$M3$ and $E4$ K-forbidden decays of the $K^{\pi} = 23/2^-$ isomer in ^{177}Lu

F. G. Kondev,[1] S. Zhu,[1] M. P. Carpenter,[1] R. V. F. Janssens,[1] I. Ahmad,[1] C. J. Chiara,[1,2] J. P. Greene,[1] T. Lauritsen,[1] D. Seweryniak,[1] S. Lalkovski,[3] and P. Chowdhury[4]

[1]*Argonne National Laboratory, Argonne, Illinois 60439, USA*

[2]*Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA*

[3]*Faculty of Physics, University of Sofia, BG-1164 Sofia, Bulgaria*

[4]*Department of Physics, University of Massachusetts Lowell, Lowell, Massachusetts 01854, USA*

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Decay of the long-lived ($T_{1/2} = 160.44$ d) $K^{\pi} = 23/2^-$ isomer in ^{177}Lu was investigated using a chemically purified source and the Gammasphere array. New, high-multipolarity *M3* and *E4* deexcitation branches to the known $I^{\pi} = 17/2^-$ and $15/2^-$ members of the $\pi 9/2^-[514]$ band were discovered. The reduced hindrance factors per degree of K forbiddenness deduced for these two transitions are found to be relatively large when compared to similar decays from the $K^{\pi} = 37/2^-$ ($T_{1/2} = 51.4$ min) and $K^{\pi} = 16^+$ ($T_{1/2} = 31$ yr) isomers in ^{177}Hf and ^{178}Hf, respectively. This is attributed to significant configuration changes that occur in the decay of this ^{177}Lu isomer.

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The properties of K isomers play an important role in understanding the structure and collective modes of deformed, axially symmetric nuclei. While considerable progress has been made in the past 30 years in identifying and characterizing many K isomers in different areas of the nuclear chart, predictions of their lifetimes and associated transition strengths still remain a challenge for theory. The lifetime can be particularly long, especially when the isomer is being classified as both a "K trap" (with a large difference in the K quantum numbers of the isomer and the final state to which it decays) and a "spin-trap" (with a large change in nuclear spin enabling the decay to proceed only via high-multipolarity transitions) [1]. In the rare-earth region, high-multipolarity *M4* and *E5* transitions were established in the decay of the $K^{\pi} = 16^+$ isomer ($T_{1/2} = 31$ y) in ^{178}Hf [2–5]. Searches for such exotic decay modes have also been performed in other regions of the nuclear chart. The most notable example is the *E6* decay of the high-spin isomer in ^{53}Fe [6], the highest multipolarity transition known in any nucleus [7], whose strength was recently calculated in a shell-model approach [8].

High-multipolarity transitions can also be expected to occur in the decay of the $K^{\pi} = 23/2^-$ isomer ($T_{1/2} = 160.44$ d) in ^{177}Lu, denoted here as ^{177m}Lu. This isomer was discovered by Jørgensen *et al.* [9] and assigned the three-quasiparticle $\pi 7/2^+[404] \otimes \nu(7/2^-[514], 9/2^+[624])$ configuration. The latter was confirmed by the measured magnetic moment of the isomer (see Refs. [10,11] and references therein) and by the properties of the rotational band built on this state [12]. Previous studies (see for example Ref. [13] and references therein) found that the isomer partially decays by β^- emission to a similar three-quasiparticle, $K^{\pi} = 23/2^+$ $\pi(7/2^+[404], 9/2^-[514]) \otimes \nu 7/2^-[514]$ isomer in ^{177}Hf and by means of an *E3*, K-forbidden γ-ray transition to the $I^{\pi} = 17/2^+$ member of the $\pi 7/2^+[404]$ ground-state band of ^{177}Lu.

Here, we report on the discovery of high-multipolarity *M3* and *E4* γ-ray decay branches from the isomer to members of the previously known one-quasiparticle $\pi 9/2^-[514]$ band in ^{177}Lu. These transitions are found to be unusually hindered, and this is attributed to the significant configuration changes that occur in the decay between the isomer and the final levels.

