Decay of ^{179}Lu to levels in the 107-neutron nucleus ^{179}Hf†

J. C. Hill* and R. A. Meyer
Lawrence Livermore Laboratory, University of California, Livermore, California 94550
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The decay of ^{179}Lu to levels in ^{179}Hf has been investigated using Ge(Li) detectors. In addition to the one γ ray at 214 keV reported in previous decay studies, 26 γ rays with energies up to 1199 keV were observed depopulating 12 levels. These results are compared with findings from single-neutron-transfer reactions and neutron-capture γ-ray experiments.

[RADIOACTIVITY ^{179}Lu [from ^{180}Hf(γ,p) and ^{179}Hf(n,p)]; measured $E\gamma$, $I\gamma$, γ-γ; ^{179}Hf deduced levels, J,π, logft. Enriched and natural targets, Ge(Li) detector.]

I. INTRODUCTION

The decay of ^{179}Lu was first reported by Butement[1] and later investigated by Kuroyanagi *et al.*[2] No studies of its decay have been reported since that of Stensland and Voigt[3] in 1962. They observed only one γ ray of 214 keV. The levels in ^{179}Hf below 1.5 MeV have been studied by (d,p),[4] (d,t),[5] and (n,γ)[6-12] reactions. Two isomeric levels representing the $\frac{1}{2}^-[510]$ bandhead[13-15] and a three-quasiparticle $\frac{25}{2}^-$ state[16-18] have been observed with half-lives of 18 s and 24.8 h,[18] respectively. States in ^{179}Hf below 800 keV are well understood in terms of rotational bands built upon the $\frac{9}{2}^+[624]$, $\frac{7}{2}^-[514]$, $\frac{1}{2}^-[510]$, $\frac{5}{2}^-[512]$, $\frac{1}{2}^-[521]$, and $\frac{3}{2}^-[512]$ one-quasiparticle neutron states. Information on some of these states has been summarized in the review article of Bunker and Reich.[19] We have reported preliminary results[20] of this study. They also appear in the *Nuclear Data Sheets*[21] for mass 179.

II. EXPERIMENTAL

A. Source preparation

Initially, sources were produced by irradiating natural HfO_2 targets with 14.8-MeV neutrons from the Livermore rotating target neutron source. More intense sources were obtained using the ^{180}Hf(γ,p)-^{179}Lu reaction induced by 60- or 80-MeV bremsstrahlung from the Lawrence Livermore Laboratory (LLL) linac. In these experiments, a 1-g target of $^{180}HfO_2$ (enriched to 98.28% ^{180}Hf) was irradiated for about 8 h. Following the irradiation, the target was dissolved in a mixture of $HF + HNO_3$ and lutetium precipitated as LuF_3. The lutetium was next separated from other rare earths on a high-pressure ion-exchange column.[22] Three hours after the end of irradiation, the lutetium was ready either for counting or for introduction into the LLL mass separator.

B. γ-ray measurements

The γ-ray spectrum below 150 keV was measured using a high-resolution Ge(Li) low-energy photon spectrometer. Spectra of γ rays above 100 keV were measured using a large-volume Ge(Li) detector. In typical experiments, three successive 3-h spectra were collected to distinguish γ rays from ^{179}Lu on the basis of half-life. In some cases, Pb and Cd absorbers were used to reduce sum peaks from x rays and intense low-energy γ rays. Energies for the more intense γ rays were obtained by counting simultaneously ^{179}Lu and a group of a well-known γ-ray standards. The peak positions and energies were determined using the computer program GAMANAL.[23] The energies of the lowest-intensity ^{179}Lu γ rays were determined using the more intense γ rays in ^{179}Lu as secondary standards. The energies, intensities, and errors of all ^{179}Lu γ rays are given in Table I.

A mass-separated source was used to obtain a γ-ray spectrum below 150 keV, which is shown in Fig. 1. The photopeak of 59 keV could not be definitely associated with ^{179}Lu. A detail of the 122-keV doublet is shown in the inset. The γ-ray spectrum above 100 keV, also obtained using a mass-separated source, is shown in Fig. 2. The 214-keV photopeak is, in fact, a doublet containing a 215-keV low-intensity component. The 270-keV peak is due to summing of the Hf K x rays and the 214-keV γ ray, and the 1073-keV peak is due to summing of the 214- and 859-keV γ rays.

