Novel Decay Modes of High-K Isomers: Tunneling in a Triaxial Landscape

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The nucleus ^{176}W has been studied using the reaction ^{150}Nd(^{30}Si,4n), with prompt and delayed γ-γ coincidence techniques. A $K = 14$ isomer ($t_{1/2} \approx 70$ ns) is found to exhibit a unique decay pattern, primarily decaying to $K = 0$ states, in contrast to all previously studied high-K isomers. Calculations have been performed of both Coriolis mixing and tunneling through a potential barrier in the triaxial degree of freedom to understand these unusual decays. While Coriolis mixing models do not reproduce the variations in the decay patterns in neighboring nuclei, the tunneling calculations are remarkably successful.

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Conserved quantum numbers are a consequence of specific symmetries of the Hamiltonian describing a physical system. In a complex many-body system, such as a nucleus at high spin, the violation of conserved quantum numbers provides valuable insight into the dynamics and interactions between various degrees of freedom of the system which conspire to break these symmetries. An example of such a conserved quantum number in deformed nuclei with axial symmetry is the projection, K, of the total angular momentum on the axis of symmetry.

High-spin states in prolate deformed nuclei are formed by a combination of collective rotation and the alignment of individual nucleonic spins. The alignment phenomenon most often observed is rotational alignment, in which the Coriolis force causes pairs of nucleons in time-reversed orbits in the ground state band (g band) to decouple and align their spins along the axis of collective rotation, perpendicular to the symmetry axis, with $\langle K \rangle=0$. The lowest-energy band containing two rotation-aligned particles is known as the s band. Valence nucleons may also align their individual spins along the axis of symmetry. This $K \neq 0$ part of the angular momentum is completely noncollective, since a quantum rotor cannot rotate about an axis of symmetry. High-K states compete with rotation-aligned $\langle K \rangle=0$ states as energetically favorable modes only in nuclei which have many orbitals available near the Fermi surface with large components of their spins along the axis of symmetry.

Conservation of K naturally leads to electromagnetic selection rules. Transitions between states with $|\Delta K| > \lambda$, where λ is the multipolarity of the transition, are approximately K forbidden, and $\nu = |\Delta K| - \lambda$ is defined as the degree of K forbiddenness. Such transitions are hindered by large factors, typically 100 per degree of K forbiddenness [1], which leads to high-K isomers. Usually, such high-K isomers decay to rotational states built on lower-K bandheads, some of which are isomeric themselves. These have been observed [2] in prolate Hf, W, and Os (Z =72–76) nuclei with $A \approx$180. More recently, however, decay modes of high-K isomers with unusually low hindrances (2–5 per degree of K forbiddenness) have been observed [3–5] in a handful of nuclei. These anomalous decay modes are the subject of intense study, and are not adequately understood. One of the most surprising features of these decays is the observation [4,5] of direct branches from the high-K isomers to the $\langle K \rangle=0$ states, which severely violate normal K selection rules. Mechanisms suggested for such decays include Coriolis mixing of different K values [5] and tunneling through a potential barrier in the γ (triaxial) degree of freedom [4]. The former involves fluctuations in K, from the mixing of wave functions corresponding to the same shape, but different orientations of the nucleus with respect to the angular momentum. The latter involves shape fluctuations in which the nucleus tunnels from an initial configuration, where the angular momentum and symmetry axis are aligned, to one where they are perpendicular. The tunneling occurs through a barrier in the triaxial shape degree of freedom, although the nucleus is axially symmetric (prolate) in the initial and final states.

If Coriolis mixing is the dominant mechanism, then the unusual decay patterns should depend on the quasiparticle configuration, deformation, and rotational frequency, but if γ tunneling plays an important role, then the measured hindrances should be strongly correlated with the height of the barrier, which varies rapidly with Z in the $A \approx$180 region. The nucleus ^{176}W is an excellent candidate for distinguishing between the two mechanisms. It is a neighboring even-even isotone of ^{174}Hf, where unusual decay modes of a 14^+ isomer have been observed [5]. Hints of delayed feeding of states in the g band of ^{176}W had been observed earlier [6]. The goal of this experiment was to locate and study isomers in ^{176}W at similar spin.

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The nucleus ^{176}W was studied using the reaction ^{150}Nd(^{30}Si,4n), with a pulsed (82 ns period) beam of 133 MeV ^{30}Si from the ATLAS superconducting linear accelerator at Argonne. The target consisted of 1.1 mg cm^{-2} of ^{150}Nd on a 53 mg cm^{-2} Pb backing, with a very thin layer of Au evaporated on the front surface to prevent oxidation. The γ rays were detected with twelve Compton-suppressed Ge detectors and fifty BGO detectors. A total of 45×10^6 events were recorded with a master trigger of at least two Ge detectors (firing within 120 ns of each other) in coincidence with signals from at least four BGO elements. Delayed firing of BGO elements was used to tag the decay of a high-K isomer. Gating on a delayed BGO fold parameter provided an extremely sensitive and efficient trigger for improving the signal-to-noise ratio for the low-intensity transitions associated with the isomer. The level scheme was constructed by studying both prompt and delayed γ-γ coincidences, and directional correlation intensity ratios were extracted for mutipolarity assignments [7].

