Shape coexistence in ^{186}Hg and the decay of ^{186}Tl

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Details of the identification of ^{186}Tl and its decay to ^{186}Hg as investigated with an isotope separator are presented. Conversion electrons, γ, γ-γ, and e-γ studies establish two bands in ^{186}Hg; one built on a near-spherical ground state and one on a more strongly deformed shape with a band head at 522 keV. The levels are discussed in the framework of recent theoretical calculations.

[RADIOACTIVITY ^{186}Tl, ^{186}Tl^m from ^{181}Ta (^{16}O,11n), E = 145 MeV; ^{182}W(^{14}N,10n), E = 168 MeV; mass separated radioactivities. Measured $T_{1/2}$, E_γ, E_{ce}, I_γ, I_{ce}, $\gamma\gamma$ coin, $e\gamma$ coin, ICC, ^{186}Hg deduced levels, I, π, multipolarities.]

INTRODUCTION

In an earlier letter,[1] we reported evidence for the crossing of near-spherical and deformed bands in ^{186,188}Hg from the decays of the new isotopes ^{186,188}Tl. These results[1] established the coexistence of bands built on near-spherical and deformed shapes with states in both bands observed above and below the crossings so that neither band is terminated by the crossing. The discovery of the new isotope ^{186}Tl was first reported at the Nashville Conference.[2] In this paper we report details of our discovery of ^{186}Tl and its decay to ^{186}Hg. Our work agrees with the results of an independent investigation by Beraud *et al.*[3]

EXPERIMENTAL PROCEDURES

The first ^{186}Tl sources were produced by bombarding ^{181}Ta foils in the ion source of the UNISOR separator with 145 MeV ^{16}O ions from the Oak Ridge isochronous cyclotron. More intense mass separated sources were subsequently obtained by bombarding 99% enriched ^{182}W with 168 MeV ^{14}N ions. In the latter reaction the target was separated from the ion source with a graphite cloth.[4] The activities in the 186 mass chain were mass separated in the Scandinavian-type isotope separator. The mass 186 sources were collected on aluminized Mylar which was moved periodically to bring a freshly collected source in front of the detectors.

Spectra of γ rays and conversion electrons were recorded in the multiscale mode to establish the half-lives of the ^{186}Tl sources and the transitions associated with them and their daughters. For singles and coincidence γ-ray studies, large volume Ge(Li) detectors with 10–18% efficiencies were used. The γ–x-ray and conversion-electron–x-ray data were used to assign transitions to levels in ^{186}Tl and ^{186}Hg while the γ-γ and e-γ data established the energy levels. Conversion electrons were detected in a Si(Li) detector cooled to liquid nitrogen temperature. In the coincidence studies, energy signals from the two detectors and the time between the events were digitized in an 8192 channel analog-to-digital convertor and stored on magnetic tape for each coincident event.

EXPERIMENTAL RESULTS

The γ-ray singles spectrum was measured in several different runs. A typical γ-ray spectrum which is the sum of the 10 time planes is shown in Fig 1 and an electron and γ-ray spectrum in Fig. 2. The results of the singles measurements and the conversion coefficients extracted from those data are given in Tables I and II.

The energies of the transitions in the yrast cascade of ^{186}Hg as reported by in-beam spectroscopy[5] were used to identify the decay of ^{186}Tl to ^{186}Hg. Decay curves for the prominent transitions are shown in Fig. 3. These data establish that the half-life for the decay of the high spin isomer of ^{186}Tl is 27.5 ± 1.0 sec. A 374.0-keV transition has a half-life of 4.5 ± 1.3 sec. The conversion coefficient and K/L ratio of this transition are in agreement with those of an $E3$ transition. These half-lives are in agreement with those of Beraud *et al.*[3] of 27 ± 3 and 3 ± 1 sec. In our first report,[2] there was evidence for a possible longer lived, $T_{1/2} \sim 1$ min, component in the 405.3-keV transition but this was not seen in our subsequent studies. As seen in Fig. 3 there is some evidence that the 8-6 transition has a somewhat longer half-life and in one run the 6-4 transition had a somewhat longer half-life too. These differences, however, are thought to be from statistical uncertainties in these weaker lines. In the ^{190}Tl decay[6] and those of the heavier Tl isotopes the spins and parities of the two isomers are assigned 7^+ and 2^-. The $E3$ character of the 374.0-keV isomeric transition indicates

