PHYSICAL REVIEW C VOLUME 10, NUMBER 5 NOVEMBER 1974

Decay of ^{173}Hf and measurement of the half-life of the 128.3-keV state in ^{173}Lu[†]

E. G. Funk, D. R. Zolnowski,[*] M. C. Madden,[‡] R. A. Belt,[§] and J. W. Mihelich
Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556

(Received 17 June 1974)

The γ-ray and internal-conversion-electron spectra associated with the decay of ^{173}Hf (23.9 h) to ^{173}Lu have been studied using Ge(Li) and Si(Li) detectors. Approximately 70 transitions have been assigned to the ^{173}Hf decay and conversion coefficients and multipolarities have been obtained for 35 transitions. The results of γ-γ coincidence measurements confirmed the placement of many transitions previously proposed by other investigators and were utilized in the construction of a decay scheme including about 50 transitions and several newly proposed levels. The existence of at least three transitions with significant $E0$ content has been established. These depopulate states in two $K^\pi = \frac{1}{2}^+$ bands based at 981.7 and 1246.3 keV which are probably octupole-vibrational and β-vibrational bands, respectively. γ-ray branching ratio data are presented, and Nilsson state assignments and possible vibrational-state assignments are discussed. The half-life of the 128.3-keV ($\frac{1}{2}^-$) state in the $\frac{1}{2}^-[541]$ band has been measured as 5.2± 0.5 nsec, and the $B(E2)$ value for the enhanced 4.8-keV rotational transition depopulating the 128.3-keV state has been deduced using theoretical predictions for the internal-conversion coefficient.

RADIOACTIVITY ^{173}Hf [from ^{172}Yb$(\alpha,3n)$]; measured E_γ, I_γ, I_{ce}, $t_{1/2\gamma}$ γ-γ coin; deduced logft. ^{173}Lu deduced levels, J, π, ICC. Enriched target; Ge(Li), Si(Li) detectors.

I. INTRODUCTION

The electron-capture decay of ^{173}Hf (23.9 h) was first studied extensively by Valentin, Horen, and Hollander[1] (VHH) who employed magnetic spectrometers, NaI detectors, and γ-γ coincidence techniques. They identified most of the expected low-lying Nilsson orbitals in ^{173}Lu, i.e., $\frac{7}{2}^+[404]$, $\frac{1}{2}^-[541]$, $\frac{1}{2}^+[411]$, and $\frac{5}{2}^+[402]$, and several rotational levels in bands based on these states. They also proposed six higher-lying states for which they could not assign definite spins and parities. Discrepancies exist between their conversion-electron intensities and those reported earlier by Harmatz, Handley, and Mihelich[2] (HHM). O'Neil, Burke, and Alford[3] have investigated the states in ^{173}Lu via (^{3}He, d) and (α,t) proton transfer reactions and have identified states in bands associated with the $\frac{9}{2}^-[514]$, $\frac{1}{2}^-[530]$, and $\frac{3}{2}^-[532]$ Nilsson orbitals in addition to states in the low-lying bands.

In a preliminary account[4] of our work on the decay of ^{173}Hf, the existence of at least three transitions with significant $E0$ content was reported and these were assigned as depopulating members of two $K=\frac{1}{2}$ bands which are probably of octupole-vibrational or β-vibrational character. Subsequent to this, Gnatovich *et al.*[5] reported an investigation of the γ-ray spectrum of the ^{173}Hf decay using Ge(Li) detectors. They combined their results with the conversion-electron data of VHH[1] to obtain internal-conversion coefficients (ICC) for about 30 transitions, two of which have high ICC values and were assigned as $E0$ admixtures in agreement with our results. From the ICC results and limited coincidence data they proposed a $\frac{3}{2}^-$ level ($\frac{3}{2}^-[532]$) at 889.2 keV, a $\frac{3}{2}^+$ level ($\frac{3}{2}^+[411]$) at 975.1 keV, $\frac{1}{2}^+$ and $\frac{3}{2}^+$ members of a $K=\frac{1}{2}$ band at 981.8 and 1003.4 keV, a $\frac{3}{2}^-$ level (member of a $\frac{1}{2}^-[532]$ band) at 1162.4 keV and a $\frac{3}{2}^-$ level at 1334.0 keV. Gnatovich *et al.* assigned the 981.8- and 1003.4-keV levels as members of a β-vibrational band based on the $\frac{1}{2}^+[411]$ state.

Recently, Kemnitz *et al.*[6] have performed in-beam γ-ray spectroscopy experiments using the ^{173}Yb$(p, n\gamma)$ and $(d, 2n\gamma)$ reactions. They proposed a level scheme for ^{173}Lu involving rotational bands based on the low-lying intrinsic states $\frac{7}{2}^+[404]$, $\frac{1}{2}^+[411]$, $\frac{5}{2}^+[402]$, $\frac{1}{2}^-[541]$, and $\frac{9}{2}^-[514]$ up to spin $\frac{23}{2}$, $\frac{17}{2}$, $\frac{19}{2}$, $\frac{25}{2}$, and $\frac{23}{2}$, respectively. They were able to explain the energies of states in the highly perturbed $\frac{1}{2}^-[541]$ band by considering rotation-particle coupling with other negative parity bands.

The half-life of the 123.6-keV state was first measured as 70 μs by Ward *et al.*,[7,2] and the results of other measurements are 77± 5 and 88 ± 3 μs.[8,9] Löbner, Bennett, and Bunker[10] determined the half-lives of the 425.0- ($\frac{1}{2}^+$) and 435- ($\frac{3}{2}^+$) keV states in the $\frac{1}{2}^+[411]$ band as 0.82 ± 0.20 and 0.46± 0.20, respectively, and Andrejtscheff *et al.*[11] reported a value of 0.68± 0.08 ns for the half-life of the 425.0-keV state. Schilling *et al.*[12] have obtained upper limits of 0.5 and 1 ns for half-lives of the 356.8- ($\frac{5}{2}^+[402]$) and 449.0-keV ($\frac{9}{2}^-[514]$) states.

In the present paper, a complete report of the ^{173}Hf decay is presented. In addition to studies of the γ-ray and conversion-electron spectra with Ge(Li) and Si(Li) detectors, coincidence and half-life measurements have been carried out. Multipolarities obtained from ICC data and coincidence results permit unambiguous spin and parity assignments for seven states between 800 and 1350 keV, and several additional levels in this region are proposed. Branching ratio data are presented and possible one-quasiparticle and vibrational state assignments for all proposed levels are discussed.

II. EXPERIMENTAL PROCEDURE

A. Source preparation

The ^{173}Hf (23.9-h) activity was produced by irradiating an enriched ^{172}Yb target (91.5%) in the oxalate form with 37-MeV α particles in the Argonne 1.5-m cyclotron. The ^{173}Hf was separated from the target material by means of the solvent extraction method of Harmatz and Handley.[13] The resulting sources were found to contain traces of ^{170}Lu (2.0 day), ^{171}Lu (8.3 day), ^{172}Lu (6.7 day), ^{173}Lu (1.37 yr), ^{175}Hf (70 day), and ^{24}Na (15 h) as impurities.

B. Transition energies and intensities

Conversion-electron spectra of ^{173}Hf were obtained with a 3-mm×110-mm^2 Si(Li) conversion-electron spectrometer having a resolution of 1.5 keV [full width at half-maximum (FWHM)] at 234 keV and 2.5 keV (FWHM) at 836 keV. Intensities were obtained from the observed relative peak areas using an empirically obtained efficiency curve.

γ-ray singles spectra were taken with an Ortec 7-mm×4-cm^2 planar Ge(Li) detector, a 40-cm^3 coaxial Ge(Li) detector (resolution of 2.2 keV at 1332.5 keV), and also the Si(Li) detector. The energies of the stronger transitions were obtained by running standard sources concurrently with the ^{173}Hf source and these energies were then used to obtain values for the weaker transitions.

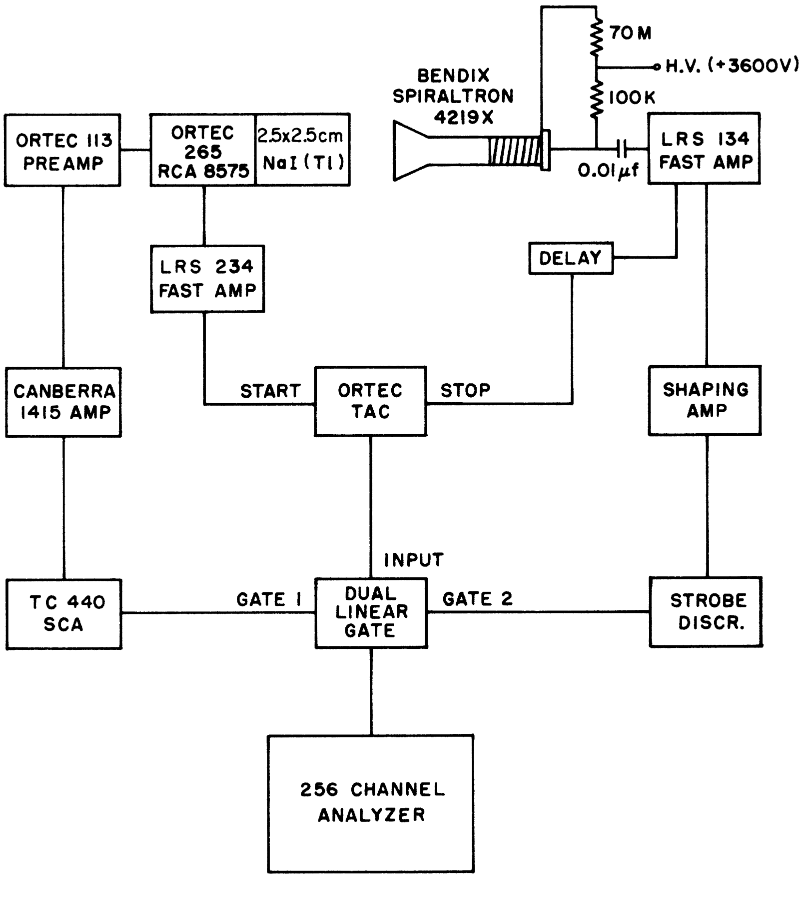

FIG. 1. Block diagram of the fast coincidence system used in measuring the half-life of the 128.3-keV state.

C. Coincidence measurements

In the coincidence experiments a 20-cm^3 Ge(Li) detector was used as a gating detector and the 40-cm^3 coaxial detector was employed to obtain the coincidence spectrum. The coincidence system employed Canberra-1416 amplifiers, Canberra-1435 timing single-channel analyzers, and a Canberra-1441 fast coincidence unit. Energy gates were set with a digital-band selector and, for each photopeak gated, a second gate of similar width was set on the adjacent Compton background to provide an interference correction. The coincidence resolving time was ≈110 ns, and chance coincidence corrections were made, although they were practically negligible.

D. Half-life measurements

A block diagram of the system used for the 128.3-keV state half-life measurement is shown in Fig. 1. A Bendix Spiraltron[14] continuous channel electron multiplier (Type 4219X) was utilized for detection of low energy x rays and conversion electrons. This detector has a high efficiency for photons of energy up to ≈10 keV, while the efficiency for electrons is ≈30% at 1 keV, 20% at 4 keV, and 8% at 50 keV. The detector has a collecting cone of 4 mm diameter and was operated (in vacuum) in a two-terminal pulse saturated mode. With 3600 V on the anode, negative pulses of height ≈100 mV, width ≈10 ns, and rise time ≈3 ns were obtained. These output pulses were amplified by a fast amplifier and fed into the fast and slow systems as shown. In the slow system a shaping amplifier and discriminator were used for rejection of noise pulses.

As a check of the system, the half-lives of the 166-keV state in ^{139}La and 8.4-keV state in ^{169}Tm were measured. For the first case, the Auger electrons and *L* x rays resulting from the electron-capture decay of ^{139}Ce were detected with the Spiraltron and the 166-keV γ rays with a NaI detector. The result was 1.61 ± 0.09 ns which agreed within errors with the previously measured value of 1.47 ± 0.09 ns.[15] For the second case, a ^{169}Yb source was deposited on 2-μ thick Mylar; the *M* and *N* conversion electrons from the 8.4-keV transition were detected with the Spiraltron and the (94–109)-keV γ rays with a NaI detector. The result was 4.10 ± 0.21 ns, in agreement with the value of 4.13 ± 0.12 ns obtained by McAdams, Eakins, and Hatch.[16] With a 2-μ thick Mylar absorber, the apparent half-life observed was 0.60 ns, which was verification that low-energy electrons were being detected with no absorber present.

For other half-life measurements with the ^{173}Hf source the fast-slow system consisted of various plastic and NaI detectors, Chronetics discriminators, and an overlap time to amplitude converter (TAC). A digital gate and routing circuit allowed simultaneous acquisition of four TAC spectra which corresponded to four different regions of the energy spectrum from one detector.

