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C00-3255-8

Single-Particle States of ^{173}Lu Observed in Decay of $^{173}\text{Hf}^*$

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Abstract: The level scheme of ^{173}Lu as populated by the decay of 23.9-h ^{173}Hf has been studied using Ge(Li) detectors in singles and coincidence γ -ray spectrometers. The coincidence data provide strong support for nearly all the previously proposed levels. Singles data obtained with a Compton-suppression spectrometer have enabled us to identify very weak transitions which were not seen by previous experimenters. Some of these transitions are used to establish new levels at 721.56, 734.63, 1359.32 and 1408.90 keV and arguments are presented for assignment of these levels as the $1/2[660]$, $7/2[523]$, $3/2[402]$ and $1/2[400]$ Nilsson states.

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E RADIOACTIVITY ^{173}Hf [from $^{172}\text{Yb}(\alpha, 3n)$, $^{173}\text{Yb}(\alpha, 2n)$]; measured E_γ , I_γ , $\gamma\gamma$ -coin, $T_{1/2}$; deduced log ft. ^{173}Lu deduced levels, J, π . Ge(Li) detectors, enriched targets.

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I. INTRODUCTION

In a recent article Funk et al.¹ reported a detailed investigation of the decay of 23.9-h ^{173}Hf . Their work included the measurement of γ -ray and internal-conversion electron spectra using Ge(Li) and Si(Li) detectors and γ - γ coincidence measurements. We report here our recent γ -ray data obtained using Ge(Li) singles and coincidence spectrometers. Because of the greater sensitivity of some of our counting systems, in particular, a Compton-suppression Ge(Li) spectrometer and a PDP-9-disk Ge(Li) coincidence spectrometer we were able to identify additional lines in ^{173}Hf decay and to establish the coincidence relationship among lines with a much greater certainty than previously reported. We present these data and focus our comments on the new results gleaned from our measurements and on the results which add support to the scheme presented by Funk et al. Recent experiments by Gnatovich et al.² and O'Neil et al.³ are also very pertinent to this presentation. For a more complete bibliography concerning ^{173}Hf decay refer to Funk et al.

II. EXPERIMENTAL METHODS AND RESULTS

A. Source Preparation

Radioactive sources of ^{173}Hf were produced by (α, xn) reactions on $^{172}\text{Yb}_2\text{O}_3$ and $^{173}\text{Yb}_2\text{O}_3$ isotopically enriched to 97.2% and 95.0%, respectively. Targets which were irradiated at the Berkeley Cyclotron accumulated, typically, 100 μAh of

the ^4He beam. Following irradiation samples were returned to the Lawrence Livermore Laboratory for chemical separation and counting.

A simple chemical procedure was used to separate Hf from the target material and radioactive contaminants. The irradiated Yb_2O_3 was dissolved in a mixture of concentrated HNO_3 and HCl . The rare earth elements were precipitated as fluorides and finally Hf was separated from the supernate by co-precipitation with barium fluorozirconate. The precipitate was washed and separated into several sources for concurrent counting on various detector systems.

B. γ -Ray Singles Measurements

A variety of detector systems at the Lawrence Livermore Laboratory were used in measurements of the singles γ -ray spectra from ^{173}Hf decay. Several large volume $\text{Ge}(\text{Li})$ detectors ($\sim 50\text{cm}^3$) of moderate resolution ($\sim 2.2\text{keV}$ FWHM at 1332keV) were used to periodically record spectra over the energy range 0-3 MeV during the week following the bombardment. Various combinations of Cd and Pb absorbers were used to suppress low-energy γ -rays and x-rays in some of the experiments. These spectra provided half-life data for assignment of lines to ^{173}Hf decay and also were used for photopeak intensity determinations. The measurements were supplemented at low energies with spectra taken on a planar $\text{Ge}(\text{Li})$ detector equipped with a Be window. The identification of weaker lines below 1 MeV in energy was facilitated

by using a Ge(Li) Compton-suppression spectrometer. The spectrometer consists of a 7cm^3 Ge(Li) detector with a NaI(Tl) anticoincidence shield as reported by Camp⁴. Half-life studies of γ -ray transitions were also done with this instrument.

