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DISCLAIMER

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Rotational bands and isomeric states in ^{175}Lu

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Abstract

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 most of the existing known bands, and to tentatively assign a new band, based on the $7/2^-[523]$ configuration, from its band head to spin 13/2. The 3-quasiparticle $K^\pi = 19/2^+$ isomer is confirmed and its half life determined to be $984 \pm 13(\text{stat.}) \pm 30(\text{sys.})$ μs, in agreement with previous results.

There has been a renewed interest in isomeric states in the Hf region recently, in part due to reports [1] of stimulated emission from the 31 y, 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. Nuclei on the neutron-rich side of the valley of stability are a promising laboratory for isomer studies, and access to these nuclei has recently become accessible through fragmentation reactions (e.g. Ref.[3]) or deep inelastic collisions. 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 [4] three-quasiparticle $19/2^+$ isomer has been confirmed and its lifetime re-measured. While the lack of statistics and the spectral complexity has prevented the detailed study of the band properties, the present results are useful to future detailed studies of this nucleus.

The measurements were performed at the Los Alamos Neutron Science Center (LANSCE) Weapons Neutron Research facility. Spallation neutrons were produced by bombarding a $^{\rm nat}$W target with 800 MeV protons from the LANSCE linac. 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-mm-thick pieces of $^{nat}Lu_2O_3$ loaded VCE plastic 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 (FWHM) "beam" at the scattering sample. In order to reduce the number of low-energy neutrons and to reduce 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 11 planar and 15 25% HPGe coaxial detectors, whose front faces were located 14 cm from the scattering sample. All planar and 9 of the coaxial detectors were equipped with suppression shields. The planar detectors were concentrated at the most forward and backward angles, and γ-ray events of ≤ 1 MeV were processed, while the coaxial detectors were positioned around $90 \pm 40^{\circ}$ with respect to the beam direction and γ-ray events were recorded with energies up to 4 MeV. The data were collected 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 [5].

During playback of the data, events were separated depending on whether they occurred during the macropulse (in-beam) or after (out-of-beam). Matrices, including E_γ *vs.* time-of-flight (TOF) and $\gamma\gamma$ coincidences, both prompt and delayed, were created. The prompt $\gamma\gamma$ coincidences were created by placing a time condition that events occur within ≈ 100 ns of each other and correspond to $E_n = 1$–8 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. 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. [6].

The 1.49(7) μs isomer [7], 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 transitions have been placed previously [8, 9] 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.* [8], were not adopted in the most recent Nuclear Data Sheets [10]. 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 $11/2^+$ levels 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, supports 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. [9]. Also shown is the extension of the $5/2^+$[402] band to $17/2^+$ 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 band head, 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 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] band head fits in 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 [4] 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) reactions studies [11], where it was assigned as the $K^\pi = 19/2^+$, $7/2^+[404]_\pi \otimes 7/2^-[514]_\nu \otimes 5/2^-[512]_\nu$ 3-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 $E2$ transition; a half life of 984(13) μs is extracted after a time-dependent dead time correction was applied. The uncertainty does not include an estimated ≈ 30 μs systematic uncertainty due to this dead time correction. The present measured half life is in agreement with, but more precise than, the measurement of Wheldon *et al.* [4] 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 3-quasiparticle $K^\pi = 19/2^+$ isomer is observed, and its half life measured to be $984 \pm 13(\mathrm{stat.}) \pm 30(\mathrm{sys.})$ μs.

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REFERENCES

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[1] C.B. Collins, F. Davanloo, M.C. Iosif, R. Dussart, J.M. Hicks, S.A. Karamian, C.A. Ur, I.I. Popescu, V.I. Kirischuk, J.J. Carroll, H.E. Roberts, P. McDaniel, C.E. Crist, Phys. Rev. Lett. **82**, 695 (1999); *ibid*, Phys. Rev. Lett. **84**, 2541 (2000).

[2] I. Ahmad, J.C. Banar, J.A. Becker, D.S. Gemmell, A. Kraemer, A. Mashayekhi, D.P.

McNabb, G.G. Miller, E.F. Moore, L.N. Pangault, R.S. Rundberg, J.P. Schiffer, S.D. Shastri, T.F. Wang, J.B. Wilhelmy, Phys. Rev. Lett. **87**, 072503 (2001).