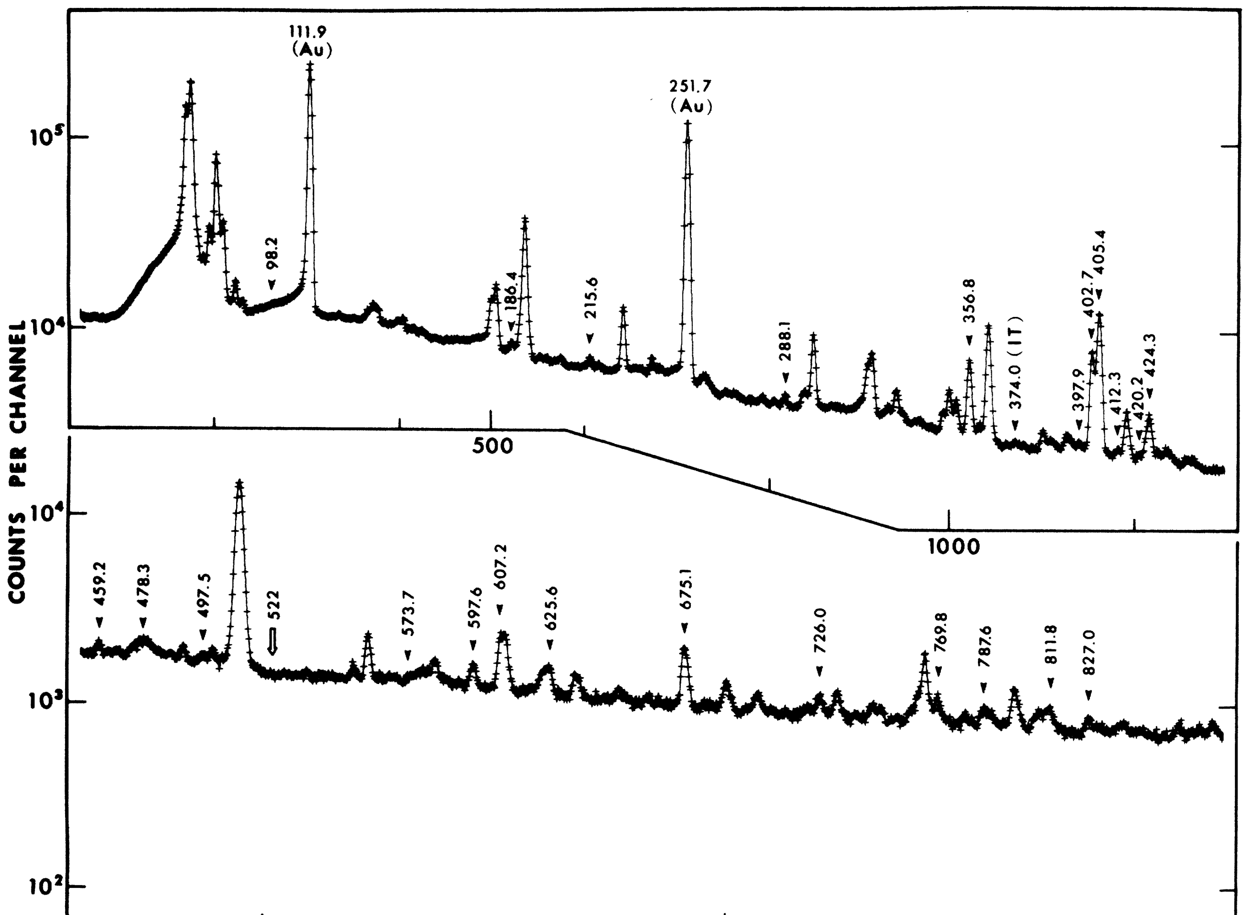

FIG. 1. Gamma-ray spectrum of the 186 mass separated chain. The labeled peaks are from the decay of ^{186}Tl to ^{186}Hg except for the 374.0-keV isomeric transition and two lines in ^{184}Au.