Detector efficiencies were determined with standard sources distributed by the International Atomic Energy Agency. A number of nuclides whose relative γ -ray intensities are well known were used as secondary intensity standards. Energy calibrations were made using combinations of the above sources as internal standards during data acquisition.

The complex γ -ray spectra were analyzed with the computer code, GAMANAL, developed by Gunnik et al.⁵ Decay data helped to establish the contribution of impurity lines in most instances. For very weak lines at high energies the half-life data in some cases were insufficient to make a definitive assignment to ^{173}Hf decay. Where no alternative assignment to a known impurity substance is reasonable, we have attributed the weak lines to ^{173}Hf decay. The detailed results of γ -ray energies and intensities are given in Table I. In general, we are in agreement with Funk et al. for the majority of the more intense transitions. In all cases the multipolarity assignments of Ref. 1 remain unchanged when our γ -ray intensities are used and therefore we do not tabulate the results here. The differences between our results and those of Funk et al. concern weaker lines where we report a number of additional lines while failing to observe some of those reported previously.

C. $\gamma\gamma$ Coincidence Measurements

Coincidence among γ -rays were recorded with a Ge(Li)-Ge(Li) detector system using coaxial geometry. Cadmium absorbers were positioned in front of each detector to reduce counting rates from low-energy γ -rays and x-rays. Coincidences were recorded with the aid of a PDP-9 computer interfaced to a magnetic disk⁶ with a resolution capability of 1024 x 2048 channels. After completion of data acquisition coincidence spectra were assembled into peak gates using the interactive capability of the PDP-9-disk spectrometer. In each case an approximate background gate was subtracted and the resulting two-dimensional data slice was read-out onto magnetic tape for later fitting using the GAMANAL computer code. Gamma ray coincidences established in this way are listed in Table II. The abundance of coincidence information from our experiments establishes the major portion of the decay scheme with more confidence than previously possible.

III. DECAY SCHEME OF ^{173}Hf

The decay scheme which best fits the experimental data is shown in Fig. 1. Coincidence evidence, intensity balance, energy sums and multipolarities are taken into account. Level assignments in terms of Nilsson orbitals are indicated to the left and $\log ft$ values are shown to the right. Transitions whose placement in the decay scheme are based on coincidence data are designated by a filled circle in Fig. 1. Evidence which supports new levels proposed here is presented below. Our discussion is

limited to levels not previously reported in decay studies or the cases where alternate assignments to those of Funk et al. are possible. The reader is asked to consult Ref. 1 for a discussion of previously assigned single-particle states and collective states.

A. Single-Particle States

In order to aid in the identification of new single-particle states we present in Fig. 2 the results of a calculation of the single-quasiparticle level energies for $A=173$. The single-particle calculations were performed with the code of Nilsson et al.⁷ by Wilhelmy⁸ using the parametric values $K = 0.0631$ and $\mu = 0.605$. The effect of the residual pairing force was roughly accounted for by compressing the energy scale by one-half.⁹ In general the level ordering and energy scale of the previously well-characterized levels are satisfactorily reproduced by the theory. With this as a guide we then sought evidence for several of the single particle states which were not previously identified.

The $1/2 [660]$ state at 721.56 keV. A level at 721.56 keV is proposed as the band head of the $1/2 [660]$ Nilsson state. O'Neil et al.³ investigated the level structure of ^{173}Lu using the $(^3\text{He}, d)$ and (α, t) reactions on ^{172}Yb to populate proton states in ^{173}Lu . They observed a weakly populated level at 721 keV in their $(^3\text{He}, d)$ spectra but did not see this level in the (α, t) spectra. We suggest that the 721 keV level is the

1/2[660] Nilsson state for the following reasons. Two low intensity γ -rays (593.22 and 458.21 keV) are seen in our spectra which sum with the $1/2^+$ and $3/2^+$ members of the 1/2[541] band to give a level of 721.56 keV. This decay pattern is what one expects to observe from a spin $1/2^+$ level. Decay to the 5/2 1/2 [541] band member is not observed. Assignment as the 1/2[660] band head is suggested by the calculations (Fig. 2) since the 1/2[660] orbital is the only unidentified spin 1/2 state in this energy region. Absence of additional deexciting transitions is suggestive of a 1/2[660] assignment since the $\Delta N=2$ decay is expected to be retarded to low-spin members of the 1/2[411] band near 400 keV; also decay to all other low-lying levels should be forbidden.

