Structure Of Multi-Quasiparticle Isomers In The Region Of ^{177}Lu

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Abstract. High-*K* states in the region of ^{177}Lu have been studied using multi-nucleon transfer reactions with ^{136}Xe beams and Gammasphere. Results include identification of the predicted 5-quasiparticle K^{π} = 39/2 $^-$ isomer in ^{177}Lu, a 7-quasiparticle K^{π} = 49/2 $^+$ isomer in ^{179}Ta with an anomalously fast decay, and numerous other examples in a range of Yb close to stability. The results are discussed in the context of the expectations for multi-quasiparticle states near Z = 72 and the factors which may both govern isomer formation and also give an insight into *K*-purity, specifically chance degeneracies, and statistical mixing above the yrast line.

INTRODUCTION

The region of deformed nuclei near Z = 72 and N $\sim$ 106 is known to be prolific in high-*K* isomers, formed by combining high-Ω orbitals present near both proton and neutron Fermi surfaces. Although some profound examples are known, including the 31-year isomer K^{π} = 16$^+$ in ^{178}Hf and the 160-day K^{π} = 23/2$^-$ isomer in ^{177}Lu, many more are predicted in the region near the stability line, but very few are accessible by conventional reactions. Multi-nucleon transfer or "deep-inelastic" reactions, offer an alternative, if non-selective, means of accessing such nuclei [1]. Favored configurations and therefore low excitation energies are required for the formation of long isomers [2], but more precisely the absence of decays paths to other low-lying, high-*K* states is necessary. Large changes in the projection *K* require large multipolarity changes and high-multipolarity γ-ray emission is slow, especially at low energies.

Favored Configurations

Pairwise combination of the orbitals that lie near the proton and neutron Fermi surface provides the building blocks for two- and four-quasiparticle configurations which commonly occur in the region. Namely the π^2, 6$^+$ and 8$^-$ states from the 5/2$^+$[402]$\otimes$7/2$^+$[404] and 9/2$^-$[514]$\otimes$7/2$^+$[404], configurations, the competing ν^2, 6$^+$ and 8$^-$ states from 5/2$^-$[512]$\otimes$7/2$^-$[514] and 9/2$^+$[624]$\otimes$7/2$^-$[514] configurations, the ν^2 (“t-band") 7/2$^+$[633]$\otimes$9/2$^+$[624] and higher up in the neutron shell, the ν^2, 10$^+$ and 10$^-$ states from the 9/2$^+$[624]$\otimes$11/2$^+$[615] and 9/2$^-$[505]$\otimes$11/2$^+$[615] configurations. Addition of the π^2, 6$^+$ and ν^2, 8$^-$ configurations, for example, gives a 14$^-$ state while combination of the ν^2 and π^2 8$^-$ configurations leads to the famous 16$^+$ isomer in ^{178}Hf. The approximate independence of these configurations can be seen from the fact that the simple sum of the energies of the two 8$^-$ configurations in ^{178}Hf observed at 1147 and 1479 keV gives 2626 keV, compared to the observed energy of 2447 keV for the 16$^+$ isomer. Additional residual interactions are important but at the level of $\sim$ 100 keV.

Multi-quasiparticle calculations which usually use fixed deformation, include the calculation of the Fermi levels and

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pairing gaps for given proton and neutron pairing strengths, self-consistently for each configuration, taking blocking into account. Their predictions (see for example ref [3]) have been successful in reproducing energies to about 100 keV, when residual interactions – essentially linear sums of empirical 2-particle ($\pi - \pi$, $\nu - \nu$ and $\pi - \nu$) splittings from low-energy multiplets, are included. Fig. 1 from [4] shows calculations for a range of Hf istopes, with reasonable reproduction of the energies of known isomers, and predictions of very low-lying states in the neutron-rich region, specifically at N = 116 where the spin-10 building blocks alluded to above become available.

