PHYSICAL REVIEW C, VOLUME 62, 031303(R)

Normal and anomalous K-hindered decays from four-quasiparticle isomers in ^{176}Lu

T. R. McGoram,[1] G. D. Dracoulis,[1] T. Kibédi,[1] A. P. Byrne,[2] R. A. Bark,[1] A. M. Baxter,[2] and S. M. Mullins[1]
[1]*Department of Nuclear Physics, RSPhysSE, Australian National University, Canberra ACT 0200, Australia*
[2]*Department of Physics and Theoretical Physics, Faculty of Science, Australian National University, Canberra ACT 0200, Australia*

(Received 3 April 2000; published 14 August 2000)

Two four-quasiparticle isomers, with $K^{\pi}=12^{+}$ and (14^{+}) and mean lives of 450(100) ns and 58(5) μs, have been identified in ^{176}Lu, at excitation energies of 1515 and 1588 keV, respectively. The 12^{+} isomer exhibits a large number of K-forbidden decay branches, populating the rotational sequences based on the $K^{\pi}=7^{-}$ ground state, two $K^{\pi}=8^{+}$ states, and a $K^{\pi}=4^{+}$ state from the $\nu\{7/2^{-}[514]\}\otimes\pi\{1/2^{-}[541]\}$ configuration. Most branches have decay rates that are consistent with normal K-hindrances except for the branch to the $K^{\pi}=4^{+}$ band. It has an anomalously low hindrance factor, which is attributed to two-state mixing due to a near-degeneracy between the 12^{+} isomer and the 12^{+} member of this band. The implied mixing matrix element has a value of only 5 eV, showing explicitly that very small mixing matrix elements may be responsible for anomalous K-hindered decays.

PACS number(s): 27.70.+q, 21.10.Tg, 21.10.Re, 23.20.Lv

The deformed nucleus ^{176}Lu resides in a region of the nuclear chart where several high-Ω Nilsson orbitals lie close to both the proton and neutron Fermi surfaces. Multiparticle states with a large projection, K (where $K=\Sigma_i\Omega_i$), of the total angular momentum on the nuclear symmetry axis, may thus be formed at low excitation energy. Much of the interest in ^{176}Lu has centered on its role as a possible s-process chronometer [1,2] for nucleosynthesis, and in particular its effective mean life within the stellar environment, due to the possibility of excitations from the $K^{\pi}=7^{-}$ ground state to the $K^{\pi}=1^{-}$, $\tau_m=5.3\ h$, β-decaying isomer, purported to be mediated by a state of intermediate K. Another imperative for the study of intermediate and high-K states is the question of the resilience of the K-quantum number in the presence of several possible K-mixing mechanisms. For example, anomalous decays have been ascribed to either shape changes involving the γ degree of freedom [3], or ''statistical'' K mixing with unobserved states [4], resulting in a spread in K values, either in the initial state, or in the final state, or in both.

High-spin investigations of ^{176}Lu have been limited by its inaccessibility with heavy-ion, xn reactions, restricting studies to (n,γ), (d,p) [5], and (t,α) [6] experiments. However, recent studies [7,8] of similar nuclei have exploited incomplete fusion (breakup) reactions which can also be used here. The most prolific residual nuclei of the ^{7}Li bombardment of ^{176}Yb are ^{179}Ta and ^{178}Ta, populated via the $4n$ and $5n$ channels, while ^{176}Lu is produced reasonably strongly via the $\alpha 3n$ ''breakup'' channel, albeit at intermediate spins.

We report here the discovery of two four-quasiparticle isomers in ^{176}Lu of predominantly $\nu^3\pi$ character. In apparent violation of the K-selection rule, the shorter-lived isomer exhibits an $E2$ ($\Delta K=8$) decay with an anomalously low hindrance factor. The same state has $M1$ and $E2$ decays with $\Delta K=4$ and more typical hindrance factors. We show that this anomalous behavior is due specifically to mixing between the isomeric state and a member of a two-quasiparticle rotational band, due to a near degeneracy, showing explicitly how anomalous decays may arise, even with very small mixing matrix elements.

