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Study of ^{173}Hf Levels Populated in the Decay of ^{173}Ta

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The decay of ^{173}Ta was studied using high resolution Ge(Li), Si(Li), and Si surface-barrier detectors in singles and coincidence modes. The ^{173}Ta activity was produced via the reaction ^{165}Ho(^{12}C,4n)^{173}Ta, at a carbon beam energy of 6.3–6.9 MeV per nucleon. All spectra were obtained from chemically separated Ta sources. Besides the previously known energy levels of ^{173}Hf, the following levels in keV were determined: 255.5, 451.9, 508.9, 635.8, 775.5, 785.3, 811.7, 927.5, 942.5, 1020.3, 1111.4, 1127.0, 1192.8, 1248.3, 1450.0, 1574.2, 1655.6 1667.1, 1694.3, and 2263.3. Rotational bands based on the $(1/2)^-$[521] (g.s.), $(5/2)^-$[512] (107.2 keV), and $(7/2)^+$[633] (197.5 keV) Nilsson states were observed. The half-lives of the $(5/2)^-$[512] and the $(1/2)^+$[633] band heads were determined to be (182 ± 20) nsec and (160 ± 40) nsec, respectively. The probability of the radiative $E1$ transition between the [633] and [512] band heads was calculated within the framework of Nilsson model including the pairing and Coriolis interactions. From measurement of the β^+ end-point energy, the mass difference between ^{173}Ta and ^{173}Hf was determined to be 3670 ± 200 keV.

1. INTRODUCTION

In-beam γ-ray spectroscopic studies have recently revealed substantial deviations from the strong coupling model[1,2] in the even-parity bands of odd-neutron deformed nuclei in the rare-earth region. This development initiated new interest in the investigation of the level structure of these nuclei as populated in radioactive decay. The quieter environment of radioactivity experiments as compared with the in-beam work enables one to perform experiments crucial for the confirma-

tion of the in-beam data but not feasible in the in-beam experiments. The low-lying high-spin states of the ^{173}Hf nucleus were recently studied in the ^{171}Yb(α, $2n$) reaction[3,4] and although there was ample evidence for the existence of the strongly perturbed rotational band associated with the $\frac{7}{2}^+[633]$ Nilsson orbital, some uncertainties concerning the lowest rotational levels and the band-head transitions remained.

The nucleus ^{173}Ta decays with a 3.7-h half-life[5] to the ground and excited states of ^{173}Hf. This decay was previously investigated by scintillation γ-ray spectroscopy[5,6] and by electron spectrosocpy.[7,8] In the present study, we report results of γ-ray singles and γ-γ coincidence experiments carried out with Ge(Li) detectors. Preliminary results have been reported elsewhere.[9] While this manuscript was in preparation, we received a report

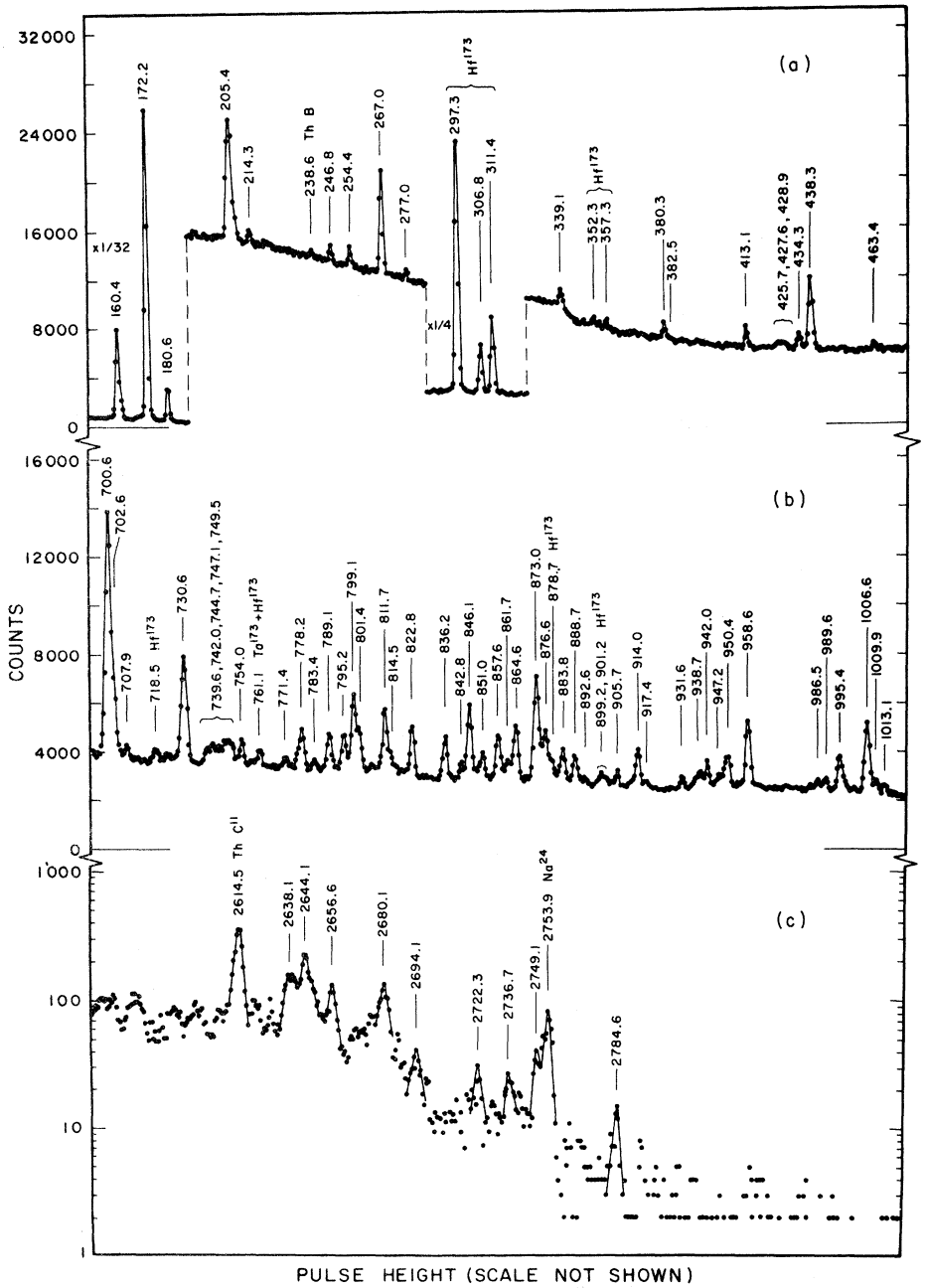

FIG. 1. Selected portions of the ^{173}Ta γ-ray spectrum measured with a 35-cm^3 Ge(Li) detector.

prior to publication of similar work on ^{173}Ta decay by Bocev *et al.*[10] from the Joint Institute of Nuclear Research in Dubna, USSR. Our results agree well with the Dubna work in the areas where they overlap.

2. EXPERIMENTAL PROCEDURE AND RESULTS

A. Target and Irradiation

The ^{12}C ion beam from the Yale heavy ion accelerator[11] was used to bombard metallic holmium foil rolled to the thickness of about 10 mg/cm^2. The energy of the carbon beam was varied by degradation with Al foil; an energy of ~83 MeV was found from determination of the excitation function to give the highest yield for the ^{165}Ho(^{12}C, 4n)-^{173}Ta reaction.

B. Isolation of Ta Activity

Chemical isolation of Ta activity from the Ho target material was achieved in a way similar to that described by Felber.[12] Following the irradiation the target was dissolved in hot 6 N HCl and 2–3 drops of concentrated HF were added to precipitate the rare-earth fluorides. The mixture was centrifuged and the supernate was transferred to a separatory funnel where 5 ml of di-isopropylketone was used to extract the Ta activities. The tantalum was back extracted from the organic phase with 15 ml H_2O and the carrier-free solution containing the Ta activity was evaporated to ~2 ml. For some experiments this solution was used as a counting sample; for other measurements, e.g. electron, β-ray, and low-energy γ-ray spectroscopy, the volume of the sample was further reduced to a few drops which were then deposited on a Teflon disk and evaporated to dryness.

