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Abstract:

The locations of 13 energy levels have been deduced from γ-ray singles and γ-γ coincidence measurements on the EC-β^+ decay of ^{177}Ta to ^{177}Hf. Four energy levels and fourteen γ-rays associated with ^{177}Ta decay were unknown from the previous NaI(Tl) work. The log*ft* values have been assigned to ^{177}Ta EC-β^+ decay, and multipolarities of several transitions have been determined with use of earlier conversion electron data.

I. INTRODUCTION

Recent years have seen intense study of the odd neutron Hf and W isotopes because of the presence near the ground state of the positive parity states associated with the strongly mixed $i_{13/2}$ family of Nilsson single particle orbitals. Much of this earlier work employed in-beam γ-ray spectroscopy, using primarily $(\alpha,xn\gamma)$ reactions on appropriate Yb or Hf targets. The study of the rotational band structure in such nuclei can yield significant information on the wave functions associated with the intrinsic single particle configurations. Such data are of special interest because of their apparent relevance to the phenomenon of "backbending" rotational structure recently observed in several even-even rare earth nuclei. Theoretical analysis of the perturbed rotational band structure in both odd-A and even-even nuclei requires as much information as possible about the higher-lying perturbing Nilsson states and their associated rotational bands that mix into the lower-lying bands observed in the $(\alpha,xn\gamma)$ experiments. Such information on higher states can often be obtained from decay scheme studies.

The EC-β^+ decay of ^{177}Ta to levels in ^{177}Hf offers hope for a better understanding of at least one such case where the $i_{13/2}$ single particle Nilsson orbits lie low in the quasiparticle spectrum; the high spin behavior of neighboring even-even isotopes may be directly influenced by the intrinsic configuration of these high-j neutrons. The most recent ^{177}Ta decay scheme is that proposed by West, Mann, and Nagle[1] from their work using NaI(Tl) scintillation detectors. It thus seemed reasonable to expect that Ge(Li) detectors might produce a considerable amount of new data on this decay.

II. EXPERIMENTAL

A. Target and Source Preparation

Sources of 56.6-hr ^{177}Ta were produced by the MSU sector-focused cyclotron by the ^{175}Lu(α,2n)^{177}Ta reaction on foil targets of natural lutetium. Typical bombardments lasted 8-10 hours at a beam current of 1 μa. The activity was allowed to decay for 3-4 days to eliminate 8-hr ^{176}Ta before beginning chemical separation of Ta.

The Ta activity was separated from other reaction products by dissolving the foil in 6*N* HCl and extracting the Ta with *2*,*4*-dimethyl-*3*-pentanone (diisopropyl ketone), a procedure described in detail by Felber.[2] The γ-ray sources were prepared on sheets of plastic film by evaporating to dryness small amounts of the extracted carrier free Ta in aqueous solution.

B. Experimental Apparatus

The γ-ray singles data were taken using a Ge(li) detector with 1333-keV photopeak efficiency of 7.5% (relative to a 7.6×7.6 cm NaI(Tl) detector) and resolution of 2.1 keV FWHM. The source was counted at a source-to-detector distance greater than 5 cm, and a graded Cd-Cu absorber was employed to attenuate the intense x-rays which result from predominant (98%) EC-β^+ feeding to the ground and first excited states of ^{177}Hf. The absorber-detector combination was calibrated for efficiency using ^{75}Se, ^{182}Ta, ^{110m}Ag, and ^{177m}Lu as standards.

The γ-γ coincidence data were obtained using the previously mentioned detector and another of 7% efficiency. The detectors were placed at 180° geometry to maximize coincidence efficiency and the activity was sandwiched between graded Pb-Cd-Cu absorbers to eliminate x-rays. Two-parameter γ-γ coincidence data were collected and stored serially on magnetic tape for later analysis on the MSU Sigma-7 computer. A description of data aquisition and analysis programs can be found in Ref. 3.

C. Experimental Results

A typical γ-ray singles spectrum produced by ^{177}Ta is shown in Fig. 1. A total of 46 γ-rays seen in singles were placed in the ^{177}Hf level scheme; the corresponding γ-ray energies are listed in Table 1. Also present in the singles data were several small γ-rays (<1% the intensity of the 208.3-keV transition) with half-lives similar to ^{177}Ta. These could not be placed in the ^{177}Hf level scheme on the basis of energy sums and differences and were not in coincidence with known ^{177}Hf transitions. Finally, weak γ-rays associated with ^{183}Re (70-day) decay were seen to "grow" into the singles spectra, and are believed to result from ^{181}Ta impurity present in the target.