[3] Zs. Podolyak, P.H. Regan, M. Pfutzner, J. Gerl, M. Hellstrom, M. Caamano, P. Mayet, Ch. Schlegel, A. Aprahamian, J. Benlliure, A.M. Bruce, P.A. Butler, D. Cortina Gil, D.M. Cullen, J. Döring, T. Enqvist, F. Rejmund, C. Fox, J. Garces Narro, H. Geissel, W. Gelletly, J. Giovinazzo, M. Gorska, H. Grawe, R. Grzywacz, A. Kleinbohl, W. Korten, M. Lewitowicz, R. Lucas, H. Mach, M. Mineva, C.D. O'Leary, F. De Oliveira, C.J. Pearson, M. Rejmund, M. Sawicka, H. Schaffner, K. Schmidt, Ch. Theisen, P.M. Walker, D.D. Warner, C. Wheldon, H.J. Wollersheim, S.C. Wooding, F.R. Xu, Phys. Lett. **B491**, 225 (2000).

[4] C. Wheldon, R. D'Alarcao, P. Chowdhury, P.M. Walker, E. Seabury, I. Ahmad, M.P. Carpenter, D.M. Cullen, G. Hackman, R.V.F. Janssens, T.L. Khoo, D. Nisius, C.J. Pearson, and P. Reiter, Phys. Lett. **B425**, 239 (1998).

[5] S.A. Wender, S. Balestrini, A. Brown, R.C. Haight, C.M. Laymon, T.M. Lee, P.W. Lisowski, W. McCorkle, R.O. Nelson, W. Parker, and N.W. Hill, Nucl. Instrum. Methods Phys. Res. **A336**, 226 (1993).

[6] P.E. Garrett, W. Younes, J.A. Becker, L.A. Bernstein, E.M. Baum, D.P. DiPrete, R.A. Gatenby, E.L. Johnson, C.A. McGrath, S.W. Yates, M. Devlin, N. Fotiades, R.O. Nelson, and B.A. Brown, Phys. Rev. C **68**, 024312 (2003).

[7] K.H. Johansen, B. Bengtson, P.G. Hansen, P. Hornshoj, Nucl. Phys. **A133**, 213 (1969).

[8] C. Foin, S. André, and S.A. Hjorth, Nucl. Phys. **A219**, 347 (1974).

[9] G. Winter, W. Andrejtscheff, L. Funke, P. Manfrass, and H. Sodan, Nucl. Phys. **A223**, 320 (1974).

[10] A.O. Macchiavelli and E. Browne, Nucl. Data Sheets, **69**, 903 (1993).

[11] M. Minor, R.K. Sheline, and E.T. Jurney, Phys. Rev. C **3**, 766 (1971).