This Letter will concentrate on results directly relevant to the K-violating mechanisms. Most striking is the identification and detailed spectroscopy of the feeding and decay of a 14$^+$ isomer with $t_{1/2} \approx 70$ ns, which received less than 2% of the population of the 4n evaporation channel (Fig. 1). Rotational band structures built on many intermediate-K states were mapped out in detail in prompt spectroscopy, but no decays of the K=14 isomer to any of these states were observed. Instead, more than half the decay flux of the isomer is carried by *direct* decays to $\langle K\rangle$=0 states of the g, s, and $0_2{}^+$ bands. This is the only known K isomer with such decay characteristics. In all previous examples of unusual decays of high-K isomers, the direct decay branches from the high-K isomer to $\langle K\rangle$=0 states were only a small fraction of the total decay [4,5], for example, 2% of the total for the K=14 isomer in ^{174}Hf [5].

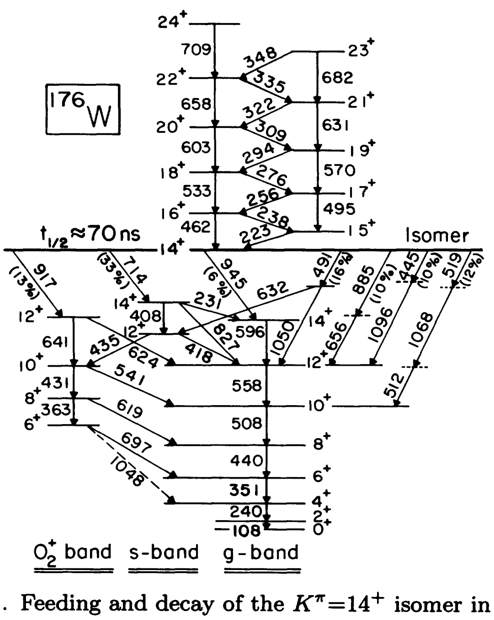

FIG. 1. Feeding and decay of the K^π=14$^+$ isomer in ^{176}W.

The isomeric state in ^{176}W is assigned J^π=14$^+$ from an analysis of the pattern of decays to states whose spins and parities were determined from prompt spectroscopy. The 14$^+$ state is assigned a configuration [7] of $\pi7/2^+[404] \otimes \pi9/2^-[514] \otimes \nu7/2^+[633] \otimes \nu5/2^-[512]$, based on (a) the observed B(M1)/B(E2) branching ratios for the rotational band built on the isomer, which agree very well with those calculated for the above configuration and (b) Woods-Saxon calculations, which predict this configuration to be the four-quasiparticle state closest to the yrast line, at an excitation energy of 3.5 MeV, in good agreement with the observed value of 3.746 MeV. In the band built on the isomer, no rotational alignment is observed for $\omega < 0.35$ MeV $\hbar^{-1}$, as expected for this configuration, in which the $\nu i_{13/2}$ alignment would be blocked.

The configuration suggested for the 14$^+$ isomer in ^{174}Hf is the same as that in ^{176}W, and again detailed branching ratios are available [5] for its decay. Thus, it is possible for the first time to put to a systematic test the two models that have been proposed to date to explain these unusual decays, i.e., Coriolis mixing and γ tunneling. An explanation suggested for the ^{174}Hf results [5] was that a change in Coriolis mixing occurs because of the change in the structure of the yrast states from the g-band to the s-band configuration. Although the mean K value of the s-band states is also zero, because the two quasineutrons are in a coupling scheme aligned perpendicular to the symmetry axis, admixtures of various K values are to be expected in the s-band wave function, ranging from $K = 0$ to $K \approx K_{\rm max}$, where $K^2_{\rm max} = j^2_{\rm max} - i^2$. Here $j_{\rm max}$ is the maximum spin to which the two neutrons can be coupled subject to the Fermi exclusion principle, and i is their rotation-aligned angular momentum. This might explain the highly K-violating decays to the s-band states as due to Coriolis mixing, with essentially normal values of the hindrance per degree of K forbiddenness of about 100, but with a reduced degree of K violation, $\nu' = \nu - K_{\rm max}$. The observed decays to the g-band states in ^{174}Hf were attributed to the mixing of the g-band and s-band configurations in the band-crossing region. A test of this model requires a measurement of the interaction matrix element which mixes the s-band states with the other $K = 0$ states. The present experiment provides the relevant data for ^{176}W, because the decay of the isomer has made possible the observation of a variety of the nonyrast $K = 0$ states.