Because of the low source strength of mass-separated sources, it was necessary to study the low-intensity high-energy γ rays from ^{179}Lu decay using a source that was not mass separated. The resulting spectrum between 500 and 1200 keV is shown in Fig. 3. A 0.32-cm-thick Pb absorber with a thin sheet or Cd was placed between the source and the detector. The sum peak at 1073

TABLE I. Energies and intensities of γ rays observed in the decay of ^{179}Lu.

E_γ (ΔE_γ) (keV)	I_γ (ΔI_γ)[a] (Relative)	Assignment From	To
122.79 (7)	540 (100)	123	g.s.
123.38 (4)	1 650 (170)	338	214
214.33 (4)	42 000 (4000)	214	g.s.
215.01 (10)	1 670 (600)	338	123
279.2 (2)	7 (2)	617	338
304.03 (15)	23 (5)	518	214
337.67 (5)	670 (70)	338	g.s.
532.51 (20)	15 (3)	870	338
655.85 (10)	100 [a]	870	214
680.2 (5)	2 (1)	1200	518
735.78 (15)	62 (10)	1073	338
789.4 (6)	0.8 (5)	1003	214
830.37 (20)	10 (3)	1168	338
859.16 (6)	370 (40)	1073	214
870.14 (7)	210 (25)	870	g.s.
891.5 (3)	8 (2)	1106	214
953.9 (3)	4.9 (1.5)	1168	214
983.17 (20)	33 (6)	1106	123
999.1 (6)	1.0 (5)	1121	123
1003.32 (15)	43 (8)	1003	g.s.
1045.63 (20)	14 (3)	1168	123
1073.5	(<1)	1073	g.s.
1076.9 (2)	30 (6)	1200	123
1105.92 (10)	99 (10)	1106	g.s.
1120.8 (4)	3 (1)	1121	g.s.
1168.4 (3)	5.1 (1.5)	1168	g.s.
1199.5 (2)	18 (4)	1200	g.s.

[a] Intensities are normalized to 100 for 656-keV γ ray. To convert these values to γ rays in percent decays multiply I(rel) by 2.923×10^{-4}. This conversion value is based on our γ-ray data, an intensity balance technique, and a feeding of 87% to the ground state as reported by Stensland and Voigt (Ref. 3).

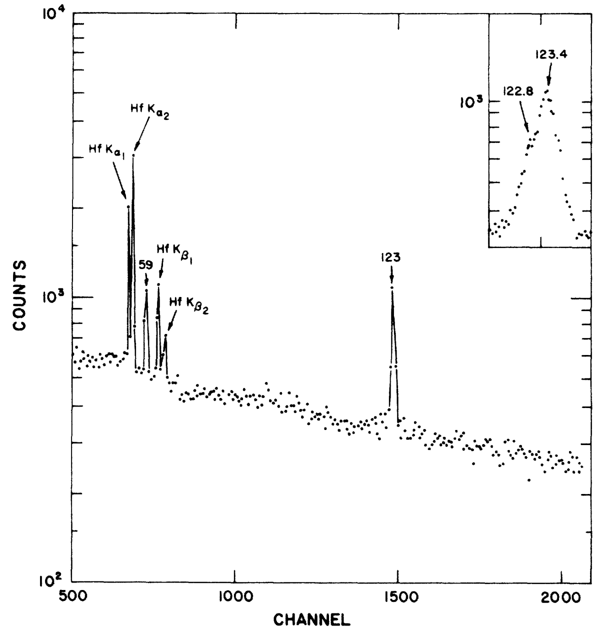

FIG. 1. Spectrum of low-energy γ rays accompanying the decay of ^{179}Lu using a mass-separated source. All energies are in keV.

