Rotational bands and isomeric states in ^{175}Lu

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(Received 10 October 2003; published 14 January 2004)

Rotational bands in ^{175}Lu have been extended through investigation with the $(n,n'\gamma)$ reaction. Spallation neutrons bombarded Lu samples, and the resulting γ rays were detected in a large-scale Compton-suppressed Ge detector array. Prompt- and delayed-$\gamma\gamma$ coincidences have been used to extend the $5/2^+[402]$ band to spin 17/2, the $3/2^+[411]$ band to spin 11/2, the $1/2^+[411]$ band to spin 15/2, and the $1/2^-[541]$ and $9/2^-[514]$ bands to spin 21/2. A new band, based on the $7/2^-[523]$ configuration, is tentatively assigned from its bandhead to spin 13/2. The three-quasiparticle $K^\pi=19/2^+$ isomer is confirmed and its half-life determined to be $984\pm13(\text{stat.})\pm30(\text{sys.})$ μs, in agreement with previous results.

DOI: 10.1103/PhysRevC.69.017302 PACS number(s): 21.10.Tg, 23.20.Lv, 25.40.Fq, 27.70.+q

There has been a renewed interest in isomeric states of nuclei in the Hf region recently, in part due to reports [1] of stimulated emission from the 31 yr, 16^+ isomer in ^{178}Hf. While the result [1] has been refuted [2], the physics interest in the high-*K* multi-quasiparticle isomers in the region is driven by the quest to understand the purity of the *K* quantum number and its persistence to high excitation energy. Systematic investigations that study the evolution of intrinsic excitations as a function of proton and neutron number are required in order to make firm configuration assignments and to assess the *K* purity. It is the purpose of this Brief Report to communicate results of measurements taken on ^{175}Lu with neutrons originating from a spallation neutron source. In these experiments, rotational bands have been extended based on analysis of prompt- and delayed-$\gamma\gamma$ coincidences, a new rotational band built on the $7/2^-[523]$ configuration is suggested, and the known [3] three-quasiparticle $19/2^+$ isomer has been confirmed and its lifetime remeasured.

The measurements were performed at the Los Alamos Neutron Science Center (LANSCE) Weapons Neutron Research facility. The 800-MeV protons from the LANSCE linac bombarded a $^{\text{nat}}$W target resulting in spallation neutrons with energies varying from <1 MeV to nearly 800 MeV. The pulsed proton beam was delivered with a 1.8-μs spacing for 625 μs macropulses at a macropulse rate of (typically) 80 Hz. The scattering sample consisted of two 3-min-thick pieces of $^{\text{nat}}\text{Lu}_\text{u}\text{O}_3$-loaded vinyl chloride-ethylene resin with weight percents of 69.57% Lu (with a natural abundance of 97.4% ^{175}Lu), 14.20% O, 15.77% C, 0.20% H, and 0.26% N. The sample was placed at the focus of the GEANIE spectrometer located at a distance of 20.34 m from the production target on the 60°R flight path. The neutrons were collimated to produce a 1.5-cm-diameter (full width at half maximum) "beam" at the scattering sample. To reduce the number of low-energy neutrons and the intensity of γ rays from the neutron production target, 7.5 cm of polyethylene and 2.9 cm of Pb were placed in the neutron beam 14-m upstream of the scattering sample. The GEANIE spectrometer consisted of eleven planar and fifteen 25% HPGe coaxial detectors. All planar and nine of the coaxial detectors were equipped with suppression shields. The planar detectors were placed at the most forward and backward angles, and γ-ray events of ≤ 1 MeV were processed, while the coaxial detectors were positioned around $90\pm40°$ with respect to the beam direction and γ-ray events were recorded with energies up to 4 MeV. The data were collected

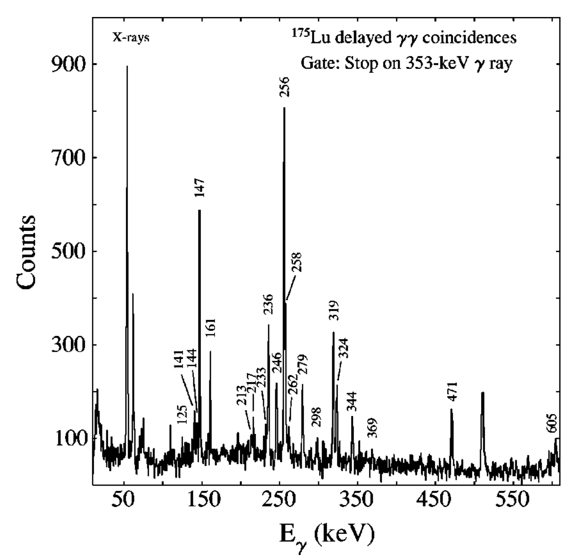

FIG. 1. Spectrum observed for a gate taken on the 353-keV transition serving as the "stop" transition for delayed-$\gamma\gamma$ coincidences. The γ rays placed above the 1.49(7)-μs 353-keV level in ^{175}Lu are labeled with their energies in keV.