Internal calibration of prominent ^{177}Ta γ-ray energies was achieved with ^{177m}Lu and ^{110m}Ag standards, using energies from Refs. 4 and 5, respectively. Subsequent spectra were analyzed for peak energies by a least squares fit to the calibrated prominent lines. The 71.7-keV γ-ray line was very weak in the decay spectrum; the energy and relative intensity of this transition were taken from the ^{177m}Lu work of Haverfield, *et al.*[4] Conversion coefficients listed in Table I were calculated with use of the electron data of West, *et al.*[1] by normalization to the 249.7-keV transition, known from ^{177m}Lu decay to be $E2$. The normalization is supported by the ability to reproduce reasonable values of α_K and α_L for the predominantly $E1$ 632.9- and 745.9-keV transitions from the level at 745.9 keV, assigned by West, *et al.* as the $7/2^+[633]$ band head, and confirming evidence for which was provided by the transfer reaction work of Rickey and Sheline.[6] Multipolarities of the γ-ray transitions were then determined from the conversion coefficients with use of the theoretical values of Hager and Seltzer.[7]

In calculating β-decay feeding, the 78% branching to the ground state of ^{177}Hf and the value Q_{EC} = 1.165 MeV proposed by West, *et al.* were assumed to be correct, and the transition intensity balances to each state were determined from the measured γ-ray relative intensities. The calculated logft values were taken from the tables of Gove and Martin.[8]

D. Proposed Level Scheme

In Fig. 2 is shown the proposed level scheme for decay of ^{177}Ta to ^{177}Hf. The level assignments are based primarily upon coincidence relationships, the only exception being the level at 873.0 keV, which was established through energy sums and differences. This decay scheme agrees in most respects with the NaI(Tl) work of West, *et al.* The multipolarities determined from the normalized conversion coefficients of the various transitions in ^{177}Hf are for the most part consistent with the spin and parity assignments of West, *et al.*, and with the (*d*,*p*) and (*d*,*t*) reaction work of Rickey and Sheline.[6] There has been a significant change, however, in the levels associated with the 420.8-keV transition, upon which West tentatively based a $3/2^+$ rotational band with levels at 421.0, 488.8, and 585.8 keV. Shown in Fig. 3a and 3b are spectra of γ-rays in coincidence with the 420.8- and 424.6-keV transitions. These spectra are similar; both show a definite coincidence relationship with the 208.3-keV γ-ray. However, two major differences are apparent: (1) A 256.9-keV γ-ray is in coincidence with the 424.6-keV γ-ray. This 256.9-keV line was previously thought to be a transition to the 488.8-keV level, and was an important argument for the existence of that level. (2) The 420.8-keV line is in coincidence with γ-rays of 105.3, 177.0, and 313.8 keV, all consistent with a transition from the 847.4-keV level to the 426.7-keV level. The level at 426.7-keV is well-known from ^{177m}Lu decay, but was not placed by West, *et al.* The experimental value of $\alpha_K = 0.051$ and the K/L - conversion ratio of 5.2 reported by Harmatz[9] for the 420.8-keV transition are in reasonable agreement with the theoretical values for an *M*1 transition of $\alpha_K = 0.066$ and $\alpha_K/\alpha_L = 6.6$, especially if some *E*2 admixture is present.

Fig. 3c is the 805.7-keV gated coincidence spectrum. The 197.1-keV and 142.4-keV coincidence lines are evidence for the previously unknown levels at 1002.8 and 948.0 keV, respectively. The choice of even parity for the 1002.8-keV level is based on the *K*-conversion coefficient of the 256.9-keV γ-ray. The large error in this number, and the ambiguity inherent in assigning multipolarities solely on the basis of *K*-conversion coefficients requires that this parity assignment be considered tentative.

The odd parity assignment for the 805.7-keV level is based on the multipolarity of the 297.7-keV transition and the large log*ft* value associated with this state. While the conversion coefficient for the 297.7-keV transition is relatively more precise than that for the 256.9-keV transition, the parity assignment is still subject to the ambiguity in interpreting α_K. The odd parity assignment is in agreement, however, with the reaction work of Rickey and Sheline, in which states were seen at 804 and 878 keV and were assigned as the lowest two members of a rotational band based on the $3/2^-[512]$ state.