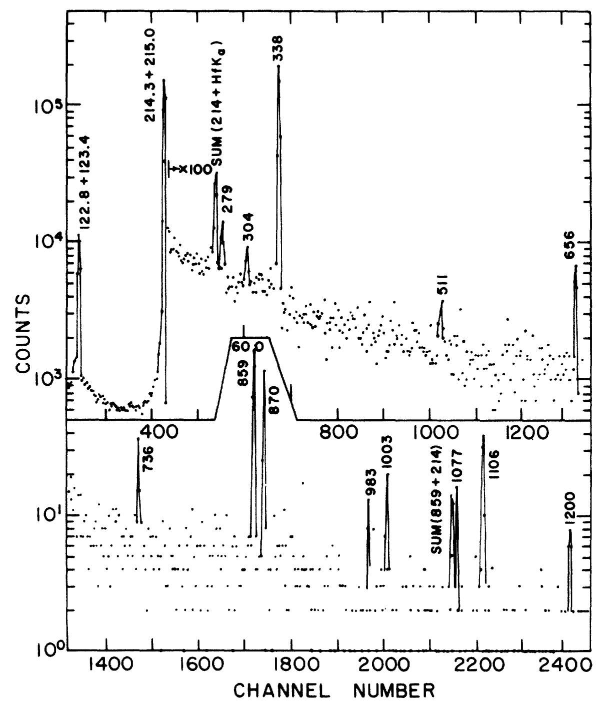

FIG. 2. Spectrum of γ rays above 100 keV accompanying the decay of ^{179}Lu using a mass-separated source. All energies are in keV.

keV is not present because of absorption of 214-keV γ rays. To obtain intense ^{179}Lu sources, an 80-MeV bremsstrahlung spectrum was used, and thus peaks from several other Lu isotopes were present. (These γ rays are indicated by isotope in Fig. 3.) The γ rays which were observed to follow a 4.59-h half-life were assigned to the decay of ^{179}Lu.

The γ-γ coincidence measurements were made using two large-volume Ge(Li) detectors in conjunction with a megachannel coincidence spectrometer. This spectrometer is discussed in detail elsewhere.[24] A gate at 123 keV revealed coincidences with the 214- and 736-keV γ rays and a gate at 214 keV revealed coincidences with the 123-, 304-, 656-, and 859-keV γ rays consistent with the level assignments in Table I.

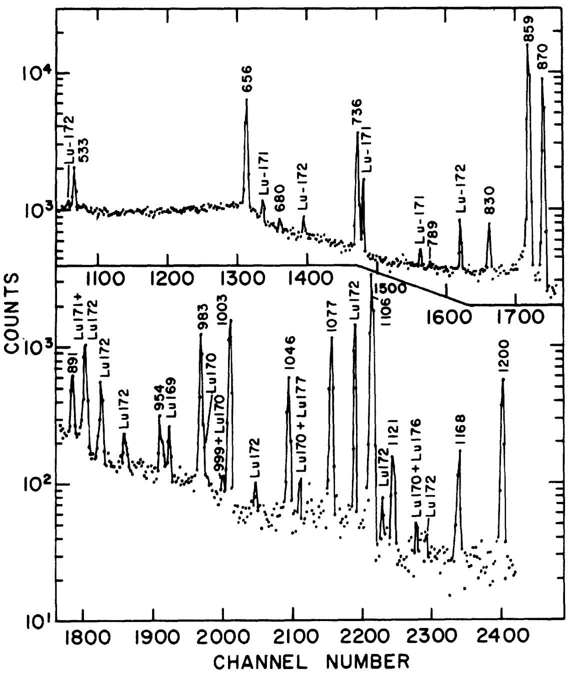

FIG. 3. Spectrum of γ rays above 500 keV accompanying the decay of ^{179}Lu. All energies are in keV. Lu impurities are indicated by isotope.

III. DISCUSSION

The γ-ray energies, intensities, and coincidence relationships were used in conjunction with previous studies to construct the decay scheme shown in Fig. 4. Of particular importance was the overlap of data from this study and neutron-capture γ-ray studies of Casten and Kane.[11] Of the ^{179}Hf levels observed in this study, only the one at 214 keV was seen in previous[2,3] decay studies. Log*ft* values for the β branches were obtained using our γ-ray intensities and a ground-state β^--branching intensity of 87% determined by Stensland and Voigt.[3] The effects of internal conversion were neglected, except for the 123.4-keV transition. In ^{177}Hf, the corresponding transition[25] is only 6% $M1$. We therefore assumed a pure $E2$ multipolarity in calculating its total intensity, which was used in the log*ft* calculation for the 214- and 338-keV levels. A large $M1$ mixing for the 123.4-keV transition would change the corresponding log*ft* values by less than 0.2.