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

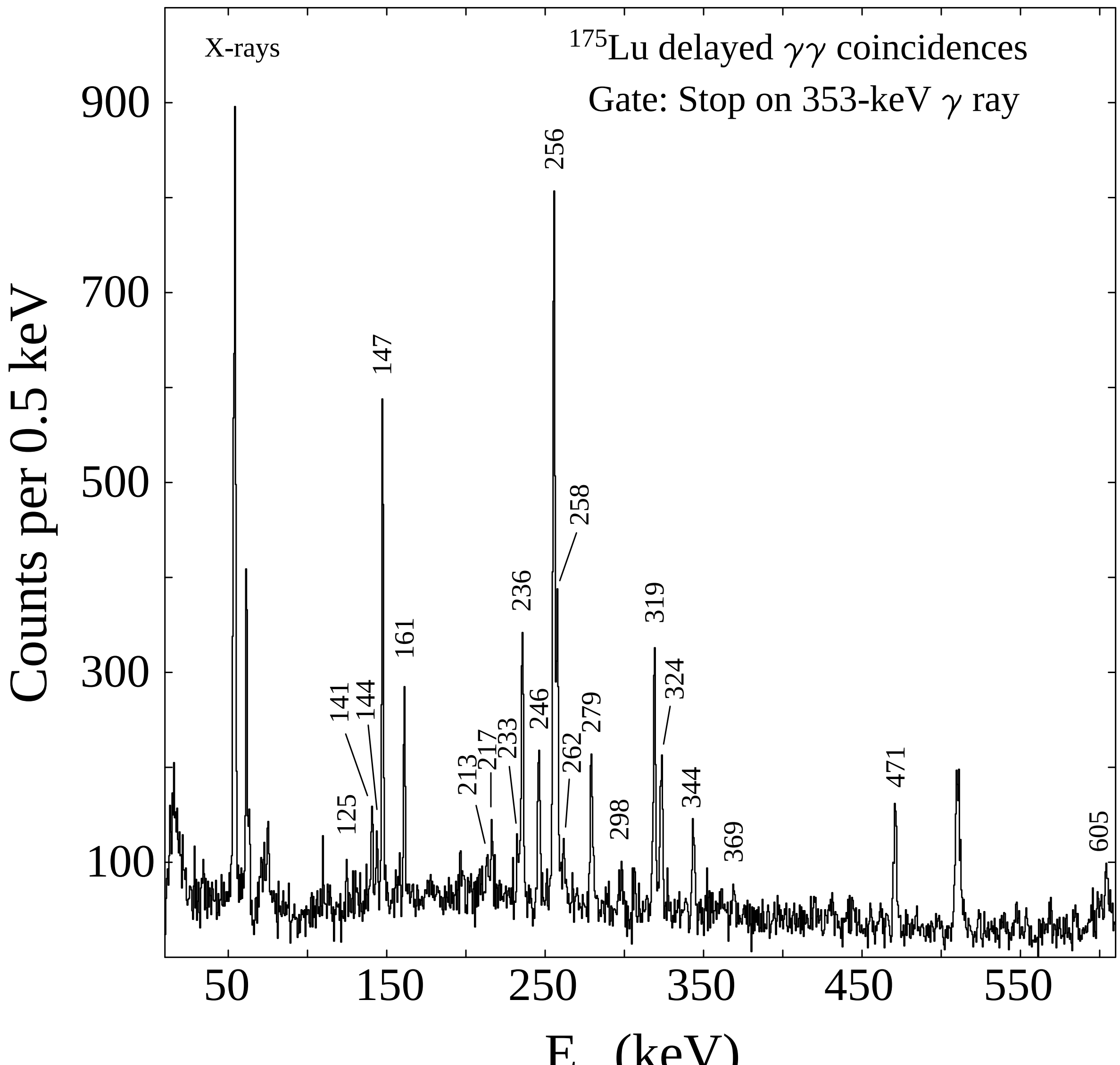

FIG. 1: Spectrum observed for a gate taken on the 353-keV transition serving as the "stop" transition for delayed $\gamma\gamma$ coincidences. The γ rays placed above the 1.49(7) μs 353-keV level in ^{175}Lu are labeled with their energies in keV.