E. Discussion and Conclusions

Several ambiguities which existed from previous work on ^{177}Ta decay have been clarified, and the objective of identifying high-lying Nilsson states and their associated rotational bands has been somewhat successful. The state at 1002.8-keV is apparently even-parity, and therefore would offer some prospect for association with the $i_{13/2}$ family of Nilsson orbitals. The most likely candidate for this state is the $5/2^+[642]$ Nilsson orbital and the γ-ray transitions to lower-lying states in the spectrum are consistent with this interpretation. Better conversion-electron data are clearly needed to confirm this assignment, but the log*ft* value associated with this state is consistent with it being $5/2^+[642]$; the log*ft*'s for both the $9/2^+[624]$ and $7/2^+[633]$ band heads are very similar to that of the 1002.8-keV state. All three log*ft* values are quite high for "allowed" β-decay. This is not surprising, in view of the transition over two major oscillator shells required by the $7/2^{+}[404] \rightarrow 5/2^{+}[642]$, $7/2^{+}[633]$, $9/2^{+}[624]$ β-decay transformations.

In an attempt to determine whether the 1002.8-keV level is consistent with a $5/2^{+}[642]$ state assignment, Coriolis calculations for mixing between the known band members from other $i_{13/2}$ orbitals have been carried out. The experimental input spectrum of states used in the calculation includes all members of the $9/2^{+}[624]$ band known from ^{177}Lu decay[4] and the two members of the $7/2^{+}[633]$ band confirmed in this study. With an appropriate selection of input parameters (cf. footnote *e*, Table 2), the complete Coriolis interaction matrix was constructed for each experimentally known spin state, and a best least squares fit to those energies was used as the basis for predicting the location of the $5/2^{+}[642]$ state. The general method used has been well-summarized elsewhere,[10] and we adopt the additional first order correction to the rotational moment of inertia suggested by the Stockholm group in their sophisticated treatment of such data.[11] The diagonal and off-diagonal energies in the Coriolis interaction matrix are then:

$$E_{diag} = \left\{ \frac{\hbar^2}{2\mathcal{J}} + B[I(I+1)-K^2] \right\} \left\{ I(I+1)-K^2+(-1)^{I+\frac{1}{2}} a(I+\tfrac{1}{2})\delta_{K,\frac{1}{2}} \right\}$$

$$E_{Cor} = - \left[\frac{\hbar^2}{2\mathcal{J}} + BI(I+1) \right] \sqrt{I(I+1)-K_{>}K_{<}}\, \langle j\Omega | j_{\mp} | j\Omega\pm1 \rangle N_{\Omega,\Omega+1} R(U,V)$$

where R(UV) are the usual Coriolis pairing reduction factors $(U_1U_2+V_1V_2)$ and the $N_{\Omega,\Omega+1}$ represent *ad-hoc* reduction factors for the Coriolis matrix elements.

Such reductions, though still not understood, are known to approach 0.50 near the Fermi surface.

Results of the calculations are summarized in Table 2. It is seen that the energy fits (calculation I) to all known experimental data for even-parity states are quite good for reasonable values of $\hbar^2/2J$ and B, and for the Nilsson single-particle energies defined by deformation parameters $\varepsilon_2 = 0.25$ and $\varepsilon_4 = 0.05$. The predicted location of the $5/2^+$[642] state is about 1400 keV, however, considerably higher in energy than the 1002.8-keV candidate.

A second set of calculations (II) is also shown that assumes the 1002.8-keV state is predominantly $5/2^+$[642]. The fit in this case is considerably worse; it was necessary to decrease unrealistically the $5/2^+$[642] quasiparticle energy by 500 keV, and the Coriolis matrix elements also required unusually large attenuations in this fit. It was impossible to improve the situation by any reasonable choice of deformation parameters.

These calculations do not lend strong support to the $5/2^+$[642] assignment for the 1002.8-keV level. It is certainly possible to imagine seniority three states which could have the indicated even parity for this state, and one can even postulate states at this energy which could be formed by coupling octupole vibrations with the $7/2^-$[514] or $5/2^-$[512] single particle states. The possibility that this state may be odd parity also cannot be dismissed until more detailed conversion electron or transfer reaction data are available.