Given the lack of previous spectroscopic information on ^{176}Lu and the likely presence of isomeric states, it was necessary to use a range of techniques. Excited states in ^{176}Lu were populated by the bombardment of foils enriched (97%) in ^{176}Yb with 45 MeV ^{7}Li beams from the ANU 14UD accelerator. γ rays were detected with the CAESAR array, which consisted of six Compton-suppressed hyperpure n-type germanium detectors. α-γ-γ coincidences were recorded in a continuous beam experiment using a compact particle-detector system [9] in conjunction with CAESAR, the results of which will be reported on later [10]. Longer time regimes were explored using chopped ^{7}Li beams at 45 MeV with beam pulse width/separation intervals ranging from 3 μs/54 μs to 107 μs/1.07 ms. A subsequent time-correlated γ-γ coincidence measurement was performed using the optimized conditions of 11 μs/321 μs.

In the latter measurement, an electronic veto of width 11 μs was used to reject events detected during beam pulses, thus ensuring that only γ-ray cascades from the decay of long-lived isomers were recorded. The absolute times of each γ ray with respect to the beam pulses were measured with a resettable ADC clock [11]. Approximately 80×10^{6} coincidence events were sorted into prompt (±150 ns coincidence overlap), early (-800 to -150 ns), and delayed ($+150$ to $+800$ ns) E_{γ}-E_{γ} matrices.

To obtain direct multipolarity information, conversion electrons were measured using a superconducting, solenoidal spectrometer, operated in ''lens'' mode [12], again using the ^{176}Yb(^{7}Li,$\alpha 3n$) reaction at 45 MeV, with a beam pulse width/separation ratio of 21 μs/321 μs and a 2.3 mg/cm^{2} target mounted at 30° to the beam axis, to optimize the energy resolution. The data were sorted into E_{e^-}- and E_{γ}-time matrices, allowing the construction of γ-ray and electron spectra, matched in time.

A partial level scheme for ^{176}Lu deduced mainly from the coincidence data obtained in the chopped beam measurement is displayed in Fig. 1. For reference, we include the higher-spin states of the $K^{\pi}=7^{-}$ and 4^{+} bands deduced from the α-γ-$\gamma(t)$ study. We have extended the $K^{\pi}=8_1^{+}$ band to I^{π}