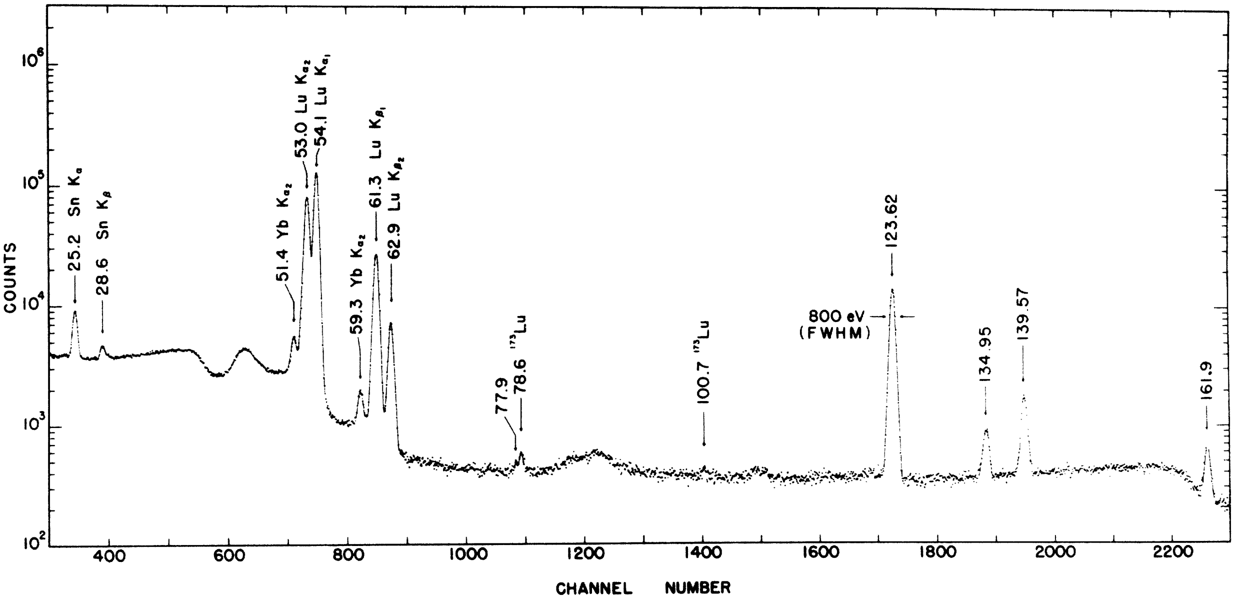

FIG. 2. Low-energy photon spectrum of ^{173}Hf obtained with a 3-mm × 110-mm^2 Si(Li) detector (1.5-mm Lucite absorber).

III. RESULTS

A. Transition data and coincidence results

The low energy photon spectrum obtained with the Si(Li) detector is shown in Fig. 2, and portions of the γ-ray spectra obtained with the 40-cm^3 Ge(Li) detector are displayed in Fig. 3. In the energy range above 350 keV, the transitions are weak and only about 10 γ rays have intensities above 3% of that for the 311-keV transition. A few weaker transitions between 1300 and 1900 keV are not shown. An internal-conversion-electron spectrum obtained with the Si(Li) detector is presented in Fig. 4.

Approximately 70 γ-ray transitions have been observed to decay with a half-life of ≈24 h and are assigned to the ^{173}Hf decay. The transition data are presented in Table I, together with the conversion-electron data of HHM[2] and an average of the two sets of data given by VHH.[1] In a few cases, e.g. for the 171.5-, 556.8-, and 929.1-keV transitions, the observed intensities were corrected for contributions due to transitions at these energies from impurities of ^{172}Lu and ^{173}Lu. The γ-ray intensities are in satisfactory agreement with those of Gnatovich *et al.*[5] although we observe a large number of weaker transitions which are not reported by them.

In general, our conversion-electron data are in good agreement with those of VHH.[1] However, satisfactory agreement with HHM[2] can only be obtained if their intensities for the transition energy regions 0–165, 165–425, and above 425 keV are normalized separately to the intensities determined in our work for the 139.6-, 311.2-, and 540-keV *K* lines, respectively. (The data of HHM shown in Table I are normalized in this manner.)

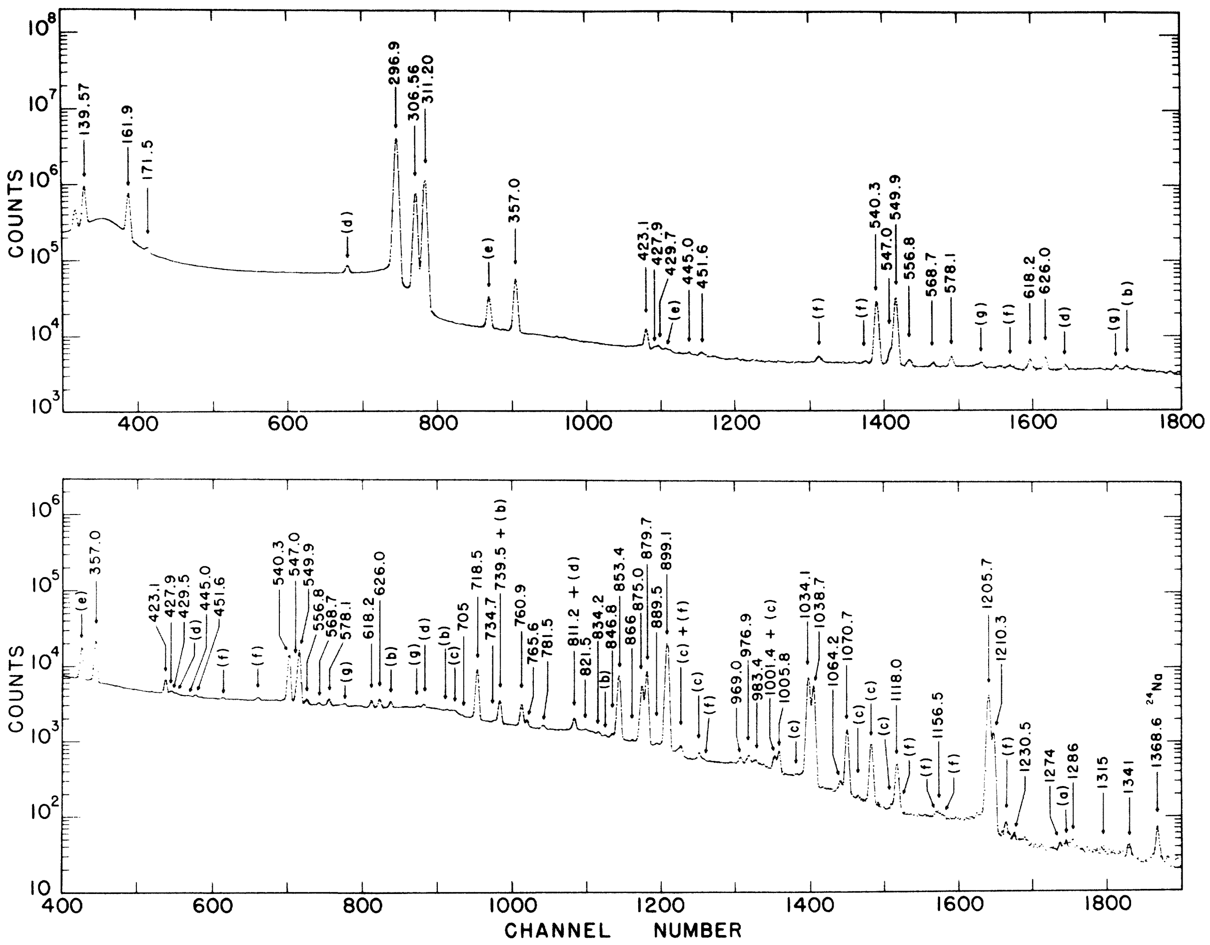

FIG. 3. Upper figure shows a portion of the γ-ray spectrum of ^{173}Hf obtained with a 40-cm^3 Ge(Li) detector and 0.7-mg/cm^2 Pb and 1.5-mg/cm^2 Cu absorbers. Lower figure shows a higher energy portion obtained using 2.8-mg/cm^2 Pb and 1.5-mg/cm^2 Cu absorbers. Peaks not due to ^{173}Hf are labeled as follows: (a) ^{170}Lu, (b) ^{171}Lu, (c) ^{172}Lu, (d) ^{173}Lu, (e) ^{175}Hf, (f) background, and (g) peaks due to summing or pileup.

TABLE I. Transition data for the decay of ^{173}Hf. Additional unplaced weak γ rays observed only in Ge(Li) spectra which have been tentatively assigned to ^{173}Hf decay. (Approximate γ-ray intensities in parentheses): 734.7(0.6), 846.8(0.5), 1156.5(0.5), 1230.5(0.1), 1274(0.09), 1286(0.10), 1302(0.06), 1341.2(0.14), 1434(0.03), 1505(0.05), 1557.7(0.06), 1749(0.08), 1836(0.03), and 1897(0.03) keV. Additional (unplaced) transitions which were observed only in the internal conversion electron studies of Ref. 2: 1351.2, 1485.1. and 1551.0 keV.

Transition energy^{a} (keV)	Photon intensity	K-conversion e^- intensity HHM^{e}	VHH^{f}	Present work	Total intensity^{g}	α_K (exp)^{h} ($\times 10^2$)	α_K (theor)^{c} ($\times 10^2$)	Multipolarity^{d} assignment	Placement Initial level	Final level
77.9 (2)	4.7 (12)^{h}	≈8.66	≈7.0		≈42	≈184	$M1$: 640	$M1 + E2$	434.8	357.0
116.7^{i}	5.9 (10)^{h}				≈20^{j}			$(M1)^{k}$	551.5	263.2
123.62 (8)	9115 (730)	1350	1550	1500 (120)	10 940 (880)	17.0 (17)	$E1$: 16.7	$E1$	123.6	0
134.95 (8)	507 (40)	460	460	468 (38)	1140 (90)^{j}	89.6 (86)	$M1$: 133	$M1$ +74% $E2^{l}$	263.2	128.3
139.57 (8)	1345 (110)	1731 (N)	1825	1731 (140)	3190 (260)^{j}	126 (12)	$M1$: 120	$M1$ +14% $E2^{l}$	263.2	123.6
161.9 (1)	662 (53)	64	64	53.2 (27)	730 (60)	7.6 (6)	$E1$: 8.2	$E1$	425.2	263.2
171.5 (2)	13.4 (30)		0.9		14.6 (33)	6.7 (20)	$E1$: 7.0	$E1$	434.8	263.2
288.3^{i}	1.53 (50)		W		1.57 (50)			$E1^{m}$	551.5	263.2
296.9 (1)	4045	64.4	72 (N)	72^{n}	4134	1.78	$E1$: 1.78	$E1$	425.2	128.3
306.56 (8)	743 (40)	11.9	11.3	12.3 (7)	758 (41)	1.67 (13)	$E1$: 1.64	$E1$	434.8	128.3
311.20 (8)	1235 (60)	19.2 (N)	18.3	19.2 (8)	1260 (60)	1.47 (10)	$E1$: 1.58	$E1$	434.8	123.6
357.0 (1)	51.8 (25)	≈5.7	6.1	6.0 (5)	57.8 (28)	11.6 (11)	$M1$: 9.6	$M1$	357.0	0°
423.1 (3)	6.30 (60)	0.47	0.77	0.43 (4)	6.75 (64)	6.8 (9)	$M1$: 5.9	$M1$	975.1	551.5
427.9 (5)	0.75 (30)				0.76 (30)			$E1^{m}$	551.5	123.6
429.7 (5)	0.98 (20)				1.01 (20)			$E2^{m}$	981.7	551.5
445.0 (6)	0.33 (16)			0.024 (9)	0.35 (17)	7.3 (44)	$M1$: 5.1	$M1$	1333.9	889.2
451.6 (4)	0.96 (18)			0.028 (9)	1.02 (19)	2.9 (11)	$M1$: 5.0	$M1 + (E2)$	1003.3	551.5
540.3 (1)	40.5 (20)	1.43 (N)	1.7	1.43 (10)	42.0 (21)	3.53 (30)	$M1$: 3.20	$M1$	975.1	434.8
547.0 (4)	3.18 (40)			0.092 (15)	3.29 (40)	2.9 (6)	$M1$: 3.00	$M1$	981.7	434.8
549.9 (1)	48.1 (24)	1.7	2.0	1.57 (9)	49.8 (25)	3.27 (25)	$M1$: 2.9	$M1$	975.1	425.2
556.8 (3)	1.3 (3)	0.37	0.43	0.47 (3)	1.9 (4)	36.2 (88)	$M1$: 2.8	$E0 + M1$	981.7	425.2
568.7 (4)	0.80 (15)	0.31	0.40	0.32 (2)	1.2 (4)	40.0 (80)	$M1$: 2.77	$E0 + M1 + (E2)$	1003.3	434.8
578.1 (2)	2.52 (25)	0.093	0.10	0.080 (12)	2.60 (26)	3.17 (57)	$M1$: 2.73	$M1$	1003.3	425.2
596	<0.2	≈0.03		<0.06	<0.3	>15	$M1$: 2.7	$(E0 + M1)$	1578	981.7
618.2	2.50 (25)		0.04	<0.07	2.55 (26)	<2.6		$M1$	975.1	357.0
626.0	3.24 (24)	≈0.04		0.063 (10)	3.32 (25)	1.95 (34)	$M1$: 2.15	$M1$	889.2	263.2
718.5 (1)	32.3 (16)	0.07	0.10	0.091 (13)		0.28 (4)	$E1$: 0.25	$E1$	981.7	263.2
739.7 (5)	2.1 (5)								1003.3	263.2
760.9 (2)	7.66 (38)	0.12	0.18	0.112 (12)		1.46 (17)	$M1$: 1.32	$M1$	889.2	128.3
765.6 (3)	1.65 (35)	≈0.04	0.05	<0.05		<3.0	$M1$: 1.3		889.2	123.6
781.5 (5)	0.49 (25)								1333.9	551.5
811.2 (4)	1.84 (35)								1246.3	434.8
821.5 (5)	0.29 (14)	≈0.033		0.021 (4)		7.2 (40)	$M1$: 1.08	$E0 + M1$	1246.3	425.2
834.2 (5)	0.48 (20)								1097.4	263.2
853.4 (1)	35.8 (18)	0.08	0.14	0.076 (11)		0.22 (3)	$E1$: 0.175	$E1$	981.7	128.3
857.4 (10)	<0.2		0.05	<0.03		>10	$M1$: 0.97	$E0 + M1 + (E2)$	1292.4	434.8