The remaining levels in ^{177}Hf populated by the ^{177}Ta decay are for the most part well-characterized. Members of the rotational band based on the $7/2^-$[514](gnd.), $9/2^+$[624](321.3-keV), $5/2^-$[512](508.1-keV), and $7/2^+$[633](745.9-keV) states are known from previous work and are confirmed in this decay investigation. The level at 805.7 keV was found by Rickey and Sheline (804 keV) to be strongly populated in ^{176}Hf(d,p), and to have an angular distribution consistent with its assignment as the $3/2^-$[512] band head. The γ-ray deexcitation pattern from this state, and the logft value from ^{177}Ta decay to this state support the assignment. The γ-ray singles spectrum of ^{177}Ta also contains weak lines which, on the basis of energy sums and differences, indicate a level at 873.0-keV. While the existence of this level was not confirmed by coincidence data, a level at 878 keV was seen by Rickey and Sheline and assigned as the $5/2^-$ member of the $3/2^-$[512] band. Since the logft value and γ-ray deexcitation pattern determined in our decay study are consistent with this interpretation, the 873.0-keV level is believed to be correctly placed, and is presumed to belong to the $3/2^-$[512] band. It is tempting to assign the state at 948.0 keV to this band as well, but Rickey and Sheline identify a level at 979 keV which they assign instead as $I^\pi K = 7/2^- 3/2$[512]. Moreover, the energy spacing between our 948-keV level and the $5/2^-$ band member at 873.0 keV makes it most unlikely that the 948-keV state belongs to the same band, despite the γ-ray feeding into the $3/2^-$[512] band-head at 746 keV. (The expected strong Coriolis coupling between the $3/2^-$[512] and $1/2^-$[521] bands argues further against associating the 948-keV state with the $3/2^-$[512] band.)

Finally, the state at 1057.8 keV is assigned as $7/2^-$[503], also in agreement with the transfer reaction data. This assignment is consistent with the similar logft values to the ground and 1057.8-keV states, since the EC-decay transformations $7/2^+[404] \rightarrow 7/2^-[514]$ or $7/2^-[503]$ are both first-forbidden unhindered in the asymptotic selection rules.

We conclude that probable Nilsson assignments can be made for most of the states populated in ^{177}Ta decay. Though more precise conversion electron and perhaps transfer reaction data are needed to characterize the states at 948.0 and 1002.8 keV, decay scheme studies can provide valuable information on the ordering of the quasiparticle spectrum and thereby provide indirect information on nuclear deformations in this region.

ACKNOWLEDGEMENTS

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Table 1

The γ-ray Transitions Seen in Decay of ^{177}Ta to Levels in ^{177}Hf

γ-Ray Energy[a] (keV)	Relative γ-ray Intensity[b]	α_K[c]	α_L[c]	Multipolarity
71.7[e]	14 (2)			
96.3	9.7 (15)	----	1.2 (3)	
105.3	6.9 (8)	----	----	$M1+E2$[e]
112.9	7700 (800)	0.63 (10)	1.1 (2)	$E2+M1$[e]
129.9	1.1 (2)	----	----	
136.7	8.2 (6)	0.42 (4)	0.39 (3)	$E2$
142.4 (2)	0.58 (9)	----	----	
177.0	2.2 (3)	----	----	
197.1	3.1 (3)	----	----	
208.4	1000 (80)	0.043 (4)	0.0070 (6)	$E1$
249.7[c]	33 (3)	[0.090][c]	0.035 (3)	$E2$
256.9	0.93 (9)	0.6 (4)	----	$M1$
268.6 (2)	0.14 (4)	----	----	
283.2	0.59 (6)	----	----	
297.7	1.4 (1)	0.10 (2)	----	$E2+M1$
311.9 (2)	0.52 (9)	----	----	
313.8 (2)	0.76 (9)	<0.3	<0.1	
319.3	2.5 (3)	----	----	
321.3	23 (3)	0.078 (7)	0.017 (2)	$E1$[g]
354.9	2.0 (3)	0.06 (2)	0.03 (2)	$M1+E2$[f]
365.1 (2)	0.17 (4)	----	----	
395.2	5.6 (5)	0.036 (5)	----	$E2+M1$[f]
398.3 (2)	0.60 (9)	----	----	
420.8	33 (3)	0.051 (9)	0.011 (3)	$M1+E2$
424.6	110 (10)	0.058 (6)	0.010 (2)	$M1$
439.9 (2)	0.37 (8)	----	----	
453.2	2.4 (3)	0.047 (7)	----	$M1$
491.5	33 (3)	0.042 (4)	0.0064 (7)	$M1$
494.7	4.5 (4)	----	----	

Table 1 (Contd.)