Starting from transitions identified in the decay of the isomer, it was possible to extend both the g and s bands to states above and below the g-s crossing, respectively (Fig. 2). These states are normally extremely difficult to isolate and study. An upper limit of 33 keV is obtained for the interaction matrix element, V_{gs}, between the g

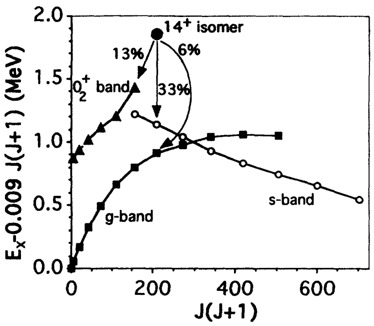

FIG. 2. Excitation energy as a function of $J(J+1)$ for the g, s, and $O_2{}^+$ bands in ^{176}W. Decay branches of the 14^+ isomer to the $\langle K \rangle$=0 bands are shown.

and s bands in ^{176}W, based on the 66 keV separation of the two closest 16^+ states. The third band is identified as the band built on the first excited O^+ state.

The Coriolis mixing mechanism described above seemed to be a reasonable one to account for the ^{174}Hf data, but it fails to explain the new ^{176}W data. The ^{174}Hf data contained only two decays to $K=0$ states whose s-band admixtures were known, making it difficult to determine whether there was truly any correlation between the hindrance factors and the s-band admixtures. Such a correlation is the most direct prediction of this model. The present experiment provides an extended data set, with measured interaction matrix elements, which allows the band mixings to be quantitatively examined within the framework of this simple model. No correlation is observed between the hindrance factors and the s-band admixtures [7]. While a more detailed treatment of Coriolis mixing would be valuable, we do not expect results that are qualitatively different from our estimates, and it is difficult to imagine how the lack of correlation can be explained in this way.

The alternative mechanism, γ tunneling, had been proposed to explain the direct decay of a 25^+ isomer to $K=0$ states in ^{182}Os [4]. Subsequent calculations of the decay rate, using a model of pairing-assisted tunneling [8], had yielded reasonable results for the particular case of ^{182}Os. The unique character of the ^{176}W isomer decay, where the intermediate-K states are bypassed in favor of larger K violations, naturally steers one from orientation-fluctuation scenarios (where decays to intermediate-K states are expected to prevail) to shape-tunneling scenarios (where direct decays might prevail). A test of the tunneling mechanism can now be made with the 14^+ isomers in ^{176}W and ^{174}Hf, searching for the predicted correlation with Z. For an adiabatic tunneling process, the only quantities needed to calculate the tunneling probability are the potential, V, and the inertial parameter, D, which corresponds to the mass in the Schrödinger equation. While quite sophisticated methods currently exist for calculating reliable potential energy surfaces, an estimation of D, which contains the information on the dynamics, is not straightforward, and different theoretical estimates give very different results. The approach here is to see whether all the available data from the unusual decays of the 14^+ isomers in ^{174}Hf and ^{176}W can be accounted for by a reasonable choice of an inertial parameter.

The calculated hindrance factor is $F^{\text{calc}} = 1/TS$, where $T = \exp[-2\hbar^{-1}\int\sqrt{2D(V-E)}\,d\gamma]$ is the WKB tunneling probability and S is the normalization factor to compare decays of different multipolarities on the same footing. The experimentally measured quantity is $F^{\text{exp}} = t_{1/2}/t^W_{1/2}$, the ratio of the measured partial half-life of the transition compared to the Weisskopf estimate. S is chosen to cover a typical range of unhindered transition strengths (0.03–0.3 W.u. for M1 and 10–100 W.u. for E2). If one neglects, for the moment, the more minor dependence of the zero-point energy, E_{zp}, on the inertial parameter, D, and assumes that D does not vary with γ, then a log-log plot of F^{exp} vs F^{calc} would have a slope which is proportional to $\sqrt{D}$. Here, in addition, the dependence of E_{zp} on D is also taken into account.

