Eur. Phys. J. A **22**, 23–27 (2004)
DOI 10.1140/epja/i2004-10025-9

THE EUROPEAN PHYSICAL JOURNAL A

K-Mixing and fast decay of a seven-quasiparticle isomer in ^{179}Ta

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Received: 7 March 2004 / Revised version: 3 May 2004 /
Published online: 5 October 2004 – © Società Italiana di Fisica / Springer-Verlag 2004
Communicated by W. Henning

Abstract. A seven-quasiparticle isomer with $K^\pi = (49/2^+)$ and $T_{1/2} = 53(^{+3}_{-7})$ ns has been identified in ^{179}Ta. By comparing its excitation energy with results from multi-quasiparticle calculations that include the effects of blocking and residual nucleon-nucleon interactions, the isomer is assigned the $\pi^3(5/2^+[402], 7/2^+[404], 9/2^-[514]) \otimes \nu^4(5/2^-[512], 7/2^-[514], 7/2^-[503], 9/2^+[624])$ configuration. The decay of this isomer is found to be unusually fast, a feature that is attributed to a mixing with a specific collective level. The interaction strength is found to be orders of magnitude lower than that observed between interacting collective levels.

PACS. 21.10.Re Collective levels – 21.10.Tg Lifetimes – 23.20.Lv γ transitions and level energies – 27.70.+q $150 \leq A \leq 189$

Metastable (isomeric) states formed by combining the spins of individual nucleons along the symmetry axis (Ω_i) are frequently observed in deformed rare-earth nuclei near $A \sim 180$ [1]. The long lifetimes arise from large changes in the K quantum number ($K = \sum \Omega_i$) between the initial and final states, thus resulting in highly hindered (K-forbidden) transitions. In most cases the isomer's decay paths obey the so-called K selection rule, *i.e.* they proceed through intermediate states so that ΔK is minimized. However, in some cases, unexpectedly large branches to levels with much lower K value are observed. Such decays have been commonly associated with various degrees of K-mixing introduced by shape changes involving the γ degree of freedom [2], or with random mixing because of the high density of states above the yrast line [3], although the exact mechanism remains uncertain. Recent studies of ^{176}Lu [4] and ^{182}Re [5] provided evidence that collective levels lying within a few keV of the isomer can affect the half-life and, hence, the corresponding decay properties, significantly.

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Here, we report on the discovery of a seven-quasiparticle isomer in ^{179}Ta that exhibits unusually fast decays. This is attributed to a local mixing between the isomeric state and a nearby member of a collective, five-quasiparticle band. The interaction mixing matrix element is found to be a few orders of magnitude smaller than that typically observed between interacting levels in the collective domain.

The results presented here were obtained from measurements using i) a 820 MeV ^{136}Xe pulsed beam (1 ns on/825 ns off) from the ATLAS accelerator at Argonne National Laboratory (ANL) incident on a 6 mg/cm^2 thick Lu target, enriched to 47% in ^{176}Lu, with a 25 mg/cm^2 Au foil directly behind it to stop recoils at the target position, and ii) the ^{176}Yb(^{7}Li, 4n) reaction with pulsed beams from the 14UD Pelletron accelerator of the Australian National University (ANU). Details regarding the ^{176}Yb(^{7}Li, 4n) experiment have been published in full [6].

The beam energy used in the ANL experiment ($\sim 20\%$ above the Coulomb barrier) allowed a number of nuclei to be populated by transferring nucleons between target and projectiles, as detailed recently [7]. The recoils decayed at the focus of the Gammasphere spectrometer [8], comprised for this experiment of 96 Compton-suppressed Ge detectors. A total of approximately 3×10^9 events,