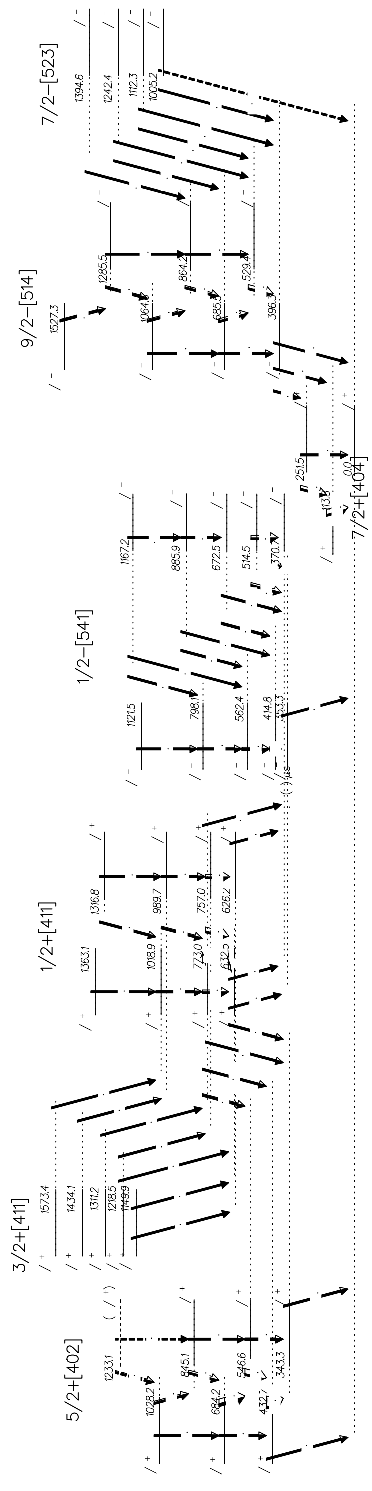

FIG. 2: Partial level scheme leading to new results in ^{175}Lu constructed from analysis of prompt and delayed $\gamma\gamma$ coincidence. The 6-keV $3/2^+ \rightarrow 1/2^+$ and 16-keV $7/2^+ \rightarrow 5/2^+$ transitions in the $1/2^+[411]$ band are placed due to the observation of cross-talk between 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.

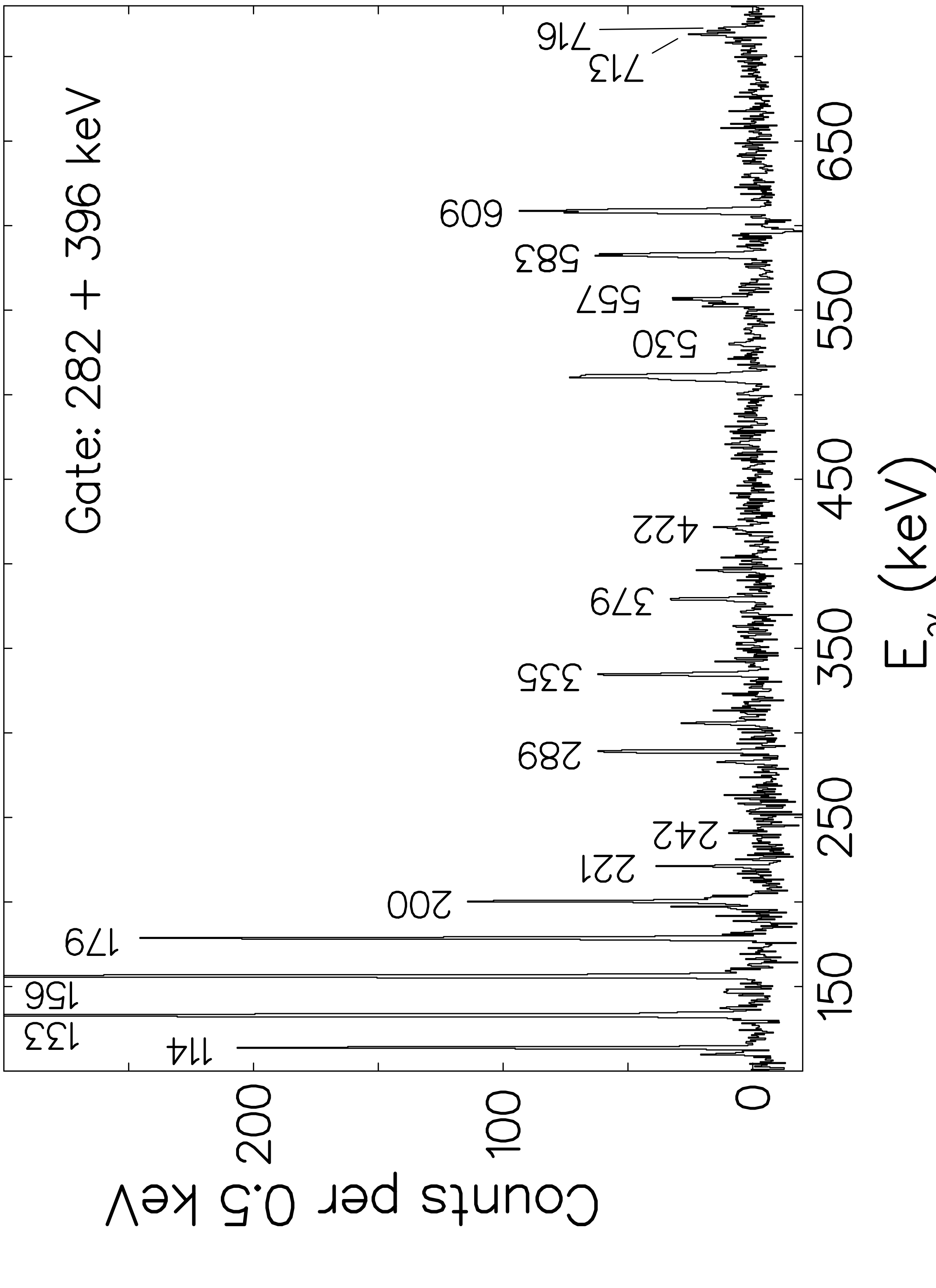

FIG. 3: Spectrum obtained from the prompt $\gamma\gamma$ coincidences with a sum of gates taken on the 282 keV and 396-keV transitions.