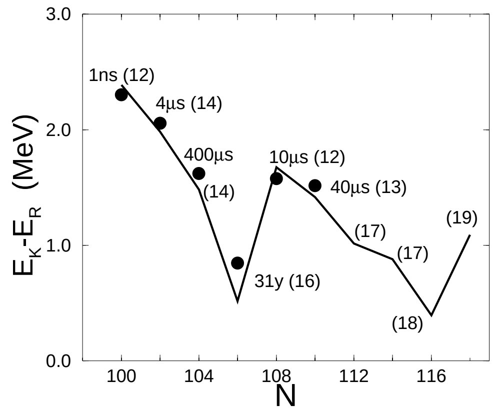

FIGURE 1. Predicted [4] and observed energies of four-quasiparticle isomers in Hf nuclei relative to an arbitrary rigid-rotor. Figure reprinted with kind permission of Springer Science and Business Media.

Expectations For Lower-Z

A move from the favored region of Hf to lower-*Z*, specifically the Yb isotopes, will also result in qualitative changes in the formation of multi-quasiparticle isomers. The orbital closest to the proton Fermi surface will not be a high-Ω orbital, but rather the $1/2^+[411]$ orbital that is observed as the ground state in the odd-A Tm isotopes.

The absence of some high-Ω proton orbitals has several (possible) consequences:

- The highest-*K* states that can be formed are likely to be non-yrast,
- ν^4 configurations could compete with more "balanced" configurations, such as $\nu^2\pi^2$, for example, which are common at higher-*Z*. (The lowest states usually involve approximately equal numbers of quasiprotons and quasineutrons.)
- states with non-maximum *K*-coupling such as K_{max}-1 in configurations involving the opposite coupling of the $1/2^+[411]$ proton may be significant. (This comes from the mixture of attractive and repulsive interactions in the multi-quasiparticle configurations.)

Hindered Transitions

A low energy is not, by itself, sufficient for the formation of long isomers since that will depend crucially on the disposition of other states below, so that precise predictions of lifetimes is not feasible. In any case the focus should be on transition strengths rather than lifetimes; these can be classified in terms of the hindrance factor f = T/T$_W$, the ratio of partial γ-ray lifetime to the Weisskopf estimate. The hindrance scales by approximately two orders of magnitude for each level of forbiddenness ν, the mismatch between the transition multipolarity λ and the required change in K. That is, $f_\nu = f^{1/\nu} \sim 100$. These reduced hindrances show a wide variation, but as a rule-of-thumb, values < 20 need explanation while values > 300 are not very likely.

K-Mixing

"Forbidden" transitions presumably occur through small admixtures of other K-components which will naturally be present, for example, when Coriolis mixing occurs. Other mechanisms which may effect the "goodness" of the nominal K-quantum number include

- local (two-state) mixing due to chance degeneracies
- statistical mixing which might be expected when high-K states are embedded in a region of high level density above the yrast line
- asymmetric shape oscillations - the breaking of the axial symmetry which defines the projection K

Transition matrix elements will also depend on the extent of orbital changes, with the expectation that complex configuration changes will further retard transition rates.

RECENT EXAMPLES

^{177}Lu

The 231-day (meanlife) β-decaying isomer at 970 keV in ^{177}Lu has been known for many years, but little was known of the excited states that should lie above it. A K^{π} = 23/2$^-$ three-quasiparticle configuration, ν^2 7/2$^-$[514] 9/2$^+$[624] $\otimes$ π 7/2$^+$[404], was assigned but other low-lying intrinsic states are predicted and analysis of the properties of its associated rotational band would add additional support for the configuration. A 25/2$^-$ rotational state was tentatively assigned at 1243(5) keV in early (d,p) studies [5] but it was only recently that band members up to a 29/2$^-$ state were firmly identified using ^{7}Li-induced incomplete-fusion reactions [6]. Multi-quasiparticle-state calculations [6] reproduce the excitation energy of the 23/2$^-$ isomer, and also predicted the presence of a K^{π} = 39/2$^-$ 5-quasiparticle state at about 3300 keV [6]. This is favored in energy and is thus likely to lead to a higher-lying isomer. The predicted state is related to the 23/2$^-$ isomer by an additional 2-proton (7/2$^-$[523]9/2$^-$[514]) excitation.