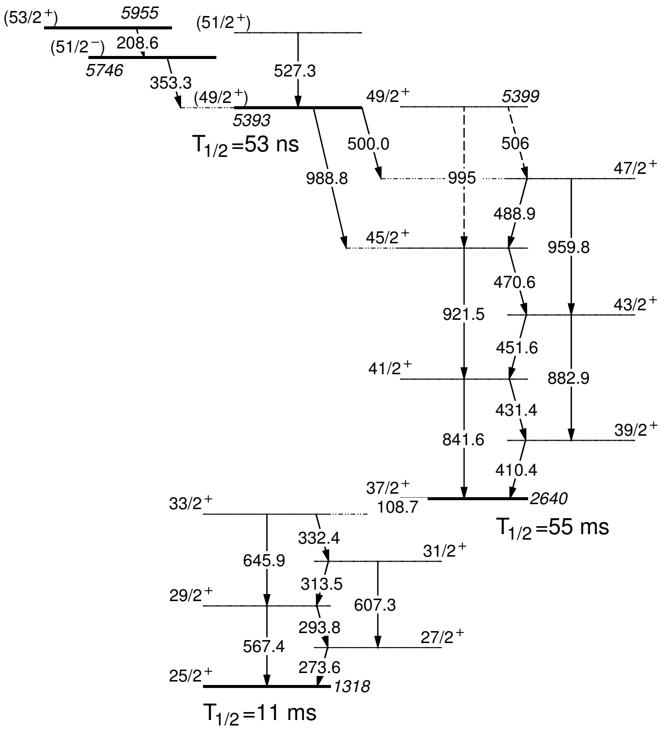

Fig. 1. Partial level scheme of ^{179}Ta showing the decay of the $K^{\pi} = (49/2^{+})$ and previously known [6,9] $37/2^{+}$ isomers. Transition energies are accurate to within ± 0.5 keV.

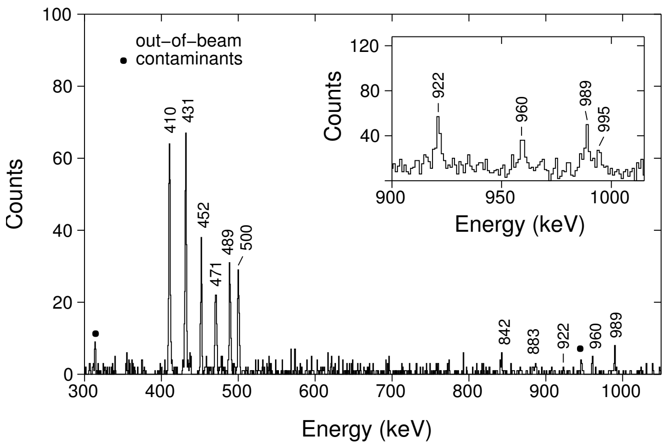

Fig. 2. Coincidence gamma-ray spectrum in the out-of-beam time region from the ANL experiment produced by summing gates on pairwise combinations of the 451.6, 470.6, 488.9 and 500.0 keV γ-rays. The insert shows the high-energy part of a gamma-ray coincidence spectrum from the ANU experiment [6], produced by summing gates on the 410.4 and 431.4 keV γ-ray in a ± 170 ns wide time window centered on the in-beam region.

with fold ≥ 3, was collected. The data were sorted off line into *BLUE* database formats [10], from where a variety of γ-γ and γ-γ-γ histograms were produced with different relative and absolute time conditions, and energy gating conditions as reported recently [7].

A new isomer was observed at 5393 keV in ^{179}Ta, feeding the $I^{\pi} = 45/2^{+}$ and $47/2^{+}$ members of the previously known $K^{\pi} = 37/2^{+}$ band [6]. A partial level scheme, showing the decay path of the isomer is presented in fig. 1. An out-of-beam coincidence gamma-ray spectrum produced by double gating on pairwise combinations of the 452, 471, 489 and 500 keV γ-rays is shown in fig. 2. All transitions previously assigned to the $K^{\pi} = 37/2^{+}$ band [6] can be clearly seen, including the 500 and 989 keV γ-rays that are proposed here to directly depopulate the 5393 keV isomer.

In the earlier work [6], the 5393 keV state (actually given at 5391 keV because of a small difference in energy calibration) had been assigned as a possible band member since the fact that the state has a significant lifetime was overlooked in the earlier analysis, even though its energy was several keV lower than expected. Re-examination of those data agrees with the current assignment and has also allowed the identification of a more weakly populated candidate band member, connected by the 995 keV transition, as seen in the spectrum shown as an insert in fig. 2.

Levels were also identified above the isomer, as shown in fig. 1. The 353.3 and 208.6 keV γ-rays, whose ordering is based partly on their relative intensities, were assigned to depopulate levels at 5746 and 5955 keV, respectively. The order is not unambiguous, but if the 208.6 keV transition is indeed the higher transition, it cannot have $M1$ or $E2$ multipolarity since that would imply a relatively large conversion coefficient and cause an intensity imbalance. The 527.3 keV γ-ray is interpreted as the first cascade ($\Delta I = 1$) transition within the band associated with the isomer, primarily on the basis of its energy. The half-life of the 5393 keV state is deduced as $T_{1/2} = 53(^{+3}_{-7})$ ns by fitting background subtracted time spectra from the ANU experiment, produced by gating on $K^{\pi} = 37/2^{+}$ in-band cascade transitions.