TABLE I *(Continued)*

Transition energy[a] (keV)	Photon intensity	K-conversion e^- intensity HHM[e]	VHH[f]	Present work	Total intensity[g]	α_K (exp)[b] ($\times 10^2$)	α_K (theor)[c] ($\times 10^2$)	Multipolarity[d] assignment	Placement Initial level	Final level
866	0.1								1129	263.2
									1292	425.2
875.0 (2)	25.3 (13)	0.05	0.05	0.055 (8)		0.22 (3)	$E1$: 0.170	$E1$	1003.3	128.3
879.7 (2)	42.9 (22)	0.09	0.10	0.092 (10)		0.22 (3)	$E1$: 0.168	$E1$	1003.3	123.6
889.5 (5)	0.48 (20)								1246.3	357.0
899.1 (1)	1.19 (24)[h] 109.3 (60)	0.93	1.0	0.98 (6)		0.89 (7)	$M1$: 0.87	$M1$	1333.9 1162.3	434.8 263.2
929.1 (5)	0.53 (25)								1192.4	263.2
969.2	0.58 (25)								1097.4	128.3
976.9 (4)	1.04 (20)								1333.9	357.0
983.4 (5)	0.37 (18)								1246.3	263.2
1001.4 (4)	1.14 (25)								1129.5	128.3
1005.8 (3)	2.30 (25)								1129.5	123.6
1034.1 (1)	46.4 (23)	0.28	0.32	0.32 (2)		0.69 (6)	$M1$: 0.62	$M1$	1162.3	128.3
1038.7 (1)	35.3 (18)	0.21	0.26	0.23 (2)		0.65 (7)	$M1$: 0.60	$M1$	1162.3	123.6
1064.2 (4)	0.60 (18)								1192.4	128.2
1070.7 (1)	8.65 (45)	0.043	0.052	0.043 (6)		0.50 (7)	$M1$ (0.56)	$M1$	1333.9	263.2
1118.0 (4)	2.75 (30)								1246.3	128.3
1205.7 (1)	33.0 (17)	0.14	0.17	0.15 (1)		0.45 (4)	$M1$ (0.43)	$M1$	1333.9	128.3
1210.3 (2)	9.80 (50)	0.05	0.07	0.038 (6)		0.39 (6)	$M1$ (0.42)	$M1$	1333.9	123.6
1315 (1)	0.07 (4)								1578	263.2
1450 (1)	0.05 (3)								1578	128.3
1778.4 (7)	0.08 (4)	W								

[a] Determined from our γ-ray data except for cases noted.

[b] Using our conversion-electron data, except for cases where no value is listed under present work.

[c] Obtained from Ref. 17.

[d] Based on ICC values except where noted.

[e] Data for three energy regions are normalized to the three peaks indicated by (N), as described in text.

[f] Normalization at 296.9-keV K line. Average of two sets of data from Ref. 1.

[g] For $E_\gamma < 400$ keV, total intensities are determined from our γ-ray intensities and theoretical ICC values of Ref. 17. For 400 keV$< E_\gamma <$700 keV, α_{tot} is taken to be $1.2\alpha_K$ for $E1$ and $M1$ transitions and $1.3\alpha_K$ for $E2$ transitions. For $E_\gamma > 700$ keV, total intensities are determined from $I_\gamma(1+\alpha_K)$.

[h] Intensity determined from coincidence experiment.

[i] Energy quoted is the difference between energies of initial and final levels.

[j] Total intensity obtained assuming multipolarity (column 9) determined from L-subshell ratios (Ref. 1).

[k] Multipolarity assumed.

[l] Multipolarity from Ref. 1 (determined from L-subshell ratios).

[m] Multipolarity assignment deduced from placement of the transition.

[n] Normalized to give theoretical value of α_K for the 296.9-keV $E1$ transition.

[o] A weak transition of this energy may also exist between levels at 1246.3 and 889.2 keV.

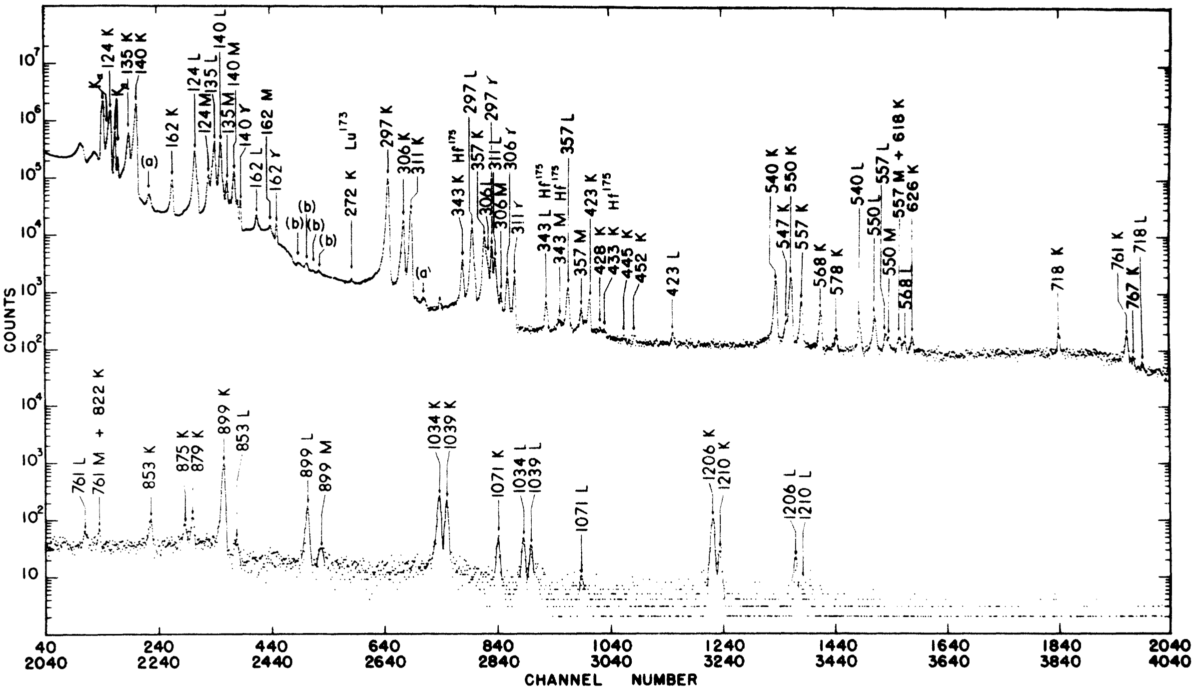

FIG. 4. Internal-conversion-electron spectrum from ^{173}Hf. Peaks labeled (a) and (b) are due to summing with L x rays and K x rays, respectively.

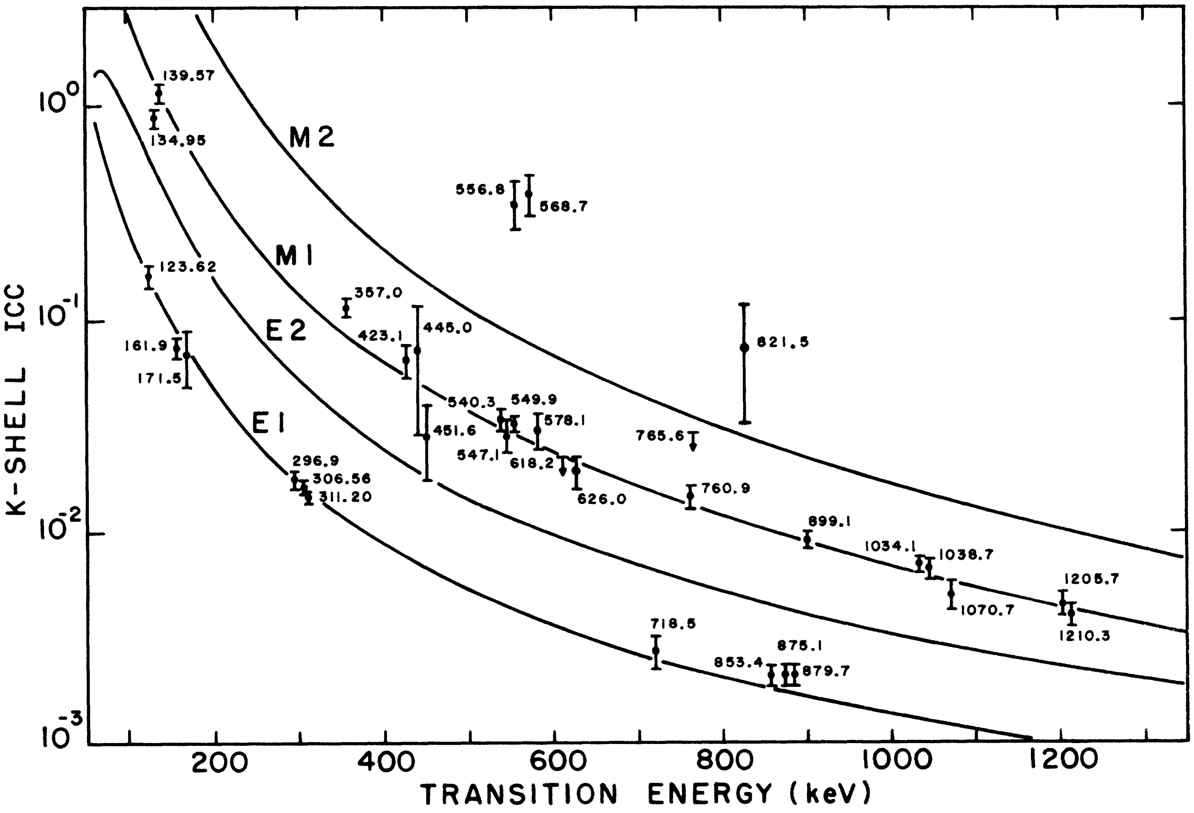

FIG. 5. Comparison of experimental K-shell internal-conversion coefficients with theoretical values of Ref. 17.

TABLE II. Coincidence data for ^{173}Hf.

Gate transition(s) (keV)	Coincident transitions (keV)	Relative coincidence intensity	Singles intensity
134.95+	162	843 (80)	619 (31)
139.57	171	a	13.4 (30)
	288	1.53 (50)	
	423	0.66 (23)	6.30 (60)
	550	4.6 (5)	48.1 (24)
	626	2.8 (5)	3.24 (24)
	718	32.3 (norm)	32.3 (16)
	740	2.1 (4)	2.1 (5)
	899	88.8 (50)	110.5 (60)
	1071	6.9 (7)	8.65 (45)
296.9	423	1.2 (3)	6.30 (60)
	540	6.8 (6)	40.5 (20)
	550	48.1 (norm)	48.1 (24)
	557	1.1 (2)	1.3 (3)
	578	2.9 (3)	2.52 (25)
	810	0.17 (7)	1.84 (35)
	821	0.19 (8)	0.29 (14)
306.56+	117	5.9 (8)	
311.2	423	5.1 (3)	6.30 (60)
	429	0.46 (20)	0.98 (20)
	452	0.82 (15)	0.96 (18)
	540	40.5 (norm)	40.5 (20)
	547	3.0 (2)	3.18 (40)
	568	0.89 (14)	0.80 (15)
	(609)	0.47 (13)	
	811	2.42 (30)	1.84 (35)
	899	1.19 (24)	110.5 (60)
357.0	77	4.7 (12)	<31
	423	0.38 (8)	6.30 (60)
	540	0.89 (14)	40.5 (20)
	618	2.50 (norm)	2.50 (25)
	890	0.35 (12)	0.48 (20)
	977	0.75 (18)	1.04 (20)

[a] Observed to be in coincidence, but intensity could not be determined due to scattering effects.

It is possible that the problem with the HHM intensities resulted from difficulties in the normalization of data obtained with various permanent-magnet spectrographs. It should also be noted that the values of HHM for the transition energies above 500 keV are systematically larger than our values.