Before the present measurements [7] , Al-Garni *et al* [8, 9] reported the observation of γ-rays from the well-known K$^{\pi}$ = 37/2$^-$, 51-min isomer at 2740 keV in ^{177}Hf which they attributed to indirect population through β-decay from the predicted 39/2$^-$ high-K isomer in ^{177}Lu. A half-life of approximately 7 min was deduced from the growth curve for the decay of the 51-min Hf isomer, but no γ-rays within ^{177}Lu were identified. Association with the predicted state is therefore uncertain, although plausible. Importantly, the excitation energy and, therefore, the β-decay logft values were unknown. The scheme obtained since from our Gammasphere studies [7] shown in Fig. 2 contains three new

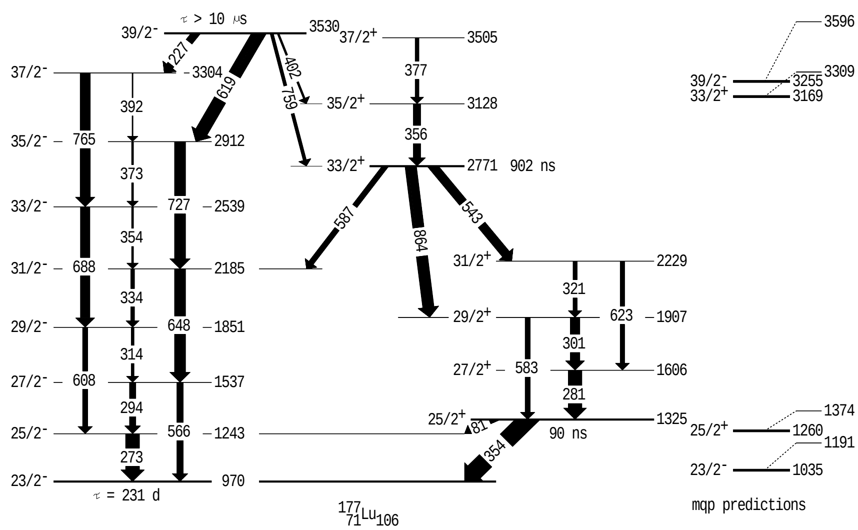

FIGURE 2. Partial level scheme showing the decay of 39/2$^-$, 33/2$^+$ and 25/2$^+$ isomers in ^{177}Lu [7]. Intrinsic state energies from multi-quasiparticle-state calculations [6] are given on the right, with and without residual interactions . Reprinted from ref [7] with permission from Elsevier (Copyright 2004).

isomers, the predicted $25/2^+$ three quasiparticle state observed at 1325 keV (τ = 90 ns), and two five quasiparticle states, a $K^\pi = 39/2^-$ state at 3530 keV with a lifetime which was outside the range of these particular measurements, and a 902 ns isomer, assigned $K^\pi = 33/2^+$, at 2771 keV.

The surprise in these results is the low energy of the $33/2^+$ isomer which is assigned a configuration equivalent to the coupling of a $1/2^+[411]$ proton to the 16^+ isomer in ^{178}Hf. This state is observed at an energy which is 400 keV *below* that predicted by multi-quasiparticle calculations which in general (in this region and others) tend to *underestimate* the excitation energies. One implication is that the energy of the $1/2^+[411]$ proton in the model is overestimated by a substantial amount, a possibility which will be examined with new results on the Yb isotopes.