The spin of the ^{179}Hf ground state has been measured[26] as $\frac{9}{2}$ by optical spectroscopy methods. The ground state of ^{179}Lu is most likely $\frac{7}{2}^+[404]$ by analogy with other odd-mass Lu isotopes.[19] The log*ft* of 6.7 for the β^- transition to the ^{179}Hf ground state is consistent with the value of 6.9 for the β transition $\frac{7}{2}^+[404]$ to $\frac{9}{2}^+[624]$ in ^{177}Lu.[27] The 123-,

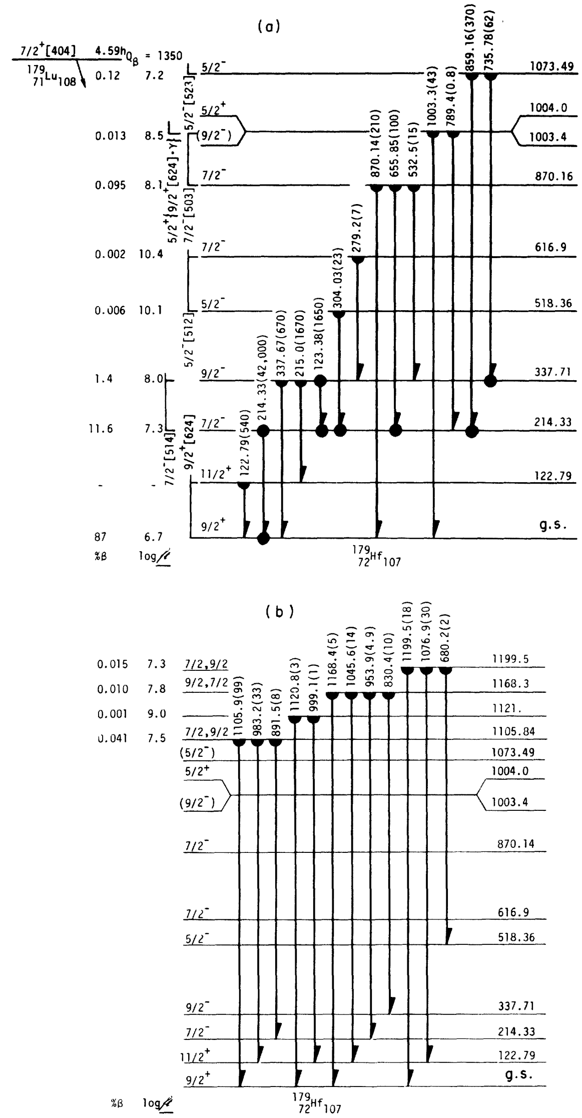

FIG. 4. Decay scheme of ^{179}Lu from the present studies: (a) levels below 1100 keV; (b) levels above 1110 keV. A full dot at the top of the arrow indicates that a γ-γ coincidence gate was set at this energy, a dot below the line signifies that the γ ray was observed in a gate, and a half circle at the top of the arrow indicates placement by the Ritz combination principle.

214-, 388-, 518-, and 617-keV levels have been identified by other techniques[4-12] and can be described[19] as members of the $\frac{9}{2}^+[624]$, $\frac{7}{2}^-[514]$, and $\frac{5}{2}^-[512]$ bands. The level at 870 keV has been identified as the $\frac{7}{2}^-[503]$ bandhead.[19]

We propose a level at 1003.4 ± 0.3 keV from observation of γ rays at 1003.3 ± 0.2 and 789.4 ± 0.6 keV. The $\frac{9}{2}^-$ member of the $\frac{7}{2}^-[503]$ band is expected to occur at about this energy, but our γ-ray branching ratios are more consistent with the $\frac{5}{2}^+[\frac{9}{2}^+[624], K-2]$ γ-vibration band. Casten and