The experimental K internal-conversion coefficients (ICC's) have been obtained from our data (except in the few cases noted in the table), and the γ-ray and electron intensities are normalized to yield the theoretical $E1$ K-conversion coefficient of 0.0178 for the 296.9-keV transition. The theoretical K-conversion coefficients were determined by interpolation from the values of Hager and Seltzer.[17] A graphical presentation of the ICC data is shown in Fig. 5, and it can be seen that the values for most of the transitions lie near those for $M1$ or $E1$ with the exception of the 556.8-, 568.7-, and 821.5-keV transitions, which have large ICC's.

The results of γ-γ coincidence experiments, gating with the (135.0+139.6)-, 296.9-, (306.6 +311.2)-, and 357.0-keV transitions, are presented in Table II. These data have been corrected for chance coincidences and interference effects, and the singles intensities are given for comparison.

B. Decay scheme

Since the ^{173}Hf ground state is $\frac{1}{2}^-$ (Ref. 1), only low-spin levels (predominantly $\frac{1}{2}$ and $\frac{3}{2}$) are expected to be populated in the electron-capture decay. Approximately 50 of the observed transitions have been placed in the decay scheme, which is shown in Fig. 6. Those transitions whose placement is supported by coincidence data are indicated by a dot at the level which they populate. γ-ray intensities for transitions depopulating the states above 889 keV are given in parentheses, and multipolarities are listed for these transitions in the cases where ICC data were obtained. Transitions labeled by asterisks have two possible placements, and the placement of the dashed transitions is very tentative. Only the well-established Nilsson assignments are shown in Fig. 6. Electron-capture branchings and logft values are presented in a later table.

1. Levels below 600 keV

The levels up to 425 keV and the intensities and multipolarities of the depopulating transitions have been well established previously.[1,4,5] However, the 9.6-keV intraband transition between the 434.8- and 425.2-keV states in the $\frac{1}{2}^+[411]$ band has never been observed. By comparing the intensity of the 540.3-keV transition in singles with that observed in coincidence with the 297-keV transition, a total intensity of 420± 50 is obtained for the 9.6-keV transition. This implies that about 16% of the depopulation of the 434.8-keV state occurs via this transition. Using this branching ratio and the 0.46-ns value for the half-life for the 435-keV state measured by Löbner *et al.*,[10] the partial half-life for the 9.6-keV ($\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$) intraband transition is found to be 2.9 ns. This compares favorably with similar transitions in the $\frac{1}{2}^+[411]$ bands in ^{169}Tm

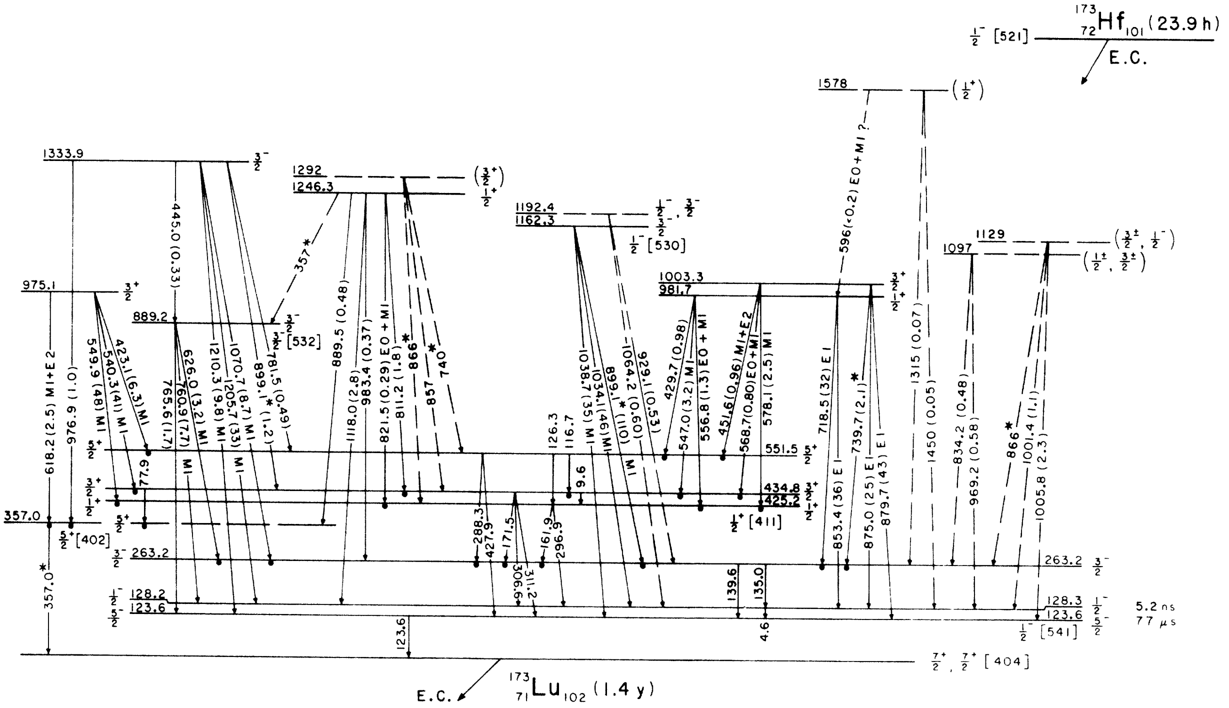

FIG. 6. Proposed decay scheme for ^{173}Hf.

and ^{171}Tm.

In the work of VHH[1] tenuous evidence was obtained for a weakly populated level at ≈546 keV. O'Neil *et al.*[3] reported that two unresolved states at ≈550 keV are populated in the proton transfer reactions, and they assigned these as the $\frac{5}{2}^+$ and $\frac{7}{2}^+$ members of the $\frac{1}{2}^+[411]$ band. On the basis of our observation of the 116.7-keV γ ray in coincidence with the 307- and 311-keV transitions and the 288.3-keV γ ray in coincidence with the 135- and 139.6-keV transitions, a level is placed at 551.5 keV. It is most likely $\frac{5}{2}^+$ since depopulating transitions proceed to $\frac{1}{2}^+$, $\frac{3}{2}^\pm$, and $\frac{5}{2}^-$ levels but apparently not to the $\frac{1}{2}^-$ level at 128.3 keV. Gnatovich *et al.*[5] do not report any evidence for the 551.5-keV level in the ^{173}Hf decay, but the recent

TABLE III. Ratios of reduced transition probabilities for dipole transitions between $K=\frac{1}{2}$ bands.

	From $\frac{1}{2}^+[411]$ band to: $\frac{1}{2}^-[541]$ band ($E1$ transitions)		From $K^\pi=\frac{1}{2}^+$ band at 981.7 keV to: $\frac{1}{2}^-[541]$ band ($E1$ transitions)		From $K^\pi=\frac{1}{2}^+$ band at 981.7 keV to: $\frac{1}{2}^+[411]$ band ($M1$ transitions)		From $\frac{1}{2}^-[530]$ band to: $\frac{1}{2}^-[541]$ band ($M1$ transitions)	
$\frac{B(1;I_i\to I_f)}{B(1;I_i\to I_f')}$	Ratio	b [a]	Ratio	b	Ratio	b	Ratio	b
$\frac{B(1;\frac{1}{2}\to\frac{3}{2})}{B(1;\frac{1}{2}\to\frac{1}{2})}$	0.94 (7)	−0.19 (2) 6.4 (10)	2.58 (68)	0.05 (5) 2.39 (56)	1.51 (11)	−0.067 (15) 3.58 (28)	1.33 (74)	−0.10 (14) 4.1 (6)
$\frac{B(1;\frac{3}{2}\to\frac{1}{2})}{B(1;\frac{3}{2}\to\frac{3}{2})}$	9.6 (21)	−0.17 (5) −0.44 (6)	3.00 (64)	−0.15 (50) −0.57 (6)	7.3 (18)	−0.14 (6) −0.50 (7)	0.24 (2)	−8.9 (30) −0.92 (1)
$\frac{B(1;\frac{3}{2}\to\frac{5}{2})}{B(1;\frac{3}{2}\to\frac{3}{2})}$	16.3 (38)	−0.11 (6) −0.76 (13)	2.40 (64)	0.22 (9) −2.02 (54)	12.1 (30)	−0.04 (4) −0.84 (16)	0.18 (2)	0.78 (3) 3.7 (3)
$\frac{B(1;\frac{5}{2}\to\frac{3}{2})}{B(1;\frac{5}{2}\to\frac{5}{2})}$	6.7 (24)	−0.087 (64) 0.76 (33)						

[a] Obtained from $\frac{B(L,I_iK_i\to I_fK_f)}{B(L,I_iK_i\to I_f'K_f)}=\left[\frac{\langle I_iLK_iK_f-K_i|I_fK_f\rangle+b(-)^{I_f-K_f}\langle I_iLK_i,-K_f-K_i|I_f-K_f\rangle}{\langle I_iLK_iK_f-K_i|I_f'K_f\rangle+b(-)^{I_f'+K_f}\langle I_iLK_i,-K_f-K_i|I_f'-K_f\rangle}\right]^2$.

TABLE IV. Ratios of reduced $M1$ transition probabilities for transitions from proposed $I=\frac{3}{2}$, $K=\frac{3}{2}$ states.

$\frac{B(L;I_i\rightarrow I_f,K_f)}{B(L;I_i\rightarrow I'_f,K_f)}$	Theory [a] (Alaga)	From 889.1 keV state to $\frac{1}{2}^-$[541] band	From 975.0 keV state to $\frac{1}{2}^+$[411] band	From 1334.0 keV state to $\frac{1}{2}^-$[541] band
$\frac{B(1;\frac{3}{2}\rightarrow\frac{5}{2},\frac{1}{2})}{B(1;\frac{3}{2}\rightarrow\frac{3}{2},\frac{1}{2})}$	0.25	0.28 (6)	0.32 (3)	0.78 (6)
$\frac{B(1;\frac{3}{2}\rightarrow\frac{1}{2},\frac{1}{2})}{B(1;\frac{3}{2}\rightarrow\frac{3}{2},\frac{1}{2})}$	1.25	1.32 (12)	1.13 (18)	2.67 (20)

[a] Theoretical value for $K_i=\frac{3}{2}$ obtained from ratio of squares of Clebsch-Gordan coefficients.

work of Kemnitz *et al.*[6] confirms the assignment of this state as the $\frac{5}{2}^+$ member of the $\frac{1}{2}^+$[411] band.

The weak 126.3-keV transition, which is shown in Fig. 6 as depopulating the 551.5-keV level, is not observable in the singles spectra from the ^{173}Hf decay. However, it has been observed in $(p, n\gamma)$ and $(d, 2n\gamma)$ studies by Kemnitz *et al.*,[6] and their intensity is consistent with that inferred indirectly from our coincidence results with the 297- and (307-311)-keV gates.

The branching ratios for $E1$ transitions between the $\frac{1}{2}^+$[411] and $\frac{1}{2}^-$[541] bands are given in Table III. It is apparent that reasonable consistency is obtained for a value of ≈ -0.16 for the parameter b.

The evidence for the spin, parity, and Nilsson orbital assignments for the other proposed levels is discussed in the following sections.

2. *889.2-keV level*

Valentin *et al.*[1] proposed a level at 887.7 keV (spin and parity $\frac{1}{2}^-$ or $\frac{3}{2}^-$) and Gnatovich *et al.*[5] a $\frac{3}{2}^-$ level at 889.2 keV. Our observation of the 626.0-keV transition in coincidence with the 135.0- and 139.6-keV transitions confirms the existence of a level at 889.2 keV. Since this state depopulates by $M1$ transitions to the $\frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$ members of the $\frac{1}{2}^-$[541] band, it must have a spin and parity of $\frac{3}{2}^-$; furthermore, the ratios of reduced transition probabilities presented in Table IV are in good agreement with the predictions for a $K=\frac{3}{2}$, $I=\frac{3}{2}$ state.

O'Neil *et al.*[3] have observed states at 958 and 1151 keV in the proton transfer reactions. The measured spectroscopic factors agreed well with an assignment of these levels as the $\frac{5}{2}$ and $\frac{9}{2}$ members of a band built on the $\frac{3}{2}^-$[532] orbital which is strongly coupled by the Coriolis interaction with the $\frac{1}{2}^-$[541] and $\frac{1}{2}^-$[530] orbitals. They observed a state at $\approx$890 keV which could be the $\frac{3}{2}^-$ bandhead predicted to be at $\approx$881 keV on the basis of the Coriolis coupling calculations.

On the basis of all the existing evidence, it is very likely that the 889.2-keV state is a fairly pure $\frac{3}{2}^-$[532] single quasiparticle state.

3. *975.1-keV level*

Valentin *et al.*[1] proposed a positive parity level at 974.0 keV and Gnatovich *et al.*[5] a $\frac{3}{2}^+$ level at 975.1 keV. This 975.1-keV state is supported by our coincidence data, and since it depopulates via $M1$ transitions to the $\frac{1}{2}^+$, $\frac{3}{2}^+$, and $\frac{5}{2}^+$ members of the $\frac{1}{2}^+$[411] band, the 975.1-keV state must be $\frac{3}{2}^+$. The $B(M1)$ ratios for transitions from this level (Table IV) suggest that this state is the spin $\frac{3}{2}$ bandhead of a $K=\frac{3}{2}$ band; it is most likely the $\frac{3}{2}^+$[411] Nilsson hole state which is expected at about this energy and is observed in neighboring nuclei.[18] The state was not observed in the single-proton transfer studies,[3] but hole states are not expected to be strongly excited in such reactions.