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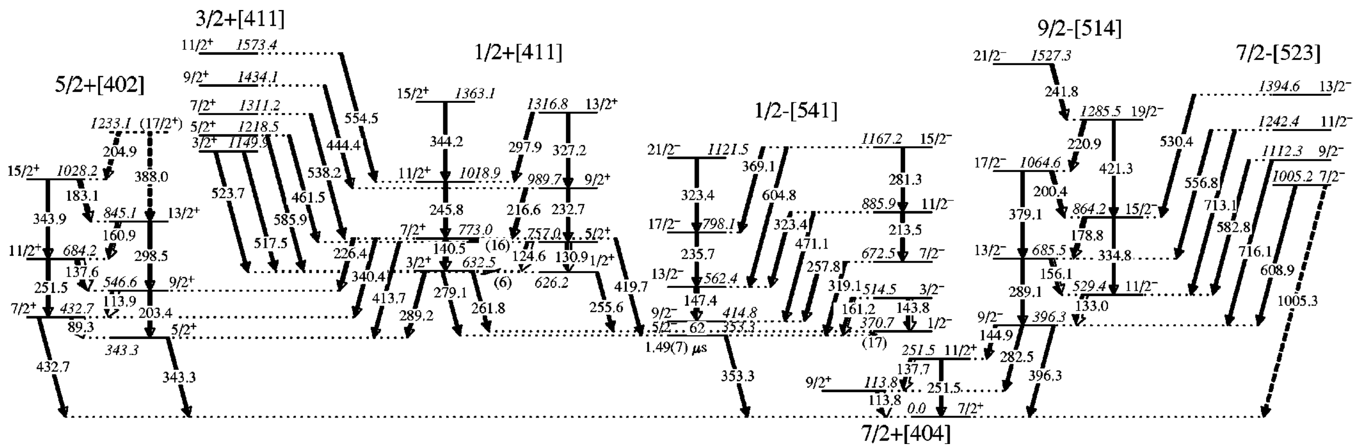

FIG. 2. Partial level scheme leading to new results in ^{175}Lu constructed from analysis of prompt- and delayed-$\gamma\gamma$ coincidence. The 6-keV $3/2^+ \rightarrow 1/2^+$ and 16-keV $7/2^+ \rightarrow 5/2^+$ transitions in the $1/2^+[411]$ band are placed due to the observation of cross talk between the two signatures in the prompt-coincidence spectra. The 17-keV $1/2^- \rightarrow 5/2^-$ transition in the $1/2^-[541]$ band is placed due to the observation of the 144-keV transition in the 353-keV delayed coincidence gate (see Fig. 1). Uncertainties on the γ-ray energies are estimated at 0.1 keV.

in singles- and higher-fold mode. The time relative to the start of the macropulse (CLOCK, recorded in 100-ns intervals), the energy E_γ and, if in-beam, the time t_γ relative to the proton micropulse were collected for each detector that indicated an event. The neutron flux was monitored using a fission chamber with both ^{235}U and ^{238}U foils [4], where the neutron energy was determined using the time of flight between the time of the proton pulse incident on the W spallation target and the event time in any of the detectors. The neutron flux integrated from 1 to 8 MeV incident on the target was $\approx 7 \times 10^4$ cm^{-2} s^{-1}.

During playback of the data, events were separated depending on whether they occurred during the macropulse (in-beam) or after (out-of-beam). A prompt-$\gamma\gamma$ coincidence matrix was created by placing a time condition that events occur within $\approx$100 ns of each other and correspond to neutron energies $E_n = 1-8$ MeV. This neutron energy range was chosen in order to minimize the background from other reaction channels, especially the ^{175}Lu$(n,2n)$ channel that has a threshold of 7.7 MeV. A total of 2.6×10^6 events were sorted into the prompt matrix. The delayed-$\gamma\gamma$ coincidence matrix had the condition that the times between events be in the range of 150–750 ns, with the further condition that they correspond to $E_n < 600$ MeV (in order to suppress the large background of γ rays from the spallation target). The out-of-beam data were sorted into E_γ vs CLOCK and $\gamma\gamma$ matrices. Additional details of the experimental setup and data analysis are given in Ref. [5].