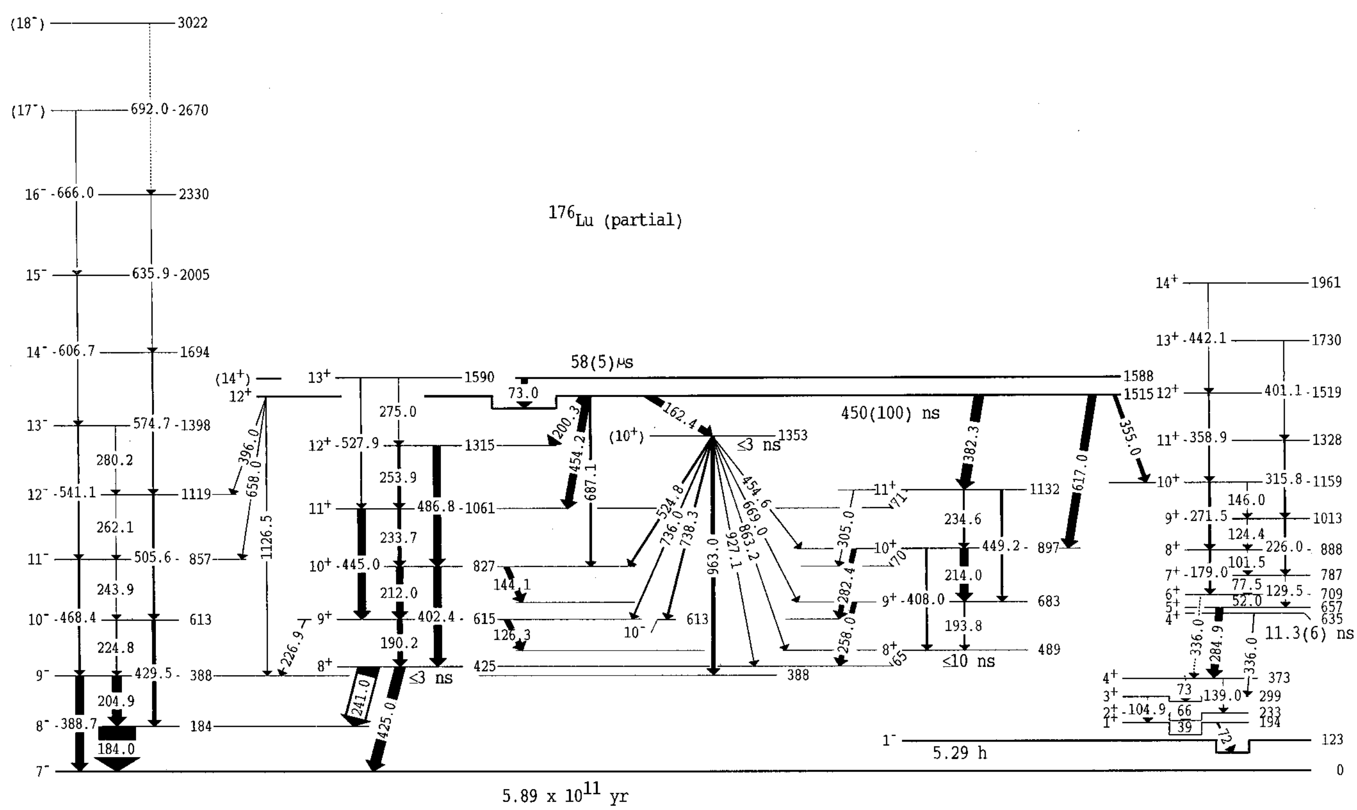

FIG. 1. Partial level scheme of ^{176}Lu deduced mainly from the coincidence data in the out-of-beam time region.

$=13^+$ at 1590 keV, and the $K^\pi=8_2^+$ band to $I^\pi=11^+$ at 1132 keV. Our scheme differs from the most recent compilation [13] as we interpret the 5^+ state at 657.1 keV, not as a bandhead, but as the 5^+ member of the $K^\pi=4^+$ band, with a bandhead at 635.2 keV, consistent with the observed coincidences between in-band transitions and the 336 keV transition which depopulates the 635.2 keV state, and also consistent with the in-band branching ratios and alignments expected for the $\nu\{7/2^-[514]\}+\otimes\pi\{1/2^-[541]\},K^\pi=4^+$ configuration.

Figure 2(a) shows a sum of coincidence gates on the 184 ($8^-\rightarrow7^-$) and 241 keV ($8_1^+\rightarrow8^-$) transitions, which collect most of the delayed intensity. The insert in the upper right of the figure displays the time spectrum of specific γ rays with respect to the beam burst, indicating feeding from an isomeric state with a mean life of 58(5) μs. Figure 2(b) shows a γ-γ coincidence spectrum demonstrating the 355 keV branch from the 1515 keV state. That state is independently shown, from time-difference spectra, to have a mean life of 450(100) ns. A spectrum of transitions detected 150–800 ns before the 184, 162, 402, 487, and 617 keV lines is displayed in Fig. 2(c). The presence of a 73 keV line in this figure places the 58(5) μs isomeric level at 1588 keV.

