High-K Barrier Penetration in ^{174}Hf: A Challenge to K Selection

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A sensitive study of the decay of the deformation-aligned $K=14$, 4-μs isomer in ^{174}Hf has revealed a multitude of K-forbidden branches to the ground-state rotational band and other low-K bands, in competition with the known decays to high-K bands. The isomeric transitions have consistently low hindrance factors. These anomalous findings in an axially symmetric deformed nucleus severely test our understanding of the K-selection rule. The isomeric decay to an $I=12$ rotation-aligned state, and its mixing with the $I=12$ yrast state, provide a partial explanation.

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Angular momentum selection rules have wide application to transitions between quantum states. In the study of nuclear structure, the K-selection rule has provided useful predictions for electromagnetic transitions between different quasiparticle excitations in deformed nuclei. The projection (K) of the total angular momentum on the symmetry axis of a deformed spheroidal nucleus is a constant of the motion, except that to some extent collective rotation itself destroys the time-reverse symmetry of the paired neutron and proton orbits. Thus, the breakdown of K conservation in electromagnetic transitions (i.e., when the change in K is greater than λ, the transition multipolarity) yields information regarding both the departures from axial symmetry, and the effects of the inertial forces of rotation on the otherwise paired orbits.

A striking example of the breakdown of K conservation was recently identified[1,2] in ^{182}Os, where a 130-ns, $I=25$ K isomer has a significant $\lambda=1$ electromagnetic decay branch directly to the low-K yrast band, in competition with complicated decay paths through other high-K configurations. The anomalous branch to the yrast band has been discussed[2] in terms of tunneling through a potential barrier in the axially asymmetric γ degree of freedom, akin to the β-deformation tunneling from fission isomers. Potential-energy-surface calculations[3] indicate that the ground state of ^{182}Os is soft to γ distortions, observed experimentally as a low energy (891 keV) of the γ vibration. Hence in ^{182}Os, although there is a strong indication of severe violation of the K-selection rule, there are ambiguities regarding the validity of the K quantum number. Furthermore, the isomer decay feeds the yrast band above its first band crossing, where its structure is complex.

In an effort to improve our experimental knowledge of anomalous K violations, we have carried out a careful search in the hafnium isotopes. The hafnium ($Z=72$) isotopes contain the best known sequences of high-K deformation-aligned isomeric states,[4] in what are usually considered to be axially symmetric deformed nuclei. The high-K values arise from the alignment of individual-particle angular momenta along the deformation axis. "Normal" K selection is well established; i.e., the observed transitions involve the smallest possible changes in K value. The normal decay of high-K isomers in ^{176}Hf has been specifically contrasted[1,2] with the anomalous decay in ^{182}Os. Therefore, any observation of violations of the K-selection rule in the hafnium isotopes would severely test our understanding of the validity of the K quantum number.

Experiments have been performed with the European Suppressed Spectrometer Array[5] (ESSA-30) at the Daresbury Laboratory Nuclear Structure Facility. Bunched and chopped beam pulses (2 ns wide) of ^{48}Ca were incident on a 2-mg cm^{-2} ^{130}Te target, gold backed for mechanical support. The target itself was shielded from direct view of the thirty Compton-suppressed germanium detectors, but the recoiling fusion-evaporation reaction products were caught on a lead foil in the center of the germanium detector array. γ-γ coincidence events were recorded, with the additional optional requirement that the events were between beam pulses, thus giving high selectivity to transitions occurring following isomer formation at the target. The method is sensitive to isomer decays having half-lives longer than about 10 ns, and is appropriate in particular to search for weak branches below the known $K=14$, 4-μs isomer[4] in ^{174}Hf, and the $K=\frac{35}{2}$, 1-μs isomer[6] in ^{175}Hf, both of which are strongly populated at the ^{48}Ca beam energy of 198 MeV.

The sorting of the event-by-event coincidence data reveals that at least twenty transitions decay directly from the $K=14$ isomer in ^{174}Hf, into twelve different structures. The transition energies and relative intensities are given in Table I. In several cases the direct transitions from the isomer are not themselves observed, due to high electron conversion or low-energy discrimination by the

TABLE I. Transitions depopulating the $K^\pi = 14^+$, 4-μs isomer in ^{174}Hf.