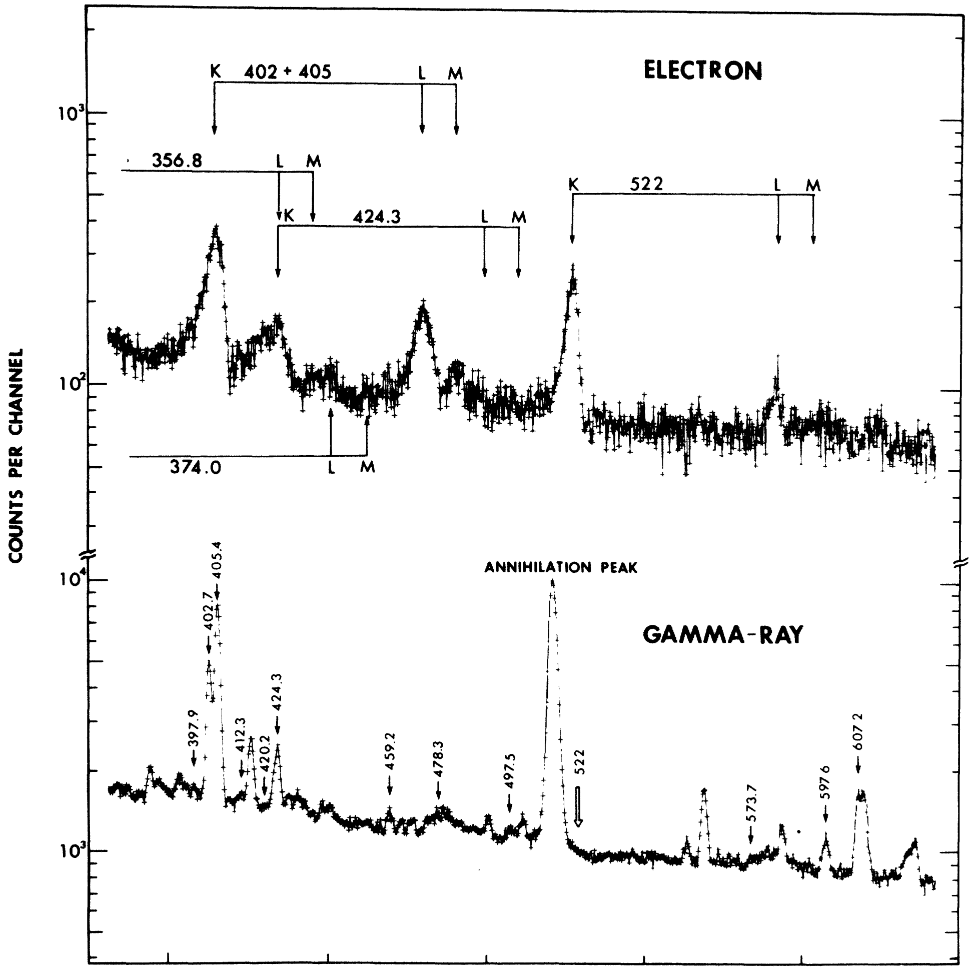

FIG. 2. A portion of the electron and γ-ray spectra from the decay of ^{186}Tl to ^{186}Hg. The $E0$ character of the strong 522-keV electron transition is seen by comparing the two spectra.

that a second level is probably present between the 7^+ and 2^- states in ^{186}Tl. The intensity of the 374.0-keV transition is very weak (2.0%) and within errors one cannot exclude β population of this amount to the 4^+ or 2^+ states. Thus we cannot say whether the low spin isomer is above the 7^+ feeding into it, or below with β decay out. The γ-ray intensity of the 373.8-keV transition in the work of Beraud *et al.*[3] is 5.3 ± 0.5 compared with 2.0 ± 0.1 in our work. This difference in intensities indicates that we are not populating the isomer as strongly. They used the ^{3}He, 14n reaction and we the ^{14}N, 10n reaction. The high spin isomer should have been populated more strongly in our work. This coupled with the change in the isomeric transition intensity suggests that the isomer is the low spin member and that it lies above the 7^+ ground state. This assignment leaves open the question of whether the low spin state is 2^- with a 5^+ state between it and the 7^+ or whether here the low spin isomer spin in 4^-. It also raises the question of why essentially no β decay to ^{186}Hg is observed from the low spin isomer.

The results of our γ-γ and e-γ coincidence studies which were used to establish levels in ^{186}Hg are shown in Table III. The level scheme is shown in Fig. 4. Of particular importance are the 0^+ and 2^+ members of the deformed band. The K electrons of the 522-keV transition are in coincidence with Hg K x rays but not with the strong γ rays in ^{186}Hg. Coupled with the large α_K and K/L ratio of this transition, it depopulates a 0^+ state of this energy. The assignment of 2^+ to the level at 621.0 keV is based on the α_K and K/L data which together show a large $E0$ component in the 215.6-keV transition. The spin-parity assignments for the states at 1080.5 and 1678.1 keV are based on the cascade character of their decays to levels of known spin-

TABLE I. γ-ray energies and intensities in the decay of ^{186}Tl.