γ-Ray Energy[a] (keV)	Relative γ-ray Intensity[b]	α_K[c]	α_L[c]	Multipolarity
508.1	75 (6)	0.031 (3)	0.0050 (5)	*M*1+*E*2
526.1	18 (2)	0.027 (2)	0.0046 (8)	*M*1+*E*2
549.6	6.4 (5)	0.030 (3)	----	*M*1
597.7	10 (8)	0.005 (3)	----	*E*1
604.4	23 (3)	0.0092 (10)	<0.002	*E*2+(*M*1)
632.9	31 (3)	0.0033 (4)	<0.0008	*E*1
681.5	0.8 (1)	----	----	
734.4	42 (4)	<0.0037[d]	----	*E*1
736.4	17 (2)	<0.0093[d]	----	*E*1
745.9	220 (18)	0.0023 (3)	----	*E*1
760.0	0.71 (7)	----	----	
805.7	2.9 (3)	----	----	
847.4	29 (3)	0.0015 (2)	0.0009	*E*1
873.0	0.92 (9)	----	----	
944.8	59 (5)	0.0079 (8)	0.0016 (2)	*M*1
1002.8	1.1 (1)	----	----	
1057.8	310 (30)	0.0057 (5)	0.0010 (1)	*M*1+(*E*2)

[a] Unless otherwise indicated, errors may be taken as ±0.1 keV.

[b] Normalized to 208.3-keV γ-ray. Errors in parentheses.

[c] Conversion electron data taken from West *et al.*[1] normalized to 249.7-keV line.

[d] Doublet not resolved in conversion electron spectra. The values of α_K represent in both cases the total electron intensity produced by the 734.5-keV doublet.

[e] Known from ^{177m}Lu decay.

[f] This mixture is implied by experimental values. However, spin assignments for this decay do not allow *M*1 admixture.

[g] This assignment is taken from ^{177m}Lu decay. The experimental values imply a multipolarity assignment of *E*2+*M*1 for the transition.

Table 2

Results of Coriolis-Mixing Energy Fit for Even-Parity States in ^{177}Hf

I (K)	Experimental Energy	Fit I[e]	Fit II[f]
5/2 + 5/2	(1002.8)	1401.3	1002.9
7/2 + 7/2	745.9	745.9	746.2
9/2 + 7/2	847.4	847.4	847.6
13/2 + 7/2	1101[a]	1101	1100
9/2 + 9/2	321.3	321.3	323.9
11/2 + 9/2	426.6[b]	426.6	425.7
13/2 + 9/2	555.1[b]	555.0	552.9
15/2 + 9/2	708.4[b]	708.3	706.3
17/2 + 9/2	882.8[b]	882.7	882.9
19/2 + 9/2	1086.9[b]	1086.9	1086.7
21/2 + 9/2	1301.3[b]	1301.3	1306.9
23/2 + 9/2	1560.9[c]	1561.3	1558.2
	[d]Deviation	$\Sigma(\Delta E^2)=0.20$	$\Sigma(\Delta E)^2=58.2$

[a]Ref. 6.

[b]Ref. 4.

[c]Ref. 12.

[d]$\Sigma(\Delta E^2)$ is the sum of the squared deviations between experimental and calculated energies.

[e]Parameters adopted for this fit were:

$\hbar^2/2J$ = 15.6 keV; B = -0.005 keV; Δ_n = 750 keV;

λ_n = 51.883 MeV; *ad hoc* Coriolis reduction factors $N_{\Omega,\Omega+1}$ = 0.99, 0.80, 0.86, 0.66, 0.84, 0.99 for Ω = 1/2 through 11/2. The quasi-particle energy for the $7/2^+$[633] band head was decreased by 52 keV from theory.

[f]Parameters for this fit: $\hbar^2/2J$ = 16.0 keV; B = -0.01 keV;

Table 2 (Contd.)

$N_{\Omega,\Omega+1}$ = 0.96, 0.70, 0.58, 0.68, 0.88, 0.96. The $5/2^+$[642] quasiparticle energy was decreased unrealistically by 510 keV.