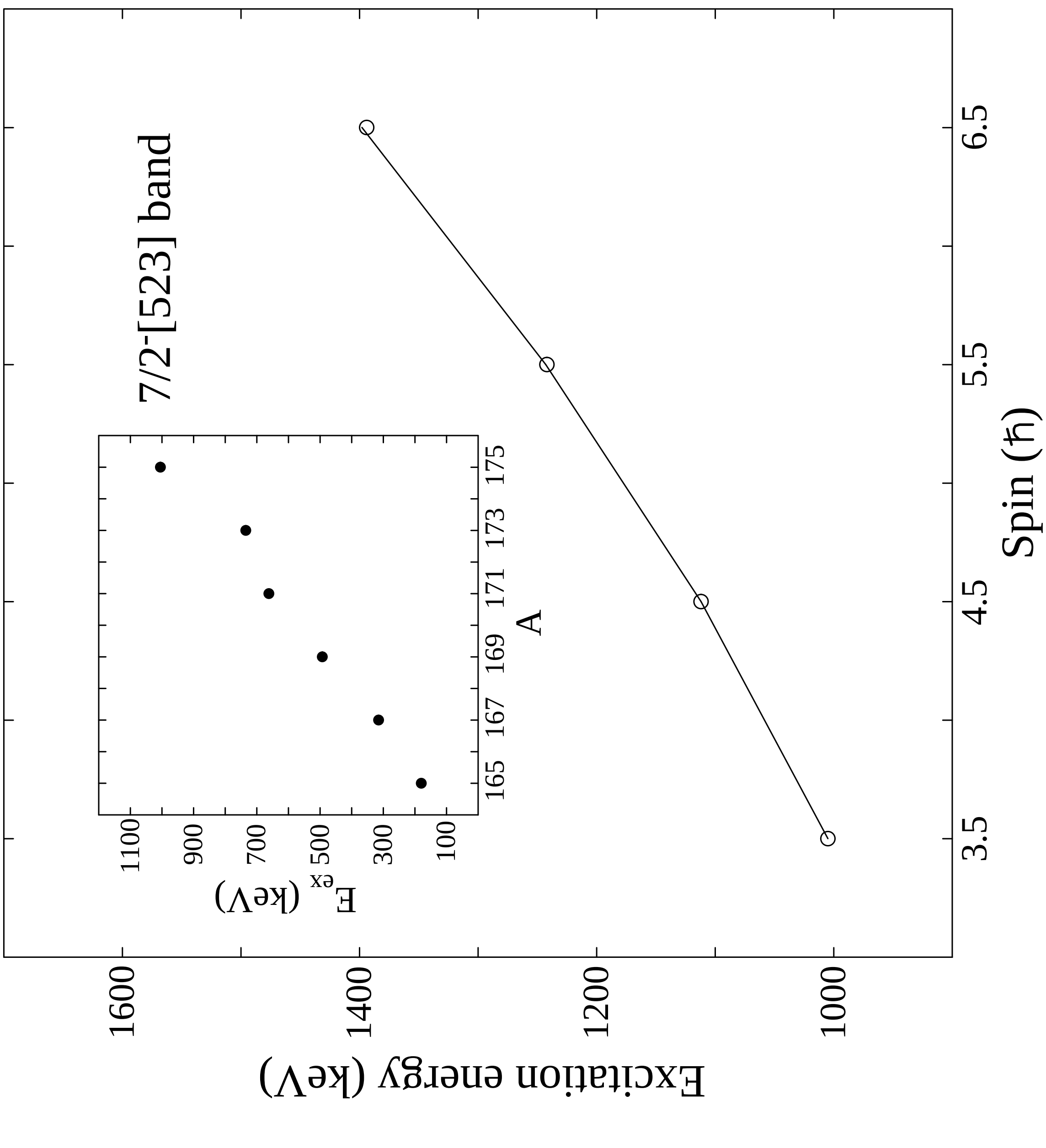

FIG. 4: Fit to proposed members of the $7/2^{-}[523]$ band. The data points are the observed level energies, and the line is the fit using a rotational formula with $K = 7/2$ and a rotational parameter of 11.9 keV. The inset shows the experimental band heads of the $7/2^{-}[523]$ configuration, where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