The more important fact that bears on the formation of very long-lived isomers however, is that the presence of the $K^\pi = 33/2^+$ intrinsic state provides a 759 keV E3 decay path from the $39/2^-$ isomer, a path which is not K-forbidden. As discussed in ref [7], if the $39/2^-$, $\tau > 10$ μs state identified in these studies is also the source of the proposed β-decay, the 7 min half-life (and assumptions about the β-γ branching) implies K-hindered M1 and E2 transitions to the $K^\pi = 23/2^-$ band which have acceptable reduced hindrances f_ν, ranging from 130 to 180, and also acceptable logft values for a β-decay to ^{177}Hf. The E3 branch to the $33/2^+$ isomer however would have a strength of only 10^{-9} Weisskopf units. Part of the explanation may be that this E3 transition is j-forbidden, but the lifetime expected would still be in the region of milliseconds, rather than minutes. Experiments are in progress to measure the lifetime of the γ-ray decaying isomer, and if that is indeed found to be in the millisecond region, the source of the proposed β-decay will become an open question.

^{176}Lu And ^{179}Ta; Chance Degeneracies And K-Separation

McGoram *et al*. have reported [10] the presence of a 58 μs four-quasiparticle isomer in ^{176}Lu decaying via a 73 keV transition to a $K^\pi = 12^+$ four-quasiparticle intrinsic state with a lifetime of about 450 ns. The latter isomer decays by *ten* branches, nine of which have reduced hindrances in the expected range of about 80-130, indicating good-K, but with one E2 transition to the 10^+ member of a $K^\pi = 4^+$ band, (i.e $\Delta K = 8$ and $\nu = 6$) with $f_\nu = 4$. This is a factor of more than 10^6 faster than expected. The explanation given [10] was the close proximity of the 12^+ band-member of the 4^+ band to the intrinsic 12^+ state resulting in a small admixture of a collective component in the isomeric state. Because of the collectivity only a minute admixture is required to dramatically affect the transition rate compared to hindered values. That and the small energy difference (4 keV between the *perturbed* states in this case) implies a mixing matrix element of a few *eV*, rather the order-*keV* interactions usually observed in nuclei. The important factors here are that other transitions are hindered as expected, while the M1, and E2 decay branching ratio to the rotational band should mimic the in-band branching ratios [11]. (The M1 branch in this case was below the sensitivity of [10] but has been observed in the present measurements [12].) This scenario of chance degeneracies between a high-K state and

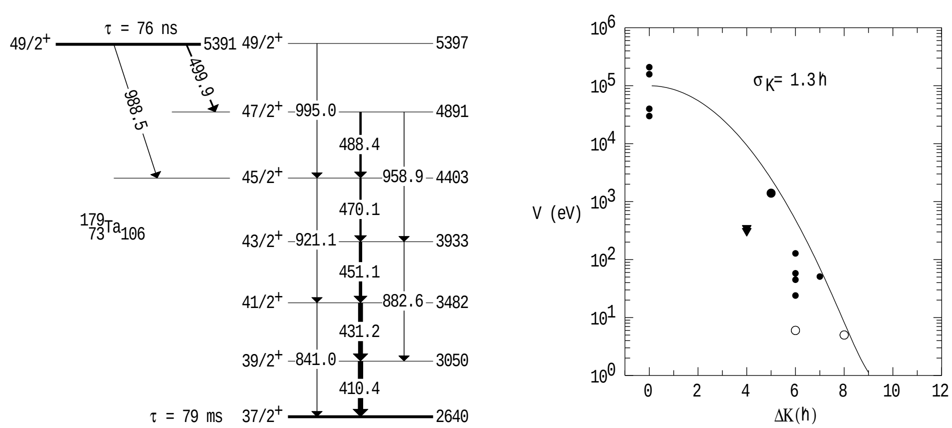

FIGURE 3. Partial scheme of ^{179}Ta [13], (left panel) and interaction matrix elements as a function of the nominal K-difference (right panel). The solid curve shows the expected dependence for two gaussian K-distributions of half-width $\sigma\hbar$ [14]. The open circles represent the ^{179}Ta (ΔK =6) and ^{176}Lu (ΔK = 8) results.

