9.9 b,[2] significantly lower than the experimentally determined values. Since the assertion of triaxiality is based solely on the UC results, such a large discrepancy is cause for concern.

A second TSD minimum appears to be located near minimum II and has been labeled IIA in Fig. 6. This minimum has deformation parameters of $\epsilon_2 \approx 0.47$ and $\gamma \approx 18°$, corresponding to a quadrupole moment of ~ 12.2 b. Perhaps some of the SD bands in ^{174}Hf can be associated with this minimum, since the predicted quadrupole moment lies near the experimental

[2] The hexadecapole parameter was assumed to be $\epsilon_4 = 0.020$.

value. However, in the UC calculations, this minimum is only observed over a short spin range (50–56 $\hbar$) and is only found for the $(\pi, \alpha) = (+, 0)$ combination. One may also consider minimum IA to possibly describe the bands. Minima similar to IA are found in all of the parity/signature combinations with $\epsilon_2 \approx 0.35$ and $\gamma \approx 8^\circ$. However, its predicted quadrupole moment (~ 9.9 b) is again lower than that observed. Therefore, it appears that the UC is not able to accurately account for the strongly deformed bands in ^{174}Hf. Further theoretical investigation is clearly needed to explore the nature of the observed excitations.

It is also interesting to note that only a single SD band is found in the odd-A neighbors ^{173}Hf and ^{175}Hf [14] nuclei, in sharp contrast with the multiplicity of bands seen in ^{174}Hf. This observation is not a question of sensitivity: as can be seen from Fig. 4, the candidate SD band in ^{173}Hf was populated with nearly the same strength as SD 1 in ^{174}Hf. Since a family of bands was found with SD 1, a family of sequences would also be expected in ^{173}Hf if the strongly deformed structures were indeed triaxial, and if similar energies were associated with the wobbling phonons. If the wobbling excitations were at higher energies in ^{173}Hf, however, a lower population could account for their absence. Another possible explanation for the missing bands is that the strongly deformed structure in ^{173}Hf does not lie in a TSD minimum. It seems unlikely, however, that, if a stable triaxial minimum were present, it would not exist in both ^{173}Hf and ^{174}Hf.

In summary, the measurement of quadrupole moments confirms the large deformation of the four previously known SD bands in ^{174}Hf. Four additional, presumably strongly deformed, bands were observed in ^{174}Hf, as well as one in ^{173}Hf. However, the non-observation of linking transitions, the discrepancy between measured and calculated Q_t moments, and the absence of comparable families of bands in ^{173,175}Hf raise serious questions about an interpretation in terms of triaxiality. From the present investigations it is clear that the Hf SD bands are associated with more complex configurations than the TSD bands found in lighter Lu nuclei. Whether the bands are triaxial or not, the UC is unable to predict any minimum able to account for the large quadrupole moments found in the data. These new results thus constitute a considerable challenge for the interpretation of the behavior of Hf nuclei.

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