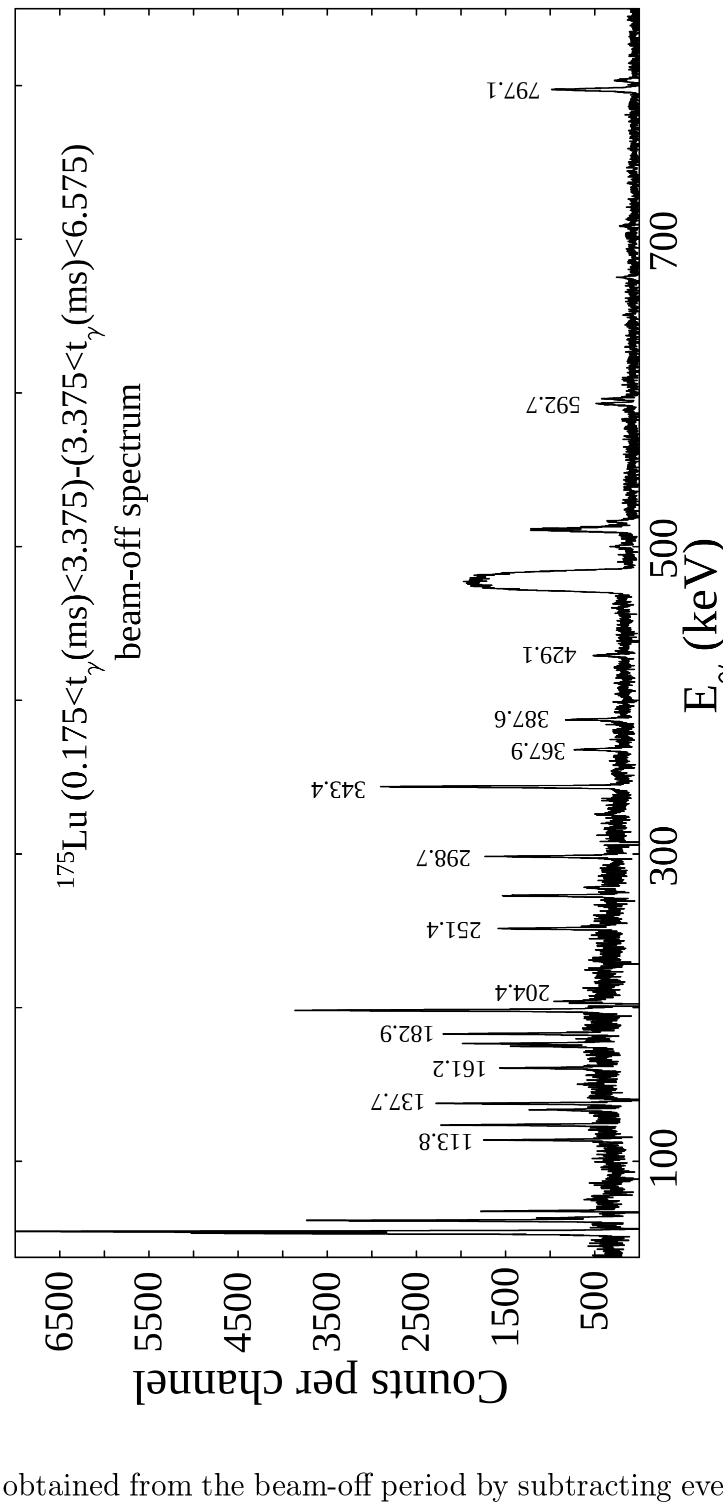

FIG. 5: Spectrum obtained from the beam-off period by subtracting events with a time gate of $3.375 < t_\gamma(\text{ms}) < 6.575$ from that with a time gate of $0.175 < t_\gamma(\text{ms}) < 3.375$. The γ rays belonging to the decay path of the $K^\pi = 19/2^+$ isomer are labeled with their energies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