E_γ (keV) Present	Beraud *et al.* [a]	I_γ Present	Beraud *et al.* [a]
98.2 ± 0.7		0.6 ± 0.3	
117		< 0.3	
186.4 ± 0.4		2.5 ± 0.5	
215.6 ± 0.3	215.5 ± 0.3	3.7 ± 0.4	4.5 ± 0.5
288.1 ± 0.4 [b]	287.9 ± 0.3 [b]	1.3 ± 0.3 [b]	< 1.8 [b]
356.8 ± 0.2	356.7 ± 0.3	32 ± 2	32 ± 1
374.0 ± 0.5 [c]	373.8 ± 0.3 [c]	2.3 ± 0.3 [c]	5.3 ± 0.5 [c]
397.9 ± 0.4	397.8 ± 0.3	2.0 ± 0.2	1.6 ± 0.2
402.7 ± 0.2	402.6 ± 0.3	50 ± 2	50 ± 1
405.4 ± 0.2	405.3 ± 0.2	100	100
412.3 ± 0.4	412.6 ± 0.3	1.8 ± 0.2	1.5 ± 0.2
420.2 ± 0.4	421.3 ± 0.3	0.8 ± 0.2	0.7 ± 0.1
424.3 ± 0.3	424.1 ± 0.2	12.7 ± 0.5	14.0 ± 0.7
459.2 ± 0.5	459.2 ± 0.3	2.4 ± 0.4	2.7 ± 0.5
478.3 ± 0.5 [d]	477.9 ± 0.3	3.0 ± 1.2 [d]	1.8 ± 0.2
497.5 ± 0.7 [b]	497.6 ± 0.3 [b]	2.0 ± 1.0 [b]	0.60 ± 0.15 [b]
522 ± 1	523 ± 1	< 0.4	< 0.5
573.7 ± 0.4	573.5 ± 0.3	1.5 ± 0.3	1.5 ± 0.5
597.6 ± 0.4	597.5 ± 0.2	4.3 ± 0.3	4.6 ± 0.3
607.2 ± 0.3 [e]	607.5 ± 0.3	8.3 ± 0.8 [f]	6.7 ± 0.5
621.9 ± 0.4 [d]		2.9 ± 0.4 [d]	
625.6 ± 0.3 [d]	626.1 ± 0.3	6.2 ± 0.3 [d]	3.1 ± 0.2
675.1 ± 0.3 [e]	675.5 ± 0.3	15.3 ± 0.8	15.5 ± 0.8
726.0 ± 0.7 [d]	726.5 ± 0.3	3.6 ± 0.5 [d]	1.7 ± 0.4
769.8 ± 0.4	770.2 ± 0.3	4.8 ± 0.6	5.0 ± 0.3
787.6 ± 0.7	788.4 ± 0.4	3.0 ± 1.0	2.9 ± 0.3
811.8 ± 1.0	811.1 ± 0.4	3.0 ± 0.5	2.3 ± 0.5
827.0 ± 0.7	826.4 ± 0.4	3.2 ± 0.5	2.4 ± 0.3
870	870.0 ± 0.4	< 0.5	1.0 ± 0.2
1178 ± 1.0	1177.1 ± 0.4	0.8 ± 0.4	0.8 ± 0.2
1209 ± 1	1209.7 ± 0.5	2.3 ± 0.7	1.1 ± 0.2
1247 ± 1	1247.6 ± 0.5	1.4 ± 0.5	1.4 ± 0.2
1272 ± 1	1272.6 ± 0.5	1.4 ± 0.4	1.4 ± 0.2

[a] Reference 3.

[b] Present in decays of levels in ^{186}Hg and ^{186}Au.

[c] This transition is in ^{186}Tl and the different intensities presumably reflect different populations of the high spin isomer.

[d] Doublet with long life component in our work.

[e] This result is from on line data and has a 27 sec half-life. In one off line run this intensity was 14.5 and had a $T_{1/2}$ the order of several minutes.

[f] Coincidences with K x rays show these transitions depopulate levels in both ^{186}Hg and ^{186}Pt.

parity and so are considered tentative.

The even parity band structures will be considered in the next section. A major difference seen in decay of ^{186}Tl to levels in ^{186}Hg compared with the ^{188}Tl decay, and the decay of the heavier Tl isotopes is the lack of strong population of the 5^-, 7^-, 9^- members of an odd parity band. For example, in ^{188}Hg a level at 1909.7 keV is assigned as 5^-, and its γ decay is 13.2 units. The 2295.4-keV level is assigned 7^- and has 3.7 units of γ intensity out. There are no such strongly populated states seen in ^{186}Hg. One possible explanation for this decrease may be that the β-decay strength is carried off by the deformed band, which is not seen in ^{190}Hg and heavier Hg isotopes and is significantly lower in energy in ^{186}Hg than ^{188}Hg.