Despite difficulties due to the predominance of γ decays from ^{178}Ta and ^{179}Ta in the singles spectra, some multipolarity information was obtained from intensity balances. The total conversion coefficient of the 200 keV transition [$\alpha_T=0.24(40)$], which connects the isomer at 1515 keV with the 12^+ member of the $K^\pi=8_1^+$ band, was sufficient to exclude $M2$ and higher multipolarities, while that of the 73 keV transition [$\alpha_T=9(4)$] is consistent with both $M1$ (9.51) and $E2$ (12.2). From the conversion-electron measurement, clean γ-ray and electron spectra were available only for the 617 keV transition for which a K-conversion coefficient of $\alpha_K=0.010(3)$ was obtained. This restricts the 617 keV line to $E2$ or mixed $E1/M2$ in character, and thus the spin and parity of the 1515 keV state to 12^+ or 11^-. We obtain $\alpha_T=0.9(4)$ for the 162.4 keV transition, consistent with either $M1$ (0.969) or $E2$ (0.576), and, assuming 12^+ for the 1515 keV level, this results in 11^+ or 10^+ for the 1353 keV state. [Spins and parities of 12^+ for the 1515 keV state and (10^+) for the 1353 keV state have been adopted on the basis of implied hindrances, as will be explained shortly.] While no firm assignment can be made, we prefer $E2$ for the 73 keV transition, and thus (14^+) for the 1588 keV level. The $M1$ alternative would imply a reduced transition strength of 1.3×10^{-7} W.u., more than two orders of magnitude weaker than expected for a K-allowed $M1$ transition [14]. In contrast, the assumption of $E2$ multipolarity implies a reduced transition strength within the expected range.

While the lifetime of the (14^+) isomer is largely attributed to the low energy of the 73 keV $E2$ transition, that of the 1515 keV state arises because its decays are K forbidden. The degree of K forbiddenness is given by $\nu=|\Delta K|$-λ, where ΔK is the change in K in the transition and λ is the multipole order of the transition. The reduced hindrance per degree of K forbiddenness, denoted f_ν, is defined as $f_\nu=F_W^{1/\nu}$, where $F_W=(\tau_\gamma/\tau_W)$, τ_γ is the partial γ-ray mean life, and τ_W is the Weisskopf estimate. This quantity is listed

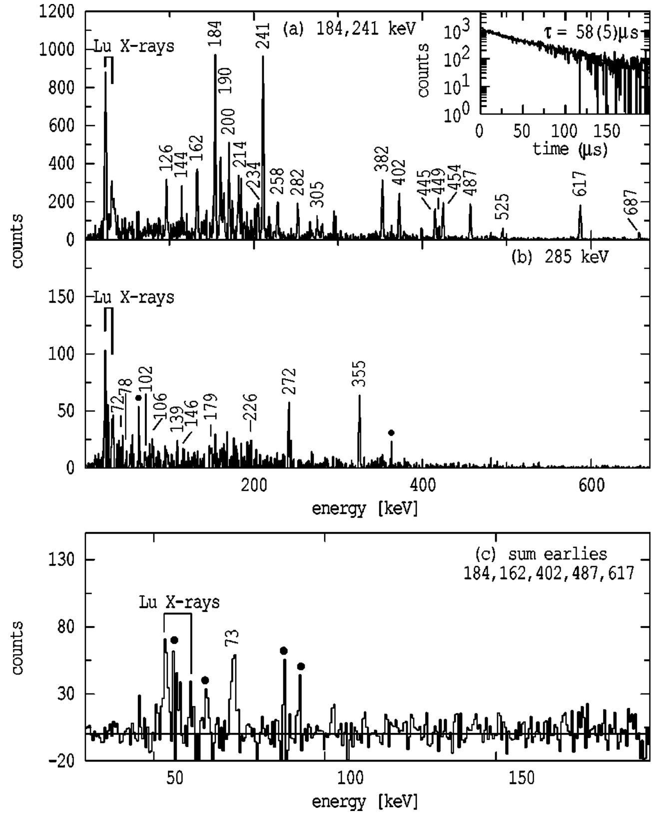

FIG. 2. Coincidence spectra used in establishing the [176]Lu level scheme. (a) Prompt spectrum gated on the 184 and 241 keV γ rays. The insert displays the time spectrum gated on the 162, 184, 241, 258, 402, 487, and 617 keV transitions. (b) Prompt spectrum gated on the 285 keV transition. (The filled circles indicate known contaminant transitions.) (c) Spectrum of γ rays detected 150–800 ns before the 184, 162, 402, 487, and 617 keV transitions.