The ^{177m}Lu isomer was produced in a neutron-capture reaction on ^{176}Lu at the University of Massachusetts Lowell research reactor facility. A natural lutetium metallic sample was irradiated for about three years. This was followed by an approximately 3-yr radiation cooling period that allowed all short-lived nuclides to decay away. The ^{177m}Lu source ($\sim$0.5 μCi) was prepared at Argonne National Laboratory following radiochemical separation of lutetium and ^{182}Ta radionuclides. The latter was produced from natural tantalum impurities in the target material via the ^{181}Ta(n,γ) reaction. The ^{182}Ta radionuclide has a half-life of $T_{1/2} = 114.74$ d [14], comparable to that of ^{177m}Lu, and its decay generates substantial Compton-scattered background in the γ-ray spectra owing to the presence of several high-energy transitions of relatively high intensity. Since the tantalum material was insoluble in most dilute acids, the irradiated lutetium sample was dissolved in a 0.2-mol HNO_3 solution, leaving behind the tantalum metal pieces. The solution was separated from the insoluble solid, placed on a quartz plate, and dried.

Several γ-ray measurements were carried out with the lutetium source including: (i) γ-ray singles measurements using 2-cm^2 × 1-cm planar Low Energy Photon Spectrometer (LEPS) and 25% coaxial Ge detectors; (ii) γ-ray coincidence measurements using two $LaBr_3$(Ce) scintillation detectors and the Gammasphere array of 100 Compton-suppressed, large-volume Ge detectors [15]; and (iii) γ-ray coincidence measurements using the Gammasphere alone. The results from the first two series of measurements have been presented elsewhere [16,17].

In the Gammasphere standalone experiment, the source was placed at the center of the array and data were collected with the requirement that at least one γ ray was detected. In the subsequent analysis, the collected data were sorted offline into γ-γ and γ-γ-γ histograms with required coincidence