Energy (keV)	I_γ [a] (%)	States populated [b] $I^\pi K$	Structure	Hindrance f_ν [c]
(11.6)	(8.5 ± 0.4)	13^-12	4-qp	5×10^6 ($E1$)
(15.4)	(< 0.1)	15^-1	$L=3$ vib	> 5.5 ($E1$)
(32.0)	(< 0.1)	13^+4	2-qp	> 7.9 ($M1$)
(42.7)	(42.2 ± 0.9)	13^+6	2-qp	6.1 ($M1$)
(51.5)	(< 0.1)	14^-1	$L=3$ vib	> 6.2 ($E1$)
(81.5)	(0.6 ± 0.1)	12 11	4-qp	
(131.0)	(< 0.1)	14^-6	2-qp	> 34 ($E1$)
153.8	1.9 ± 0.8	13^-8	2-qp	81 ($E1$)
194.3	0.1 ± 0.1	13^+3	$L=4$ vib	8.2 ($M1$)
222.5	9.5 ± 0.3	12^-12	4-qp	··· ($M2$)
319.1	0.1 ± 0.1	14^+0	β-vib	5.6 ($M1$)
328.4	32.4 ± 0.9	12^+6	2-qp	4.1 ($E2$)
342.0	< 0.1	12^+4	2-qp	> 6.1 ($E2$)
379.0	2.0 ± 0.2	13^-6	2-qp	34 ($E1$)
457.7	0.5 ± 0.1	12^+3	$L=4$ vib	4.9 ($E2$)
539.7	0.1 ± 0.1	13^-1	$L=3$ vib	11 ($E1$)
627.1	0.7 ± 0.1	12^+	S band [d]	> 3.7 ($E2$)
714.2	1.1 ± 0.1	14^+0	Yrast	5.7 ($M1$)
822.8	0.2 ± 0.1	12^+0	β-vib	4.5 ($E2$)
1291.2	0.2 ± 0.1	12^+0	Yrast	5.5 ($E2$)

[a] γ-ray intensities. Parentheses indicate that the presence of the transition is inferred from isomeric feeding of lower levels in ^{174}Hf, with total transition intensity estimated from the presently observed strength of these lower transitions.

[b] Quasiparticle (qp) and vibrational (vib) assignments are mostly from Ref. 4.

[c] Hindrance per degree of K forbiddenness (conversion corrected).

[d] The K value and structure are discussed in the text ($f_\nu = 3.7$ for $K=0$).

spectrometers, but must exist because of delayed feeding of known[4] states below the isomer. Of great significance is the unambiguous identification of direct transitions from the $K=14$ isomer to the ground-state band. The isomer also decays directly to all of the $K<14$ rotational bands that were previously known[4] up to high spin, whether high K or low K, demonstrating an apparent collapse of the K-selection rule. Two new bands with $K=4$ are also identified through their isomeric feeding, and many new transitions in the $K=3$ hexadecapole-vibrational band have been found. Details of these findings will be presented in a separate publication.

One way to compare K-forbidden transitions in a quantitative manner is through the hindrance f_ν per degree of K forbiddenness. The K forbiddenness of a transition is defined as $\nu = \Delta K - \lambda$, and $f_\nu = (T_\gamma / T_W)^{1/\nu}$, where T_γ is the partial γ-ray half-life and T_W is the corresponding Weisskopf single-particle estimate. The hindrance factors for transitions depopulating the ^{174}Hf $K=14$, 4-μs isomer are given in Table I. This is a unique list in the sense that, for the first time, many different transitions from a single isomer can be compared. Of special note is the observation that all $M1$ and $E2$ decays, with ν covering the range 6–13, have $f_\nu \simeq 5$, a much lower value than expected from usual K-hindrance considerations.[7]

The direct decay to the ground-state band is particularly surprising, due to the simple structure[4] of both the isomer (a four-quasiparticle state) and the ground-state band. The latter takes the form of a straightforward rotational band, closely approximating $I(I+1)$ behavior. The observed highly K-forbidden transitions identify a dramatic change in the way that the nucleus accommodates angular momentum, from individual particle motions about the symmetry axis of the prolate spheroid (in the four-quasiparticle isomer) to collective rotation perpendicular to the symmetry axis. While the shape rearrangement between two contrasting nuclear symmetries can be conceived macroscopically as tunneling through a barrier in the γ-deformation potential-energy surface,[2] a more microscopic description may be based on the Coriolis mixing of rotational states with different K quantum numbers.