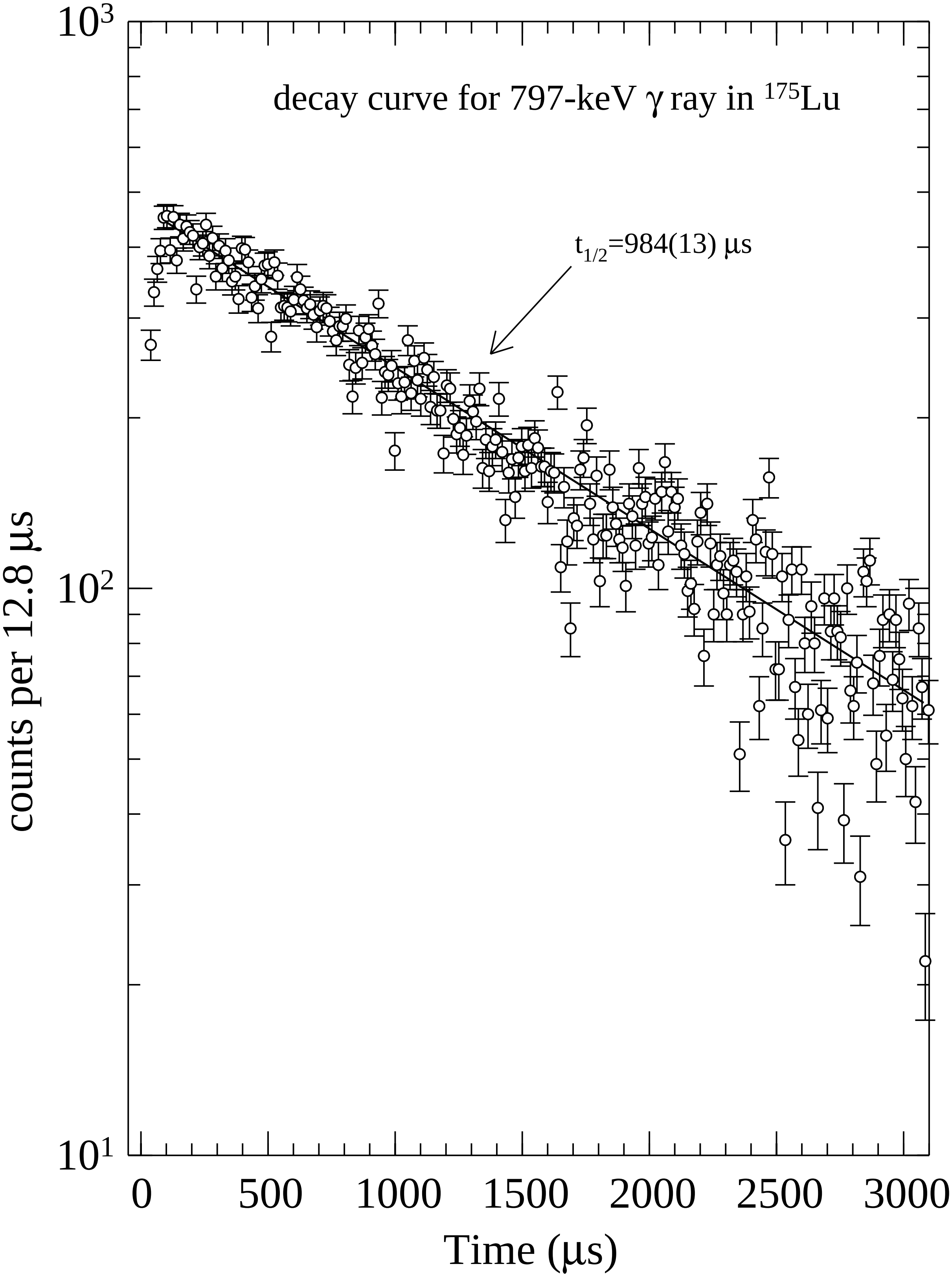

FIG. 6: Decay curve obtained for the 797-keV transition depopulating the $K^\pi = 19/2^+$ isomer. A time-dependent dead time correction has been applied to the data. The fit yields a half life of 984 ± 13(stat.)± 30(sys.) μs.