in Table I, for the adopted $K^{\pi}=12^{+}$ alternative, and plotted in Fig. 3, for both $K^{\pi}=11^{-}$ and $K^{\pi}=12^{+}$. (The hindrance factors for the $E1$ transitions have been multiplied by a factor of 10^3 before calculating F_W, since $E1$ transitions are intrinsically hindered.) We have taken $10 \leqslant f_\nu \leqslant 400$ (shaded region, Fig. 3) as a range to guide the spin and parity assignment for the 1515 keV isomer. The largest value known in the mass-180 region is 330 [15], while values of $f_\nu \leqslant 10$ are unusual and imply violation of K conservation.

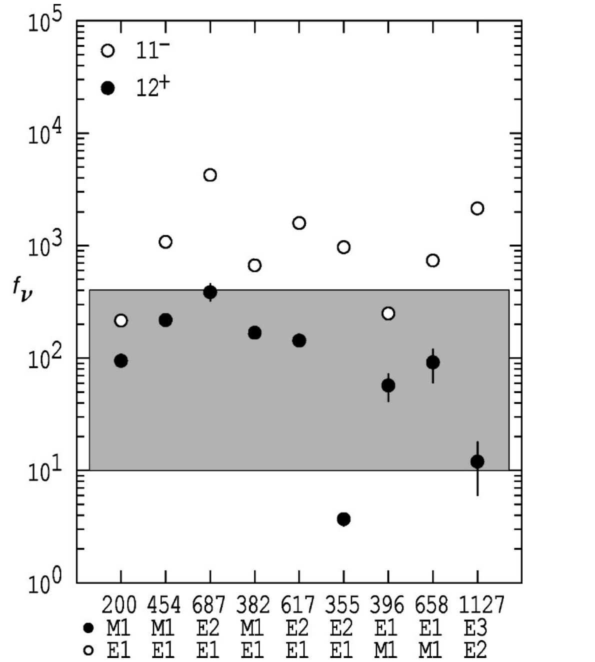

FIG. 3. Reduced hindrance factors per degree of K forbiddenness for transitions depopulating the isomer at 1515 keV, for the two initial spin and parity possibilities.

For the 11^{-} alternative, most of the transitions from the 1515 keV isomer would be hindered beyond any value expected from the systematics [14]. In contrast, the f_ν values in the 12^{+} case are within the expected range, except for the 355 keV transition. Similar arguments apply to the state at 1353 keV, where the alternatives are 10^{+} or 11^{+}. The latter alternative, together with the absence of an observable mean life for this state, implies a K-forbidden $M2$ transition to the 9^{-} member of the $K^{\pi}=7^{-}$ band, with an extremely low hindrance factor ($f_\nu \leqslant 2.4$), favoring 10^{+} over 11^{+}.

The anomalous value of $f_\nu = 3.7$ for the 355 keV transition implied by the 12^{+} assignment for the 1515 keV isomer is attributed to its proximity to the 12^{+} member of the $K^{\pi}=4^{+}$ band, as displayed in Fig. 4. As the strength of the 355 keV transition will be dominated by any mixing between the isomeric level and the collective 12^{+} state, β, the implied mixing amplitude of the collective state in the $K^{\pi}=12^{+}$ isomer can be estimated from

TABLE I. Decay rates and reduced hindrances for the (12^{+}), 1515 keV isomer.