C. Singles γ-Ray Spectroscopy

The γ-ray spectrum of ^{173}Ta was studied in the region 60–4000 keV with a 35-cm^3 coaxial Ge(Li) detector. The resolution of the system in actual experiment was ≈1.1 keV full width at half maximum (FWHM) at 120 and 2.0 keV at 660 keV. In order to suppress further the possible admixtures of neighboring tantalum isotopes ^{172}Ta and ^{174}Ta with half-lives[13] of 44 m and 1.2 h, respectively, the separation and measurements were begun 3 h after the end of the irradiation. Due to this precaution, and by the use of relatively thin targets, no γ lines of the short-lived neighbors and their daughter products were observed in our spectra. The only contribution found was the continuum at the high-energy end of the spectrum above 2600 keV. This γ-ray continuum decayed with a half-life of 40 m and apparently originated in the bremsstrahlung spectrum of high-energy positrons from the ^{172}Ta decay. Accurate energy values for the γ transitions were determined in separate experiments by simultaneously measuring the ^{173}Ta sample and radioactive standards with well-known γ-ray energies.

Representative parts of the γ-ray spectrum mea-

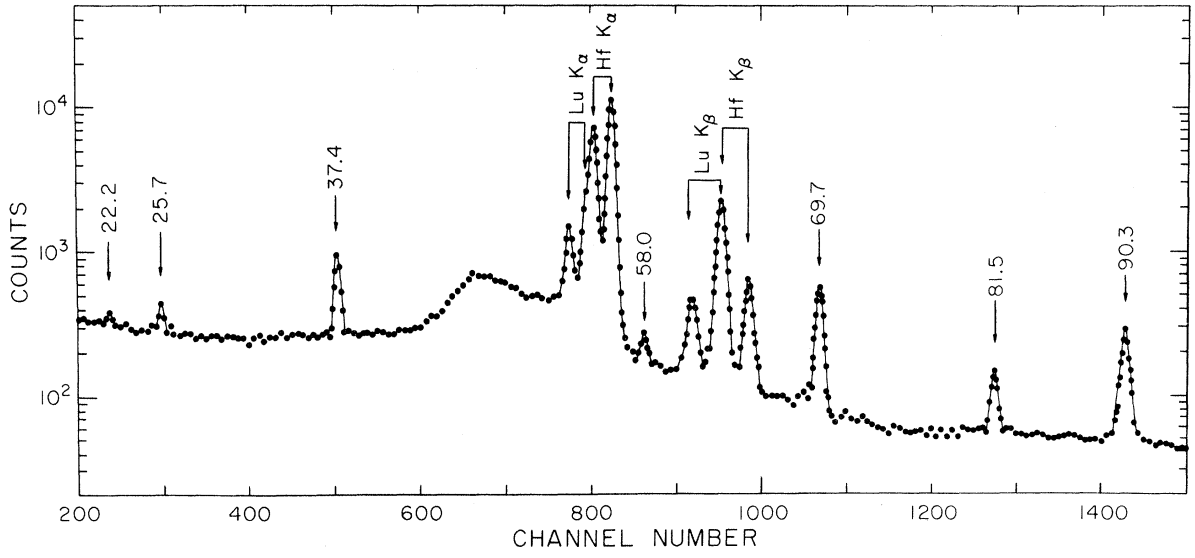

FIG. 2. The low-energy portion (20–95 keV) of the ^{173}Ta γ-ray spectrum. The data shown were taken with a Si(Li) detector.

TABLE I. Energies and relative intensities of γ-ray transitions from ^{173}Ta decay.

E_γ (keV)	I_γ [a] (Relative units)	E_γ (keV)	I_γ [a] (Relative units)
22.2 ± 0.1	0.2	739.6 ± 0.4	≈0.6
25.7 ± 0.05	0.8	742.0 ± 0.4	≈0.6
37.4 ± 0.05	7.1	744.7 ± 0.4	≈0.4
58.0 ± 0.05	2.8	747.1 ± 0.4	≈0.6
69.7 ± 0.05	34.0	749.5 ± 0.4	≈0.6
81.5 ± 0.1	8.4	754.0 ± 0.2	0.7
90.3 ± 0.1 [b]	31.0	771.4 ± 0.2	0.4
115.0 ± 0.1	2.2	778.2 ± 0.2	2.9
139.4 ± 0.3	Weak	783.4 ± 0.2	0.4
160.4 ± 0.1	28.3	789.1 ± 0.2	1.2
172.2 ± 0.1	100.0	795.2 ± 0.2	1.2
180.6 ± 0.1	12.4	799.1 ± 0.2	2.5
205.4 ± 0.1	0.9	801.4 ± 0.2	1.2
214.3 ± 0.1	0.3	811.7 ± 0.2	2.3
246.8 ± 0.1	0.7	814.5 ± 0.2	0.5
254.4 ± 0.1	0.2	822.8 ± 0.2	1.8
267.0 ± 0.1	1.9	836.2 ± 0.2	1.4
277.0 ± 0.1	0.15	842.8 ± 0.2	0.6
380.3 ± 0.2	0.3	846.1 ± 0.2	2.6
382.5 ± 0.2	0.1	851.0 ± 0.2	0.7
413.3 ± 0.1	0.5	857.6 ± 0.2	1.6
425.7 ± 0.2	<0.1	861.7 ± 0.2	0.5
427.6 ± 0.2	<0.2	864.6 ± 0.2	1.9
428.9 ± 0.2	<0.1	873.0 ± 0.2	4.0
434.3 ± 0.1	0.3	876.6 ± 0.2	2.0
438.3 ± 0.1	1.7	883.8 ± 0.2	1.2
463.4 ± 0.1	0.15	888.7 ± 0.2	1.05
529.8 ± 0.2	2.6	892.6 ± 0.4	0.1
530.2 ± 0.2	1.0	905.7 ± 0.2	0.4
549.6 ± 0.2	2.1	914.0 ± 0.2	1.6
557.1 ± 0.2	0.4	917.4 ± 0.2	0.2
559.0 ± 0.2	0.6	931.6 ± 0.2	0.3
566.5 ± 0.2	0.3	938.7 ± 0.2	0.6
569.6 ± 0.2	0.4	942.0 ± 0.2	1.0
577.6 ± 0.2	0.2	947.2 ± 0.2	0.2
587.8 ± 0.2	1.2	950.4 ± 0.2	1.4
615.3 ± 0.2	0.9	958.6 ± 0.2	2.9
635.4 ± 0.2	<0.3	986.5 ± 0.2	0.4
640.9 ± 0.2	<0.3	989.6 ± 0.2	0.5
660.0 ± 0.2	0.2	995.4 ± 0.2	1.5
662.7 ± 0.2	1.1	1006.6 ± 0.2	3.2
667.7 ± 0.2	1.9	1009.9 ± 0.2	0.6
675.1 ± 0.2	3.2	1013.1 ± 0.2	0.4
680.2 ± 0.2	0.5	1030.0 ± 0.2	9.0
685.6 ± 0.2	0.7	1045.2 ± 0.2	1.7
691.6 ± 0.2	1.3	1052.4 ± 0.2	0.7
700.6 ± 0.2	7.1	1057.3 ± 0.2	0.3
702.6 ± 0.2	1.7	1067.5 ± 0.2	0.6
707.9 ± 0.2	0.3	1070.3 ± 0.2	0.6
730.6 ± 0.2	3.4	1085.5 ± 0.2	1.7