The 1.49(7)-μs isomer [6], located at 353 keV, decays by a 353-keV $E1$ transition from the $5/2^-$ member of the $1/2^-[541]$ configuration to the ground state, which has the $7/2^+[404]$ configuration. The spectrum of delayed coincidences with the 353-keV transition, shown in Fig. 1, displays transitions that are emitted 150–750 ns before the 353-keV transition, i.e., these γ rays feed levels located above the 353-keV isomeric level. Most of the γ rays have been placed previously [7,8] in the ^{175}Lu level scheme. Some additional transitions are observed, and from Fig. 1 and results of gates placed on the prompt-$\gamma\gamma$ matrix, allow the extension of the $1/2^+[411]$ and $1/2^-[541]$ bands to higher excitation energy as shown in Fig. 2. The $15/2^+$ and $21/2^-$ members of these bands, observed by Foin *et al.* [7], were not adopted in the most recent Nuclear Data Sheets [9]. The present work confirms the existence of these levels. Three new levels, at 1311.2 keV, 1434.1 keV, and 1573.4 keV, are established based on prompt-$\gamma\gamma$ coincidence results. The decay patterns to the $7/2^+$, $9/2^+$, and $11/2^+$ members of the $1/2^+[411]$ band, and the very good agreement with the level energies predicted based on a rotational parameter of 13.6 keV extracted from the $5/2^+ - 3/2^+$ energy difference, support the assignment of these levels as the $7/2^+$, $9/2^+$, and $11/2^+$ members of the $3/2^+[411]$ band tentatively assigned in Ref. [8]. Also shown is the extension of the $5/2^+[402]$ band to $17/2^+$ level based on $M1/E2$ in-band transitions, and the assignment of the $21/2^-$ band member of the $9/2^-[514]$ band. Table I lists the relative γ-ray intensities for each level where it was possible to extract the uncontaminated peak areas from the coincidence gates.

Shown in Fig. 3 is the spectrum obtained from summing gates of 396 keV and 282 keV placed on the prompt-$\gamma\gamma$ coincidence matrix. In addition to the in-band members, γ rays with energies of 609 keV, 583 keV, 557 keV, 713 keV, 716 keV, and 530 keV are observed. These transitions are placed as is illustrated Fig. 2. With dipole or quadrupole transitions, the spin of the 1005-keV level is limited to the range 5/2–13/2. Assuming that the levels established by the above listed γ rays form a rotational band, and that the 1005-keV level is the bandhead, rotational-model fits were performed for different values of I and K. A very good fit was found for an $I(I+1)$ sequence with $K = 7/2$ and a rotational parameter of 11.9 keV from the 1112–1005 keV energy difference, as shown in Fig. 4. The lack of any observed transitions to other bands, the absence of stretched $E2$ transitions, and the (presumably) dipole nature of the transitions

TABLE I. Relative γ-ray intensities for rotational levels in ^{175}Lu. Only those levels where new branching-ratio information could be obtained are listed.

Band	Level (keV)	Spin	E_γ	I_γ^{rel}
$1/2^-[541]$	514.5	$3/2^-$	143.8	35(6)
			161.2	100
	672.5	$7/2^-$	257.8	94(11)
			319.1	100
	885.9	$11/2^-$	213.5	17(3)
			323.4	92(12)
			471.1	100
$9/2^-[514]$	685.5	$13/2^-$	156.1	100
			289.1	15(2)
	864.2	$15/2^-$	178.8	100
			334.8	33(4)
	1064.6	$17/2^-$	200.4	100
			379.1	41(6)
	1285.5	$19/2^-$	220.9	100
			421.3	117(22)
$7/2^-[523]$	1112.3	$9/2^-$	582.8	100
			716.1	27(5)
	1242.4	$11/2^-$	556.8	100
			713.1	69(12)
$1/2^+[411]$	632.3	$3/2^+$	261.8	23(3)
			279.1	38(4)
			289.2	100
	757.0	$5/2^+$	124.6	100
			130.9	15(3)
	773.0	$7/2^+$	140.5	100
			226.4	19(3)
			340.7	46(6)
			413.7	13(2)
			420.1	28(4)
	989.7	$9/2^+$	216.6	100
			232.7	70(9)
	1316.8	$13/2^+$	297.9	50(8)
			327.2	100
$3/2^+[411]$	1149.9	$3/2^+$	517.5	100
			523.7	93(14)
	1218.4	$5/2^+$	461.5	87(13)
			585.9	100