E_γ (keV)	Mult.	I_γ (Rel.)	α_T	τ_γ (s)	F_W	ν	f_ν
200.3	$M1$	207(21)	5.36×10^{-1}	$3.4(4)\times10^{-6}$	$8.5(1.0)\times10^{5}$	3	95(3)
454.2	$M1$	197(30)	5.93×10^{-2}	$3.5(5)\times10^{-6}$	$1.04(15)\times10^{7}$	3	218(12)
687.1	$E2$	51(19)	8.77×10^{-3}	$1.4(5)\times10^{-5}$	$1.5(5)\times10^{5}$	2	390(70)
382.3	$M1$	257(12)	9.31×10^{-2}	$2.7(1)\times10^{-6}$	$4.74(18)\times10^{6}$	3	168(4)
617.0	$E2$	217(29)	1.10×10^{-2}	$3.2(4)\times10^{-6}$	$2.05(26)\times10^{4}$	2	143(11)
355.0	$E2$	106(21)	5.00×10^{-2}	$6.5(1.3)\times10^{-6}$	$2.64(53)\times10^{3}$	6	3.7(5)
396.0	$E1$	13(6)	4.70×10^{-2}	$5.3(2.6)\times10^{-5}$	$1.06(52)\times10^{7}$	4	57(16)
658.0	$E1$	9(4)	3.56×10^{-3}	$7.7(4.0)\times10^{-5}$	$7.05(3.7)\times10^{7}$	2	90(30)
1126.5	$E3$	12(5)	6.56×10^{-3}	$5.8(5.8)\times10^{-5}$	$1.40(1.4)\times10^{2}$	2	12(6)

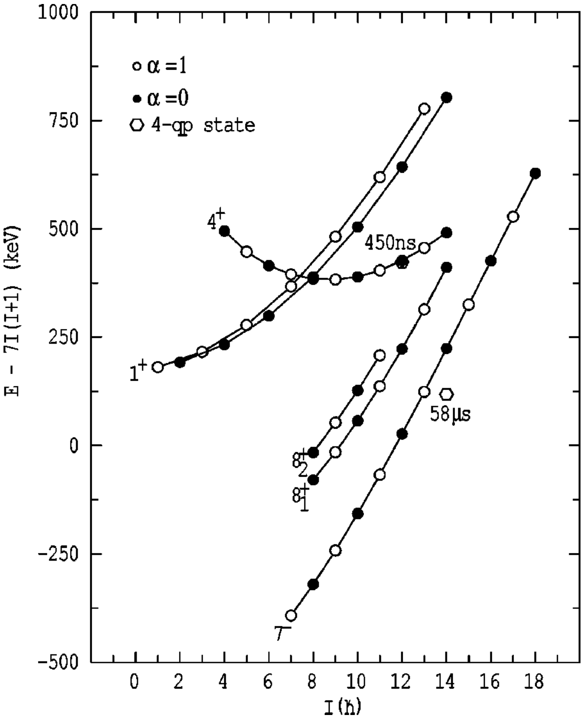

FIG. 4. Excitation energies for selected states in ^{176}Lu, from which an arbitrary rotor energy has been subtracted.

$$\beta^2 = \alpha^2 \cdot \frac{B(E2;355)^{expt}}{B(E2;355)^{coll}},$$

where $B(E2;355)^{coll} = (5/16\pi) Q_o^2 |\langle I_i K 20 | I_f K_f \rangle|^2$, $Q_0 = 7.4$ e b [13], and the mixing amplitudes α and β are defined by

$$|12^+;1515\rangle = \alpha|12^+;K=12\rangle - \beta|12^+;K=4\rangle,$$

$$|12^+;1519\rangle = \beta|12^+;K=12\rangle + \alpha|12^+;K=4\rangle.$$

Experiment implies $\beta = 1.2(2)\times 10^{-3}$ and a mixing matrix element $|V|$ of only 5(1) eV. Thus a squared amplitude of 1.4×10^{-6} of the collective $K^\pi = 4^+, I^\pi = 12^+$ state in the four-quasiparticle isomer, caused by a very small mixing matrix element, is sufficient to account for the anomalously-low reduced hindrance factor. In contrast to the 355 keV $E2$ transition, the competing decays from the 1515 keV isomer exhibit large f_ν values despite the $K=4$ admixture deduced above. This is because the admixture introduces no *collective* contribution to any other of the observed $M1$ or $E2$ transitions.