One can infer support for a low-spin assignment from the reaction data of O'Neil et al. For an $\ell=0$ transfer reaction at 721 keV into ^{173}Lu the cross-section ratio, $\sigma(^3\text{He},d)/\sigma(\alpha,t)$, is expected to be at least 5. The fact that the 721 keV level is weakly populated in the $(^3\text{He},d)$ spectra and not seen in the (α,t) spectra is consistent with a low ℓ -transfer given the apparent level of sensitivity of the (α,t) experiments. The ratio of reduced transition probabilities for the presumed E1 transitions, $593.22 (1/2 \ 1/2^+ \rightarrow 1/2 \ 1/2^-) / 458.21 (1/2 \ 1/2^+ \rightarrow 3/2 \ 1/2^-) = 0.9 \pm 0.4$, compares reasonably with the theoretical ratio of 0.5. Taken together the evidence supports the assignment of 1/2[660] for the 721.56 keV level with a moderate degree of confidence. This Nilsson state has not previously been identified in this mass region.

The $7/2[523]$ state at 734.63 keV. The decay measurements and reaction data are consistent with an assignment of a level at 734.63 keV as the $7/2[523]$ Nilsson state. O'Neil et al. have reported the population of a level at 736 keV in their (α, t) experiments while failing to observe this level in their $(^3\text{He}, d)$ data. Kemnitz et al.¹⁰ have reported a level at 734.1 keV from in-beam reaction γ -ray studies which was assigned $13/2\ 9/2[514]$. We identify two γ -rays, 734.53 and 377.71 keV, which can be placed in the decay scheme as deexciting a 734.63 keV level to the $7/2[404]$ ground state and to the $5/2[402]$ state at 357.01 keV.

We suggest that the level observed in the (α, t) experiments is the same as the level which is weakly populated in our decay measurements but different from the level at 734.7 keV seen in the in-beam studies. The assignment of Kemnitz et al. of the $13/2\ 9/2[514]$ rotational band member at 734.7 keV seems well established since it is supported by in-beam γ -ray coincidence data. While O'Neil et al. do not report an assignment for their 736 keV level it seems clear that this level cannot be the $13/2\ 9/2[514]$ state since the cross section for population of the $13/2^-$ member of rotational band in the (α, t) reaction is expected to be vanishingly small. Since the 736 keV level was not populated in the $(^3\text{He}, d)$ reaction at a detectable level one can infer from the cross section data that $\ell > 2$. With this in mind and considering the deexcitation pattern of the level, it seems likely that the spin is either $5/2$ or $7/2$ since higher spin states would not be populated to any extent in radioactive decay.

Referring to the level scheme of Kemnitz et al. one can eliminate all rotational members of lower lying Nilsson states as possible candidates for the 734.63 keV level. Vibrational levels built on low-lying states are unlikely candidates as well since they are not expected to be populated in transfer reactions and are predicted to lie above 1 MeV in excitation energy. Looking again at Fig. 2 we conclude that the spin 5/2 or 7/2 level can only be the 7/2[523] band head or a rotational member of some as yet undiscovered Nilsson orbital. The only viable candidates in this energy region would be members of the 3/2[651] band where the spin 5/2 member might be expected to be significantly populated in the (α, t) reaction. There is no convincing evidence which allows us to choose between these possibilities. Because we do not know the location of the 3/2[651] band head, and since according to Fig. 2 the 7/2[523] orbital and the 1/2[660] orbital cross while the 3/2[651] parallels the 1/2[660] with change in deformation and lies about 100 keV higher in excitation, we tend to favor a 7/2[523] assignment for the 734.63 keV level.