to the $9/2^-[514]$ band favors a $7/2^-[523]$ configuration assignment. The suggestion of the 1005-keV level as the $7/2^-[523]$ bandhead fits perfectly with the trend in excitation energy observed with increasing A for the $7/2^-[523]$ orbital in the lighter Lu isotopes.

Based on results [3] from inelastic collisions of a ^{238}U beam on a ^{175}Lu target, an isomer at 1391 keV in ^{175}Lu was located and measured to have a half-life of 930(80)μs. This level was known from earlier ^{176}Lu(d,t) reaction studies [10], where it was assigned as the $K^\pi=19/2^+$, $7/2^+[404]_\pi$

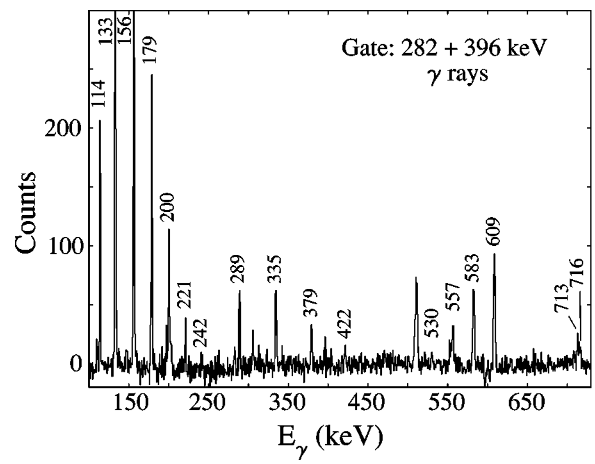

FIG. 3. Spectrum obtained from the prompt-$\gamma\gamma$ coincidences with a sum of gates taken on the 282-keV and 386-keV transitions.

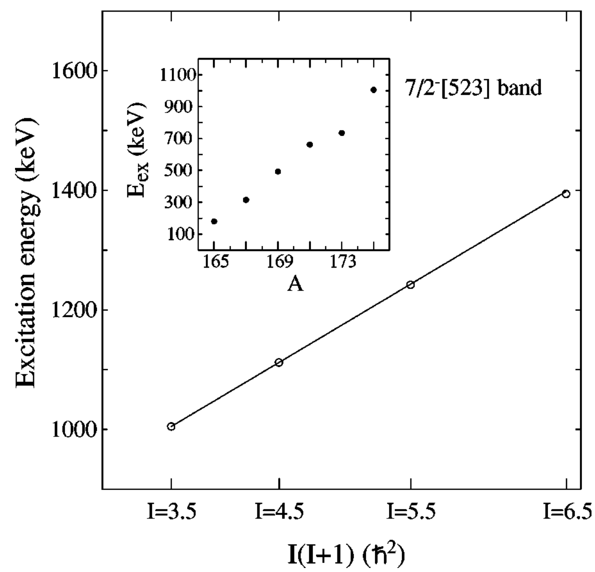

FIG. 4. Fit to proposed members of the $7/2^-[523]$ band. The data points are the observed level energies, and the line is the fit using a rotational formula with $K=7/2$ and a rotational parameter of 11.9 keV. The inset shows the experimental bandheads of the $7/2^-[523]$ configuration, where known, in the Lu isotopes.

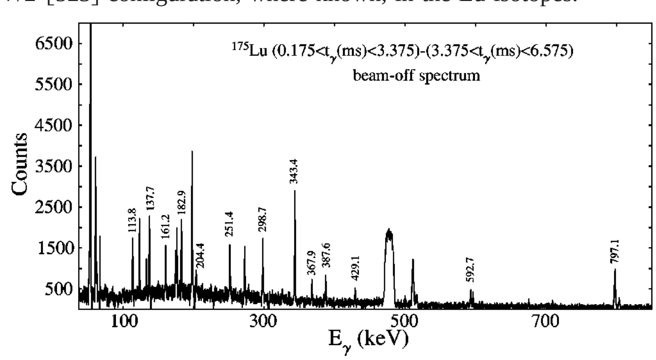

FIG. 5. Spectrum obtained from the beam-off period by subtracting events with a time gate of $3.375 < t_\gamma(\mathrm{ms}) < 6.575$ from that with a time gate of $0.175 < t_\gamma(\mathrm{ms}) < 3.375$. The γ rays belonging to the decay path of the $K^\pi=19/2^+$ isomer are labeled with their energies in keV.