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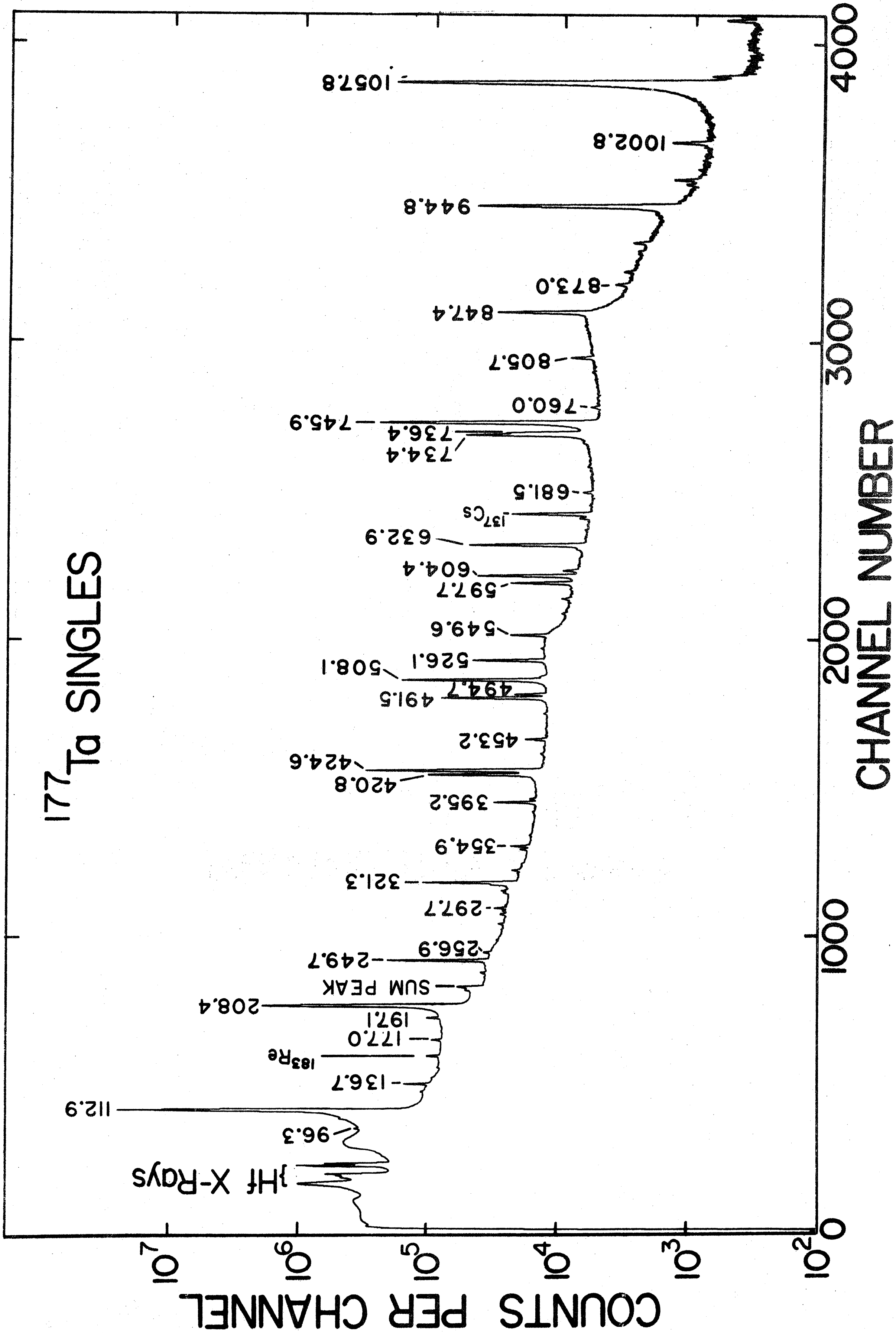
FIGURE CAPTIONS

Fig. 1. The γ-decay singles spectrum of ^{177}Ta. Several weak lines seen in this spectrum are caused by background radiation accumulated during the counting period needed to obtain these statistics.

Fig. 2. Level scheme for the decay of ^{177}Ta to ^{177}Hf. All transitions placed in this level scheme are supported by coincidence data except those associated with the level at 873.0 keV. Intensities in italics are normalized to the 208.3-keV transition.

Fig. 3. Selected γ-γ coincidence data from decay of ^{177}Ta.



^{177}Ta SINGLES
COUNTS PER CHANNEL
CHANNEL NUMBER
10^2
10^3
10^4
10^5
10^6
10^7
0
1000
2000
3000
4000
}Hf X-Rays
96.3
112.9
136.7
^{183}Re
177.0
197.1
208.4
SUM PEAK
249.7
256.9
297.7
321.3
354.9
395.2
420.8
424.6
453.2
491.5
494.7
508.1
526.1
549.6
597.7
604.4
632.9
^{137}Cs
681.5
734.4
736.4
745.9
760.0
805.7
847.4
873.0
944.8
1002.8
1057.8