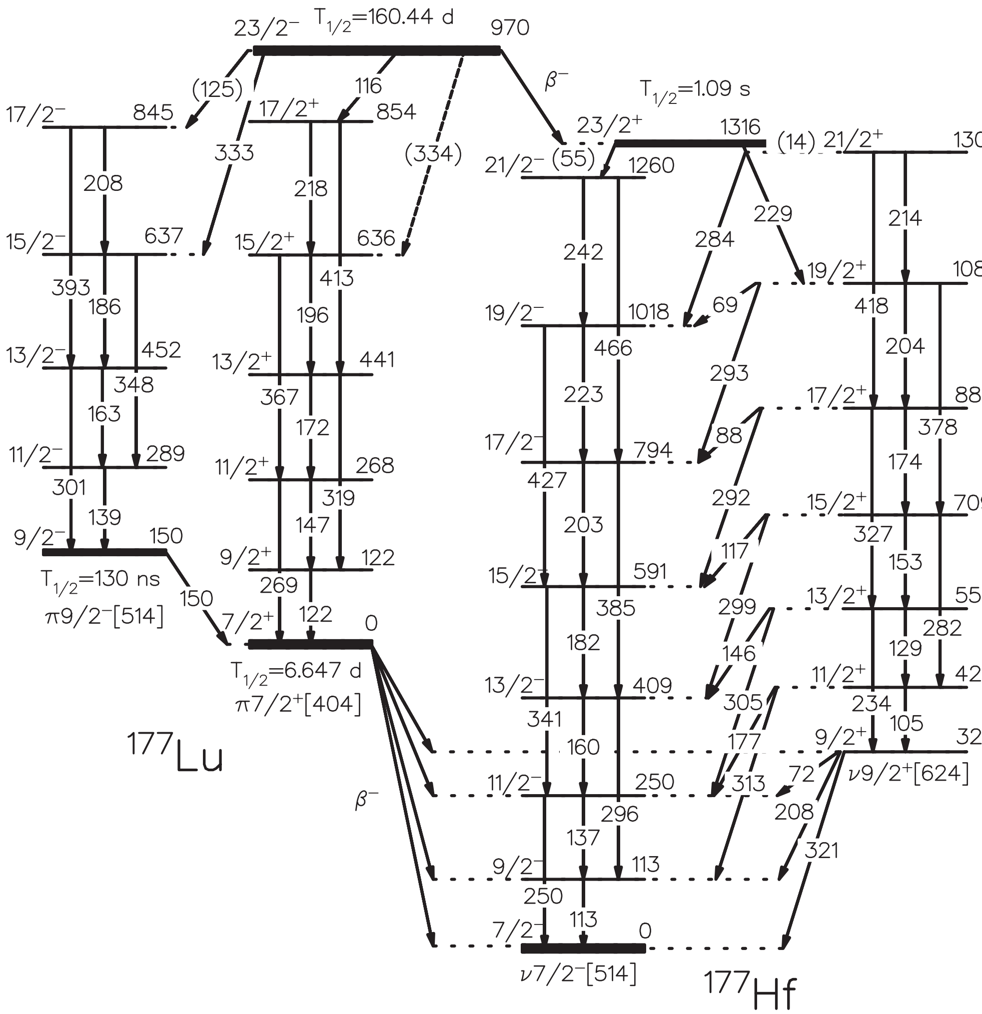

FIG. 1. ^{177m}Lu decay level scheme deduced in the present work. The quoted lifetimes are from Ref. [13].

windows of ±25 ns and ±170 ns. The latter condition was used to minimize the distortion of γ-ray intensities due to time walk by the timing discriminators for transitions with energies below 200 keV. Since single- and double-gated spectra were used to deduce the isomer decay branches, the Gammasphere γ-ray efficiency was carefully determined using a calibrated, multinuclide source containing ^{57,60}Co, ^{85}Sr, ^{88}Y, ^{109}Cd, ^{113}Sn, ^{137}Cs, ^{139}Ce, ^{203}Hg, and ^{241}Am and monoisotopic sources of ^{152}Eu, ^{182}Ta, and ^{243}Am. These measurements were carried out in the same geometry as adopted for the ^{177m}Lu source. The existence of a number of cascade and crossover transitions in the ^{177m}Lu decay scheme itself allowed the corresponding γ-ray efficiencies to be checked internally using intensity balances, and these were found to be in good agreement with values deduced using the source measurements.

The decay scheme deduced in the present work for the $K^\pi = 23/2^-$ isomer is presented in Fig. 1. The main decay paths via the three-quasiparticle $K^\pi = 23/2^+$ isomer in ^{177}Hf and the $I^\pi = 17/2^+$ member of the $\pi 7/2^+[404]$ ground-state band of ^{177}Lu, established previously [13], were confirmed in the present studies. Figure 2(a) provides a γ-ray coincidence spectrum that isolates the decay via the $\nu 9/2^+[624]$ band in ^{177}Hf. The 14-keV transition that feeds the $I^\pi = 21/2^+$ level was not observed directly, since it is highly converted. However, its existence is confirmed by the observation of the 214- and 418-keV transitions depopulating this $I^\pi = 21/2^+$ level. The coincidence spectrum of Fig. 3, produced by gating on γ rays in the $\nu 7/2^-[514]$ band, shows many of the connecting E1 transitions between the $\nu 9/2^+[624]$ and $\nu 7/2^-[514]$ bands in ^{177}Hf. The 55-keV transition that feeds directly the $21/2^-$ level was not observed, because of the overlap with the Hf $K\alpha_1$ x ray. Figure 2(b) provides a coincidence spectrum where the decay via the $\pi 7/2^+[404]$ ground-state band of ^{177}Lu is isolated. A thorough search for the 334-keV *M4* transition that would connect the isomer with the $I^\pi = 15/2^+$ level was carried out, but this γ ray was not observed and only a limit for this branch was deduced, as indicated in Table I.