The 3/2[402] state at 1359.32 keV. A level at 1359.32 keV is proposed on the basis of the singles γ -ray data alone. Six transitions depopulate this level to the $1/2^-$, $3/2^-$ and $5/2^-$ members of the 1/2[541] band, the $1/2^+$ and $5/2^+$ members of the 1/2[411] band and also to a collective state at 1129.65 keV. This deexcitation pattern defines the spin of the 1359.32 keV level as 3/2 with no certainty in parity assignment. Fig. 2 suggests that this level could be the 3/2[402] band head. Of

the other spin $3/2$ states, the $3/2[651]$ orbital is expected at much lower energy and the $3/2[521]$ orbital, which should be easily recognizable because it should be fed by an au β -transition from the $1/2[521]$ ground state of ^{173}Hf , is predicted at somewhat higher energy than 1359.32 keV. A level at this energy was not seen in the reaction studies of Ref. 3. Since there exists the possibility that $\Delta N=2$ mixing occurs between the $3/2[402]$ and $3/2[651]$ orbitals in ^{173}Lu the suggestion that the 1359.32 keV level is $3/2[402]$ does not exclude the possibility of large admixtures of $3/2[651]$ or that there are significant vibrational components of the type predicted in Ref. 11.

The $1/2[400]$ state at 1408.90 keV. O'Neil et al. report a level at 1410 keV which was assigned $I=1/2$ because it is strongly populated in the $(^3\text{He},d)$ reaction but not observed in the (α,t) experiments. Three weak γ -rays measured in our decay experiments sum with lower-lying level energies to fix a level at 1408.90 keV which is possibly the same spin $1/2$ state seen in the $(^3\text{He},d)$ work. The deexcitation to the $1/2^-$ and $3/2^-$ members of the $1/2[541]$ band and to a collective level at 981.88 keV is consistent with a low spin assignment. The strong population of this level in transfer reactions is consistent with an assignment as a single-particle level. Identification of this level as the $1/2[400]$ band head is suggested by Fig. 2.

B. Collective States

Several collective vibrational states in ^{173}Lu were identified by Funk et al. and Gnatovich et al. Our data support the

existence of collective levels at 981.88, 1003.41, 1246.54 and 1344.05 keV but do not provide any new evidence to permit a higher degree of certainty in interpreting the structure of these states than is available in Ref. 1. In general we prefer the assignments given in Ref. 1 over those in Ref. 2 and have shown these on our decay scheme (Fig. 1).

Levels at 1292 and 1578 keV which were tentatively proposed by Funk et al. are not supported by our data. A level at 1097.45 keV first suggested by Ref. 1 is shown in our scheme but we wish to point out that one of the transitions can be accommodated elsewhere if population in radioactive decay of the $5/2^- 3/2^- [532]$ rotational state at 957.74 keV is accepted. This level is known from the reaction studies of O'Neil et al. Another rotational level that appears to be weakly populated in decay, the $9/2^- 7/2^- [404]$ state at 117.20 keV, was also previously identified in the in-beam reaction γ -ray experiments of Kemnitz et al.

IV. SUMMARY AND CONCLUSION

A level scheme of ^{173}Lu has been elucidated which accommodates better than 99.9% of the transition intensity observed in the decay of 23.9-h ^{173}Hf . A decay scheme similar to those in Refs. 1 and 2 is presented and supported by a substantial amount of coincidence data. In addition, tentative identification of new single-particle states based on singles γ -ray data and some reaction data are proposed as follows: 721.56 keV, $1/2^- [660]$; 734.63 keV, $7/2^- [523]$; 1359.32 keV, $3/2^- [402]$; and 1408.90 keV

1/2[400]. The decay scheme appears to account for all single-particle states expected below 1 MeV in excitation in ^{173}Lu except for the 3/2[651] orbital. The agreement between theory and experiment is very satisfactory for the energies of the single-particle states.

ACKNOWLEDGEMENTS

The authors wish to thank J. Wilhelmy, currently of the Los Alamos Scientific Laboratory, for the Nilsson level calculations. One of us, (D. S. B.), wishes to express his gratitude for the hospitality extended him by members of the Radiochemistry Division of the Lawrence Livermore Laboratory, especially, R. Anderson and L. Maynard, who assisted in data acquisition and processing.

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*Supported by the U.S. Atomic Energy Commission at the Lawrence Livermore Laboratory and in part by the U.S. Atomic Energy Commission at Clark University.