An important part of the K-mixing interpretation of the fragmented isomer decay pattern comes from the identification of the $I=12$ member of the rotation-aligned $(i_{13/2})^2$ S band (i.e., the band structure that becomes energetically favored over the ground-state band by alignment of two $i_{13/2}$ neutrons to the rotation axis at[8] $I \sim 18$). There is direct feeding from the isomer to a level at 2685 keV (627-keV transition) labeled "S" in Fig. 1, which itself decays to both the $I=12$ yrast state and the $I=12$ member of the β-vibrational band. From angular momentum considerations, the S level has a spin of at least $12\hbar$. The level is isolated in the sense that it has

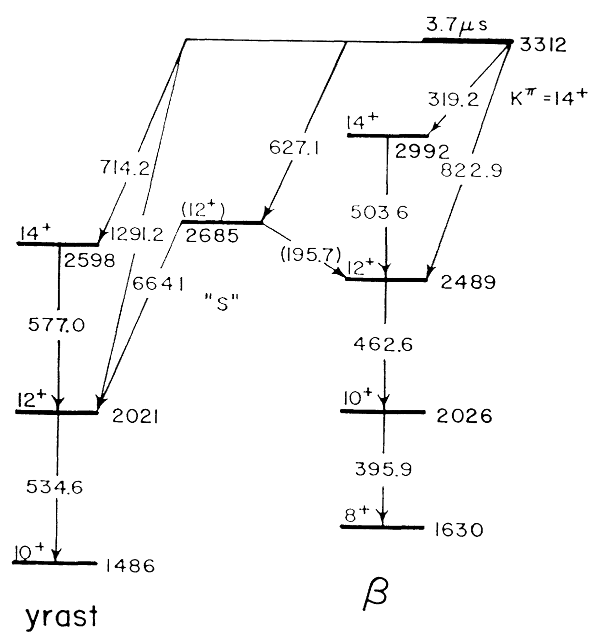

FIG. 1. Partial decay scheme from the 3312-keV isomer in ^{174}Hf, to the yrast band and the β-vibrational band. The 2685-keV level, labeled "S," is discussed in the text.

no identifiable decays within its own rotational band, in contrast to the other nine distinct rotational bands populated by the decay of the $K=14$ isomer. The decay of the S level exclusively to the $K=0$ ground-state and β bands forbids a four-quasiparticle high-K band-head interpretation of its isolated position. Also, it is closer to yrast than all other bands except the β-vibrational band. However, an $I=12$ S-band interpretation is able to account for these otherwise anomalous features. Mixing with the ground and β bands (see also below) can explain its decay to these in preference to lower-spin members of the S band, and its excitation energy is consistent with extrapolation (see below) from the higher-spin[8] S-band members (i.e., from above the S-band to ground-state-band crossing). The lack of identified $E2$ branches to the 10^+ members of the ground-state and β bands is consistent with the favoring of $\Delta I=0$ transitions found in other nuclei (e.g., ^{164}Er, Ref. 9) immediately below a band crossing. From these considerations, we give an $I=12$ assignment to the S level, although the present experimental data are not able to rule out the $I=13$ and 14 alternatives.

The following discussion will focus on the role of the 2685-keV S level in the interpretation of the decay of the $K=14$ isomeric level. Since the S band involves rotation-aligned $i_{13/2}$ neutrons, the projection of the individual particle angular momentum on the rotation axis J_x becomes a constant of the motion, rather than the projection K on the symmetry axis. These good J_x states may, however, be expressed as a linear sum of K-conserved wave functions, with a broad range of K values. (A typical spread in K values induced by $\Delta K=1$ Coriolis mixing can be seen in the wave-function amplitudes calculated[10] for a single $i_{13/2}$ neutron in ^{175}W.) A reasonable estimate of J_x in the S band may be made from the dependence of the total angular momentum on the rotational frequency.[11] In ^{174}Hf we find that $J_x \sim 6\hbar$, as illustrated in Fig. 2, similar to other nuclei in this mass region.[12] Assuming that $J_x^2+K^2=J^2$, where $J=12$ for two $i_{13/2}$ neutrons, it follows that $K \sim 10\hbar$. This simple estimate yields a maximum K value, but $\langle K\rangle \simeq 0$ due to precession around the rotation axis. The presence of such high-K components is consistent with the position of the Fermi surface, close to the $\Omega=\frac{7}{2}$, $i_{13/2}$ orbital, and could account for the strong population of the 2685-keV S-band level from the $K=14$ isomer. We note that the extrapolation of the low-spin part of the S band shown in Fig. 2 predicts that the $I=12$ state will be at about 2670 keV (before mixing) in support of the assignment to the observed level at 2685 keV.