The $K^\pi = 9/2^-$ band head at 150 keV, associated with the $\pi 9/2^-[514]$ orbital, and the corresponding rotational band were known from previous studies [13]. The sum of coincidence spectra in Fig. 4 was produced with double gates on the 150-, 139- and 163-keV transitions with the 186-keV γ ray. It is apparent that the $I^\pi = 15/2^-$ and $17/2^-$ members

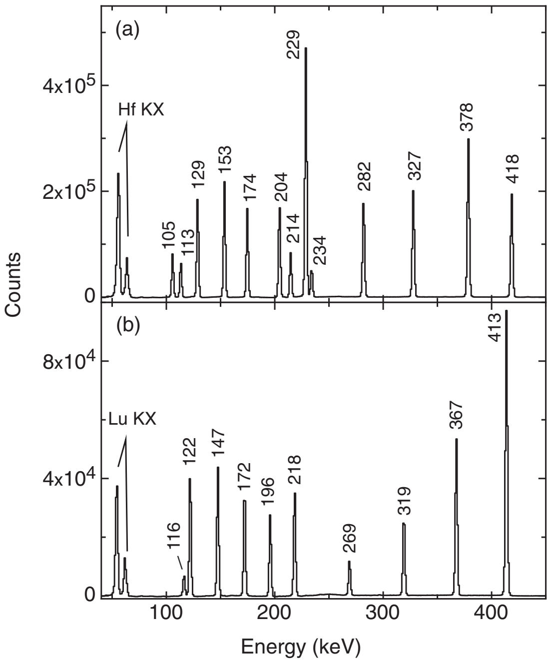

FIG. 2. (a) Background-subtracted γ-ray coincidence spectrum produced by summing $\gamma_1\{105, 113\}\gamma_2\{208\}$ double gates, i.e., $\gamma_1\{105\}\gamma_2\{208\} + \gamma_1\{113\}\gamma_2\{208\}$, showing the isomer decay path via the $\nu 9/2^+[624]$ band in ^{177}Hf; (b) Gamma-ray coincidence spectrum produced by summing $\gamma_1\{122, 147, 172, 196, 218\}\gamma_2\{122, 147, 172, 196, 218\}$ double gates (the diagonal contributions were excluded) associated with the $\pi 7/2^+[404]$ ground-state band in ^{177}Lu.

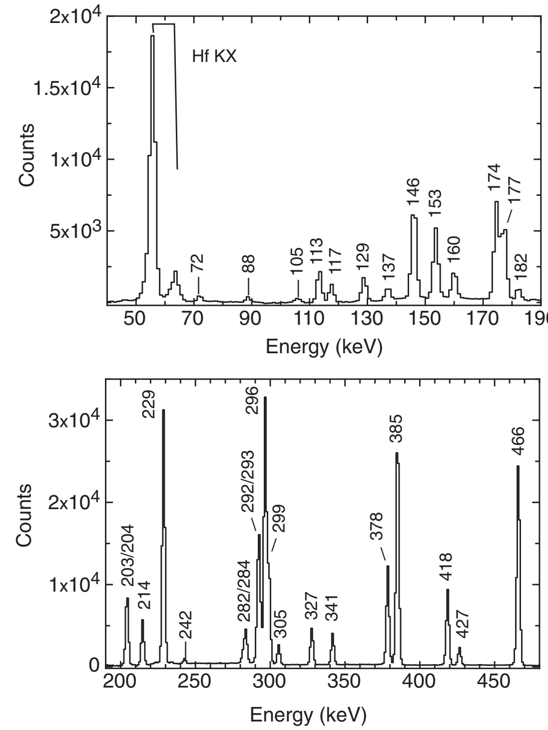

FIG. 3. Background-subtracted γ-ray coincidence spectrum produced by summing $\gamma_1\{113\}\gamma_2\{296, 385, 466\}$, $\gamma_1\{137\}\gamma_2\{341, 427\}$, and $\gamma_1\{113\}\gamma_2\{137\}$ double gates associated with the $\nu 7/2^-[514]$ band in ^{177}Hf.

of the $\pi 9/2^-[514]$ band are fed by the $K^\pi = 23/2^-$ isomer via the 333- (*E4*) and 125-keV (*M3*) transitions. While the former γ ray is clearly seen in the coincidence spectrum of Fig. 4, the latter was not directly observed, owing to the large conversion coefficient for such an *M3* transition ($\alpha_T(M3) = 94.3$ [18]). With the relative γ-ray intensities deduced from the spectrum of Fig. 4 and the intensity balance at the $I^\pi = 17/2^-$ level, the relative intensity of the 125-keV γ ray is expected to be ∼1.5% of the 208-keV yield. Hence, the former is not observable

TABLE I. Reduced hindrances per degree of K forbiddenness for high-multipolarity transitions in ^{177}Lu, ^{177}Hf, and ^{178}Hf. The transitions shown in parenthesis were not observed directly.

