Anomalous Isomeric Decays in ^{174}Lu as a Probe of K Mixing and Interactions in Deformed Nuclei

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A $K^\pi = 13^+$, 280 ns four-quasiparticle isomer in the odd-odd nucleus ^{174}Lu has been identified and characterized. The isomer decays to both $K^\pi = 7^+$ and $K^\pi = 0^+$ rotational bands obtained from the parallel and antiparallel coupling of the proton $7/2^+[404]$ and neutron $7/2^+[633]$ orbitals. K mixing caused by particle-rotation coupling explains the anomalously fast transition rates to the 7^+ band but those to the 0^+ band are caused by a chance degeneracy between the isomer and a collective state, allowing the mixing matrix element for a large K difference to be deduced.

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Atomic nuclei provide a unique finite quantum-mechanical system, within which intrinsic excitations can occur at energies comparable to those of the dominant collective modes. This leads to the possibility of probing dynamical effects and interactions for well-defined orbital configurations, in a system where the individual-particle and collective motions are strongly coupled. In spheroidally deformed nuclei such as those found in the mass-180 region, the major collective excitations correspond to rotations of the system around an axis perpendicular to the symmetry axis. When both intrinsic (individual-particle) and collective excitations are present, the projection (K) of the total angular momentum on the symmetry axis is, in principle, a conserved quantum number. This realization played a major part in the historical development of the unified collective model.

An important manifestation of the conservation of K is the occurrence of metastable states or isomers, caused by the inhibition imposed on transitions that violate the electromagnetic K-selection rule [1]. This rule states that transitions of multipolarity λ should not connect states with $|\Delta K| > \lambda$. Although the rule is not strictly adhered to, such transitions are severely hindered, by factors of approximately 50–100 or more, for each unit of mismatch, termed the forbiddenness (ν), and given by $\nu = |\Delta K| - \lambda$ [2]. This interpretation has led to the classification of transition strengths in terms of ν by comparing the partial γ-ray lifetimes T^γ to the expected single-particle values T_W^γ, to give the hindrance $F = T^\gamma/T_W^\gamma$, and then the reduced hindrance $f_\nu = F^{1/\nu}$. The similar magnitude of the f_ν values extracted implies that, at some level, the hindrance scale is independent of the magnitude of ν, and the complexity of the initial and final states, even though the transitions presumably proceed through very small admixtures in the wave functions.

Coriolis and centrifugal forces play a central role in the coupling of individual and rotational motion in nuclei [3], leading to a specific form of K mixing. The advantage offered by isomeric states as a probe partly rests on the combination of the defined nature of this mixing and the sensitivity of (forbidden) transition rates to very small K admixtures in the initial and/or final states.

Notwithstanding this, unexpected (highly K-forbidden) decay paths and corresponding anomalously low reduced hindrance factors have been observed for a few cases in the Hf-W-Os region [4–8]. Possible explanations have ranged from mixing in the low-K states, to tunneling through the barrier in the triaxial degree of freedom, with the latter likely to be important for γ-soft nuclei (see, for example, Refs. [5,9–13]). A consensus on the cause of these has yet to be established however, partly because it is difficult to make quantitative evaluations and also because there may not be a single cause.

The present results relate to the discovery and characterization of a four-quasiparticle isomer with anomalous decays, in the well-deformed odd-odd nucleus ^{174}Lu. Numerous branches are observed, including decays to a pair of two-quasiparticle rotational bands which arise from parallel and antiparallel coupling of the same odd proton and odd neutron. The results have been evaluated in the context of K mixing in both initial and final states, estimated quantitatively using a particle-rotor model that takes into account the different couplings. The observation of decays to states from both coupling extremes enables an internally consistent analysis to be carried out. The analysis explains some of the anomalous decays, but an additional ingredient is local mixing between the isomer and a rotational state within one of the two-quasiparticle bands. This in turn allows the extraction of the residual interaction in a case where the initial and final states have a large difference in K.