TABLE I *(Continued)*

E_γ (keV)	I_γ [a] (Relative units)	E_γ (keV)	I_γ [a] (Relative units)
1088.7 ± 0.2	0.6	1547.6 ± 0.3	1.7
1104.8 ± 0.2	0.4	1568.2 ± 0.5	Weak
1127.0 ± 0.2	0.6	1574.2 ± 0.3 [b]	1.9
1166.9 ± 0.2	0.5	1585.7 ± 0.3 [b]	0.6
1176.1 ± 0.2	0.8	1597.6 ± 0.3	1.6
1178.7 ± 0.2	1.5	1613.2 ± 0.3	2.7
1194.9 ± 0.2	<0.3	1633.9 ± 0.3	0.3
1208.2 ± 0.2	15.3	1648.2 ± 0.3	0.6
1216.2 ± 0.2	0.7	1691.0 ± 0.3	0.4
1220.9 ± 0.2	<0.2	1692.9 ± 0.5	Weak
1253.0 ± 0.2	0.9	1697.2 ± 0.5	Weak
1277.0 ± 0.4	≈0.3	1702.9 ± 0.5	0.2
1279.6 ± 0.4	≈0.4	1709.7 ± 0.5	0.4
1285.6 ± 0.4	Weak	1717.2 ± 0.5	0.3
1301.0 ± 0.4	Weak	1757.8 ± 0.5	0.4
1323.5 ± 0.4	Weak	1836.1 ± 0.5	Weak
1327.1 ± 0.4	0.4	1882.2 ± 0.5	0.2
1332.4 ± 0.4	0.5	1892.2 ± 0.5	Weak
1337.2 ± 0.4	Weak	1913.3 ± 0.5	0.2
1340.2 ± 0.4	Weak	1960.6 ± 0.5	0.2
1343.2 ± 0.2 [b]	1.0	2001.3 ± 0.5	0.6
1349.3 ± 0.4	0.4	2022.7 ± 0.6	Weak
1350.7 ± 0.4	Weak	2048.5 ± 0.5	0.3
1357.6 ± 0.4	Weak	2066.7 ± 0.5	0.2
1368.2 ± 0.2	2.2	2077.3 ± 0.5	0.3
1375.3 ± 0.2	1.4	2086.9 ± 0.5	0.2
1380.3 ± 0.2	3.1	2161.5 ± 0.4	0.7
1390.4 ± 0.4	0.6	2182.0 ± 0.4	0.4
1393.5 ± 0.3	4.1	2188.3 ± 0.4	0.6
1405.3 ± 0.3	0.6	2199.8 ± 0.4	0.6
1409.2 ± 0.3	0.3	2244.9 ± 0.4	0.6
1413.5 ± 0.3	0.7	2258.1 ± 0.4	0.2
1420.2 ± 0.5	Weak	2269.4 ± 0.4	0.7
1425.2 ± 0.5	0.8	2281.0 ± 0.5	0.2
1432.2 ± 0.3	3.2	2293.6 ± 0.5	0.2
1434.7 ± 0.5	0.5	2319.9 ± 0.5	0.2
1445.6 ± 0.3	1.1	2328.3 ± 0.5	0.2
1452.7 ± 0.5	Weak	2360.2 ± 0.5	0.3
1467.4 ± 0.5	<0.5	2460.0 ± 0.4	0.3
1481.2 ± 0.5	<0.3	2475.0 ± 0.4	0.5
1486.7 ± 0.3	1.0	2493.0 ± 0.5	0.2
1492.5 ± 0.3	0.7	2526.5 ± 0.5	0.3
1499.0 ± 0.3	1.2	2557.5 ± 0.5	0.1
1504.3 ± 0.3	0.4	2567.8 ± 0.5	0.2
1537.7 ± 0.5	Weak	2585.7 ± 0.5	0.2

TABLE I *(Continued)*

E_γ (keV)	I_γ [a] (Relative units)
2595.3 ± 0.5	0.1
2638.1 ± 0.5	0.4
2644.1 ± 0.5	0.7
2656.6 ± 0.5	0.3
2674.9 ± 0.5	0.2
2680.1 ± 0.4	0.5
2694.1 ± 0.5	0.1
2722.3 ± 0.5	0.1
2736.7 ± 0.5	0.1
2749.1 ± 0.5	0.1
2784.6 ± 0.5	0.04

[a] Errors for the γ-ray relative intensities are 10% for those lines with $I_\gamma \geq 5$ units, and 25% for those lines with $I_\gamma < 5$ units.

[b] These lines are apparently complex and contain components that can be attributed to more than one transition in the level scheme.

sured with a fresh source are shown in Fig. 1. The spectrum shown here was accumulated during the 3-h period 6–9 h after the end of irradiation. In order to distinguish the ^{173}Ta activity from the 23.6-h daughter activity[14,15] of ^{173}Hf, successive 3-h counts were taken over a period of 24 h.

The lower-energy region of the spectrum was studied with a 3-mm-deep × 10-mm-diam Si(Li) detector. The resolution of this system at 6 keV was 200 eV. In our measurement the resolution was 600 eV at 67 keV. The spectrum in the region 20–95 keV is shown in Fig. 2. Here again the transitions were assigned to the decay of ^{173}Ta according to the time dependence of their intensities.

The results of the singles γ-ray spectroscopy of ^{173}Ta are summarized in Table I. The photon intensities of the 67-, 81-, and 90-keV transitions of the overlapping portions of the spectra measured with Si(Li) and Ge(Li) detectors, respectively, were used to relate the γ-ray intensities of these two spectra.

D. γ-γ Coincidence Measurements

With the 35-cm^3 Ge(Li) detector and a second 15-cm^3 Ge(Li) detector positioned at 90° to the first, a γ-γ coincidence experiment was also performed. Standard fast-slow coincidence circuitry was employed using constant-fraction triggering[16] for generating the timing signals. Three-parameter ($E\gamma_1$-$E\gamma_2$-t) coincidence events were recorded serially on magnetic tape for later sorting on completion of the experiment. The time resolution obtained with this system was 18–26 nsec FWHM depending on the dynamic range and counting rate.

Examples of prompt γ-ray coincidence spectra recovered from the magnetic tape are shown in Fig. 3. The results of the γ-γ coincidence experiment are summarized in Table II.

E. β-γ Coincidence Measurements

In order to obtain reliable information about the decay energy of ^{173}Ta in the presence of positron groups from neighboring Ta activities, a β-γ coincidence experiment was performed.

A 3-in. × 3-in. NaI(Tl) crystal served as the γ-ray detector and a 1-in. × 1-in. anthracene crystal was used for the registration of β rays. The data-acquisition system was the same as described in Sec. D. The end-point energy of the positron group coincident with the most prominent group of γ rays around 170 keV was determined to be equal to 2480 ± 200 keV. This value is somewhat higher than the value of 2100 keV found in Ref. 10. Based on the value determined in this study the mass difference between ^{173}Ta and ^{173}Hf is 3670 ± 200 keV.

F. e^--γ Coincidences

In order to establish the coincidence relations among the low-energy transitions, e^--γ coincidence data were obtained with a surface-barrier silicon detector (depletion depth 500 μ, resolution 5 keV at 624 keV) and the 35-cm^3 Ge(Li) detector. As isomeric states were thought to exist at these low excitations, the range of the time-to-amplitude conversion was set at 4 μsec for these measurements. Signals from the γ-ray detector started the time conversion, and signals from the elec-

tron detector were used to stop conversion. During the process of sorting the data, special care was taken to compensate properly for random and background coincidence events. This could be done particularly well with the γ-ray part of the three-dimensional spectrum where the lines were narrow and well resolved. Background subtraction was more difficult, however, for the electron spectrum where lines were broader and the low-energy lines displayed considerable tailing due to finite source-thickness effects. This was important only for the very low-energy groups, e.g. for the L-conversion lines of 69.7- and 58.0-keV lines. Here, the tails of the 69.7-keV L lines extended underneath the 58.0-keV L lines and gave a contribution in the 58.0-keV gate nearly as great as that from the 58-keV L lines themselves.