The most likely spin-parity combination of the 5393 keV isomer is $49/2^{+}$. The intensity ratio $I_{\gamma}(989)/I_{\gamma}(500) = 0.44$ (4), deduced for the depopulating transitions using an out-of-beam coincidence γ-ray spectrum from the ANL experiment produced by summing gates on the 410.4 and 841.6 keV γ-rays is in agreement with the value of 0.42 (17) obtained previously [6] and would argue against $I = 47/2$. For example, if both the 500 and 989 keV transitions were of dipole character, one would expect $I_{\gamma}(989)/I_{\gamma}(500) \simeq (989/500)^{3} = 7.7$. Assignment of $49/2^{-}$ is also unlikely since the 989 keV gamma-ray would be a $\Delta K = 6$ forbidden $M2$ transition and, hence, a much longer lifetime for the isomer would be expected. Examination of the crossover/cascade branching ratios for the levels up to $I^{\pi} = 47/2^{+}$ within the $K^{\pi} = 37/2^{+}$ band yields a weighted average value of $|(g_K - g_R)/Q_0| = 0.049$ (4) $(e\mathrm{b})^{-1}$, using $Q_0 = 7.22$ (9) $(e\mathrm{b})$ [11]. It agrees very well with the value of 0.053 (5) $(e\mathrm{b})^{-1}$ [6], deduced from the ^{176}Yb(^{7}Li, 4n) reaction, thus providing a consistency check between the two data sets. Importantly, the 989/500 keV branching ratio is consistent with that expected for a band member which is in turn a signature for the generation of a K-forbidden decay through two-state mixing, as pointed out by Saitoh *et al.* [12].

Table 1. Calculated and experimental states in ^{179}Ta.

K^π	Configuration [(a)]		$E_{\mathrm{qp}}^{(\mathrm{b})}$	$E_{\mathrm{res}}^{(\mathrm{c})}$	$E_{\mathrm{calc}}^{(\mathrm{d})}$	$E_{\mathrm{calc}}^{(\mathrm{e})}$	$E_{\mathrm{expt}}^{(\mathrm{f})}$
	ν	π			(keV)		
$7/2^+$		$7/2^+$	0		0	0	0
$9/2^-$		$9/2^-$	32		32	7	31
$5/2^+$		$5/2^+$	224		224	233	238
$1/2^-$		$1/2^-$	630		630	568	627
$7/2^-$		$7/2^-$	801		801		$800^{(\mathrm{g})}$
$21/2^-$		$5/2^+$, $7/2^+$, $9/2^-$	1513	-77	1436	1504	1253
$21/2^-$	$7/2^-$, $9/2^+$	$5/2^+$	1560	-138	1422	1500	1628
$23/2^-$	$7/2^-$,$9/2^+$	$7/2^+$	1335	-156	1179	1218	1328
$25/2^+$	$7/2^-$,$9/2^+$	$9/2^-$	1367	-114	1253	1267	1318
$31/2^+$	$1/2^-$, $9/2^+$	$5/2^+$, $7/2^+$, $9/2^-$	3282	-262	3020	2966	(2655)
$33/2^-$	$7/2^-$, $9/2^+$	$7/2^+$, $9/2^-$, $1/2^-$	3270	-389	2881	2902	2791
$35/2^+$	$5/2^-$, $9/2^+$	$5/2^+$, $7/2^+$, $9/2^-$	3413	-98	3315	3320	(3183)
$37/2^+$	$7/2^-$, $9/2^+$	$5/2^+$, $7/2^+$, $9/2^-$	2848	-298	2550	2657	2640
$49/2^+$	$5/2^-$, $7/2^-$, $7/2^{-\prime}$, $9/2^+$	$5/2^+$, $7/2^+$, $9/2^-$	5484	-367	5117		5393
$49/2^-$	$5/2^-$, $7/2^-$, $7/2^+$, $9/2^+$	$5/2^+$, $7/2^+$, $9/2^-$	6142	-109	6033	5983	
$51/2^-$	$7/2^-$, $7/2^{-\prime}$, $7/2^+$, $9/2^+$	$5/2^+$, $7/2^+$, $9/2^-$	5635	-144	5491		5746
$53/2^+$	$3/2^-$, $7/2^-$, $7/2^+$, $9/2^+$	$7/2^+$, $9/2^-$, $11/2^-$	6530	-329	6201		
$53/2^+$	$7/2^-$, $7/2^{-\prime}$,$7/2^+$, $9/2^+$	$7/2^+$, $7/2^-$, $9/2^-$	6789	-181	6608		(5955)
$53/2^-$	$5/2^-$, $7/2^-$, $9/2^+$, $11/2^+$	$5/2^+$, $7/2^+$, $9/2^-$	6505	-250	6255		