The potential energy was calculated as a function of γ for the $K=14$ isomers with a cranked Nilsson-Strutinski model [9], with the deformation parameters, ϵ_2 and ϵ_4, as well as the static pair gaps, Δ_p and Δ_n, determined self-consistently. The height of the barrier changes from 2.5 MeV in ^{176}W to 3.4 MeV in ^{174}Hf. Variation of D with deformation and pairing is expected and adjusted for. Microscopic models predict a Δ^{-2} dependence [8], while an ϵ^2 dependence is expected from hydrodynamic models [10]. Motivated by the treatment in Ref. [8], the functional form for normalizing the dependence on the pair gaps is chosen as $\sum(G_i\Delta_i^{-2})/\sum G_i$, where i refers to neutrons or protons. The pairing strengths, G_i, are as defined in Ref. [8], the pair gaps are taken from the odd-even mass differences, and the quadrupole deformations from the calculated values at the saddle point. The above corrections amount to a normalization factor for log F^{calc} of 0.88 for ^{176}W compared to ^{174}Hf.

The experimental and calculated hindrance factors for the 14^+ states in ^{174}Hf and ^{176}W nuclei are shown in Fig. 3. A clear correlation is observed, with an implied inertial parameter $D \approx 60$ MeV$^{-1}\,\hbar^2\,$rad^{-2}. This is reasonable in size when compared, for example, with a previous estimate at zero spin of $D \approx 13$ MeV$^{-1}\,\hbar^2\,$rad^{-2} obtained from fits to data on fission isomers [10]. The model was further tested with a series of K^π=6^+ isomers in this region, which decay through transitions of the same multipolarity. Again, a clear correlation was observed between the experimental and calculated hindrance factors [7], with similar values of D. This is indeed remarkable, considering that the hindrance factors involved span many orders of magnitude. It should be emphasized that the goal was not to extract an accurate value of D, but simply to test whether variations in the hindrance factors could be understood in the tunneling model with a consistent, reasonable choice of D. The value of D that is consistent with the data is quite sensi-

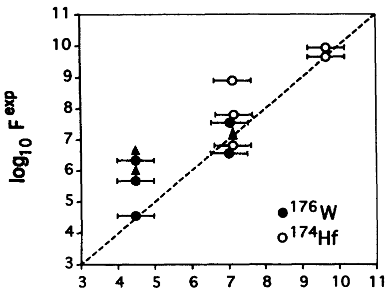

FIG. 3. Test of γ tunneling for the 14^+ isomers. The points represent the direct decays from the $K = 14$ isomer to $\langle K \rangle$=0 states. The data for ^{174}Hf are taken from Ref. [5]. For ^{176}W, the hindrance factors are calculated using the usual assumption of pure M1 multipolarity for the $J \to J$ and pure E2 character for the $J \to J - 2$ transitions. The dashed line represents an inertial parameter $D \approx 60$ MeV^{-1} $\hbar^2$ rad^{-2}. The horizontal bars show the range of choice of the unhindered transition strength S (see text). The data points with arrows represent lower limits on the hindrance factors, from upper limits on intensities of unobserved $K = 14$ to $\langle K \rangle = 0$ transitions.

tive, for instance, to the form of the normalizing function with respect to Δ. Nevertheless, the inertial parameter is a quantity of great physical interest, and the present results suggest the possibility, with further theoretical refinements, of using data on K isomers to extract information on the dynamics of motion in the shape degree of freedom at high spins. Another important topic for future theoretical work would be to explain the absence of decays to the intermediate-K states. This issue cannot be addressed using the present generation of cranking models, whose model spaces are restricted to states with their angular momenta along a principal axis of the deformation. Tilted-axis cranking models, where the rotation axis is not restricted to lie along principal axes, are currently being developed [11], and need to be explored in this context. Other possible mechanisms of K violation are accidental degeneracy and small-amplitude fluctuations in γ. The former explanation has little predictive power, and is unlikely in this case, because of the low density of states ($\approx$ 1/MeV) with fixed spin, parity, and K. Regarding small-amplitude fluctuations in γ, schematic calculations [11] suggest that they would simply enhance the normal type of K-isomer decay, in which the hindrance factors increase exponentially as a function of the degree of K forbiddenness.

In conclusion, a $K = 14$ isomer in ^{176}W exhibits a novel decay pattern where the *majority* of the decay proceeds via *direct* transitions to $K = 0$ states, bypassing all available intermediate-K states, in flagrant violation of normal K selection rules. Comparison with the decay of a $K = 14$ isomer in the neighboring isotone ^{174}Hf provides an immediate test of recent models that have been proposed for highly K-violating decays. Calculations involving tunneling from one minimum in the potential energy surface to another, through a barrier in the triaxial shape degree of freedom, achieve remarkable success in explaining the available data on the direct decays to the $K = 0$ states.

An analysis of possible mechanisms for the violation of the K quantum number, therefore, sheds new light on the limitations of the symmetries invoked in describing the dynamics of the many-body nuclear system at high spins. The concept of shape fluctuations, which break axial symmetry and cause tunneling of the quantum system from one configuration to another through nonaxial trajectories, provides a promising framework for pursuing the physics of the anomalous decay modes of high-K isomers.

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