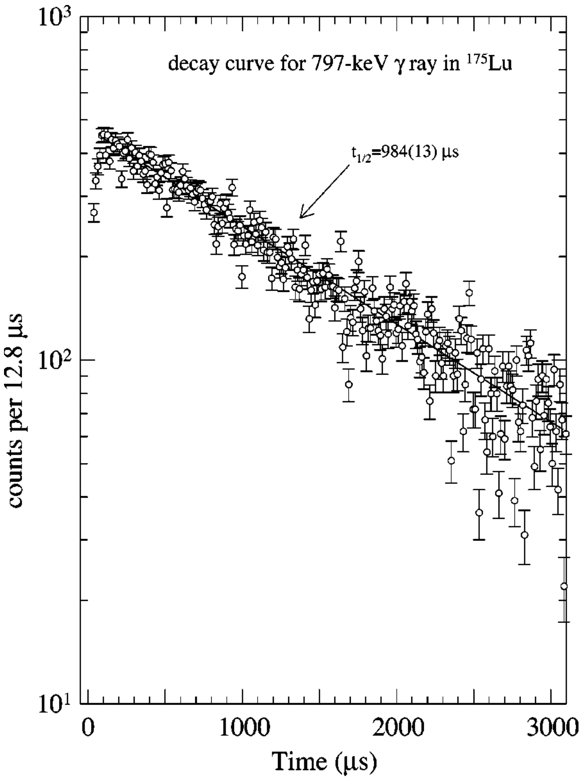

FIG. 6. Decay curve obtained for the 797-keV transition depopulating the $K^{\pi}=19/2^{+}$ isomer. The time is measured relative to the end of the proton macropulse, i.e., the start of the beam-off period. A time-dependent dead time correction has been applied to the data. The fit yields a half-life of $984\pm13(\mathrm{stat.})\pm30(\mathrm{sys.})\mu$s.

$\otimes 7/2^{-}[514]_{\nu}\otimes 5/2^{-}[512]_{\nu}$ three-quasiparticle state, and was also excited in the present work. Shown in Fig. 5 is a singles spectrum obtained during the out-of-beam period where a spectrum gated on the event times $3.375 < t_{\gamma}(\mathrm{ms}) < 6.575$ after a macropulse is subtracted from a spectrum gated on the event times $0.175 < t_{\gamma}(\mathrm{ms}) < 3.375$. This subtraction of the two time-gated spectra has the effect of removing the long-lived β decay lines from the spectrum. The remaining γ rays belong to the $19/2^{+}$ isomer decay path or are other well-known, neutron-induced, background lines. Figure 6 displays the decay curve of the 797-keV *E*2 transition; a half-life of $984\pm13(\mathrm{stat.})\pm30(\mathrm{sys.})$ μs is extracted after a time-dependent dead time correction was applied. A 30-μs systematic uncertainty due to this dead time correction is estimated. The present measured half-life is in agreement with, but more precise than, the measurement of Wheldon *et al.* [3] of 930(80) μs.

In summary, rotational bands and isomeric levels in ^{175}Lu have been observed with the $(n,n'\gamma)$ reaction using spallation neutrons. An analysis of the prompt-and delayed-$\gamma\gamma$ coincidence matrices confirm and extend the previous level schemes for the $5/2^{+}[402]$, $3/2^{+}[411]$, $1/2^{+}[411]$, $1/2^{-}[541]$, and $9/2^{-}[514]$ rotational bands. A new rotational band, suggested to have the $7/2^{-}[523]$ configuration, is assigned. The three-quasiparticle $K^{\pi}=19/2^{+}$ isomer is observed, and its half-life measured to be $984\pm13(\mathrm{stat.})\pm30(\mathrm{sys.})\mu$s.

This work was performed under the auspices of the U.S. Department of Energy by The University of California, Lawrence Livermore National Laboratory and Los Alamos National Laboratory under Contract Nos. W-7405-ENG-48 and W-7405-ENG-36.

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