The results are from measurements made using 6.0 MeV per nucleon ^{136}Xe beams provided by the ATLAS facility at Argonne National Laboratory. Nanosecond pulses, separated by 825 ns, were incident on various targets, $\sim 6\ \mathrm{mg/cm^2}$ thick, in each case with a $25\ \mathrm{mg/cm^2}$ Au foil directly behind. Gamma rays were detected with Gammasphere, with 100 detectors in operation. Targets of natural Lu (97% ^{175}Lu, 2.6% ^{176}Lu), Lu enriched to 47% in ^{176}Lu, and enriched ^{174}Yb were used. Triple coincidences were required and the main data analysis was carried out with γ-γ-γ cubes with various time-difference conditions, and also with time constraints relative to the pulsed beam to select different out-of-beam regimes. Other results from the same measurements have been reported recently [14–16].

In these experiments, depending on the target, the nucleus ^{174}Lu is populated with single and two-particle transfers, as well as by charge exchange. Because of its proximity to the stability line, ^{174}Lu is not easily accessible with the fusion-evaporation reactions that are normally used to identify high-angular momentum states. Hence, the known level scheme was limited to two-quasiparticle intrinsic states and structures up to medium spins [17]. The present combination of heavy-ion induced transfer reactions and time-correlated γ-ray techniques has allowed the establishment of a scheme including multiquasiparticle isomeric states extending up to spins of $26\hbar$ and 6 MeV in excitation energy [18].

The partial level scheme given in Fig. 1 shows the multiple decays of the newly-identified $K^\pi = 13^+$ isomer, with a mean life of 280(25) ns. As expected in an odd-odd deformed nucleus, the level spectrum is complicated because two-quasiparticle structures can be formed at similar excitation energies from the proton and neutron Nilsson orbitals close to the Fermi surface. Both parallel and antiparallel couplings are possible, thus giving intrinsic states with $K = \Omega_p \pm \Omega_n$. The proton orbital closest to the Fermi surface is the $7/2^+[404]$ Nilsson configuration while the lowest neutron orbitals are the $5/2^-[512]$ and the $7/2^+[633]$ configurations, the latter of which is of $i_{13/2}$ parentage and is substantially mixed with the other components of this orbital through the Coriolis interaction. The four, two-quasiparticle intrinsic states shown in Fig. 1 arise from the parallel and antiparallel couplings described above, giving $K^\pi = 1^-$ and 6^- and $K^\pi = 0^+$ and 7^+, pairs, each with an associated rotational band, the lower members of which were known [17].

Possible assignments for the isomer at 1856 keV are $J^\pi = 13^\pm$ or $14^\pm$, but because of the large number of branches, including decays to 11^+ states, all except the 13^+ alternative can be eliminated on the basis of unacceptable transition strengths, particularly those of $M2$ or $E3$ character. This assignment concurs with multiquasiparticle calculations (such as those carried out in Refs. [14,15]) which predict that the lowest-lying four-quasiparticle state will be a 13^+ level from the configuration: $\nu^3 5/2^-[512]7/2^-[514]7/2^+[633] \otimes \pi 7/2^+[404]$.

The interesting facet of the isomer's properties is its decay through sequences obtained from parallel and antiparallel couplings of the $7/2^+[404]$ proton and the $7/2^+[633]$ neutron resulting in $K^\pi = 0^+$ and 7^+ bands. As can be seen from Table I, the reduced hindrances for branches to the $K^\pi = 0^+$ band, evaluated using the nominal K values are very low, while those to the $K^\pi = 7^+$ band are marginal, being ~ 30 and as low as 17.

Two contributing aspects will be discussed in the following: the K mixing due to rotation-particle coupling that is expected when high-j particles are involved, as is the case for the 0^+, 7^+, and 13^+ configurations, and chance degeneracies. The former will be carried out with a simplified model [19] which treats the non-high-j particles as spectators since Coriolis mixing among their orbitals is small.