TABLE II. Relative intensities of conversion electrons in the decay of ^{186}Tl and K conversion coefficients.

Transition Energy	$I_{e_{\bar{K}}}$ Present work	I_γ Present work	K conversion coefficients Present	Beraud et al.[a]	$E2$[b]	$M1$[b]
215.5	2.45 ± 50	3.7 ± 0.4	3.1 ± 0.7	2.8 ± 0.3	0.142	0.76
356.7	33 ± 6	32 ± 2	0.049 ± 0.009	0.04 ± 0.01	0.042	0.193
402 ± 405	100	150	0.0315		0.0315	0.138
424.2	12 ± 5	12.7 ± 0.5	0.045 ± 0.019	0.031 ± 0.006	0.028	0.121
522	50 ± 5	< 0.4	> 6.0	> 6.2		
374	8.5 ± 3.0	2.3 ± 0.5	0.17 ± 0.07	0.095 ± 0.020	$E1$	$M1$ 0.18
					$E2$ 0.039	$M2$ 0.58
					$E3$ 0.105	$M3$ 1.5
					$E4$ 0.27	$M4$ 3.7

Energy	K/L Present exp.	K/L theory[b] $E0$	$M1$	$E2$	$M2$	$E3$	$M3$	$E4$	$M4$
215.5	5.3 ± 1.4	5.8	6.0	1.15					
522	5.7 ± 0.8	5.8	6.0	3.6					
374	1.5 ± 0.9		5.8	2.4	4.6	1.0	2.9	0.43	1.8

[a] Reference 3.
[b] R. S. Hager and E. C. Seltzer, Nucl. Data A4, 1 (1968); A6, 1 (1969).

TABLE III. Results of the γ-γ coincidence studies for transitions assigned to the ^{186}Tl decay. An × means a definite coincidence and a W means weak but not absolutely definite evidence. The last two entries show the coincidence between the K electron lines of the 405.4- and 522-keV transitions and γ rays as seen in the e-γ coincidence studies.

Gate \ γ ray	Hg x ray	215.6	356.8	402.7	405.4	424.3	459.2	478.3	597.6	607.2	675.1	769.8	787.6	811.8
215.6	×				×					*W*				
356.8	×			×	×	×								*W*
397.9	×				*W*							*W*		
402.7	×		×		×	×						×		*W*
405.4	×		×	×		×	*W*	*W*	×	×	×	*W*	*W*	
424.3	×		×	×	×									
459.2	×				×									
478.3	×													
597.6	×				×						×			
607.2[a]	×				×									
675.1[a]	×				×				*W*					
769.8	×			×	×									
787.6	×				*W*									
811.8	×		×	×	×									
827.0	×				×									
K-405.4 + 402.7	×		×	×	×									
K-522	×													

[a] Both the 607.2- and 675.1-keV gates show coincidences with Pt as well as Hg K x rays to confirm that these are both doublets and belong between levels in both isotopes.