4. *981.7- and 1003.3-keV levels*

Valentin *et al.*[1] proposed states at 980.9 and 1001.9 keV with the latter probably having positive parity, and Gnatovich *et al.*[5] assigned states at 981.8 and 1003.4 keV as $\frac{1}{2}^+$ and $\frac{3}{2}^+$, respectively. Our coincidence experiments confirm the existence of levels at 981.7 and 1003.3 keV, which appear to be members of the same band since they deexcite in a similar way. If one considers the multipolarities of all the depopulating transitions with the exception of the 556.8- and 568.7-keV transitions (which have high ICC values), the 1003.3-keV state is firmly established as $\frac{3}{2}^+$ and the 981.7-keV state as either $\frac{1}{2}^+$ or $\frac{3}{2}^+$, with the $\frac{1}{2}^+$ assignment being more likely since no transition is observed to the 123.6-keV ($\frac{5}{2}^-$) state. Since the placement of the 556.8- and 568.7-keV transitions is strongly supported by the coincidence data, one must conclude that the large K conversion coefficients are indicative of $E0$ admixtures, and that the spin and parity of the 981.7-keV state are definitely $\frac{1}{2}^+$.

The 556.8-keV transition ($\frac{1}{2}^+ \to \frac{1}{2}^+$) is restricted to $E0+M1$ multipolarity by angular momentum selection rules, but the 568.7-keV transition ($\frac{3}{2}^+ \to \frac{3}{2}^+$) could also contain an $E2$ admixture. Assuming no $E2$ content in the 568.7-keV transition and theoretical values for the $M1$ ICC's, the ratio of the K electrons from the $E0$ and $M1$ components would be ≈14 as compared to a value of ≈11 for the 556.8-keV transition. The ratio of the $E0$ K-electron intensity and total transition intensity is ≈0.25 for both transitions [assuming $K/(L+M)=5$].

The experimental branching ratios for the $E1$ and $M1$ transitions from the 1003.3-keV ($\frac{3}{2}^+$) state are definitely in disagreement with the predictions for a $K=\frac{3}{2}$ assignment. However, the RTP (reduced transition probability) ratios for $E1$ transitions from the 981.7- and 1003.3-keV states to the $\frac{1}{2}^-[541]$ band (see Table III) are in agreement within errors with the Alaga predictions for a $K=\frac{1}{2}$ band, with a value of $b \approx 0.1$. Furthermore, the RTP ratios for $M1$ transitions to the $\frac{1}{2}^+[411]$ band (see Table IV) also are consistent with $K=\frac{1}{2}$ and a value for b of ≈ -0.08.

The 981.7- ($\frac{1}{2}^+$) and 1003.3-keV ($\frac{3}{2}^+$) states are assigned as members of a $K=\frac{1}{2}$ band on the basis of the branching ratio data and the fact that these states depopulate in a similar manner, with $E1$ transitions to the $\frac{1}{2}^-[541]$ band whose γ-ray intensities are an order of magnitude larger than the $M1$ transitions to the $\frac{1}{2}^+[411]$ band.

If one assumes a reasonable value of 13.3 keV for the inertial parameter $\hbar^2/2\mathscr{I}$, the decoupling parameter for this band would be ≈ -0.5. It is unlikely that the band is based on a single-particle state since the only available $K^\pi=\frac{1}{2}^+$ orbitals are $\frac{1}{2}^+[400]$ and $\frac{1}{2}^+[660]$ which are expected to lie somewhat higher and have decoupling parameters of ≈0.4, and ≈6, respectively. Furthermore, states in bands based on these orbitals should be strongly populated in proton transfer reactions and no evidence for this was obtained by O'Neil *et al.*[3] The appreciable $E0$ admixtures in the 556.8- and 568.7-keV transitions would seem to indicate that the 981.7-keV state may be a vibrational excitation of a lower-lying single-particle state, and the possible interpretations will be discussed in Sec. IV B.

5. 1162.3 level and possible 1192.4-keV level

A $\frac{3}{2}^-$ level at 1162.3 keV is established by: (1) the strong 899.1-keV coincidence obtained when gating on the 135- 140-keV γ rays and (2) the $M1$ multipolarity of the three transitions proceeding to members of the $\frac{1}{2}^-[541]$ band. A negative parity level had been proposed at 1160.8 keV by VHH[1] and a $\frac{3}{2}^-$ level at 1162.4 keV by Gnatovich *et al.*[5] In the proton transfer studies,[3] $\frac{3}{2}^-$ and $\frac{7}{2}^-$ states were observed at ≈1166 and 1275 keV and assigned as members of a $\frac{1}{2}^-[530]$ band.

The $\frac{1}{2}^-$ state of the [530] band is predicted to lie ≈35 keV above the $\frac{3}{2}^-$ state[19] but should be populated weakly in the proton transfer reactions. In ^{175}Lu some evidence was obtained by O'Neil for a $\frac{1}{2}^-$ state ≈29 keV above the $\frac{3}{2}^-$ state in the $\frac{1}{2}^-[530]$ band. We have tentatively placed a state at 1192.4 keV in ^{173}Lu on the basis of energy fits of two weak transitions of 929.1 and 1064.2 keV to the $\frac{3}{2}^-$ and $\frac{1}{2}^-$ levels of the $\frac{1}{2}^-[541]$ band. This possible state (spin $\frac{1}{2}$ or $\frac{3}{2}$) might be the $\frac{1}{2}^-$ state of the $\frac{1}{2}^-[530]$ band.

The branching ratio data (assuming pure $M1$ transitions to the $\frac{1}{2}^-[541]$ band) do not give a consistent value for the b parameter (see Table III), but Coriolis mixing between the $\frac{3}{2}^-[532]$, $\frac{1}{2}^-[541]$, and $\frac{1}{2}^-[530]$ bands might account for this. Using the energies of the known $\frac{3}{2}^-$, $\frac{7}{2}^-$, and possible $\frac{1}{2}^-$ state the values of $\hbar^2/2\mathscr{I}$ and a are found to be 13.3 keV and −1.8, respectively; the theoretical prediction of a is −2.1 for $\delta=0.28$.

6. 1246.3-keV level (and possible 1291-keV level)

A newly proposed level at 1246.3 keV is established by the coincidence data obtained with the 297- and (306-311)-keV γ-ray gates. Since transitions proceed from this level to $\frac{1}{2}^+$, $\frac{3}{2}^+$, and $\frac{5}{2}^+$ states, the level must be $\frac{1}{2}^+$, $\frac{3}{2}^+$, or $\frac{3}{2}^-$ ($\frac{5}{2}^-$ is ruled out if the state is fed directly by electron capture). The large conversion coefficient for the 821.5-keV transition is certainly indicative of an $E0$-$M1$ admixture and on this basis the 1246.3-keV state is assigned as $\frac{1}{2}^+$. It should be noted that the K-conversion line of the 821.5-keV transition and the M lines of the 760.9-keV transition are composite; the 821.5-keV K intensity was obtained by assuming the theoretical values for the $K/L/M$ ratios for the 760.9-keV $M1$ transition. The ratio of the K electrons from the $E0$ and $M1$ components is ≈6 and the ratio of the $E0$ K-electron intensity and total transition intensity is ≈0.06.

Little information can be gained from the branching ratios from the 1246.3-keV state since transitions are observed to only two states in each of the $\frac{1}{2}^-[541]$ and $\frac{1}{2}^+[411]$ bands and the multipole mixtures are not known. However, it may be noted that the relative intensities of the 1118.0- and 811.2-keV transitions to the $\frac{1}{2}^-$ and $\frac{3}{2}^+$ states of the $\frac{1}{2}^-[541]$ and $\frac{1}{2}^+[411]$ bands, respectively, are 2.8 and 1.8 while the transitions to the $\frac{3}{2}^-$ and $\frac{1}{2}^+$ states of these bands are about one seventh as intense. Since the 821.5-keV transition appears to contain an $E0$ admixture, the 1246.3-keV state may also be a vibrational excitation of a low-lying particle state, and the character of the state is discussed in Sec. IV B.

No conclusive evidence has been obtained for a possible $\frac{3}{2}^+$ member of a band based on the 1246.3-keV state. However, K-conversion electrons from a transition of 857 keV have been reported by both VHH[1] and HHM,[2] and while HHM did not fully resolve the K line, VHH report an intensity of 0.05 as compared to an upper limit of 0.03 from our data. Using the upper limits from our γ-ray and electron data the value for α_K would be ≈ 0.1, while the value obtained using our upper limit for the γ-ray intensity and the electron intensity of VHH would be >0.25. Thus, it is conceivable that this transition also contains an $E0$ admixture (although it could be of high multipolarity as well), and one is tempted to consider it as being a transition between a possible $\frac{3}{2}^+$ state at 1292 keV and the $\frac{3}{2}^+$ state in the $\frac{1}{2}^+[411]$ band, in analogy to the case of the $\frac{3}{2}^+$ state at 1003.3 keV. The weak 866-keV γ-ray transition could be placed between the 1292- and 425.2-keV states although another possible placement between the 1129- and 263-keV states exists for this transition. A weak 740-keV transition to the 551.5-keV state would not be resolved from the 739.7-keV γ ray, which is placed elsewhere on the basis of coincidence data.

A $\frac{3}{2}^+$ rotational state based on the 1246.3-keV $\frac{1}{2}^+$ state should be at ≈ 1286 keV if $\hbar^2/2\mathscr{I}$ is assumed to be 13.3 keV and $a=0$. Using the value of 1292 keV for this possible $\frac{3}{2}^+$ state and $\hbar^2/2\mathscr{I}=13.3$ keV, the value of the decoupling parameter, a, would be ≈ 0.15.

7. *1333.9-keV level*

Valentin *et al.*[1] proposed a level at 1332.6 keV and Gnatovich *et al.*[5] a $\frac{3}{2}^-$ state at 1334.0 keV. Our data firmly establish a $\frac{3}{2}^-$ level at 1333.9 keV which depopulates predominantly via $M1$ transitions to the three lowest members of the $\frac{1}{2}^-[541]$ band. As seen in Table IV the branching ratios (assuming pure $M1$ transitions) are not in agreement with the Alaga predictions for a $K=\frac{3}{2}$ state, although this might be due to band-mixing effects. Furthermore, the 1070.7-, 1205.7-, and 1210.3-keV transitions could contain as much as 46%, 10%, and 42% $E2$ admixture, respectively, based on the conversion coefficient data. The 1333.9-keV state is probably a vibrational state since no additional $\frac{3}{2}^-$ single-particle states are expected at this energy and also the state was not observed in the p-transfer studies.[3] The character of this state is discussed further in Sec. IV B.

8. *Possible states at 1097.5, 1129.4, and 1578 keV*

States are tentatively placed at 1097.5 and 1129.4 keV solely on the basis of energy fits involving only two transitions in each case (although a third transition, the weak 866-keV γ ray, could be placed between the 1129.4- and 263.2-keV states). Possible spin and parity assignments are shown on Fig. 6 with a $\frac{5}{2}^-$ assignment being ruled out if these states are fed directly by electron capture. Since the multipolarities of the depopulating transitions are not known, little information can be gained from branching ratio considerations.

Another possible state may exist at 1578 keV. This is based on energy fits involving two very weak transitions of 1315 and 1450 keV observed in the γ-ray spectrum and the 596-keV transition for which the only evidence is the observation of K electrons by HHM.[2] Using the HHM ce^- intensity and our upper limit for γ-ray intensity the value for α_K would be >0.15, implying another transition having $E0$ content (or high multipolarity). If an $E0$ admixture were present in this possible transition to the $\frac{1}{2}^+$ state at 981.7 keV, the spin for the tentative state at 1578 keV would be $\frac{1}{2}^+$ and it could be another vibrational state.

C. Half-life measurements

1. *Half-life of 128.3-keV state and transition probability for the 4.65-keV E2 transition*

Before an attempt was made to measure the half-life of the 128.3-keV state, delayed coincidence experiments were carried out to determine conclusively that the ≈ 77-ns half-life observed previously[1,7] is that of the 123.6-keV state. The previous measurements could not rule out the possibility that this half-life is associated with the 128.3-keV state or that the measured value is some composite of the half-lives of these two states.

The results obtained when selecting the 123.6-keV transition with a NaI detector and the 135.0- and 139.6-keV transitions (separately) with a 7-mm planar Ge(Li) detector strongly supported the assignment of the 77-μs half-life to the 123.6-keV state; furthermore, the results indicated that the half-life of the 128.3-keV state was <20 ns. The retardation of the 123.6-keV $E1$ transition has been discussed in detail in previous papers and no further elaboration will be given here.

For the measurement of the half-life of the 128.3-keV state, a 2.5-cm×2.5-cm NaI(Tl) detector was used for selecting the strong 296.9- and 306.6-keV γ rays populating the 128.3-keV state, and the Spiraltron detector was used for detecting the M and N conversion electrons (≈ 2.5 and 4.3 keV) and Lu M x rays (≈ 1.6 keV) associated with the very highly converted 4.65-keV transition. The thin source was deposited on 0.5-mg/cm^2 aluminized Mylar. The coincidence system is described in Sec. II D.