+Participating Guest, Lawrence Livermore Laboratory, 1973-74.

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Table I
Gamma rays assigned to ^{173}Hf decay

E_{γ} (keV)	I_{γ} a)
77.88 $\pm$ 0.10	6.4 $\pm$ 0.2
117.20 $\pm$ 0.05	8.0 $\pm$ 1.6
123.69 $\pm$ 0.02	10000 $\pm$ 460
134.98 $\pm$ 0.05	576 $\pm$ 16
139.66 $\pm$ 0.05	1553 $\pm$ 43
162.02 $\pm$ 0.05	788 $\pm$ 22
171.59 $\pm$ 0.10	20.8 $\pm$ 1.0
229.72 $\pm$ 0.25	0.3 $\pm$ 0.1
239.78 $\pm$ 0.20	0.5 $\pm$ 0.2
288.88 $\pm$ 0.15	3.4 $\pm$ 0.2
296.99 $\pm$ 0.03	4089 $\pm$ 88
306.59 $\pm$ 0.03	763 $\pm$ 21
311.26 $\pm$ 0.03	1294 $\pm$ 26
357.00 $\pm$ 0.03	55.1 $\pm$ 5.5
377.71 $\pm$ 0.25	0.10 $\pm$ 0.05
423.09 $\pm$ 0.05	7.9 $\pm$ 0.4
426.95 $\pm$ 0.15	1.2 $\pm$ 0.2
428.52 $\pm$ 0.15	1.5 $\pm$ 0.2
444.94 $\pm$ 0.15	0.6 $\pm$ 0.2
451.19 $\pm$ 0.15	1.1 $\pm$ 0.2
458.21 $\pm$ 0.15	0.4 $\pm$ 0.2
492.40 $\pm$ 0.30 ^{b)}	0.15 $\pm$ 0.07
540.22 $\pm$ 0.03	45.0 $\pm$ 1.5
546.82 $\pm$ 0.10	3.7 $\pm$ 0.2
549.82 $\pm$ 0.03	53.5 $\pm$ 2.0
556.41 $\pm$ 0.10	1.6 $\pm$ 0.2
568.52 $\pm$ 0.20	1.1 $\pm$ 0.2
577.98 $\pm$ 0.10	2.9 $\pm$ 0.2
593.22 $\pm$ 0.15	0.8 $\pm$ 0.2
618.15 $\pm$ 0.05	3.0 $\pm$ 0.2
625.94 $\pm$ 0.05	3.7 $\pm$ 0.2
694.44 $\pm$ 0.25	1.2 $\pm$ 0.3
718.52 $\pm$ 0.03	36.1 $\pm$ 1.9
734.53 $\pm$ 0.20	0.4 $\pm$ 0.1
740.08 $\pm$ 0.05	3.0 $\pm$ 0.4
760.86 $\pm$ 0.05	8.1 $\pm$ 0.4
765.56 $\pm$ 0.10	1.8 $\pm$ 0.1
781.96 $\pm$ 0.15	0.5 $\pm$ 0.1
807.14 $\pm$ 0.30	0.15 $\pm$ 0.07
811.61 $\pm$ 0.05	2.0 $\pm$ 0.2
821.58 $\pm$ 0.20	0.5 $\pm$ 0.1