An admixture between two- and four-quasiparticle states at the 10^{-3} level was also recently proposed by Kondev *et al.* [16] to explain the low reduced hindrance of the decay of a $K^\pi = 16^-$, four-quasiparticle isomer in ^{182}Re. The matrix element deduced was 51 eV, while a value of 24 eV was found in ^{179}W [17] for mixing between a five-quasiparticle isomer and a member of a three-quasiparticle band. The small magnitude of these interactions is particularly apparent when compared to other nuclei in the region. Hagemann *et al.* [18], for example, have obtained values ranging from

TABLE II. Calculated and experimental two- and four-quasiparticle states in ^{176}Lu.

K^π	Configuration [a] ν	π	E_{QP} [b]	E_{res} [c]	E_{calc} [d]	E_{expt}
			(keV)			
4^+	$7/2^-$	$1/2^-$	535	−75	588	635
7^-	$7/2^-$	$7/2^+$	0	−128	0 [d]	0
8_1^+	$9/2^+$	$7/2^+$	238	+65	431	425
8_2^+	$7/2^-$	$9/2^-$	299	+50	477	488
10^+	$11/2^-$	$9/2^-$	1762	−75	1815	1353
10^+	$5/2^+7/2^-1/2^{-\prime}$	$7/2^+$	2272	−245	2155	–
11^-	$9/2^+7/2^-5/2^-$	$1/2^-$	2172	−63	2237	–
12^+	$1/2^-7/2^-9/2^+$	$7/2^+$	1822	−167	1783	1515
12^+	$7/2^-$	$7/2^+9/2^-1/2^+$	2229	−110	2247	–
13^+	$5/2^-7/2^-9/2^+$	$5/2^+$	2088	−149	2067	–
13^+	$7/2^-$	$7/2^+5/2^+7/2^-$	2577	−195	2510	–
14^+	$5/2^-7/2^-9/2^+$	$7/2^+$	1637	−44	1721	1588
15^-	$5/2^-7/2^-9/2^+$	$9/2^-$	1936	−142	1922	–
16^+	$7/2^+7/2^-9/2^+$	$9/2^-$	2239	−78	2289	–
22^+	$5/2^-7/2^-9/2^+$	$7/2^+9/2^-7/2^-$	4196	−474	3850	

[a]Configurations: (π)$9/2^-$: $9/2^-[514]$; $7/2^+$: $7/2^+[404]$; $7/2^-$: $7/2^-[523]$; $5/2^+$: $5/2^+[402]$; $1/2^-$: $1/2^-[541]$; $1/2^+$: $1/2^+[411]$; $7/2^-$: $7/2^-[523]$: (ν)$11/2^-$: $11/2^-[505]$; $9/2^+$: $9/2^+[624]$; $7/2^+$: $7/2^+[633]$; $7/2^-$; $7/2^-[514]$; $5/2^+$: $5/2^+[642]$; $5/2^-$: $5/2^-[512]$; $1/2^-$: $1/2^-[521]$; $1/2^{-\prime}$: $1/2^-[510]$.

[b]Bare quasiparticle energies from the multiquasiparticle calculations.

[c]Residual interactions.

[d]Energies are given relative to that of the 7^- state, which has been shifted to zero after the inclusion of residual interactions.