Three separate measurements were carried out and the average value obtained for the half-life of the 128.3-keV state was (5.2 ± 0.5) ns. The data for one of the runs are shown in Fig. 7 together with a prompt curve obtained with a ^{51}Cr source. The latter curve, which exhibits an apparent half-life of 1.3 ns on the right side, was obtained by gating on 320-keV γ rays with the NaI detector and detecting the vanadium K x rays (5.4 keV) and Auger electrons (accompanying electron capture) with the Spiraltron. Another " prompt" curve obtained with ^{51}Cr and a thin Mylar absorber sufficient to absorb Auger electrons yielded a similar result.

Consideration of the decay scheme of ^{173}Hf and the results of several additional delayed coincidence measurements using the ^{173}Hf source with various thin absorbers led to the conclusion that >60% of the coincidence events shown in Fig. 7 were due to delayed coincidences between 296.9- or 306.6-keV γ rays and the M and N conversion electrons from the strong 4.65-keV transition. The majority of the other coincidences are prompt events between x rays or Auger electrons (accompanying electron capture) and the 296.9-, 306.6-, or 311.2-keV γ rays. Their presence is evident on the left side of the curve in Fig. 7. Since the half-lives of the 263.2-, 425.2-, and 434.8-keV states are less than 1 ns it is almost certain that the observed half-life of 5.2 ± 0.5 ns is that of the 128.3-keV state.

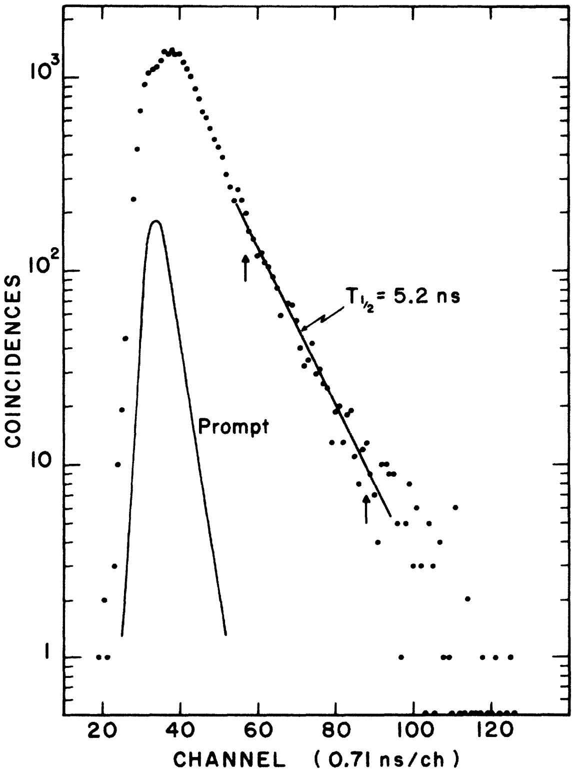

FIG. 7. Time-to-amplitude converter spectrum for measurement of the half-life of 128.3-keV state. The prompt curve was obtained using a ^{51}Cr source.

A value of 2.1×10^6 for the total internal-conversion coefficient of the 4.65-keV $E2$ transition was obtained by interpolation from the M-shell ICC's of Hager and Seltzer[17] and the N-shell ICC's of Dragoun, Pauli, and Schmutzler.[20] Using the Hager and Seltzer value $\alpha_M = 1.65 \times 10^6$ and the empirical value of $(\alpha_N + \alpha_O + \cdots)/M = 0.26$ from Ref. 21 one obtains $\alpha_{\text{tot}} = 2.08 \times 10^6$. It is difficult to assign an uncertainty to α_{tot}, but if one arbitrarily assumes a 10% error, then the partial γ-ray half-life and $B(E2; \frac{1}{2} \to \frac{5}{2})$ values for the 4.65-keV transition are $(1.09 \pm 0.14) \times 10^{-2}$ s and 2.3 ± 0.3 $e^2\,\text{b}^2$, respectively. The Weisskopf estimate (using a statistical factor of 3) is 1.45 s, and thus the enhancement for the 4.65-keV $E2$ transition is 133 ± 20.

Several $\frac{1}{2}^-[541]$ bands have been identified in neighboring odd-proton nuclei but no measurements of intraband $E2$ transition probabilities have been reported and thus no comparisons are possible. A value of $Q_0 = 6.2 \pm 0.4$ b is obtained from the $B(E2)$ value if one assumes the rotational model prediction $B(E2; \frac{1}{2} \to \frac{5}{2}) = (3e^2/16\pi)Q_0{}^2$. However, it is not clear that this simple model can be used for this highly perturbed band. The values of Q_0 obtained from $B(E2; 0^+ \to 2^+)$ values for the two neighboring even-even nuclei $^{172}_{70}\text{Yb}_{102}$ and $^{174}_{72}\text{Hf}_{102}$ are 7.8 and ≈7.0 b, respectively.[22]

The reduced $E2$ transition probability ratio for intraband transitions from the $\frac{3}{2}^-$ state of the $\frac{1}{2}^-[541]$ band obtained from our γ-ray intensities and the multipole mixtures of VHH[1] (see Table I) is:

$$B(E2; \tfrac{3}{2} \to \tfrac{1}{2})/B(E2; \tfrac{3}{2} \to \tfrac{5}{2}) = 2.36 \pm 0.57 .$$

This is in good agreement with the simple rotational model prediction of 2.34. The corresponding $M1$ transition probability ratio is 0.114 ± 0.022. Using the relation for dipole transitions shown in Table III, this yields a value of $b = -3.7 \pm 0.5$ or -0.5 ± 0.1. The former value is closer to the theoretical estimate of -4.8 ± 0.4 obtained by VHH.[1]

2. *Additional half-life measurements*

An upper limit of 0.16 ns was obtained for the half-life of the 263.2-keV state in a measurement where K x rays were detected with a 2.5×2.5-cm Sn-loaded NE140 plastic scintillator and the 135- and 139-keV K electrons were detected with a 1.8-mm thick Naton 136 scintillator. Using these detectors, with gates set on the K x rays and K conversion electrons from the 297-, 306-, and 311-keV transitions, a half-life of 0.66 ± 0.03 ns was obtained. A similar result was obtained when the Naton scintillator was replaced by a NaI detector and 300-keV γ rays were selected. The value of 0.66 ns is almost certainly a composite of the half-lives of the 425.2- and 434.8-keV states which have been determined as 0.82 ± 0.020 and 0.46 ± 0.20 ns, respectively, by Löbner *et al.*[10] Our measurement is consistent with the results of Löbner if one makes reasonable estimates of the amount of each transition present in the (297-311) gate. It is likely that the value of 0.68 ± 0.08 ns reported by Andrejtscheff *et al.*[11] is also a composite since their energy gates were similar to those employed in our measurements. An extensive discussion of the transition probabilities for the $E1$ transitions depopulating the 425.2- and 434.8-keV states has been presented by Löbner *et al.*[10]

IV. DISCUSSION

Since several states in ^{173}Lu are interpreted as possible vibrational excitations, a brief summary of relevant theoretical predictions is presented before further discussion concerning the character of the states above 800 keV.

A. Theoretical predictions

It has been verified experimentally that a number of low-lying (0.5–1.5-MeV) nonrotational states in deformed odd-A nuclei exhibit strong collective vibrational properties. It has been found, however, that the behavior of the observed vibrational states is often poorly described by this simple model and one must actually take into account mixing between the one-quasiparticle and vibrational configurations as well as the quasiparticle makeup of the vibrational phonon itself. In most cases the vibrational excitations are found to be spread over several intrinsic states. The experimental identification of odd-A vibrational excitations and the determination of the presence of particular vibrational components in a mixed state are complicated by the fact that many of these states exhibit a behavior which is not significantly different from that expected for pure one-quasiparticle states. In some cases a fairly reliable model-dependent argument can be used if the I^π of a state are known and no Nilsson states of that I^π value are predicted in that region of excitation energy.

The characteristics expected for relatively pure vibrational states are discussed at length in the review article by Bunker and Reich.[18] A few of the properties which are especially relevant for the ^{173}Lu case are briefly summarized as follows: (1) The $\hbar^2/2\mathcal{g}$ value should be approximately that of the associated one-quasiparticle band. (2) For quadrupole vibrational states, enhanced $B(E2)$ values are expected between these states and their base states (about a factor of 10 larger than asymptotically allowed transitions between pure Nilsson states). (3) The collective model predicts that β-decay transitions to a vibrational state should be highly forbidden, but the microscopic structure of the state can influence this strongly. (4) The decoupling parameter a for a $K=\frac{1}{2}$ band should be small (<0.1) although deviations are observed and can be explained. (5) The cross sections for exciting pure vibrational states by single-nucleon stripping and pickup reactions should be essentially zero.

TABLE V. Theoretical predictions of Gareev *et al.* (Ref. 27) for levels in ^{173}Lu.

Energy (keV) Theory	Energy (keV) Experiment	I^π	Structure[a]	
0	0	$\frac{7}{2}^+$	$\frac{7}{2}^+[404]$ 99%	
40	449	$\frac{9}{2}^-$	$\frac{9}{2}^-[514]$ 97%	
310	425	$\frac{1}{2}^+$	$\frac{1}{2}^+[411]$ 98%	
600	357	$\frac{5}{2}^+$	$\frac{5}{2}^+[402]$ 84%	$\{\frac{9}{2}^-[514], 2^-\}$ 14%
680	128	$\frac{1}{2}^-$	$\frac{1}{2}^-[541]$ 99%	$\{\frac{1}{2}^+[411], 1^-\}$ 1%
720		$\frac{7}{2}^-$	$\frac{7}{2}^-[523]$ 93%	$\{\frac{3}{2}^+[411], 2^-\}$ 6%
1070		$\frac{1}{2}^+$		$\{\frac{1}{2}^+[411], 0^+\}$ 100%
1080	975	$\frac{3}{2}^+$	$\frac{3}{2}^+[411]$ 67%	$\{\frac{7}{2}^-[523], 2^-\}$ 27%
1160		$\frac{1}{2}^-$	$\frac{1}{2}^-[530]$ 1%	$\{\frac{1}{2}^+[411], 1^-\}$ 98%
1170		$\frac{3}{2}^-$	$\frac{3}{2}^-[532]$ 2%	$\{\frac{1}{2}^+[411], 1^-\}$ 98%
1180		$\frac{7}{2}^+$		$\{\frac{7}{2}^+[404], 0^+\}$ 100%
1270		$\frac{3}{2}^-$		$\{\frac{1}{2}^+[411], 2^-\}$ 100%
1280		$\frac{5}{2}^-$	$\frac{3}{2}^-[532]$ 3%	$\{\frac{1}{2}^+[411], 2^-\}$ 92%
1290		$\frac{5}{2}^-$		$\{\frac{7}{2}^+[404], 1^-\}$ 95%
1330		$\frac{5}{2}^+$	$\frac{5}{2}^+[642]$ 2%	$\{\frac{1}{2}^+[411], 2^+\}$ 97%
1330		$\frac{3}{2}^+$		$\{\frac{1}{2}^+[411], 2^+\}$ 100%
1390		$\frac{7}{2}^+$		$\{\frac{9}{2}^-[514], 1^-\}$ 100%
1395		$\frac{3}{2}^-$	$\frac{3}{2}^-[532]$ 5%	$\{\frac{7}{2}^+[404], 2^-\}$ 95%
1400		$\frac{11}{2}^-$		$\{\frac{7}{2}^+[404], 2^-\}$ 100%
1450		$\frac{3}{2}^+$		$\{\frac{7}{2}^+[404], 2^+\}$ 100%
1460		$\frac{11}{2}^+$		$\{\frac{7}{2}^+[404], 2^+\}$ 100%
1500		$\frac{9}{2}^+$	$\frac{9}{2}^+[404]$ 1%	$\{\frac{7}{2}^-[523], 1^-\}$ 99%
1620		$\frac{1}{2}^-$		$\{\frac{1}{2}^+[411], 0^-\}$ 100%

[a] In the fourth column the primary one-quasiparticle component is given and in the fifth column the primary vibrational component is presented. See Ref. 18 for notation used for vibrational components.

TABLE VI. Electron-capture feedings, log*ft* values, and probable assignments for states observed in ^{173}Lu.