Fig. 1

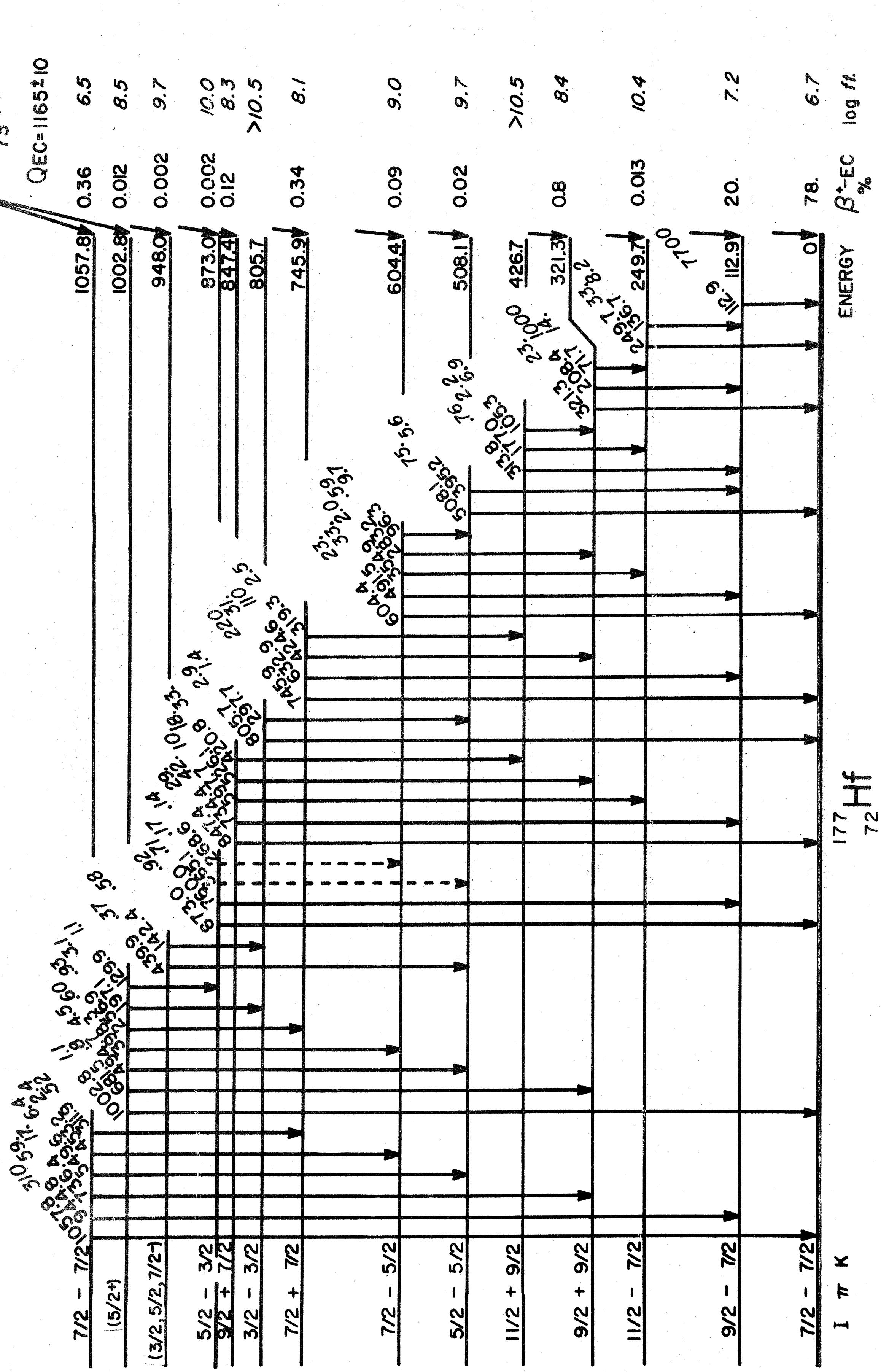
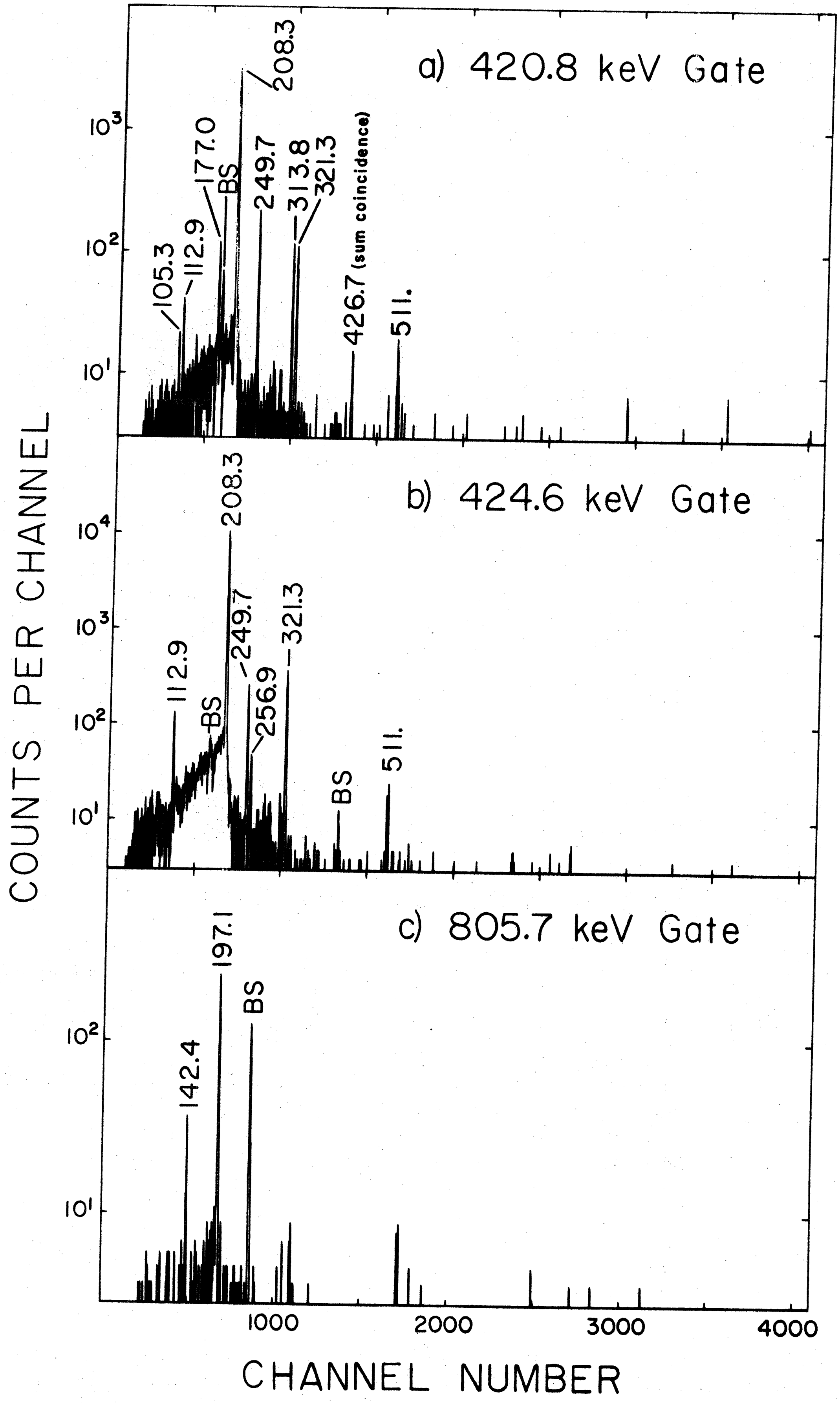