a rotational state from a lower-K configuration provides an opportunity to extract the interaction, and by implication the K-purity, in the absence of other factors. Fig. 3 shows the recent result of Kondev *et al*. for a $K^\pi = 49/2^+$ isomer in ^{179}Ta [13]. The relatively short lifetime of 76 ns means that the $\Delta K = 6$, 989 keV E2 transition has a reduced hindrance

f_ν = 11.8, corresponding again to a transition strength about 10^6 larger than expected, induced apparently by a small collective amplitude mixed into the isomeric state, and again implying a very small matrix element of $\sim$ 6 eV. The right-hand panel of Fig. 3 shows a collection of such matrix elements extracted from a variety of data satisfying the criterion that the branching ratios should match the in-band ratios, as a function of the difference in K. The curve superimposed shows the expected interaction for a simple overlap of two Gaussian distributions separated by ΔK, each of the same full-width of 2σ, taking (arbitrarily) V_0 = 100 keV so that $V = V_0 \times \exp\{-(\frac{\Delta K}{2\sigma})^2\}$. The rapid fall-off in experimental values is a clear indication that the distributions in K-space are relatively narrow for both the initial and final configurations. Superimposed on the general dependence predicted will be the possibly large fluctuations in hindrance caused by the configuration differences. Some configurations are specifically Coriolis-mixed because the constituent particles are of high-j parentage. These aspects and the K-distribution widths in typical cases are being examined [14].

^{174}Yb; Non-Yrast Isomers

Spectroscopic information on high-spin states in the N = 104 isotope ^{174}Yb is limited because it is accessible neither via fusion-evaporation reactions with stable beams nor via incomplete fusion reactions. A feature of the known level scheme, however, is the 830 μs isomer at 1518 keV populated in (d,p) and other relatively low-spin reactions. Although commonly associated with the $K^\pi = 6^+$ state from the 2-quasineutron Nilsson configuration $5/2^-[512]7/2^-[514]$, the 6^+ assignment recorded in the data compilations [15] has been the subject of considerable conjecture, partly because the E2 decays are, in contrast to the earlier discussions, extremely hindered. The 1265 keV E2 branch to the 4^+ state of the ground state band has f_ν = 322, the most hindered in the region, corresponding to 10^{-10} Weiskopf units. Identification of the rotational band based on this isomer could provide an independent characterisation, since in this region, competing two quasiparticle configurations change energy rapidly, and for example, a two-quasineutron $K^\pi = 7^-$ state is also expected at a similar excitation energy. The rapid change can be seen from the fact that the 8^- configuration leads to a very low-lying isomer in ^{176}Yb, only two neutrons away.

The lifetime of the 6^+ isomer is too long to allow correlations across it, but the first cascade transition at 153 keV was known from neutron capture and β-decay. Double-gating on candidate transitions together with the 153 keV transition resulted in observation of a band fed from a relatively short-lived isomer with τ = 80 ns, with connecting transitions at 696, 410 and 964 keV. These, and the rotational band extending to spin 14^+ are evident in the spectrum given in figure 4. This spectrum was constructed by summing double gates on the band members, as observed in the out-of-beam region, but confined to a time region of 30-100 ns after the beam pulse. The band properties (alignments