The time spectra (restored from the magnetic tape) are shown in Fig. 4 and give a rather clear answer to such problems of half-lives of the various levels and the corresponding sequences of transitions involved. The time spectrum in the lower portion of the drawing corresponds to the time correlation between the 172.5-keV γ line and the L- and M-conversion lines of the 69.7-keV transition and serves as an example of a prompt-time spectrum. The FWHM of this prompt curve is 26 nsec. The existence of a pronounced shoulder at the start side of this peak must be noted; this was an artifact from the electronic circuitry and was a consequence of the very low discriminator thresholds necessary for this experiment. Nevertheless, from the time-correlation curve of the 90.3-keV γ line and the L- and M-conversion

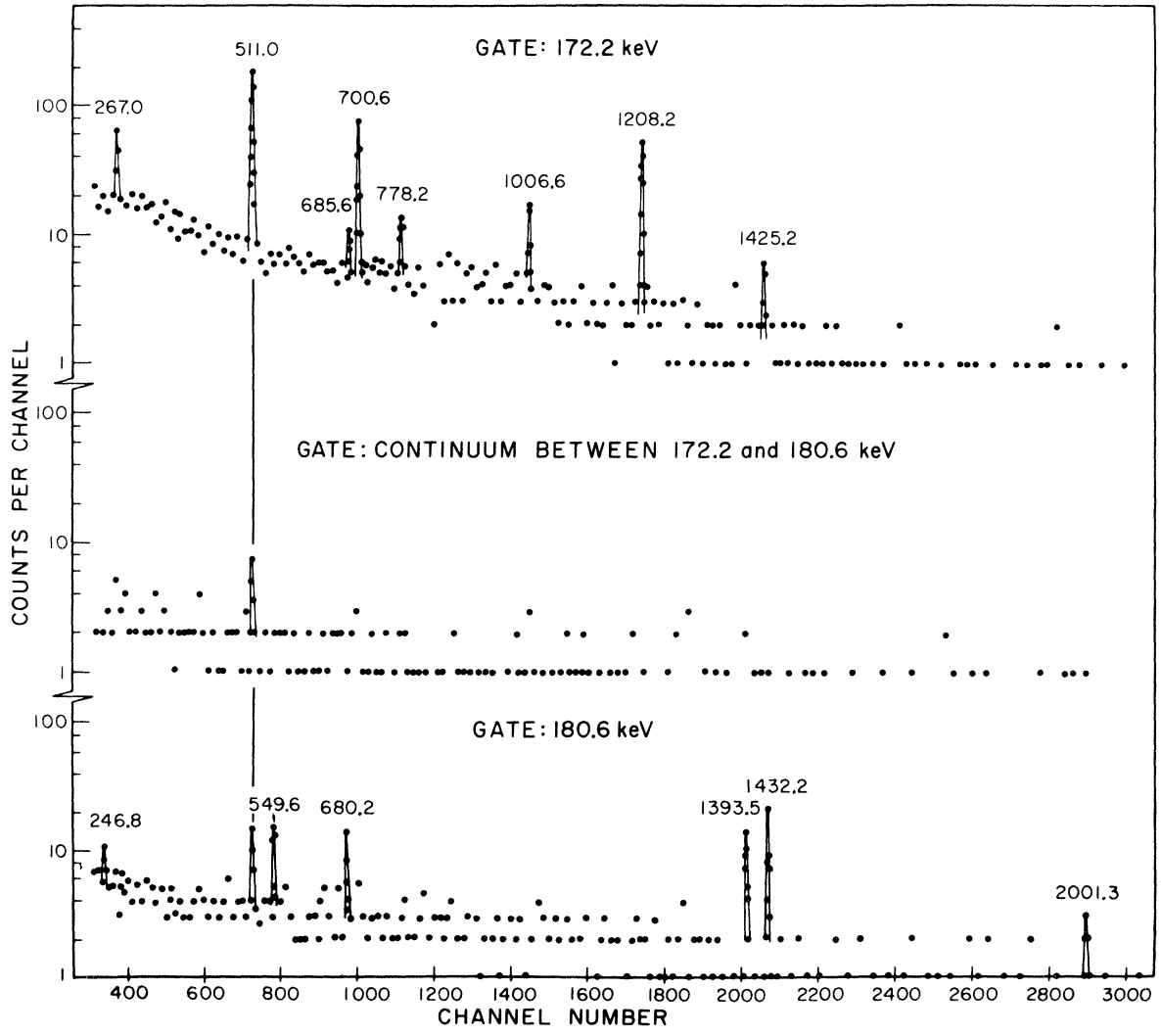

FIG. 3. The γ-ray spectra in coincidence with the 172.2- and 180.6-keV transitions from ^{173}Ta decay.

lines of the 69.7-keV transitions shown in the center of Fig. 4, it can be concluded that the 90.3-keV transition precedes the 69.7-keV transition, and that there exists an intermediate level with a half-life of 182 ± 20 nsec. The same half-life also appears in the time correlation curve of the same γ ray, 90.3 keV, and the L line of the 58.0-keV transition. As mentioned above, this is due to the tail of the conversion lines of the 69.7-keV transition. On the other hand, from the rising slope of this curve it is evident that the 58.0-keV transition precedes the 90.3-keV transition and that the intermediate level has a half-life of 160 ± 40 nsec.

In Ref. 10, a half-life of (180 ± 8) nsec was measured for the 107.2-keV level in an experiment where the L-conversion lines of both the 69.7- and 81.5-keV transitions were detected by means of a plastic scintillator, and the photons associated with the 90.3-keV transition by a NaI(Tl) scintillator. The half-life $T_{1/2} \approx 170$ nsec of the 197.5-keV level was also inferred from an experiment in which the 90.3-keV γ line was registered with a Ge(Li) detector and the K x radiation with a scintillation detector. Of course the weak 58.0-keV γ transition (cf. Fig. 2) could not be resolved from the K x rays by means of a scintillation detector. Thus, the half-life measured in Ref. 10 could have resulted from x rays associated with electron-capture feeding to isomeric levels, from decay of higher-lying levels, or from the desired 58-keV line itself. Although our results are apparently in agreement with the results of the Dubna group,[10] use of the Si(Li) electron detector permits us to associate more directly the observed delays with their corresponding isomeric states.

3. DECAY SCHEME OF ^{173}Ta

A. Levels of ^{173}Hf Below 511 keV

This part of the ^{173}Ta level scheme is of the utmost importance for comparison with the present theory as well as with the results of other studies. Therefore special attention was given to the investigation of this region.

Based on the study[13] of the decay of ^{173}Hf to the levels of ^{173}Lu and on the previous studies of ^{173}Ta

TABLE II. Coincidence relationships for γ rays from ^{173}Ta decay.

Gate (keV)	Coincident transitions (keV)
69.7	90.3 [a], 115.0, 139.6, 160.4, 172.2, 180.6, 205.4, 246.8, 267.0, 549.6, 675.1, 700.6, 730.6, 873.0, 1178.7, 1208.2, 1380.3, 1432.1, 1585.7
81.5	90.3, 115.0, 160.4, 180.6, 205.4, 267.0, 549.6, 675.1, 730.6, 846.1, 1030.0, 1045.2, 1067.5, 1351.6, 1492.5, 1574.2, 1585.7, 1738.8, 1952.0, 2001.3
90.3	58.0 [a], 69.7 [a], 81.5, 115.0, 139.6, 254.4, 413.3, 438.3, 529.8, 557.1, 587.8, 615.3, 675.1, 789.1, 799.1, 914.0, 822.8, 995.4
115.0	90.3, 139.6, 454.3, 463.4, 615.3, 660.0, 691.6, 707.9, 799.1, 1277.0, 1375.3
139.6	69.7, 81.5, 90.3, 115.0
160.4	81.5, 267.0, 659.6, 685.6, 700.6, 778.2, 1006.6, 1208.2, 1413.5, 1425.2,
172.2	69.7, 267.0, 685.8, 700.6, 778.2, 1006.6, 1208.2, 1413.5, 1425.2
180.6	81.5, 246.8, 549.6, 680.2, 1393.4, 1432.1, 2001.3
205.4	69.7, 139.6, 463.4, 707.9, 799.1
246.8	81.5, 180.6
267.0	69.7, 81.5, 160.4, 172.5, 454.3
438.5	69.7, 81.5, 90.3
511	81.5, 90.3, 160.4, 172.2, 267.0, 529.8, 587.8, 700.6, 811.7
529.8, 530.2	69.7, 81.5, 90.3
549.6	81.5, 180.6, 413.5, 947.2
700.6	69.7, 81.5, 160.4, 172.2
799.1	69.7, 90.3, 115.0

[a] A delayed coincidence was found between these transitions (see text).

decay,[5-8,10] the ground state of ^{173}Hf is presumed to have the spin and parity of $\frac{1}{2}^-$ associated with the [521] Nilsson orbital. The existence of the rotational band built on this state was very well confirmed by the (γ-γ) coincidence experiment (see Table II) which enabled us to identify this band up to the $\frac{11}{2}^-$ level. The multipolarities of the transitions were determined in Ref. 8 from L-subshell ratios and were used for the interpretation of our experimental data.