In this model there are $(2j + 1)$ possible projections of the $i_{13/2}$ orbital ranging from $\Omega = -13/2, -11/2, \ldots + 11/2, +13/2$. The $\{i_{13/2}\}$ set is coupled to either the $7/2^+[404]$ proton orbital as a spectator, or to a $K^\pi = 19/2^+$ core from the $\nu^2 5/2^-[512], 7/2^-[514] \otimes \pi 7/2^+[404]$ coupling. (Note that the sign relative to the nonparticipating orbitals needs to be retained in enumerating the set of basis states [20].) With the appropriate choice of intrinsic state energies from the Nilsson model, pairing parameters, and unperturbed moments-of-inertia, a 14 ×

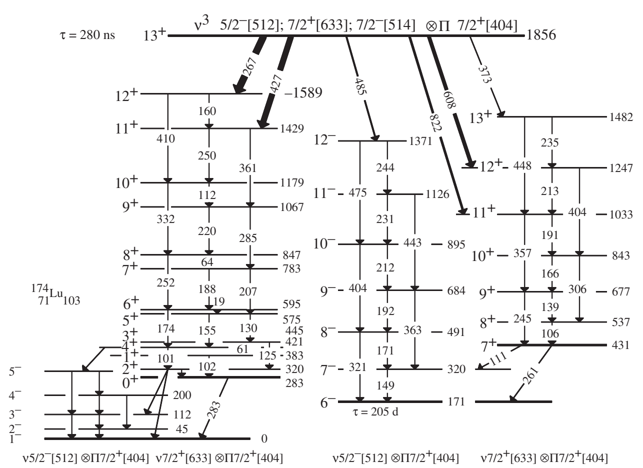

FIG. 1. Partial level scheme and decay of the isomer in ^{174}Lu.

TABLE I. Hindered transitions in the decay of the $K^\pi = 13^+$ isomer in ^{174}Lu.

E_γ (keV)	I_γ	K_f	$M\lambda$	ν	f_ν Exp.	f_ν corrected[a]
267	358(19)	0	$M1$	12	3.0	3.6
427	289(18)	0	$E2$	11	1.9	2.1
485	56(7)	6	$E1$	6	36	57
822	90(10)	7	$E2$	4	17	89
608	179(15)	7	$M1$	5	26	244
373	28(6)	7	$M1$	5	28	344

[a]See text for evaluation of K mixing.

14 matrix can be constructed for the highest spins in each case, with off-diagonal matrix elements within the $i_{13/2}$ set of orbitals connecting states of the same spin and $\Delta K = \pm 1$ (as shown schematically in Fig. 17 of Ref. [20]). The Coriolis matrix is diagonalized to give the perturbed energies and the wave function admixtures.

Since the neutron Fermi level is close to the $7/2^+[633]$ orbital, in the case of coupling to the $7/2^+[404]$ proton orbital, the two lowest unperturbed states are the $K^\pi = 0^+$ and 7^+ bandheads, but these become mixed with both lower- and higher-K components. In the four-quasiparticle case, only the $K = 13$ and lower-K bands can produce states with $J = 13$; hence only lower-K admixtures occur in this state.

Figure 2 gives the amplitudes of the calculated K distributions in the $K^\pi = 13^+$ isomer and, as an example, in the spin-11 or spin-12 states of the final 0^+ and 7^+ bands. As expected, there are significant components of $K < 13$ in the $K = 13^+$ bandhead, and a broad asymmetrical distribution around $K = 0$ and $K = 7$ for the states in the 0^+ and 7^+ bands.

We can then use the predicted K distributions rather than the nominal K values to recalculate the reduced hindrances, f_ν for transitions from the $K^\pi = 13^+$ isomer. The corrected values are given in the last column of Table I. The effective values for decays to the 7^+ band become much larger, and essentially normal. Coriolis mixing, therefore, provides the explanation for the anomalously fast rates to the 7^+ band, but, as is evident from the table, it does not solve the problem of the transitions to the 0^+ band. These are only slightly modified by the mixing and remain very low, essentially because they are close to being *unhindered*.