Level energy (keV)	Level I^π	Electron capture feeding (%)[a]	log*ft*[b]	Electron capture class.[c]	Base state energy (keV) and assignment	$\hbar^2/2\mathscr{I}$ (keV)	Decoupling parameter a	
							Exp.	Theory[d]
0	$\frac{7}{2}^+$				0 ; $\frac{7}{2}^+[404]$			
123.6	$\frac{5}{2}^-$			2	128.3; $\frac{1}{2}^-[541]$	8.56[e]	4.3[e]	3.3
128.3	$\frac{1}{2}^-$	<10	>7.5	ah				
263.2	$\frac{3}{2}^-$	31.2	7.0	ah				
357.0	$\frac{5}{2}^+$	<0.44	>8.2	1*u	357.0; $\frac{5}{2}^+[402]$			
425.2	$\frac{1}{2}^+$	39.9	6.7	1u	425.2; $\frac{1}{2}^+[411]$	13.3[e]	−0.76[e]	−0.91
434.8	$\frac{3}{2}^+$	22.1	7.0	1u				
551.5	$\frac{5}{2}^+$	0.12	9.3	1*u				
889.2	$\frac{3}{2}^-$	0.11	9.0	ah	889.2; $\frac{3}{2}^-[532]$	13.8[f]		
975.1	$\frac{3}{2}^+$	0.92	8.0	1u	975.1; $\frac{3}{2}^+[411]$			
981.7	$\frac{1}{2}^+$	0.68	8.1		981.7; $\{\frac{1}{2}^-[541], 1^-\}$[g]	(13.3)	−0.46[h]	
1003.3	$\frac{3}{2}^+$	0.68	8.1		and $\{\frac{1}{2}^+[411], 0^+\}$			
1162.3	$\frac{3}{2}^-$	1.7	7.5	ah	1192.4; $\frac{1}{2}^-[530]$	13.3[i]	−1.75[i]	−2.1
1192.4	$(\frac{1}{2}^-)$	0.01	9.7	ah				
1246.3	$\frac{1}{2}^+$	0.052	9.0		1246.3; $\{\frac{1}{2}^+[411], 0^+\}$[g]	(13.3)	0.15[j]	
(1292)[k]	$(\frac{3}{2}^+)$		>10.0		and $\{\frac{1}{2}^-[541], 1^-\}$			
1333.9	$\frac{3}{2}^-$	0.49	7.8		1333.9; $\{\frac{1}{2}^-[541], 2^+\}$[g]			
					and $\{\frac{1}{2}^+[411], 1^-\}$			
(1097.4)	$(\frac{3}{2}^\pm, \frac{1}{2}^\pm)$	0.010	9.9					
(1129.5)	$(\frac{3}{2}^\pm, \frac{1}{2}^-)$	0.031	9.4					
(1578)	$(\frac{1}{2}^+)$		>9.5					

[a] Assuming no electron-capture feeding from ^{173}Hf $(\frac{1}{2}^-)$ to $\frac{7}{2}^+$ ground state or $\frac{5}{2}^-$ state at 123.6 keV in ^{173}Lu.

[b] Assuming Q_{EC} = 1900 keV (since the highest energy γ-ray transition is 1897 keV). The value obtained from systematics, quoted in the 1971 mass table (Ref. 29), is 1600 keV.

[c] Based on assignment given in column 6 (allowed hindered: ah; first forbidden unhindered: 1u).

[d] Theoretical predictions for a deformation $\delta = 0.28$ (Ref. 19).

[e] Based on energies of $\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$ states. Kemnitz *et al.* (Ref. 6) obtained more meaningful values by considering the additional levels they observed and also the Coriolis coupling effects (see text).

[f] Based on $\frac{5}{2}^-$ level at 958 keV reported in Ref. 3.

[g] Possibly a mixture of these configurations with the most likely configuration given first.

[h] Assuming $\hbar^2/2\mathscr{I} = 13.3$ keV.

[i] Based on $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels observed in this work and on $\frac{7}{2}^-$ level at 1275 keV reported in Ref. 3.

[j] Assuming $\hbar^2/2\mathscr{I} = 13.3$ keV and energy of possible $\frac{3}{2}^+$ state at 1292 keV.

[k] Evidence for this level is tenuous.

Theoretical calculations using microscopic descriptions have been carried out by Bes and Cho Yi-Chung[23] who treat only γ-vibrational states and by Soloviev and co-workers[24–27] who consider both quadrupole and octupole phonons. In many cases (e.g., ^{167}Er) (Ref. 18) there is relatively good agreement between experiment and the extensive theoretical predictions of Gareev, Ivanova, Soloviev, and Fedotov[27] for states below 1 MeV.

Of relevance to the discussion of states in ^{173}Lu are the excitation energies of the lowest-lying nonrotational states in the even-even nucleus ^{172}Yb, which effectively constitutes the core for ^{173}Lu. These are: 0^+ mixed β-vibrational and pairing-vibrational levels at 1042 and 1404 keV, 1^-, 0^-, and 2^- octupole vibrational levels at 1154, 1599, and 1757 keV, a 2^+ γ-vibrational level at 1466 keV, and a 3^+ two-quasiparticle level at 1172 keV.[28]

The theoretical predictions of Gareev *et al.*[27] for levels in ^{173}Lu are presented in Table V with the primary one-quasiparticle and vibrational components given in the last two columns. The notation used is that of Bunker and Reich.[18] Of particular note are the following: (1) There is poor agreement between theory and experiment for the energies of the four lowest observed nonrotational excited states of primarily one-quasiparticle character. In particular, the $\frac{1}{2}^-[541]$ state is predicted to be ≈550 keV above the observed position. (2) The $\frac{3}{2}^-[532]$ state is predicted to be spread over many levels with no one level constituted primarily out of this one-quasiparticle state. This is at variance with the proton-transfer results and the predictions of Bes and Cho Yi-Chung.[23] (3) The lowest-lying states with spins $\leq\frac{3}{2}$ predicted to be of almost pure vibrational character are all based on the $\frac{1}{2}^+[411]$ state. These are the $K^\pi=0^+$ β-vibrational type excitation at 1070 keV, the $K^\pi=1^-$ and 2^- octupole-vibrational excitations at 1160, 1170, and 1270 keV and the $K^\pi=2^+$ γ-vibrational excitation at 1330 keV. It is also notable that of the vibrational excitations predicted above 1070 keV, all but one are essentially pure.

Since the $\frac{1}{2}^-[541]$ one-quasiparticle state actually occurs at an excitation energy of only 128 keV it is not unlikely that the lowest-lying excitations of primarily vibrational character would be $K^\pi=0^+$, 1^-, and 2^+ vibrational excitations based on the $\frac{1}{2}^-[541]$ or $\frac{1}{2}^+[411]$ states, or a mixture of vibrational states based on these orbitals.

B. Character of states in ^{173}Lu

The electron-capture feedings and log*ft* values are shown in Table VI, together with the probable one-quasiparticle or vibrational state assignments, electron-capture classifications, and band parameters deduced from our results. The log*ft* values are in good agreement with those reported by Gnatovich *et al.*[5] (for the states which they also observed). A level scheme showing the band structure of ^{173}Lu, including some levels observed in

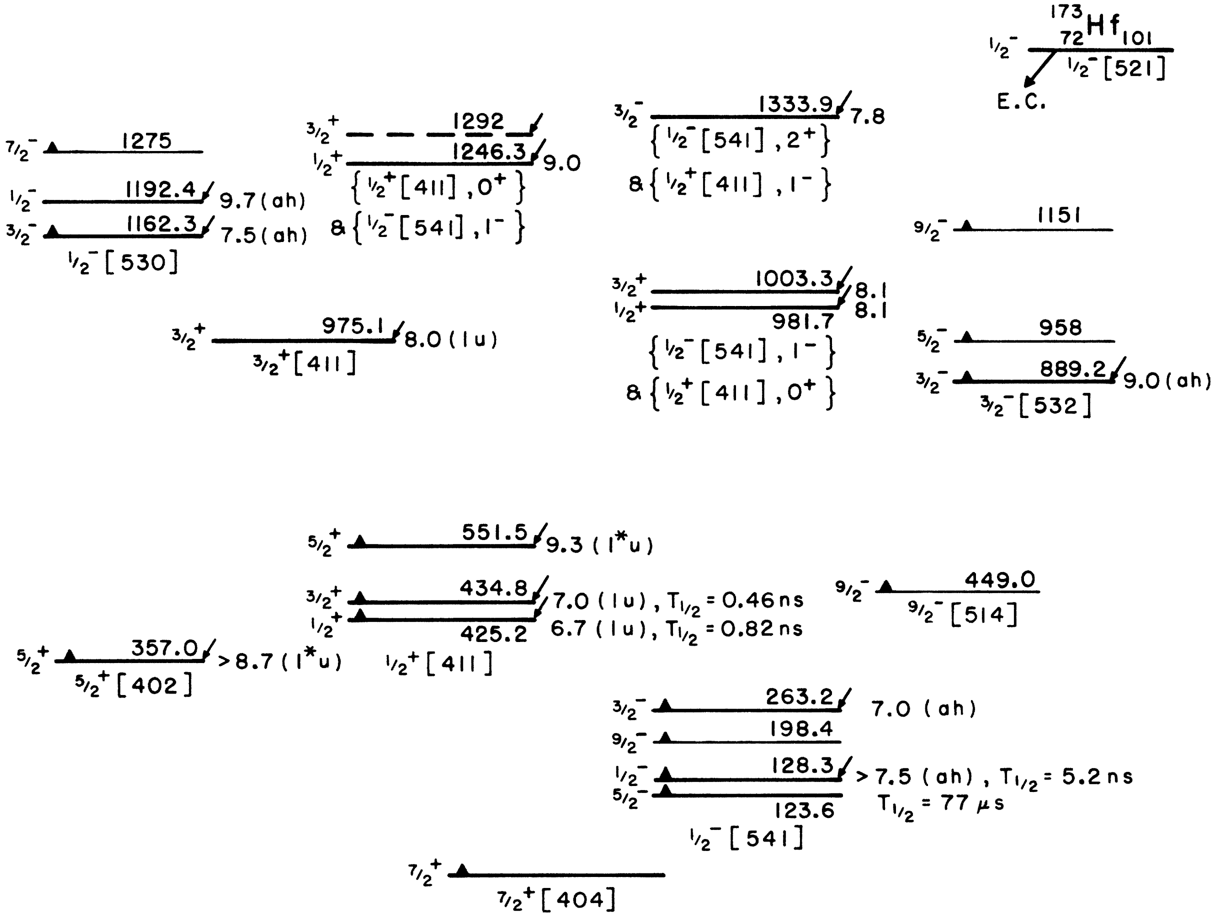

FIG. 8. Level scheme for ^{173}Lu showing assignments for states. Solid triangles indicate levels observed in proton transfer (Ref. 3) or in-beam γ-ray studies (Ref. 6). Arrows indicate levels fed by electron-capture decay of ^{173}Hf; log*ft* values and classifications are shown to the right of the levels.

proton transfer[3] and in-beam γ-ray experiments,[6] is shown in Fig. 8.

1. States below 600 keV

The log*ft* values for the electron-capture decay to states below 600 keV are all consistent with the classifications shown in Table VI. The values for the parameters of the well-established bands based on states below 600 keV are obtained using only those level energies listed in Table VI and the adiabatic formula

$$E_I = E_K + \frac{\hbar^2}{2\mathcal{I}}[I(I+1) + (-)^{I+1/2}a(I+\tfrac{1}{2})\delta_{K,1/2}].$$

It should be noted that the resultant parameters for the highly perturbed $\frac{1}{2}^-[541]$ band are poorly determined. Kemnitz *et al.*[6] observed many states in the low-lying bands and obtained more meaningful values of the coefficients A, B, C, A_{2K}, and B_{2K} using the more accurate formula containing terms up to $[I(I+1)]^3$ and an alternating term; the resulting values of A are 13.33, 8.6, 13.6, and 13.7 keV for the $\frac{7}{2}^+[404]$, $\frac{1}{2}^-[541]$, $\frac{1}{2}^+[411]$, and $\frac{5}{2}^+[402]$ bands, respectively. The results of their RPC calculation yielded $A = 13.1$ keV, $B = -2.8$ eV, and $a = 2.82$ for the $\frac{1}{2}^-[541]$ band.

2. One quasiparticle states (and associated bands) above 600 keV

$\frac{3}{2}^-[532]$ *state at 889.2 keV.* As discussed in Sec. III B, the experimental evidence strongly supports a predominantly $\frac{3}{2}^-[532]$ single-particle character for the 889.2-keV state in agreement with two theoretical predictions[23,24] but at variance with the more recent extensive predictions of Gareev.[27] This state may also contain some admixtures of the $\{\frac{1}{2}^-[541], 2^+\}$ and (or) $\{\frac{1}{2}^+[411], 1^-\}$ vibrational configurations which are possible assignments for the 1333.9-keV state.

The log*ft* value of 9.0 for electron capture to the 889.2-keV state is also consistent with a $\frac{3}{2}^-[532]$ assignment; Bunker and Reich[18] predict a value of >8.0, including a large retardation due to the pairing factor. Bunker and Reich[18] also commented on the difficulty in explaining the reported[1] large $E2$ components in γ-ray transitions between this state and the $\frac{1}{2}^-[541]$ band. For a $\frac{3}{2}^-[532]$ assignment, these should be unhindered $M1$ transitions, and our determination of predominantly $M1$ character for the 626.0- and 760.9-keV transitions removes this possible discrepancy.