(7/2+) 56.6h
177 73 Ta
QEC=1165±10
1057.8
1002.8
948.0
873.0
847.4
805.7
745.9
604.4
508.1
426.7
321.3
249.7
112.9
0
ENERGY
0.36 6.5
0.012 8.5
0.002 9.7
0.002 10.0
0.12 8.3
>10.5
0.34 8.1
0.09 9.0
0.02 9.7
>10.5
0.8 8.4
0.013 10.4
20. 7.2
78. 6.7
β+-EC %
log ft
7/2 − 7/2
(5/2+)
(3/2,5/2,7/2−)
5/2 − 3/2
9/2 + 7/2
3/2 − 3/2
7/2 + 7/2
7/2 − 5/2
5/2 − 5/2
11/2 + 9/2
9/2 + 9/2
11/2 − 7/2
9/2 − 7/2
7/2 − 7/2
I π K
177 72 Hf

Fig. 2



a) 420.8 keV Gate
208.3
177.0
BS
249.7
313.8
321.3
105.3
112.9
426.7 (sum coincidence)
511.
b) 424.6 keV Gate
208.3
112.9
BS
249.7
256.9
321.3
BS
511.
c) 805.7 keV Gate
197.1
BS
142.4
COUNTS PER CHANNEL
10³
10²
10¹
10⁴
1000
2000
3000
4000
CHANNEL NUMBER

Fig. 3