The cause is related to the second aspect mentioned earlier, the possibility of chance degeneracies. This can be seen by extrapolating the energies of states in the 0^+ band as a function of spin. The extrapolation indicates that the 13^+ collective state within the 0^+ band would have fallen at about 1868 keV, just above the 13^+ intrinsic state.

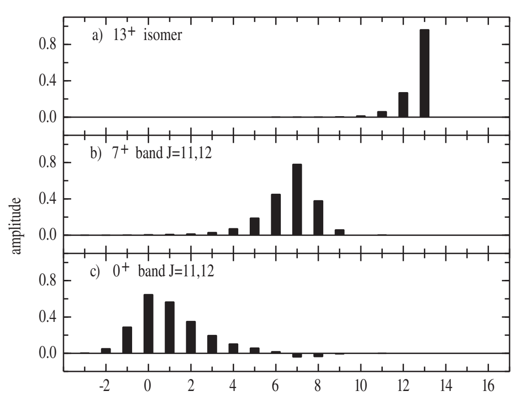

FIG. 2. Calculated K distributions for the $K^\pi = 13^+$ isomer and the $K^\pi = 0^+$ and $K^\pi = 7^+$ bands to which it decays.

This is an example (see Refs. [16,21,22]), of local mixing between a high-K state and a rotational level from a lower-K configuration, providing now an opportunity to extract the interaction in a case where the K difference is much larger. The key factor is that admixture of a small collective component into a wave function, where other transitions are forbidden, has a profound effect on the apparent hindrances.

The conditions are particularly simple because mixing only occurs between the upper pair of states since there are no high-K states below the 13^+ bandhead. As emphasized by Saitoh *et al.* [9], the crucial test of this conjecture is whether the intensities of the $M1$ and $E2$ branches from the isomer to the 12^+ and 11^+ states of the 0^+ band are in the ratio expected for the in-band states, properties specific to the intrinsic configuration of the band. That this is indeed the case can be seen from Fig. 3, where the observed branching ratios are compared with the values expected from the collective model for the 0^+ band configuration. The experimental values agree with the theoretical ones and the 13^+ state branch falls on the locus of points for the odd-spin states.

If the wave function for the 13^+ isomer is written as $\alpha|K = 13> + \beta|K = 0>$ with $\beta = \sqrt{1 - \alpha^2}$, the amplitudes can be obtained from the strength of the 427 keV $E2$ transition compared to the collective $B(E2)$ transition probability through the relation $\beta^2 = B(E2)_{427}/B(E2)^{\mathrm{coll}}$ with $B(E2)^{\mathrm{coll}} = (5/16\pi)Q_0^2|<IK20|I-2K>|^2$. Taking $Q_0 = 7.65\ e\,\mathrm{b}$ (the average of the ^{173}Lu and ^{175}Lu, $7/2^+[404]$ values) leads to a collective $B(E2)$ of $2.02 \times 10^4 e^2\ \mathrm{fm}^4$, while our measured strength of the 427 keV transition is $5.4(8) \times 10^{-2} e^2\ \mathrm{fm}^4$, implying $\beta = 1.64(6)10^{-3}$.