1 keV to 150 keV for numerous bands in ^{163}Er, and typical values in the literature are of the order of 10–20 keV. The small matrix element of 5 eV in the present case implies a large separation in configuration space (which could involve both the orbital and K changes) between the leading configurations of the 12^+ isomer and the 4^+ rotational band.

A consistency check on the spin and parity assignment of the (14^+) isomer is provided by a further near-degeneracy between the 13^+ member of the $K^\pi = 8_1^+$ band at 1590 keV and the (14^+) isomer at 1588 keV. If the isomer instead has $K^\pi = 13^+$ (the case if the 73 keV transition were $M1$), then mixing between these states, assuming a 5 eV matrix element, would give a partial γ-ray mean life of 500 ns for an $E2$ decay from the 1588 keV isomer to the 11^+ member of the $K^\pi = 8_1^+$ band, sufficient to cause the decay intensity to bypass the 12^+ state.

Specification of the multiquasiparticle configurations of the $K^\pi = (14^+)$ and 12^+ isomers is a prerequisite for understanding the influence of specific orbital changes on the decay rates and for testing residual nucleon-nucleon interactions.[1] The relatively high angular momenta and low

[1]The properties of the rotational bands associated with the isomers could provide a decisive constraint on their possible configurations, however, we have failed to identify these in the present study.

excitation energy of the isomers, together with the limited number of proton and neutron orbitals near the Fermi surfaces constrain their likely configurations to $\nu^3\pi$ or $\nu\pi^3$ character. Table II summarizes our multiquasiparticle calculations obtained using the Lipkin-Nogami approach, and including blocking and empirical residual nucleon-nucleon interactions. (A more complete description of the formalism may be found in [8], and references therein.) Fixed pairing strengths of $G_\pi = 20.8/A$ and $G_\nu = 18.0/A$ were used. The most likely configuration for the $K^\pi = 12^+$ state is $\nu^3\{9/2^+[624],7/2^-[514],1/2^-[521]\} \otimes \pi\{7/2^+[402]\}$ while that of the $K^\pi = (14^+)$ state is obtained by replacing the $1/2^-[521]$ orbit with the $5/2^-[512]$ orbit. The calculations also predict a low-lying six-quasiparticle $K^\pi = 22^+$ state of $\nu^3\pi^3$ configuration.

Another feature of the scheme is the decay pattern of the (10^+) state at 1353 keV. Our calculations predict a two-quasiparticle $K^\pi = 10^+$ state at 1815 keV from the $\nu\{11/2^-[505]\} \otimes \pi\{9/2^-[514]\}$ configuration, while the lowest 10^+ four-quasiparticle configuration is higher again, at 2155 keV. This favors the two-quasiparticle assignment, the mismatch in energy being attributed to the uncertainty in the energy of the $11/2^-[505]$ neutron orbital, whose experimental energy in the neighboring nuclei is unknown. The 1353 keV state decays to the 9^- member of the 7^- band, but also has seven branches to members of the 8_1^+ and 8_2^+ bands. The latter can be understood as a consequence of the mixed nature of the 8^+ bands [10], as any decay to a member of one band is likely to have a counterpart decay to the other.

In summary, two four-quasiparticle isomers have been identified in ^{176}Lu, and assigned $K^\pi = 12^+$ and (14^+). The $K^\pi = 12^+$ isomer exhibits $E1$, $M1$, and $E2$ K-hindered decays with reduced hindrance factors ranging from 3.7 to 390 for the $E2$ transitions. An interaction matrix element of 5 eV between the $K^\pi = 12^+$ isomer and a collective $I = 12^+$, $K^\pi = 4^+$ state accounts for the apparently small reduced hindrance factor for the 355 keV transition to the 4^+ band, but the resultant $K = 4$ admixture in the $K = 12$ isomer is insufficient to significantly alter the other decay hindrances. This clearly shows a mechanism by which anomalous and normal K-hindrances from the same state can arise.

The authors would like to thank the technical staff of the Heavy Ion Facility at the Australian National University for their assistance in the course of these studies.

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