To determine the multipolarities of the other low-energy transitions we used the photon intensities measured here and the electron intensities reported in Ref. 8. The two sets of data were normalized to the theoretical conversion coefficients of the four transitions in the $\frac{1}{2}^-$ band with known multipolarities: the L lines of the 69.7- and 81.5-keV transitions and the K lines of the 160.4- and 172.2-keV transitions. The normalization factor for the ratios I_e/I_γ was obtained by a least-squares fit to these four cases and found equal to 0.064 ± 0.005; this multiplier was then used to determine the corresponding conversion coefficient of the 58.0- and 90.3-keV γ lines. The results of this procedure are recorded in Table III. It is evident from this table that the 58.0-keV transition is predominantly of $M1$ multipolarity with some $E2$ admixture. This observation is also consistent with L-subshell ratios from Ref. 8. As for the 90.3-keV transition, its conversion coefficient falls between the values for $E1$ and $E2$. In addition, as we discuss later, there is strong evidence based on other experimental results partly from this work and partly from the in-beam studies[3,4] that this line is a doublet of two unresolved lines. The value of the conversion coefficient would indicate that one of these transitions has to be of $E1$ multipolarity. Assuming the pure $E1$ character of the first transition, the data then are consistent with a second transition of $M1$-$E2$ character and an intensity 5–30% of the former transition.

The results of the time-differential experiments (Secs. D and F) indicate a delay of 182 ± 20 nsec between the 90.3- and 69.7-keV transition with the former transition coming first. This information coupled with the existence and multipolarities of 25.7- and 37.4-keV transitions established the level at 107.2 keV, with a spin and parity of $\frac{5}{2}^-$ and a half-life $T_{1/2} = (182 \pm 20$ nsec). This state can consequently be interpreted as arising from the $\frac{5}{2}^-[512]$ Nilsson orbital. The 90.3-keV transition

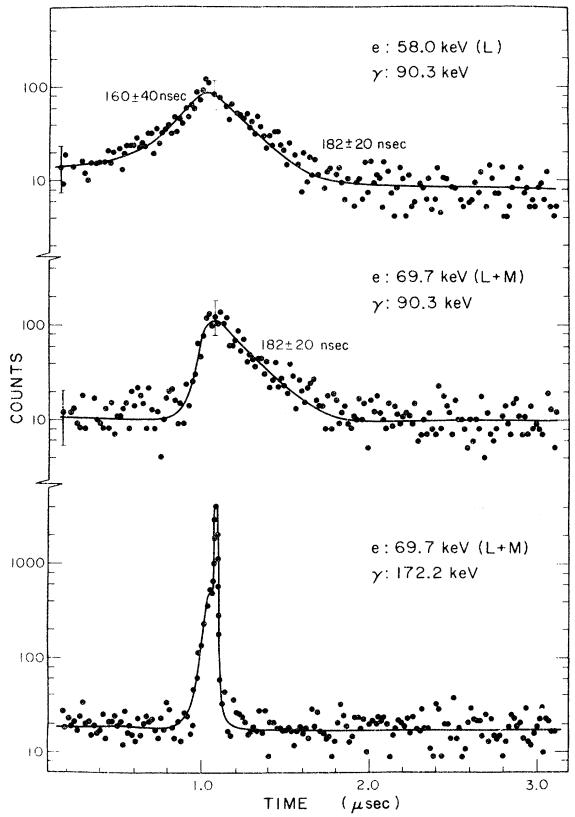

FIG. 4. Time distributions for e^--γ delayed coincidence measurement of the lifetimes of the 197.5-keV (160 nsec) and 107.2-keV (182 nsec) states in ^{173}Hf. The "start" signal was provided by the electron detector and "stop" signal by the γ-ray detector.

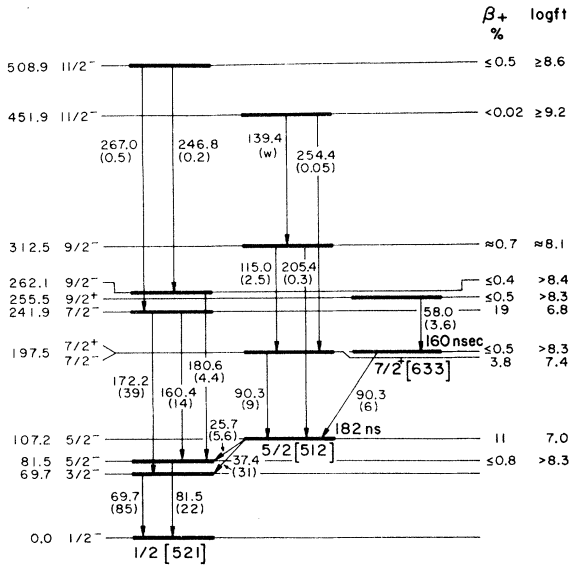

FIG. 5. The level structure of ^{173}Hf below 600 keV as determined from ^{173}Ta decay data. The total transition intensities (in transitions per hundred of ^{173}Ta decays) are shown in parentheses. The values for the β branchings refer to the intensities of positron groups only.

is in prompt coincidence with that at 115.0 keV and the 205.4-keV transition is then interpreted as the $E2$ crossover. Moreover, the spacing and γ-ray intensities here and in the in-beam study[3,4] reveal properties typical for the rotational band connected with the $\frac{5}{2}^-[512]$ orbital. On the other hand, there is a delay of (160 ± 40) nsec between the 58.0- and 90.3-keV transitions and the latter γ ray comes after the former one. This and the multipolarities of the transitions confirm the existence of another level at 197.5 keV, energetically indistinguishable within 0.2 keV from the $\frac{7}{2}^-$ first rotational state in the $\frac{5}{2}^-$ band. The spin and parity associated with this second level are $\frac{7}{2}^+$, indicating that this state is of single-particle character. As it decays preferentially to the $\frac{5}{2}^-[512]$ band head rather than to the $\frac{5}{2}^-$ level of the $\frac{1}{2}^-[512]$ band, it is quite straightforward to associate this state with the $\frac{7}{2}^+[633]$ Nilsson orbital.

These arguments were used for the determination of the level structure of ^{173}Hf below 600 keV as shown in Fig. 5. Five rotational states built on the ground $\frac{1}{2}^-[512]$ Nilsson orbital were observed, thus confirming the existence of the four lowest levels as proposed by Harmatz and Handley.[8] Similarly, three of the four members of the $\frac{5}{2}^-[512]$ band assigned here were proposed before in that work.[8] As for the two levels of the $\frac{7}{2}^+[633]$ rotational band, our assignment differs from that of Ref. 8 and supports the assignment based on the in-beam work.[3,4] The interpretation of the in-beam data was somewhat speculative on this point however, and the results of Ref. 10 and of this work now provide the needed additional direct evidence for the assignments shown.

B. Levels of ^{173}Hf Above 600 keV

The higher-lying levels in ^{173}Hf populated in ^{173}Ta decay were determined primarily from γ-γ coincidence experiments. The medium- and high-energy γ-ray spectrum of ^{173}Ta decay shown in the middle and lower part of Fig. 1 is typical of the data obtained for this decay and shows a large number of weak transitions. Only levels confirmed by coincidence relations to the low-lying levels (Fig. 5) are represented as levels of ^{173}Hf. In most cases, more than one coincidence relation was used for the identification of a level. Other transitions were fitted between the found levels when consistent with the energy fit and the other data. The transitions placed on the basis of coincidence information are shown with full dots and arrows in Fig. 6; those placed without coincidence information are represented by open dots and arrows. The logft values shown in Figs. 5 and 6 were determined from the γ- and electron-transition intensities. The integral intensity of the unplaced γ rays was taken into account in determining the lower limits shown for the logft values.