This amplitude can be used to extract the mixing matrix element V, if the final energy separation between the 13^+ states is known. Unfortunately, the 13^+ band state has not been identified, thus ΔE has been estimated using the observed energy of the isomer and an extrapolated value for the band member [23], giving $\Delta E \sim 11.6(25)$ keV. Use of the relation that $V = \beta\alpha\Delta E$ leads to the estimate of $V \sim 19(4)$ eV, a very small value in the context of normal

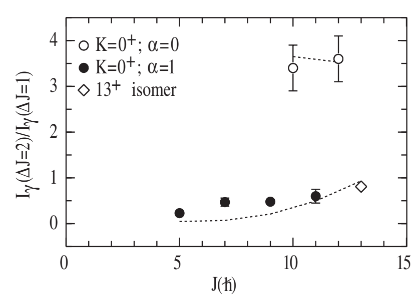

FIG. 3. Branching ratios within the odd and even-spin sequences in the 0^+ band in ^{174}Lu. Dashed lines indicate values expected for the $\nu 7/2^+[633] \otimes \pi 7/2^+[404]$ configuration.

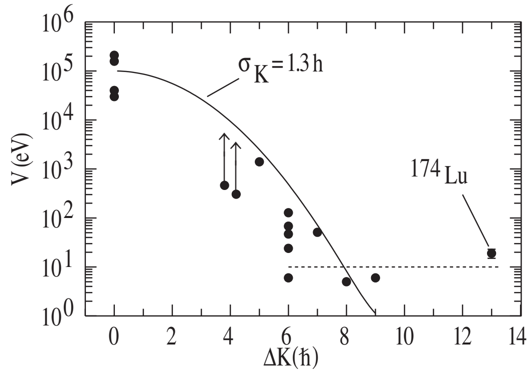

FIG. 4. Interaction matrix elements deduced from chance degeneracies as a function of the nominal K difference [25].

nuclear matrix elements, which are usually in the regime of tens of keV (see, for example, Ref. [24]).

Figure 4 shows matrix elements as a function of the difference in K, selected on the basis of the branching-ratio criterion used above, with the ^{174}Lu point included. The curve represents the behavior expected for an overlap of two Gaussian distributions separated by ΔK, each with the same full width of 2.2σ. Such an overlap also leads to a Gaussian, with $V = V_0 \times \exp\{-(\frac{\Delta K}{2\sigma_K})^2\}$. Taking $V_0 =$ 100 keV and $\sigma_K = 1.3\hbar$ gives the solid curve [25].

Independent of their precise shape, the rapid fall-off in experimental values indicates that the distributions in K space must be relatively narrow for both initial and final configurations. One would not expect a universal relationship, since superimposed on any general dependence will be the fluctuations in hindrance caused by configuration differences and Coriolis mixing, as discussed already. There are five cases, for example, of $\Delta K = 6$ transitions, with matrix elements ranging from 6 to 128 eV.

As can be seen from the data with $\Delta K = 8$ and 9 and the ^{174}Lu datum with $\Delta K = 13$, there is evidence for saturation in the region of 10–20 eV. Presumably there is some level below which interactions between nuclear states always occur. Significantly, the lowest values here are already as small as atomic interactions. The other nuclear regime where such small interactions have been observed is in the mixing between superdeformed states and states of normal deformation [26] where the wave functions are well-separated and localized in deformation space. The implication of a lower limit to nuclear interactions is of interest for the general question of how random mixing in regions of high level density can lead to the dilution of distinguishing quantum numbers and, therefore, induce a transition from order to chaos in quantum systems [27].

In summary, the discovery of a new high-K isomer with anomalous decay rates in the odd-odd nucleus ^{174}Lu has been used to examine K mixing effects in the unusual situation where decays are observed to states that originate from parallel and antiparallel couplings of the same pair of proton and neutron orbitals. Coriolis mixing in both the isomeric level and the two-quasiparticle rotational band members accounts for some of the anomalous decay rates. The additional factor is the occurrence of a chance degeneracy between the isomeric state and a collective state within the $K = 0^+$ band. Fast decays are caused by very small admixtures of a collective component induced by a mixing matrix element of only 19 eV. Although small, this is still considerably larger than the value one might expect for states with such a large ΔK, implying a possible lower limit to nuclear interactions of this kind. Discovery of other examples and confirmation of the energy of the collective 13^+ state in the present case would be valuable in substantiating this proposition.

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