$\frac{3}{2}^+[411]$ *state at 975.1 keV.* The 975.1-keV state is assigned as the $\frac{3}{2}^+[411]$ hole state (as discussed briefly in Sec. III B) although a small admixture of $\{\frac{7}{2}^+[404], 2^+\}$ may also be present. Gareev *et al.*[27] predict a $\frac{3}{2}^+$ state at 1080 keV which is 67% $\frac{3}{2}^+[411]$ and 27% $\{\frac{7}{2}^-[523], 2^-\}$. A predominantly $\frac{3}{2}^+[411]$ assignment is supported by the observation that (1) the $M1$ transitions to states in the $\frac{1}{2}^+[411]$ band (which would be unhindered for a $\frac{3}{2}^+[411]$ assignment) are much more intense than the transitions to the $\frac{5}{2}^+[402]$ state, (2) no transitions are observed to the $\frac{7}{2}^+[404]$ state or to states in the $\frac{1}{2}^-[541]$ band, (3) the state was not seen in proton-transfer reactions, and (4) the log*ft* value of 8.0 is consistent with that expected for this 1u transition when the reduction due to the pairing factor is considered.

$\frac{1}{2}^-[530]$ *band at 1162.3 keV.* The log*ft* values for electron capture (e.c.) to the well-established $\frac{3}{2}^-$ state and tentative $\frac{1}{2}^-$ state of the $\frac{1}{2}^-[530]$ band are 7.5 and ≈9.7, respectively. The e.c. transitions are of allowed-hindered type and the large *ft* value for the decay to the possible $\frac{1}{2}^-$ state is difficult to explain. One might therefore seriously question whether the state at 1192 keV could be the $\frac{1}{2}^-$ state of the $\frac{1}{2}^-[530]$ band; however, the energy is approximately that expected (discussed in Sec. II B) and the only other possible candidates for the $\frac{1}{2}^-$ state are the 1129- and 1246-keV states, which are also fed weakly (log*ft* ⩾ 9). In any case, it appears that the log*ft* value for decay to the $\frac{1}{2}^-$ state of the $\frac{1}{2}^-[530]$ band is anomalously large.

One other case of e.c. decay from a $\frac{1}{2}^-[521]$ odd-n nucleus ($^{179}_{74}\mathrm{W}^m_{105}$) to a proposed $\frac{1}{2}^-[541]$ band (in $^{179}_{73}\mathrm{Ta}_{106}$) has been reported by Konijn *et al.*[30] Their results indicated a log*ft* value of 6.4 for decay to the $\frac{1}{2}^-$ state but no decay was observed to the expected $\frac{3}{2}^-$ state of the band. This result is at variance with the $(K^\pi)_i = \frac{1}{2}^-$ to $(K^\pi)_f = \frac{1}{2}^-$ e.c. decays in the $^{173}\mathrm{Hf} \rightarrow {}^{173}\mathrm{Lu}$ case.

3. Vibrational states

$K^\pi = \frac{1}{2}^+$ *bands at 981.7 and 1246.3 keV.* On the basis of evidence presented in Sec. III B, the $\frac{1}{2}^+$ states at 981.7 and 1246.3 keV are assigned as predominantly vibrational excitations. For the proposed band based on the 981.7-keV state the value $a = 0.46$ (assuming an inertial parameter of 13.3 keV) is slightly greater than that expected for a pure vibrational excitation, but admixtures might explain this. The value $a = -0.15$ for the possible band based on the 1246.3-keV state is consistent with a vibrational character. In view of the likely vibrational excitations (discussed in Sec. IV B), the observed $E0$ admixtures, and the relative intensities of the transitions to states in the $\frac{1}{2}^-[541]$ and $\frac{1}{2}^+[411]$ bands, the proposed band based at 981.7 keV is tentatively assigned as $\{\frac{1}{2}^-[541], 1^-\}$ with a possible admixture of $\{\frac{1}{2}^+[411], 0^+\}$ and the state at 1246.3 keV as $\{\frac{1}{2}^+[411], 0^+\}$ with a possible admixture of $\{\frac{1}{2}^+[411], 1^-\}$. The log*ft* values (see Table VI) are not inconsistent with these assignments. Gnatovich *et al.*[5] assign the states at 981.7 and 1003.3 keV as members of the β-vibrational band $\{\frac{1}{2}^+[411], 0^+\}$. However, they do not report the population of a 1246-keV state, which in our opinion is a more likely candidate for the $\{\frac{1}{2}^+[411], 0^+\}$ assignment.

$K^\pi = \frac{3}{2}^-$ state at 1333.9 keV. Since the 1333.9-keV state was not observed in p-transfer studies[3] and no one-quasiparticle $\frac{3}{2}^-$ states are expected in this energy region, the 1333.9-keV state is tentatively assigned as predominantly a γ-vibrational excitation with configuration $\{\frac{1}{2}^-[541], 2^+\}$, with a possible admixture of $\{\frac{1}{2}^+[411], 1^-\}$. This assignment is consistent with the observation that this state depopulates primarily through transitions (predominantly $M1$) to states in the $\frac{1}{2}^-[541]$ band, with relatively weak transitions to the $\frac{1}{2}^+[411]$ band. The predominantly $M1$ character for the former transitions is not in conflict with a γ-vibrational assignment since the 2_γ^+ state in the "core" nucleus ^{172}Yb is not very collective as evidenced by the $B(E2)$ value for excitation of this state (1.5 single particle units[31]), which is one of the smallest observed in the rare-earth deformed region. The logft value of 7.8 for electron capture to the 1333.9-keV state in ^{173}Lu is not inconsistent with a vibrational character for this state.

Other possible vibrational states. One may only speculate as to the character of the states at 1097.4 ($\frac{3}{2}^\pm$, $\frac{1}{2}^\pm$), and 1129.5 keV ($\frac{3}{2}^\pm$, $\frac{1}{2}^-$), and the highly tentative $\frac{1}{2}^+$ state at 1578 keV, none of which have been observed in the p-transfer studies[3] or the decay work of Gnatovich *et al.*[5] Assuming that the 981.7- and 1246.3-keV states ($\frac{1}{2}^+$) have the character discussed previously (see Table VI) one might also expect a $\frac{3}{2}^+$ vibrational state arising from the configuration $\{\frac{1}{2}^-[541], 1^-\}$ and a $\frac{1}{2}^-$ state from the $\{\frac{1}{2}^-[541], 0^+\}$ configuration. These assignments are possibilities for either the 1097.4- or 1129.5-keV states. Little information can be gained from the branching ratios from these states because the multipolarities are not known. Assuming dipole character for the 834- and 969-keV transitions the branching from the 1097-keV state is consistent with that for a $K = \frac{3}{2}$ assignment.

One might speculate that the 1097-keV state is of $\frac{3}{2}^+\{\frac{1}{2}^-[541], 1^-\}$ character while the 1129-keV state could be $\frac{1}{2}^-\{\frac{1}{2}^-[541], 0^+\}$. The highly tentative state at 1578 keV might be considered as $\frac{1}{2}^+\{\frac{1}{2}^-[541], 0^-\}$ since there is a possible $E0$ admixture in a transition to the $\frac{1}{2}^+$ state at 981.7 keV (assigned as $\{\frac{1}{2}^-[541], 1^-\}$). It may be noted that the 1^- and 0^- octupole excitations in ^{172}Yb occur at 1154 and 1599 keV, respectively.

C. Summary

The character of the one-quasiparticle states and associated rotational states in ^{173}Lu below 1300 keV appear to be well established from the results of the radioactive-decay studies, the in-beam γ-ray experiments, and the proton-transfer reaction work. Additional states up to ≈2300 keV were observed in the p-transfer studies and further investigations might be fruitful if higher resolution and greater intensity could be achieved. Of particular importance would be the establishing of the energy of the $\frac{1}{2}^-$ member of the $\frac{1}{2}^-[530]$ band which we have proposed tentatively at 1192 keV.

The vibrational state assignments which are proposed in the present work are only reasonable conjectures (some based on rather meager evidence) and unfortunately there appears to be little hope of firmly establishing them by means of selected particle-transfer reactions or further in-beam γ-ray studies. (Coulomb excitation is ruled out since ^{173}Lu is unstable.) A study of the (p, t) reaction (on ^{175}Lu) would be interesting, but it is unlikely that the vibrational states would be populated.

ACKNOWLEDGMENTS

The authors wish to thank Dr. C. W. Reich and Dr. M. E. Bunker for suggestions concerning the assignments for several states and Dr. E. R. Marshalek for helpful discussions. We also acknowledge the cooperation of Mr. M. Oselka and the staff of the Argonne National Lab cyclotron for their cooperation in the production of the sources.

[†] Work supported in part by the U. S. Atomic Energy Commission and National Science Foundation.

[*] Presently at Texas A & M University, College Station, Texas.

[‡] Presently at Thomas More College, Covington, Kentucky.

[§] Presently at Wright-Patterson Air Force Base, Dayton, Ohio.

[1] J. Valentin, D. J. Horen, and J. M. Hollander, Nucl. Phys. 31, 353 (1962).

[2] B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. 114, 1082 (1959).

[3] R. A. O'Neil, D. G. Burke, and W. P. Alford, Nucl. Phys. A167, 481 (1971).

[4] E. G. Funk, D. R. Zolnowski, R. A. Belt, M. C. Madden, and J. W. Mihelich, Bull. Am. Phys. Soc. Ser. II 17, 486 (1972).

[5] V. Gnatovich, V. Zvolska, I. Zvolski, I. Rzikovoska, and A. Mastalka, Izv. Akad. Nauk. SSSR, Ser. Fiz. 36, 2131 (1972) [transl.: Bull. Acad. Sci. USSR, Phys. Ser.

36, 1875 (1972)].

[6] P. Kemnitz, L. Funke, K. H. Kaun, H. Sodan, and G. Winter, Nucl. Phys. A209, 271 (1973).

[7] T. Ward, J. W. Mihelich, B. Harmatz, and T. H. Handley, Bull. Am. Phys. Soc. Ser. II 2, 341 (1957).

[8] N. Perrin, Compt. Rend. 258, 1475 (1964).

[9] T. W. Conlon, Nucl. Phys. A100, 545 (1967).

[10] K. E. G. Löbner, M. J. Bennett, and M. E. Bunker, Nucl. Phys. A197, 553 (1972).

[11] W. Andrejtscheff, F. Dubbers, P. Manfrass, and K. D. Schilling, Nucl. Phys. A190, 489 (1972).

[12] K. D. Schilling, W. Andrejtscheff, F. Dubbers, and P. Manfrass, Nucl. Phys. A208, 417 (1973).

[13] B. Harmatz and T. H. Handley, Nucl. Phys. 81, 481 (1966).

[14] M. I. Green, P. F. Kenealy, and G. B. Beard, Nucl. Instrum. Methods 99, 445 (1972).

[15] E. E. Berlovich, G. M. Bukal, Yu. K. Gusev, V. V. Ilyin, V. V. Nikitin, and M. K. Nikitin, Phys. Lett. 2, 344 (1962).

[16] R. E. McAdams, G. W. Eakins, and E. N. Hatch, Nucl. Phys. 82, 449 (1966).

[17] R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968).

[18] M. E. Bunker and C. W. Reich, Rev. Mod. Phys. 43, 348 (1971). In this notation one specifies the base-state orbital and the multipole character of the vibrational phonon to which it is coupled (indicated by the K^π of the analogous excitation in even-even nuclei). For example, one phonon γ-vibrational, β-vibrational, and $K=1$ octupole-vibrational states based on a $\frac{1}{2}^+[411]$ state are denoted, respectively, as $\{\frac{1}{2}^+[411],2^+\}$, $\{\frac{1}{2}^+[411],0^+\}$, and $\{\frac{1}{2}^+[411],1^-\}$. In Gareev's notation these are written as $411\downarrow+Q_1(22)$, $411\downarrow+Q_1(20)$, and $411\downarrow+Q_1(31)$.

[19] R. A. O'Neil, private communication.

[20] O. Dragoun, H. C. Pauli, and F. Schmutzler, Nucl. Data A6, 235 (1969).

[21] O. Dragoun, Z. Plajner, and F. Schmutzler, Nucl. Data A9, 2 (1971).

[22] K. E. G. Löbner, M. Vetter, and V. Honig, Nucl. Data A7, 495 (1970).

[23] D. R. Bes and Cho Yi-Chung, Nucl. Phys. 86, 581 (1966).

[24] V. G. Soloviev and P. Vogel, Nucl. Phys. A92, 449 (1967).

[25] V. G. Soloviev, P. Vogel, and G. Jungclaussen, Joint Institute for Nuclear Research Report No. JINR-E4-3051, 1967 (unpublished).

[26] V. G. Soloviev and S. I. Fedotov, Izv. Akad. Nauk. SSSR, Ser. Fiz. 36, 706 (1972) [transl.: Bull. Acad. Sci. USSR, Ser. Fiz. 36, 637 (1972)].

[27] F. A. Gareev, S. P. Ivanova, V. G. Soloviev, and S. I. Fedotov, Fiz. El. Chast. Atom. Yad. 4, 357 (1973) [transl.: Sov. J. Particles Nucl. 4, 148 (1974)].

[28] R. C. Greenwood, C. W. Reich, and S. H. Vegors, Jr., Idaho Nuclear Corporation, Nuclear Technology Branch, Annual Progress Report, No. 114, 1970 (unpublished).

[29] A. H. Wapstra and N. B. Gove, Nucl. Data A9, 267 (1971).

[30] J. Konijn, B. J. Meijer, B. Klank, and R. A. Ristinen, Nucl. Phys. A37, 593 (1969).

[31] D. G. Burke and B. Elbek, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 86, No. 6, 1 (1967).