Further conclusions about the quantum characteristics of the higher-lying ^{173}Hf levels can be obtained from a comparison of the photon and elec-

TABLE III. Internal-conversion coefficients of low-energy transitions in ^{173}Hf.

E_γ (keV)	I_γ (Relative units)	Origin of conversion e^- [a]	I_{e^-} [a] (Relative units)	Theoretical conversion coefficient [b]	Deduced [c] conversion coefficient	Multipolarity
58.0	2.8	$\sum L$	165	$E1$: 0.22 $M1$: 2.6 $E2$: 25.5	3.6	$M1(+E2)$
69.7 [d]	34	$\sum L$	2950	5.6	5.4	$M1/E2 = 1.3$
81.5 [d]	8.4	$L_{II}+L_{III}$	835	5.0	6.1	$E2$
90.3 [e]	31	K	280	$E1$: 0.38 $M1$: 4.6 $E2$: 1.15	0.56	$E1$ and ($M1$ or $E2$)
160.4 [d]	28	K	290	0.69	0.63	$M1/E2 = 2$
172.2 [d]	100	K	340	0.25	0.21	$E2$

[a] From Ref. 8. The errors in electron intensities are stated there to be "about 15% for the most prominent lines."

[b] The values of the theoretical conversion coefficients were taken from R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968).

[c] The errors in the deduced conversion coefficients should be taken as ±20%.

[d] Multipolarities of these transitions were determined in Ref. 8 from L-subshell ratios; they are also implied by the level scheme of the present work. The K-conversion coefficients were obtained by multiplying the ratios I_e/I_γ by a normalization factor 0.064 obtained as described in the text. This factor was then used to deduce the unknown 58- and 90-keV multipolarities.

[e] This line is an unresolved mixture of two transitions between different levels.

TABLE IV. Multipolarities of some higher-energy transitions in ^{173}Hf.

E_γ (keV)	I_γ (Relative units) This work [a]	I_γ (Relative units) Ref. 10	I_{e_K} [b] (Relative units) Ref. 8	I_{e_K} [b] (Relative units) Ref. 10	α_K [c]	Multipolarity
529.8	37 ± 8	24 ± 8	4.5	···	0.0041	$E1$
587.8	17 ± 4	16.4 ± 1.9	7	···	0.014	$E2(+M1)$
700.6	100 ± 10	100 ± 12	28 [d]	28 [d]	0.0093	$E2(M1)$
730.0	48 ± 8	51 ± 6	28 [d]	28 [d]	0.019	$M1$
1006.6	45 ± 9	33 ± 4	···	9.0 ± 1.6	0.0068	$M1$
1030.0	127 ± 13	110 ± 18	···	5.2 ± 0.7	0.0014	$E1$
1208.2	215 ± 22	200 ± 30	···	4.3	0.000 68	$E1$

[a] Unlike Table I the γ-ray intensities here are normalized to the 700.6-keV line intensity.

[b] Errors for data from Ref. 8 are quoted as ±15% for the "most prominent" transitions. No error is given in Ref. 10 for the 1208-keV electron-line intensity.

[c] These values were obtained by multiplying the ratios I_e/I_γ by the normalization factor 0.034. The photon intensities obtained in this work (column 2 of this table) were used. Error limits ±20% should be assigned to the α_K values.

[d] Used in Ref. 10 for relating the electron-line intensities to those of Ref. 8.

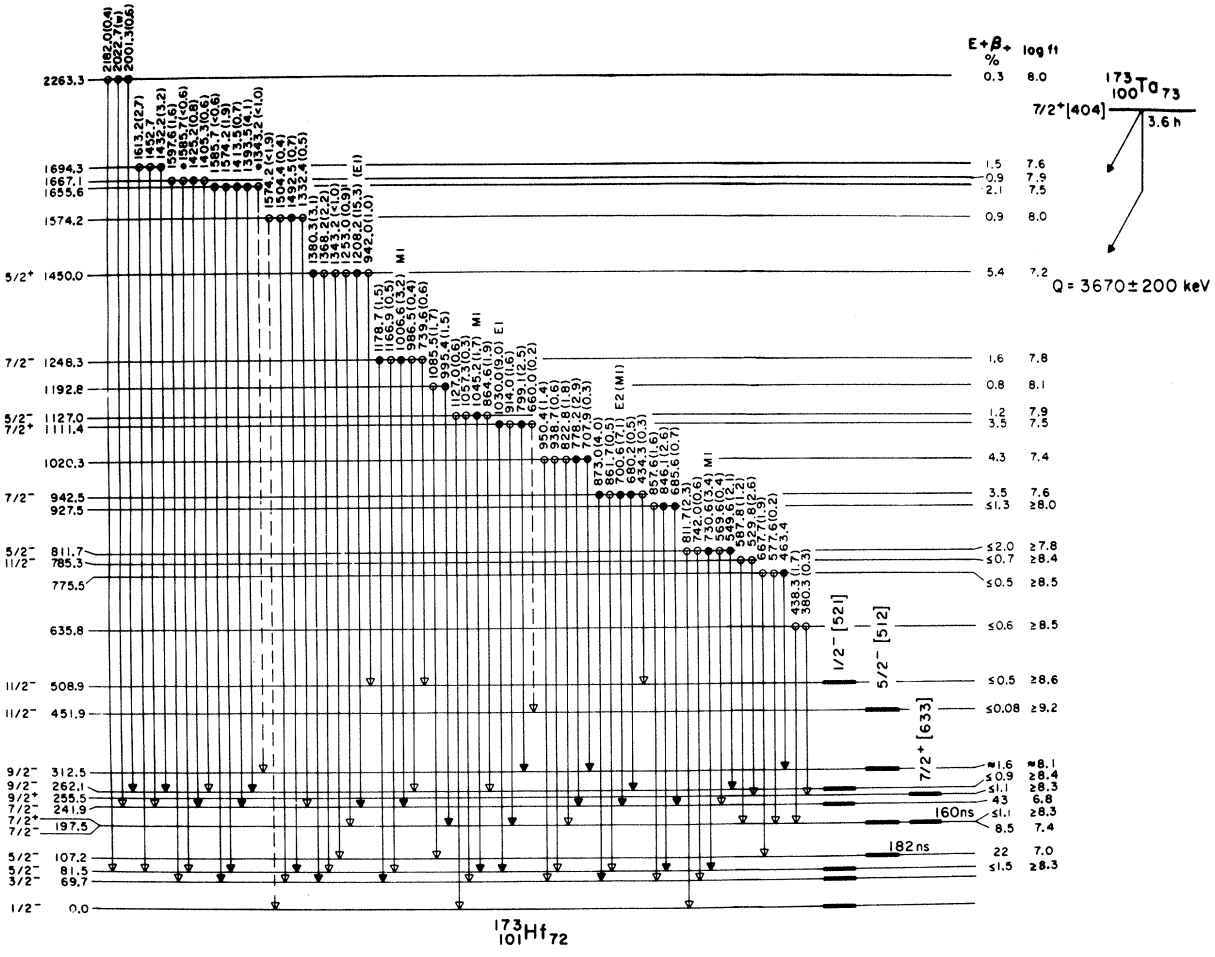

FIG. 6. Decay of ^{173}Ta to levels in ^{173}Hf. The transition intensities in parentheses are in the same units as in Table I. When a transition is placed twice in this decay scheme the assignment with the lower confidence level is marked by an asterisk.

tron intensities of the observed transitions. It is apparent from inspection of the second and third columns in Table IV that the intensities of the seven transitions for which we measured conversion electron intensities and which were placed in our level scheme (Fig. 6) agree satisfactorily with those reported in Ref. 10. Using conversion-electron intensities from the work of Harmatz and Handley[8] and from the Dubna group,[10] a procedure similar to that described in Ref. 10 can be adopted for the determination of conversion coefficients. Since the conversion-electron data as given in either of the two references cannot be directly related to the conversion-electron intensities of low-energy transitions with known multipolarities, we have made the rather plausible assumption of $E1$, $M1$, or $E2$ multipolarities for the seven most prominent lines of the spectrum. The normalization factor (0.034 ± 0.005) for the set of seven electron-to-γ-ray intensity ratios was found graphically in order to produce meaningful conversion coefficients from these ratios, as shown in Fig. 7 and Table IV. Here, as in Ref. 10 an inconsistency in electron intensities between the two parts of Table 13 of Ref. 8 was noticed. This necessitated the use of different multipliers (0.064 and 0.034) for the low- and for the medium-energy data. This empirical procedure together with the intensities of other γ rays gives further information about the spins and parities of some additional levels as shown in Fig. 6.