([a]) Configurations: neutrons (ν): $1/2^-$:$1/2^-$[521]; $3/2^-$:$3/2^-$[512]; $5/2^-$:$5/2^-$[512]; $7/2^-$:$7/2^-$[514]; $7/2^{-\prime}$:$7/2^-$[503]; $7/2^+$:$7/2^+$[633]; $9/2^+$:$9/2^+$[624]; $11/2^+$:$11/2^+$[615]. Protons (π): $1/2^-$:$1/2^-$[541]. $5/2^+$:$5/2^+$[402]; $7/2^+$:$7/2^+$[404]; $7/2^-$:$7/2^-$[523]; $9/2^-$:$9/2^-$[514]; $11/2^-$:$11/2^-$[505].
([b]) Quasiparticle energies from the multi-quasiparticle calculations.
([c]) Residual interactions energy shift. See ref. [6] for details.
([d]) $E_{\mathrm{calc}} = E_{\mathrm{qp}} - E_{\mathrm{res}}$ from the present work.
([e]) $E_{\mathrm{calc}} = E_{\mathrm{qp}} - E_{\mathrm{res}}$ from ref. [6].
([f]) Experimental energies from the present work and ref. [6].
([g]) Value estimated from the systematics of ref. [14].

Predictions of the excitation energy, spin and parity for states in ^{179}Ta have been obtained using multi-quasiparticle blocking calculations. The procedure was identical to that used in the previous work [6], where the systematics of expected multi-quasiparticle states in a chain of Ta nuclei, from ^{175}Ta to ^{179}Ta, was compared to the experimental data. Specifically, the set of single-particle orbitals originating from the $N = 4$, 5 and 6 oscillator shells were taken from the Nilsson model with parameters κ and μ from ref. [13], and deformations $\varepsilon_2 = 0.242$ and $\varepsilon_4 = 0.052$. The states close to the proton and neutron Fermi surfaces were adjusted to reproduce approximately the experimental one-quasiparticle energies in ^{179}Ta (for the protons) and the average energies of the observed states in ^{177}Hf and ^{179}W (for the neutrons). A notable difference between the present work and ref. [6] is that the energies of the $\nu 7/2^-[503]$ and $\pi 7/2^-[523]$ orbitals were adjusted here to reproduce the systematics of single-particle states compiled by Jain *et al.* [14]. Since these orbitals are involved in many of the seven-quasiparticle configurations in ^{179}Ta, this approach allows more reliable predictions of their location to be made in the present work. After that no further adjustments were allowed. The pairing correlations were treated using the Lipkin-Nogami prescription with fixed strengths of $G_\pi = 20.8/A$ MeV and $G_\nu = 18.0/A$ MeV. The predicted energies of the multi-quasiparticle states were subsequently corrected for residual interactions using the prescription of ref. [15] and the Gallagher-Moszkowski splitting energies of ref. [16]. The calculated excitation energies for yrast and near-yrast high-K states in ^{179}Ta, together with the experimental observations, are summarized in table 1. Except for the highest states, the present predictions are not significantly different from the earlier ones [6], which are also included in the table. In general, the theoretical and experimental energies for the multi-quasiparticle states agree within 100 keV.

The lowest-energy seven-quasiparticle state predicted has $K^\pi = 49/2^+$ and the

$$\pi^3(5/2^+[402], 7/2^+[404], 9/2^-[514]) \otimes \nu^4(5/2^-[512], 7/2^-[514], 7/2^-[503], 9/2^+[624])$$

configuration. It is associated with the isomer at 5393 keV. The configuration is related to that of the $37/2^+$ isomer, but with the addition of the $\nu^2(5/2^-[512], 7/2^-[503])_{6^+}$ component. Calculations predict a $K^\pi = 51/2^-$ state arising from the

$$\pi^3(5/2^+[402], 7/2^+[404], 9/2^-[514]) \otimes \nu^4(7/2^+[633], 7/2^-[514], 7/2^-[503], 9/2^+[624])$$

configuration, at 374 keV above the theoretical $K^\pi = 49/2^+$ state. It is a candidate for the level observed at 5746 keV, 353 keV above the isomer.