E_γ (keV)	Mult.	I_γ (rel)	α_T [18]	F_W (W.u.)	ν	f_ν
			^{177}Lu; $K^\pi = 23/2^-$; $T_{1/2} = 160.44$ (6) d; $IT = 22.8$ (7)%			
115.9	*E3*	100 (2)	30.7	$8.3\ (4) \times 10^8$	5	60.8 (5)
(334)	*M4*	$\leqslant 0.28$	5.58	$\geqslant 5.3 \times 10^6$	4	$\geqslant 48$
125.3	*M3*	0.032 (8)	94.3	$4.4\ (12) \times 10^{10}$	4	458 (30)
333.1	*E4*	0.26 (6)	1.007	$5.7\ (14) \times 10^8$	3	829 (70)
			^{177}Hf; $K^\pi = 37/2^-$; $T_{1/2} = 51.4$ (5) min; $IT = 100$%			
(185.3)	*M3*	0.16 (3) [a]	18.6	$5.5\ (11) \times 10^5$	3	82 (6)
214.0	*E3*	100.00 (3)	1.512	$2.47\ (6) \times 10^5$	4	22.29 (13)
			^{178}Hf; $K^\pi = 16^+$; $T_{1/2} = 31$ (1) yr; $IT = 100$%			
(12.76)	*E3*	0.050 (8) [b]	1.43×10^7	$1.2\ (3) \times 10^9$	5	65 (4)
309.5	*M4*	100 (7) [c]	8.44	$2.7\ (5) \times 10^7$	4	72 (4)
587.0	*E5*	41 (4) [c]	0.284	$5.3\ (11) \times 10^6$	3	175 (11)

[a]The existence of this branch was not known previously. It is inferred from the observation of the 120.5-keV γ ray in the decay of the $K^\pi = 37/2^-$ isomer in ^{177}Hf [22], which was subsequently assigned to depopulate the $K^\pi = 25/2^-$ bandhead in ^{177}Hf [13].
[b]From the intensity balance at the $I^\pi = 13^-$ level and the relative intensities quoted in Ref. [3].
[c]From the relative intensities given in Ref. [3].

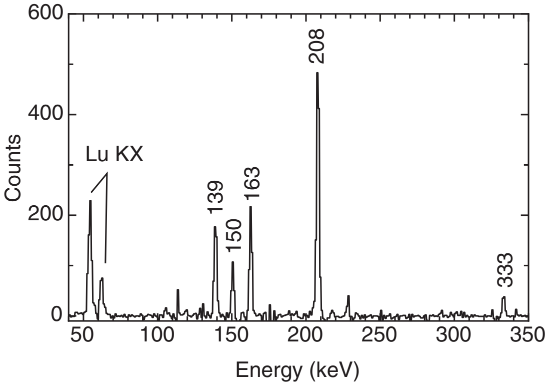

FIG. 4. Background-subtracted γ-ray coincidence spectrum produced by summing $\gamma_1\{150, 139, 163\}\gamma_2\{186\}$ double gates associated with the $\pi 9/2^-[514]$ band in ^{177}Lu.

as it is buried under the background in the spectrum of Fig. 4.

The very long half-life of the $K^\pi = 23/2^-$ isomer arises because of its low excitation energy, which results in decay paths associated with high-multipolarity and low-energy γ-ray transitions, which are in addition K forbidden. For a transition of multipole order λ, the reduced hindrance factor per degree of K forbiddenness, f_ν ($\nu = \Delta K - \lambda$), is defined as $f_\nu = F_W^{1/\nu}$, where $F_W = T_{1/2}^\gamma / T_{1/2}^W$ is the Weisskopf hindrance factor with $T_{1/2}^\gamma$ and $T_{1/2}^W$ being the partial γ-ray and the Weisskopf estimate half-lives, respectively. The deduced hindrances are presented in Table I, together with values for other high-multipolarity, K-forbidden transitions (with $\nu \geqslant 3$) measured in neighboring ^{177}Hf and ^{178}Hf nuclei. In general, the magnitude of f_ν depends on the degree of K mixing in the wave functions of the isomer itself and the final states to which the decay proceeds. A common feature of the isomers selected in Table I is that all of them are yrast and, therefore, no significant K mixing would be expected to affect their decay.