For the levels above 600 keV, the states at 785.3, 942.5, 1248.3, and 1450.0 keV are in agreement

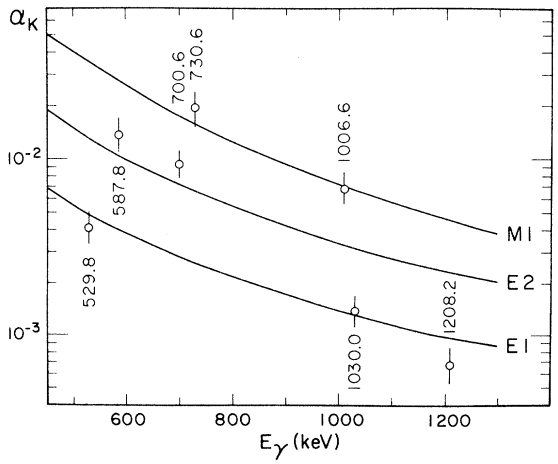

FIG. 7. Comparison of relative internal conversion coefficients for seven prominent γ-ray transitions seen in ^{173}Ta decay. The theoretical curves are constructed from values given by R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968).

with those proposed in Ref. 10; However, we found no evidence for the levels at 872 and 1209 keV which were suggested in that work. The 694.8-keV level assigned in Ref. 8 was based on different assumptions about the lower-lying levels and consequently the existence of that level is of course not consistent with our data either.

4. DISCUSSION

Complete correspondence with the Nilsson scheme has been established for levels of ^{173}Hf below 600 keV. An interesting case of two very close-lying levels at 197.5 keV, one the $\frac{7}{2}^-$ member of the $\frac{5}{2}^-[512]$ band and the other the $\frac{7}{2}^+[633]$ band head, was observed.

Using the measured half-lives of the 107.2- and 197.5-keV levels, the γ-ray intensities of this work, and the conversion-electron intensities from Ref. 8, the radiative half-lives of these levels with respect to photon transitions to lower levels can be calculated and are shown in Table V. The K forbiddenness of the transitions deexciting the $\frac{5}{2}^-[512]$ band head and populating levels of the $\frac{1}{2}^-[521]$ band contributes to the hindrance of these transitions. The $\frac{7}{2}^+[633]$ band is known to be mixed by the Coriolis interaction with other even-parity bands originating in the $i_{13/2}$ shell-model state. However, the admixtures of $K=\frac{1}{2}$ and $\frac{3}{2}$ states in the lowest level of the band are generally[17,18] weak. This is reflected by the fact that the decay by $E1$ transition to the $\frac{5}{2}^-[512]$ state ($\Delta K = -1$) is highly favored over the transition to the $\frac{5}{2}^-$ level of the $\frac{1}{2}^-[521]$ band ($\Delta K = -2$).

The probabilities of the β decay of ^{173}Ta ground state with spin and parity $\frac{7}{2}^+$ to the levels of ^{173}Hf are somewhat puzzling, especially with regard to the relatively high population of the $\frac{7}{2}^-$ state of the ground band. On the other hand, the low intensity of the positron decay to the members of the $\frac{7}{2}^+[633]$ band can be well explained since the ^{173}Ta ground state is most probably the $\frac{7}{2}^+[404]$ Nilsson orbital; this β decay would then require a major rearrangement of the particle across two major oscillator shells. For similar reasons we may infer that the level at 1450.0 keV, relatively strongly populated by β decay, likely involves at least partial character arising from the fourth oscillator shell; the most probable candidates would be the $\frac{1}{2}^+[400]$ or $\frac{3}{2}^+[402]$ orbitals.

The half-life of the $\frac{7}{2}^+[633] \rightarrow \frac{5}{2}^-[512]$ $E1$ transition in ^{173}Hf provides the second measurement of an absolute $E1$ transition rate between these two intrinsic states, ^{173}Yb being the other case for which experimental data are available.[19] Such $\Delta K = 1$ $E1$ transitions are well known to exhibit unusual branching-intensity patterns, and their

TABLE V. Measured γ-ray transition probabilities in ^{173}Hf.

Transition $I_i^\pi(K_i) \rightarrow I_f^\pi(K_f)$	E_γ (keV)	$T_{1/2\gamma}$ (exp) (sec)	$T_{1/2\gamma}$ (s.p.) [a] (sec)	Weisskopf hindrance factor, F_W
$\frac{5}{2}^-(\frac{5}{2}) \rightarrow \frac{5}{2}^-(\frac{1}{2})$	25.7	$(2.7\pm0.6)\times10^{-5}$	1.3×10^{-9}	2.0×10^{4}
$\frac{5}{2}^-(\frac{5}{2}) \rightarrow \frac{3}{2}^-(\frac{1}{2})$	37.4	$(3.0\pm0.3)\times10^{-6}$	4.3×10^{-10}	7.0×10^{3}
$\frac{7}{2}^+(\frac{7}{2}) \rightarrow \frac{5}{2}^-(\frac{5}{2})$	90.3	$(2.0\pm0.5)\times10^{-7}$	1.1×10^{-12}	1.8×10^{5}

[a] Weisskopf estimates from A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland, Amsterdam, 1959), p. 94 were used for calculating the single-particle transition probabilities.

Nilsson model hindrance factors $[F_N = B(E1)_N / B(E1)_{exp}]$ can vary over many orders of magnitude, even for transitions between the same intrinsic states.

It is therefore of interest to compare the hindrance factor for the 90.3-keV $E1$ transition in ^{173}Hf with the analogous transition in ^{173}Yb. In Table V, the partial half-life for photon decay of the 198-keV $\frac{7}{2}^+$ state in ^{173}Hf is shown to be 200 $\pm$ 50 nsec. As expected, the Weisskopf hindrance factor is quite large, but the half-life calculated with the wave functions of Nilsson[20] is much greater, 8.3 nsec, and the hindrance factor, $F_N = 24$ is proportionately less. This number is to be compared with the value $F_N = 180$ for the $\frac{7}{2}^+[633] \rightarrow \frac{5}{2}^-[512]$ transition in ^{173}Yb. In ^{173}Yb, the γ-ray branching to the $\frac{7}{2}$ and $\frac{9}{2}$ members of the $\frac{5}{2}^-[512]$ band is also observed, but the hindrance factors for these branches are only 0.7 and 0.13, respectively.

We are thus once more reminded that it is difficult to predict the absolute $E1$ transition rates between Nilsson states for which $\Delta K = \pm 1$. It is now commonly recognized that the Coriolis interaction is the primary cause of such large fluctuations in $\Delta K = 1$ $E1$ strengths between the same intrinsic states.[21,22] In the case of ^{173}Hf, the strongly admixed $\frac{5}{2}^+[642]$ component in the $\frac{7}{2}^+[633]$ band presumably gives rise to a large $\frac{5}{2}^+[642] \rightarrow \frac{5}{2}^-[512]$ amplitude which adds coherently to the principal $\frac{7}{2}^+[633] \rightarrow \frac{5}{2}^-[512]$ component. The absolute transition rate may therefore be very sensitive to the possible destructive interference between these and other Coriolis-mixed $E1$ transition amplitudes.