828.39 ± 0.25 ^{b)}	0.4 ± 0.2
834.10 ± 0.15	0.7 ± 0.1
845.42 ± 0.40 ^{b)}	0.15 ± 0.07
853.46 ± 0.05	38.2 ± 2.5
866.06 ± 0.40	0.10 ± 0.05
875.05 ± 0.05	27.5 ± 1.7
879.74 ± 0.05	46.6 ± 3.3
889.44 ± 0.20	0.4 ± 0.1
899.16 ± 0.05	122 ± 8
905.81 ± 0.20 ^{b)}	0.22 ± 0.06
929.38 ± 0.10	0.6 ± 0.1
933.88 ± 0.40	0.15 ± 0.07
969.11 ± 0.10	0.7 ± 0.2
977.08 ± 0.10	1.2 ± 0.2
983.18 ± 0.15	0.5 ± 0.1
989.99 ± 0.30 ^{b)}	0.10 ± 0.07
991.80 ± 1.00 ^{b)}	0.10 ± 0.06
1001.32 ± 0.10	1.3 ± 0.2
1005.95 ± 0.10	2.4 ± 0.3
1034.06 ± 0.10	51.9 ± 4.1
1038.74 ± 0.10	40.1 ± 2.8
1064.11 ± 0.10	0.6 ± 0.1
1070.69 ± 0.10	9.5 ± 1.0
1085.77 ± 0.30 ^{b)}	0.04 ± 0.02
1096.02 ± 0.20	0.15 ± 0.07
1100.02 ± 0.30 ^{b)}	0.06 ± 0.02
1118.11 ± 0.10	3.0 ± 0.3
1145.25 ± 0.35	0.02 ± 0.01
1205.64 ± 0.10	35.8 ± 2.9
1210.32 ± 0.10	10.9 ± 0.9
1230.86 ± 0.30	0.09 ± 0.02
1235.50 ± 0.20	0.02 ± 0.01
1274.64 ± 0.45 ^{b,c)}	0.02 ± 0.01
1280.61 ± 0.50	0.02 ± 0.01
1286.60 ± 0.20 ^{b)}	0.09 ± 0.02
1315.96 ± 0.30 ^{b)}	0.07 ± 0.02
1332.87 ± 0.20 ^{b)}	0.02 ± 0.01
1363.92 ± 0.50 ^{b)}	0.01 ± 0.01
1428.60 ± 0.40 ^{b,c)}	0.03 ± 0.01
1488.89 ± 0.30 ^{b)}	0.04 ± 0.01
1512.52 ± 0.35 ^{b,c)}	0.02 ± 0.01
2042.96 ± 1.00 ^{b)}	0.03 ± 0.01
2127.73 ± 1.00 ^{b)}	0.02 ± 0.01
2613.12 ± 1.40 ^{b,c)}	0.02 ± 0.01

a) Normalized to 10000 at 123.69 keV.

b) Transition has not been placed in the decay scheme.

c) Because of a lack of sufficient half-life data the assignment of this transition to ^{173}Hf decay is tentative.

Table II

Gamma rays in coincidence from the decay of ^{173}Hf

E_{γ} (keV)	Gamma rays in coincidence with E_{γ} ^{a)}				
134.98	162.0,	171.6			
139.66	162.0,	171.6,	288.9,	549.8,	625.9, 718.5, 899.2
162.02	135.0,	139.7,	549.8		
171.59	135.0,	139.7			
296.99	(423.1),	540.2,	549.8		
306.59	423.1,	540.2			
311.26	(117.2),	423.1,	540.2		
357.00	77.9,	(423.1),	540.2,	618.2	
423.09	117.2,	288.9,	297.0,	306.6,	311.3, 357.0, 428.5
540.22	162.0,	297.0,	306.6,	311.3,	357.0
549.82	135.0,	139.7,	162.0,	297.0	
568.52	306.6,	311.3			
577.98	162.0,	297.0			
618.15	357.0				
625.94	135.0,	139.7			
718.52	135.0,	139.7			
760.86	444.9				
811.61	162.0,	297.0,	306.6,	311.3	
853.46	None				
879.74	None				
899.16	135.0,	139.7			
977.08	357.0				
1034.06	None				
1038.74	None				
1205.64	None				
1210.32	None				

a) Weak coincidences are in parentheses.

FIGURE CAPTIONS

Fig. 1. Level scheme of ^{173}Lu as seen in decay of ^{173}Hf . Energies are in keV and relative γ -ray intensities are shown in parentheses. Transitions whose assignments are confirmed by coincidence data are marked with a filled circle. To the left of each level is shown the I^π assignment and the preferred Nilsson model designation. Electron capture feed percentages and log ft values are shown to the right.

Fig. 2. Theoretical predictions for single-proton levels in ^{173}Lu . The energy level scheme was calculated using the Nilsson code (Ref. 6) and arbitrarily corrected for pairing by halving the level excitation energies. The experimental scheme is included for comparison.

EC
23.9h

$\frac{1}{2} [52]$
173_{Hf}

$Q_{EC} \geq 2000$ keV

Fig. 1

Fig 2