Reduced hindrances per degree of K forbiddenness are also known to be sensitive to associated changes in the configuration of the states involved [19–21]. Considering the differences between the configurations of the $K^\pi = 23/2^-$ isomer and the $I^\pi = 17/2^+$ member of the $\pi 7/2^+[404]$ ground-state band, the $E3$ decay involves the

$$\pi 7/2^+[404] \otimes \nu(7/2^-[514], 9/2^+[624]) \rightarrow \pi 7/2^+[404]$$

change, which is equivalent to a $\nu^2(7/2^-[514], 9/2^+[624])_{[8^-]} \rightarrow 0^+$ transition. It is worth noting that the $E3$ decay from the $K^\pi = 16^+$ isomer in ^{178}Hf to the 13^- member of the $K^\pi = 8^-$ band (a mixture between $\nu[8^-]$ and $\pi[8^-]$ configurations) involves a similar change:

$$\pi(7/2^+[404], 9/2^-[514]) \otimes \nu(7/2^-[514], 9/2^+[624]) \rightarrow \nu(7/2^-[514], 9/2^+[624])$$

or

$$\pi(7/2^+[404], 9/2^-[514]) \otimes \nu(7/2^-[514], 9/2^+[624]) \rightarrow \pi(7/2^+[404], 9/2^-[514]).$$

Hence, the f_ν hindrances for these two $E3$ decays should be expected to be nearly identical. This is verified experimentally, as seen in Table I ($f_\nu \sim 60$). In contrast, the $E3$ decay from the $K^\pi = 37/2^-$ isomer ($\pi(7/2^+[404], 9/2^-[514]) \otimes \nu(5/2^-[512], 7/2^-[514], 9/2^+[624])$) in ^{177}Hf to the $I^\pi = 31/2^+$ member of the $K^\pi = 23/2^+$ ($\pi(7/2^+[404], 9/2^-[514]) \otimes \nu 7/2^-[514]$) band has a relatively low value of $f_\nu = 22.29$. In this case, the change in configurations between the isomer and the final level corresponds to a $\nu^2(5/2^-[512], 9/2^+[624])_{[7^-]} \rightarrow 0^+$ transition, i.e., an operation involving the $f_{7/2}$ and $i_{13/2}$ orbitals which differ by $\Delta l = 3$ and $\Delta j = 3$, a change known to lead to enhanced $E3$ transitions.

A notable feature of the ^{177m}Lu decay is the significantly larger hindrances of $f_\nu = 458$ and 829 measured for the $M3$ and $E4$ decays to the $I^\pi = 17/2^-$ and $15/2^-$ members of the $\pi 9/2^-[514]$ band, respectively. As both transitions involve rearrangements of all the orbitals between the corresponding configurations,

$$\pi 7/2^+[404] \otimes \nu(7/2^-[514], 9/2^+[624]) \rightarrow \pi 9/2^-[514]$$

one should expect larger retardation, as observed. In contrast, the $M3$ transition in the decay of the $K^\pi = 37/2^-$ isomer in ^{177}Hf to the $31/2^-$ member of the $K^\pi = 25/2^-$ band ($\pi(7/2^+[404], 9/2^-[514]) \otimes \nu 9/2^+[624]$) has $f_\nu = 82$, and involves a simple configuration change equivalent to a $\nu^2(5/2^-[512], 7/2^-[514])_{[6^+]} \rightarrow 0^+$ transition.

In summary, the decay of the long-lived, $K^\pi = 23/2^-$ isomer in ^{177}Lu was studied using a chemically-purified source in conjunction with the Gammasphere and other detection systems. High-multipolarity $M3$ and $E4$ decay branches were observed for the first time. These transitions were found to be more hindered when compared to similar exotic decays known in neighboring nuclei. This feature is proposed to arise from the significant rearrangement in configurations between the isomer and the final levels.

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