We now examine the mixing of the $I=12$ S-band state with the $I=12$ yrast state, considering energy-level perturbations as well as transition probabilities. It is well known that, where the S band crosses the ground-state band, significant mixing can be identified, with a strength that determines whether the yrast band actually backbends or not. An estimate of the mixing strength can be obtained from the experimental data, using simple two-band-mixing calculations of energy levels to reproduce the shape of the angular momentum curve as a function of rotational frequency. We find that in ^{174}Hf the ground-band and S-band interaction is in the range 100–250 keV, depending on the detailed form of the ground-band and S-band extrapolations, compared with a prediction[12] of about 130 keV. The effect of a 250-keV interaction is illustrated in Fig. 2. This ground-band and S-band mixing introduces small high-K components into the yrast band. The mixing needed to account for the relative transition probabilities to the $I=12$ yrast and S-band states from the $K=14$ isomer is calculated here to be 60 keV, somewhat less than the energy-level estimate. Although other K-mixing mechanisms may contribute, it appears that normal band mixing is able to account for the anomalous decay of the $K=14$ isomer directly to the ground-state band. Correspondingly, a β-band and S-band interaction of 50 keV accounts for the relative population of the $I=12$ member of the β band, and feeding of the hexadecapole-vibrational band may take place through a related mechanism. The existence of some common mode of K mixing is suggested by the consistently low f_ν hindrance factors for $M1$ and $E2$ transitions (Table I).

An alternative description of such highly K-forbidden

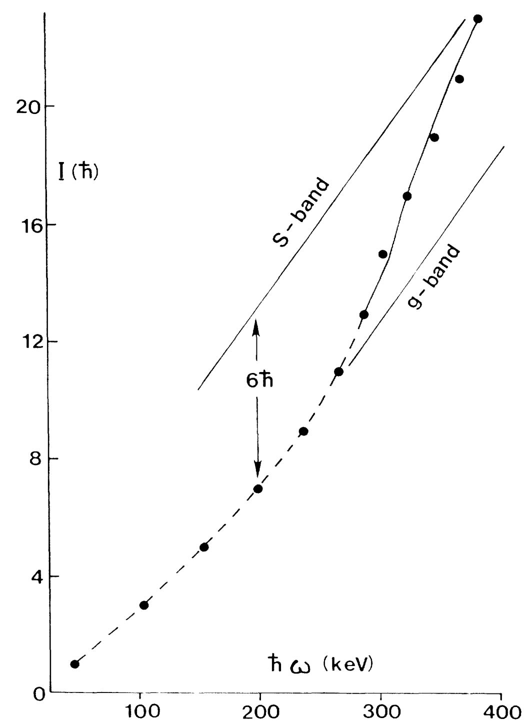

FIG. 2. Angular momentum as a function of rotational frequency for the yrast band of ^{174}Hf, plotted according to the conventions of Refs. 11 and 12. The solid line between the ground-band and S-band extrapolations represents the effect of 250-keV mixing, and is compared to the experimental yrast band (circles).

decays is given in a recent Letter by Bengtsson *et al.*[13] in terms of a tunneling through the γ-deformation degree of freedom (strongly influenced by the pairing strength) specifically with respect to ^{182}Os. A microscopic understanding of the tunneling process is discussed by Donau *et al.*[14] Whether such a description can be applied to the fragmented decay of the ^{174}Hf isomer remains an interesting open question.

In summary, we have discovered a remarkable decay pattern from the $K=14$ isomer in ^{174}Hf. The identification of the $I=12$ S-band state, and its mixing with the ground-state band, expose a possible cause of the K violations. The transition from deformation-aligned to collective structure is seen to be mediated by mixing with a rotation-aligned configuration. A quantitative comparison with ^{182}Os may be difficult because of the γ softness in the ground state of that nucleus, together with the fact that the $I=25$ isomer in ^{182}Os feeds into the yrast band above its S-band crossing. The nucleus ^{174}Hf provides a test case for the rotational model, with many rotational bands directly populated having simple quasiparticle and collective structures. Although much of the detailed experimental information can be understood with the band-mixing approach discussed here, more sophisticated theoretical treatments (e.g., Refs. 12 and 13) are undoubtedly required to achieve a fuller understanding of the way in which tunneling through the γ plane is able to account for the nuclear shape rearrangement.

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