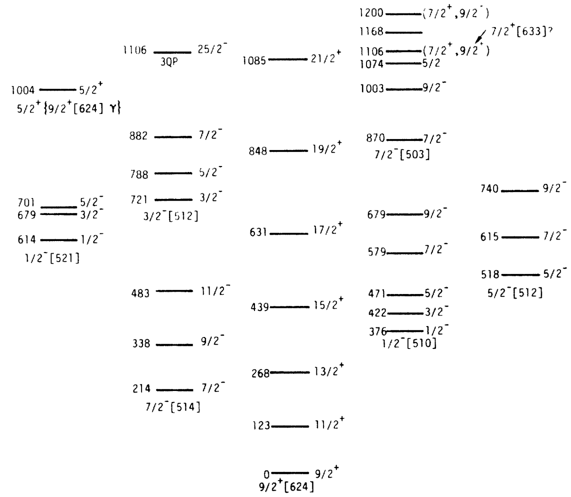

FIG. 5. Known levels in ^{179}Hf.

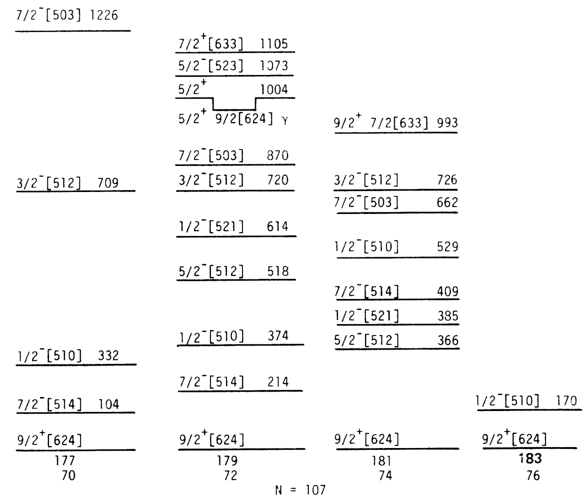

FIG. 6. Nilsson states that have been identified for the 107-neutron nuclei.

Kane[11] observed a level at 1004.0 ± 0.1 keV and suggested an assignment of $\frac{5}{2}^{+}$. In view of the above results, the existence of two levels in ^{179}Hf at about 1003 keV is suggested. The 1106-, 1168-, and 1199-keV levels have $\log f_1 t$ less than 8.5 and exhibit substantial feeding to the $\frac{11}{2}^{+}$ level at 123 keV. Thus, their spins are limited to $\frac{7}{2}$ or $\frac{9}{2}$.

Though no definite assignments can be made for the levels we observe above 1050 keV, several assignments suggest themselves. The 1073.49-keV level has no measurable decay to the ground state. For the ratio of decay to the ground state versus total decay of the 1073.49-keV level, we can set a limit of less than 1 in 430. An assignment of $\frac{5}{2}^{-}$ would be consistent for this level. Such an I^{π} value at this energy could be assigned as the $\frac{5}{2}^{-}$[523] bandhead or as the $\frac{5}{2}^{-}$ member of the $\frac{3}{2}^{-}$[521] band. We prefer the former, since we would expect the $\Delta K = 2$ β decay to be highly hindered. We note that we do not observe decay to other levels that would require $\Delta K \geq 2$ β decay.

Casten *et al.* have suggested that the $\frac{7}{2}^{+}$[633] band is strongly perturbed in ^{181}W.[28] To the extent that that is true, the levels at 1105.8 and 1168.3 keV could be the $\frac{7}{2}^{+}$ and $\frac{9}{2}^{+}$ members of the $\frac{7}{2}^{+}$[633] band, respectively.

We present in Fig. 5 all the known levels of ^{179}Hf and their assignments. These data have been taken from our results and those works cited above. The identifiable bandheads in ^{179}Hf are shown in relation to other 107-neutron nuclei[27-29] in Fig. 6. It is seen that further work on the mass-183 nucleus would greatly aid in the understanding of the role of the core in the relative ordering and energy of the Nilsson orbitals in this mass region. Of particular interest is the relative movement of the $\frac{7}{2}^{-}$[514], with respect to all other levels. The delineation of such trends will be useful in testing the theories of Immele and Struble, who have had success in calculating the properties of the odd-mass γ-vibrational levels.[30]

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*Associated Western Universities Faculty Fellowship to Lawrence Livermore Laboratory. Permanent address: Ames Laboratory-ERDA and Department of Physics, Lowa State University, Ames, Iowa 50011.

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