The higher states are less certain. As can be seen from table 1, there are two calculated seven-quasiparticle states with $K^\pi = 53/2^+$ and one with $K^\pi = 53/2^-$ at similar energies. If the $51/2^-$ assignment to the 5746 keV experimental state is correct, the 5955 keV level would be of positive parity since the connecting 209 keV transition would have to be of $E1$ character, based on intensity considerations that limit the possible value of its electron internal conversion coefficient. Of the two possibilities we tentatively favor the $K^\pi = 53/2^+$

$$\pi^3(7/2^+[404], 7/2^-[523], 9/2^-[514])$$
$$\otimes \nu^4(7/2^+[633], 7/2^-[514], 7/2^-[503], 9/2^+[624])$$

configuration, even though it has the higher energy of the pair (see table 1), since its configuration is closely related to that of the $51/2^-$ level to which it decays, and there is no lifetime observed. In this case the configuration difference involves a single-orbital change, *e.g.* $\pi 7/2^-[523] \rightarrow \pi 5/2^+[402]$, whereas in the other case several orbitals would have to be re-arranged. (It is worth noting that the configurations of the two lowest-energy $K = 53/2$ states contain orbitals whose single-particle energies were not adjusted in the calculation procedure, hence, their calculated excitation energies may be less certain.)

The isomeric nature of the $K^\pi = (49/2^+)$ state in principle arises because the depopulating transitions are K-forbidden. For a transition of multipole order, λ, the reduced hindrance factor per degree of K-forbiddenness, f_ν, where $\nu = \Delta K - \lambda$, is defined as $f_\nu = F_{\rm W}^{1/\nu}$, where $F_{\rm W} = T^{\gamma}_{1/2}/T^{\rm W}_{1/2}$ and $T^{\gamma}_{1/2}$, and $T^{\rm W}_{1/2}$ are the partial γ-ray and the Weisskopf estimate half-lives, respectively. The reduced hindrance factor obtained for the 989 keV $E2$ transition is $f_\nu = 11.8$, a value that is surprisingly low compared to those of equivalent $\Delta K = 6$ decays in neighboring Hf and Ta isotopes [17–22] which have values of ~ 20 and higher.

This is attributed to mixing between the isomer and the $49/2^+$ member of the $K^\pi = 37/2^+$ band. The candidate band member is (after mixing) only 6 (1) keV away, as displayed in fig. 1. (Note that the energy of this state falls on the energy expected for an essentially unperturbed band member.) By assuming a two-level interaction, the mixing amplitude, β, of the collective state into the $49/2^+$ isomer can be estimated as [4, 12]

$$\beta^2 = \alpha^2 \times B(E2; 989)^{\rm expt}/B(E2)^{\rm coll} \qquad (1)$$

where $B(E2)^{\rm coll} = (5/16\pi)Q_0^2|\langle IK20|I-2K\rangle|^2$ and $Q_0 = 7.22$ (9) eb [11]. The deduced value of $\beta = 9.4 \times 10^{-4}$ implies a mixing matrix element of only 6 (1) eV, a value comparable to those reported for chance mixing in the nearby nuclei ^{176}Lu [4] and ^{182}Re [5], that produces similar abnormally fast decays with $f_\nu = 3.7$ and 4.7, respectively. This value of the mixing matrix element is orders of magnitude lower than that observed between interacting collective levels which are typically of the order of tens of keV [23, 24]. The unusually fast decay in ^{179}Ta is therefore not a consequence of some erosion of the K quantum number, but is rather due to a specific mixing between two different, but closely spaced, quantum states. In contradistinction, the very small interaction matrix element is an indication of the clear separation in K configuration space of the unperturbed states.

In summary, a new seven-quasiparticle isomer has been identified in ^{179}Ta. In comparison with results from multi-quasiparticle calculations the isomer is assigned $K^\pi = (49/2^+)$ and the $\pi^3(5/2^+[402], 7/2^+[404], 9/2^-[514]) \otimes \nu^4(5/2^-[512], 7/2^-[514], 7/2^-[503], 9/2^+[624])$ configuration. The relatively fast decay of the isomer is interpreted in terms of a "local" mixing with the $49/2^+$ member of the $K^\pi = 37/2^+$ band, with a very small interaction matrix element.

The authors thank R.B. Turkentine and J.P. Greene for producing the targets and the staff of the ATLAS accelerator facility for their assistance in various phases of the experiment. This work is supported by the U.S. Department of Energy, Office of Nuclear Physics, under contract No. W-31-109-ENG-38 and grant No. DE-FG02-94ER40848, the ANSTO program for Access to Major Research Facilities, grant No. 02/03-H-05 and the Australian Research Council Discovery projects DP0343027, and DP0345844.

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