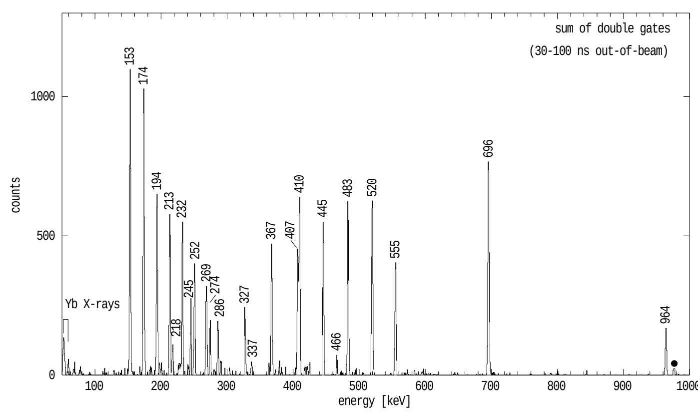

FIGURE 4. Spectrum constructed from a combination of double γ-ray gates on transitions assigned to the $K^\pi = 6^+$ band, constrained to the 30 to 100 ns region after the beam pulse.

and g_K-g_R values) are indeed consistent with the original 6^+ configuration assignment and in other extensions to the level scheme [12], the expected $K^\pi = 7^-$ intrinsic state has been identified, effectively eliminating the ambiguity, but leaving the large hindrances from the 6^+ isomer, unexplained. On the basis of the γ-ray branching ratios and decay strengths, the spin and parity of the 3699 keV state is assigned as 14^+. The 964 keV E2 branch, however, has f_ν = 9, another low value. This is not apparently due to a specific chance degeneracy but it should be noted that this four-quasiparticle isomer is well above the yrast line, in a region of relatively high level density. Fig. 5 also shows E2 and

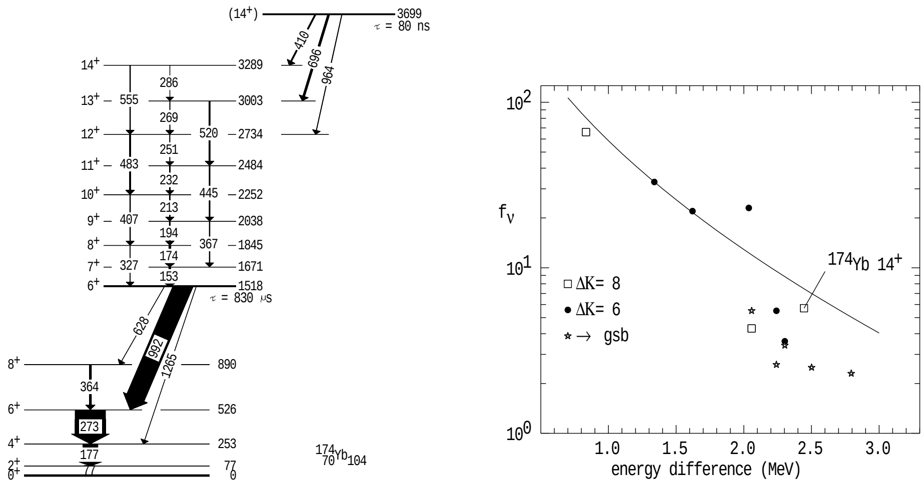

FIGURE 5. Partial level scheme for ^{174}Yb (left panel) from ref. [12] and reduced hindrances (right panel) for E2 and E3 decays of 4-quasiparticle states. The fast decay of the 14^+ isomer in ^{174}Yb is indicated. The solid curve represents the density-of-states estimate for ΔK = 6 transitions given by Walker *et al*. [16].

E3 reduced hindrances for selected four-quasiparticle isomers as originally given by Walker *et al*. [16], as a function of excitation with respect to a rigid rotor. The ^{174}Yb 14^+ case is consistent with the expected fall in hindrance due to the random mixing with background states, as indicated by the solid curve [16].

Clearly there are fluctuations which cannot be described by such a simple model. The points indicated by stars in this figure correspond to very fast decays from high-*K* states (mostly K=12^+) directly to high-spin members of ground state-bands in even-even nuclei. These belong to a category of low hindrances which arise not from admixtures in the primary isomer, but from *K*-mixing in the ground state band, in the region near and above the alignment of neutrons.

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