It is interesting to note, however, that inclusion of the principal Coriolis-admixed components in a more detailed Nilsson calculation is still often incapable of explaining observed $E1$ transition rates in such cases.[22] To illustrate, we consider the simple first-order correction to the $E1$ transition moment:

$$B(E1) = \frac{3}{4\pi} e_{\text{eff}}^2 \left(\frac{\hbar}{M\omega_0}\right) [a_{7/2^+}(\tfrac{7}{2}1\tfrac{7}{2}-1|\,\tfrac{5}{2}\tfrac{5}{2})(U_{7/2^+}U_{5/2^-} - V_{7/2^+}V_{5/2^-})G(E1;\, \tfrac{7}{2}^+ \rightarrow \tfrac{5}{2}^-)$$
$$+ a_{5/2^+}(\tfrac{7}{2}1\tfrac{5}{2}0|\,\tfrac{5}{2}\tfrac{5}{2})(U_{5/2^+}U_{5/2^-} - V_{5/2^+}V_{5/2^-})G(E1;\, \tfrac{5}{2}^+ \rightarrow \tfrac{5}{2}^-)]^2, \quad (1)$$

where the even-parity subscripts refer to the wave amplitudes for the strongly Coriolis-mixed $\Omega = \frac{5}{2}$ and $\frac{7}{2}$ members of the $i_{13/2}$ family of neutron orbitals, the $(U_i U_f - V_i V_f)$ are the usual $E1$ pairing reduction factors for the orbitals involved, the effective charge e_{eff} is taken to be $-Ze/A$ for a single-neutron transition, and $G(E1)$ is calculated in the Nilsson scheme as before. The amplitude of the $\frac{5}{2}^-[512]$ final state is presumed to be unity.

For estimates of the a_{Ω^+} we refer to the results obtained by Hultberg, Rezanka, and Ryde[4] in their fit for the perturbed energies of the $\frac{7}{2}^+[633]$ rotational band excited in the ^{171}Yb$(\alpha, 2n)^{173}$Hf reaction. The amplitudes of the $\frac{7}{2}^+[633]$ and $\frac{5}{2}^+[642]$ states contributing to the $\frac{7}{2}^+$ band head are found by these authors to be 0.98 and 0.21, respectively. Hult-

TABLE VI. Calculated $E1$ transition probability for the 90.3-keV $\frac{7}{2}^+[633] \rightarrow \frac{5}{2}^-[512]$ transition in ^{173}Hf.

Method	$T_{1/2\gamma}(E1)$ (nsec)	F_N
Nilsson model [a]	8.3	24
Nilsson model with pairing	2300	0.12
Nilsson model with Coriolis mixing and pairing (Eq. 1)	410	0.49

[a] Reference 20. The deformation parameters assumed were $\epsilon_2 = 0.26$, $\epsilon_4 = 0.02$.

berg, Rezanka, and Ryde have also carried out a BCS calculation to estimate the occupation numbers V_ν, for the various $i_{13/2}$ neutron orbitals; we have adopted their numbers. To obtain the number V_ν for the $\frac{5}{2}^-[512]$ orbital, we note the recent tabulation of Ogle *et al.*[23] where the $\frac{5}{2}^-[512]$ and $\frac{7}{2}^+[633]$ orbitals are calculated to be roughly equidistant from the Fermi surface, with the $\frac{5}{2}^-[512]$ particle state somewhat closer than the $\frac{7}{2}^+[633]$ hole state. For a semiquantitative estimate of the occupation numbers involved, we therefore choose the following:

Orbital	$\frac{7}{2}^+[633]$	$\frac{5}{2}^+[642]$	$\frac{5}{2}^-[512]$
V_ν	0.83	0.97	0.60

subject to the usual normalization condition, $U^2 + V^2 = 1$.

The results of this simple calculation are summarized in Table VI. Inclusion of the pairing-reduction factor in the Nilsson model calculations appears to overcompensate for the deficiencies of the calculation without pairing, but addition of the Coriolis-admixed $\frac{5}{2}^+[642] \rightarrow \frac{5}{2}^-[512]$ component apparently restores the result to good agreement with experiment. However, a closer examination of the pairing-reduction factors involved in Eq. (1) reveals the extreme sensitivity of the calculation not only to Coriolis admixtures but especially, in this case, to the assumed location of the Fermi surface. Most notably, the factor $(U_{7/2^+}U_{5/2^-} - V_{7/2^+}V_{5/2^-})$ in the leading term is calculated to be only -0.06. Obviously a small inaccuracy in this quantity would significantly alter our results. Consequently, the results shown in Table VI are not to be taken very seriously; we simply do not know which factors exercise the greatest influence on the total $E1$ strength for the 90.3-keV transition in ^{173}Hf. We have not even considered, for example, the possible influence of very small admixture in either the initial- or final-state wave functions which may allow the $E1$ transition to proceed via a route that is allowed by the Nilsson asymptotic selection rules. Thus, we probably should not neglect components such as $\frac{5}{2}^+[622] \rightarrow \frac{5}{2}^-[512]$ and $\frac{7}{2}^+[633] \rightarrow \frac{7}{2}^-[523]$ for which $G(E1)$ is nearly 2 orders of magnitude larger than for the two terms considered in Eq. (1). Such terms may be important in the case of ^{173}Yb, for example, where the $\frac{7}{2}^+[633] \rightarrow \frac{5}{2}^-[512]$ transition is even more strongly retarded than in ^{173}Hf. It is difficult to reconcile this strong retardation with the factors considered in Eq. (1). If anything, the pairing-reduction factor in ^{173}Yb should be considerably *larger* than in ^{173}Hf, and should therefore retard the $E1$ transition less than in ^{173}Hf, since both the $\frac{7}{2}^+[633]$ and $\frac{5}{2}^-[512]$ orbitals lie below the Fermi surface in ^{173}Yb. In addition, the $\frac{5}{2}^+[642]$ component in the $\frac{7}{2}^+$ band head is expected to be less in ^{173}Yb than in ^{173}Hf because of the smaller perturbation normally associated with the more neutron-rich isobar nearer the line of β stability. All of which points to the conclusion that, once again in ^{173}Yb, if not in ^{173}Hf, we are dealing with the partial cancellation of numerous small transition amplitudes which influence the total $E1$ strength.

The situation in such cases may be further complicated by collective $E1$ components arising from coupling of the initial and final single-particle states with octupole vibrations of the nuclear core. The influence of such octupole vibration-particle coupling on $\Delta K = 0$ $E1$ rates was first explored by Faessler,[24] and was later extended to the $\Delta K = \pm 1$ case.[22, 25, 26] Until recently, however, the weak collectivity associated with the $K = 0^-$ branch of the one-phonon octupole multiplet in the heavier rare-earth region[27] has made it difficult to rationalize the substantial collective $E1$ strength seemingly required to explain the unusual $E1$ transition rates observed in ^{177}Hf, for example. But in the very recent work of Khoo,[28] the $K = 0^-$ octupole branch has been shown to have a pronounced influence on the strongly collective, low-lying $K = 2^-$ octupole band in ^{176}Hf. The $K = 0^-$ admixture in this case apparently exerts its influence on the $E1$ strengths associated with the *odd*-spin members of the $K = 2^-$ rotational band, while transitions from the *even*-spin members, lacking any $K = 0^-$ contribution, display the $E1$-$M2$-$E3$ mixture recently measured in ^{176}Hf and other low-lying 2-2 states of even-even nuclei in this region.[29-31]

While these recent data may lend new credence to the possible influence of collective octupole strength on the $\Delta K = 1$ $E1$ transitions, considerably more information, including lifetime measurements, a detailed and accurate picture of the influence of pairing on $E1$ transitions between states near the Fermi surface, and further data on the possible role of collective influences on "single-particle" $E1$ transitions will be required before a comprehensive picture can be developed for this class of transition most sensitive to the details of nuclear structure.

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