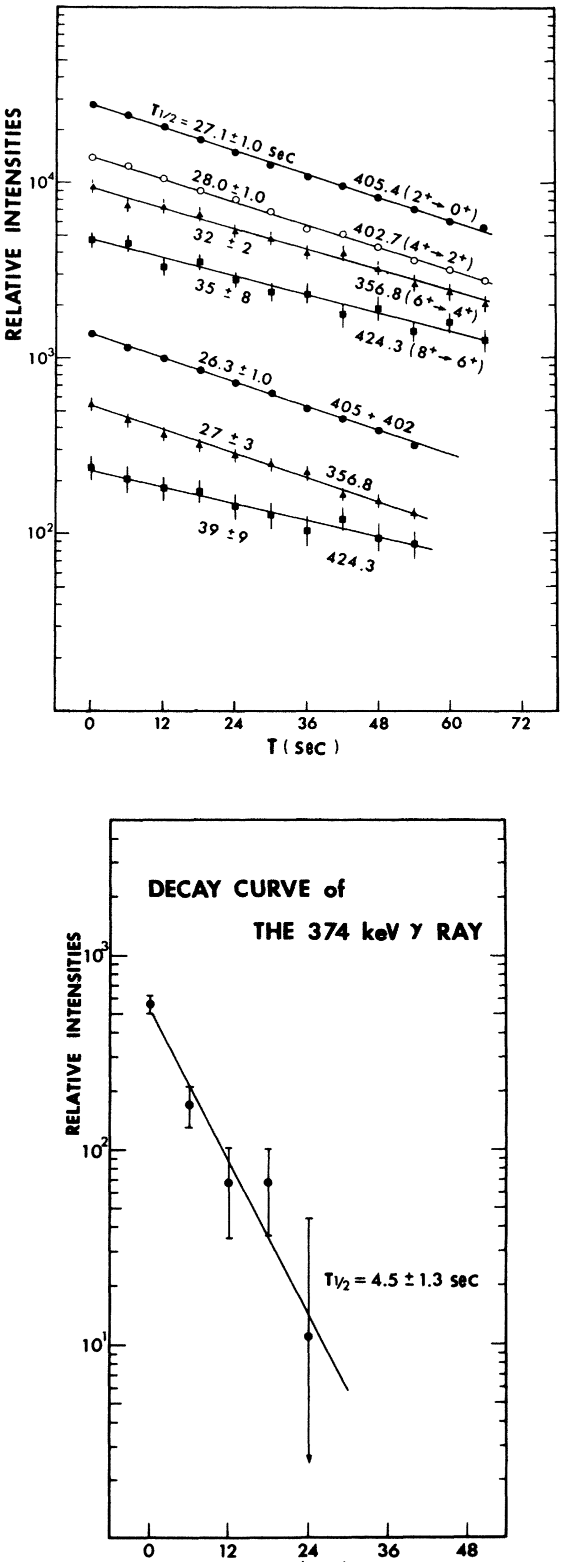

FIG. 3. Decay curves for the known yrast transitions in ^{186}Hg from two separate runs and the new 374.0-keV isomeric transition.

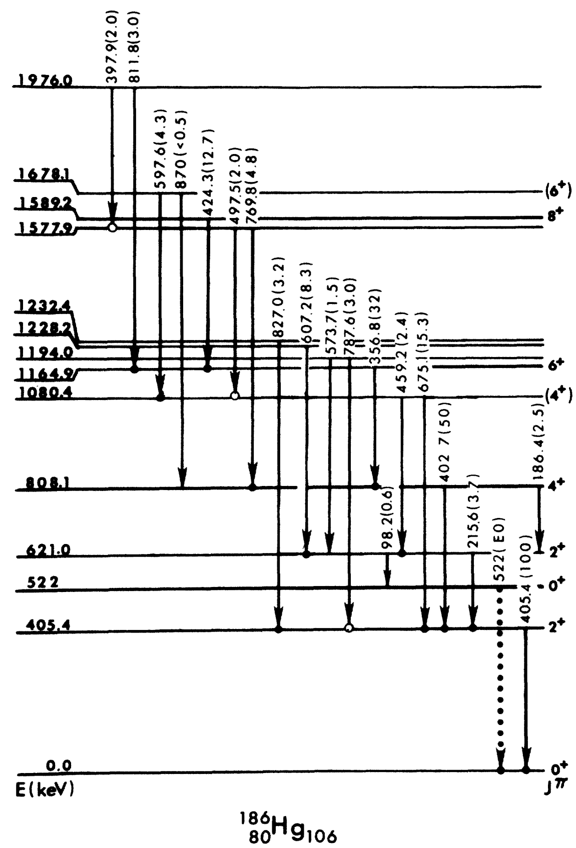

FIG. 4. Energy levels in ^{186}Hg populated by the decay of ^{186}Tl.

Beraud *et al.*[3] placed several of the weaker transitions into three additional ^{186}Hg levels. In addition, several of the weak transitions in Table I could not be analyzed for $T_{1/2}$ and may not belong to the ^{186}Tl decay. Also there are some long lived impurities that obscure lines that could be in this decay.

NEAR-SPHERICAL AND DEFORMED BANDS

In our letter,[1] we presented in more detail the bands built on near-spherical and deformed shapes in ^{188}Hg. Here we present the full results for ^{186}Hg. Figure 5 gives the levels associated with the near-spherical and deformed shapes in ^{186}Hg. The crossing of these bands so that the yrast cascade shifts from one to the other explains the unexpected "forward bending" of the usual moment of inertia plot (Fig. 6) as already shown[1] for ^{188}Hg.

A number of theoretical calculations have been carried out to explain the structure of the light mass mercury isotopes.[7-12] In each case the existence of the two bands is reproduced by a second minimum in the potential at larger deformation

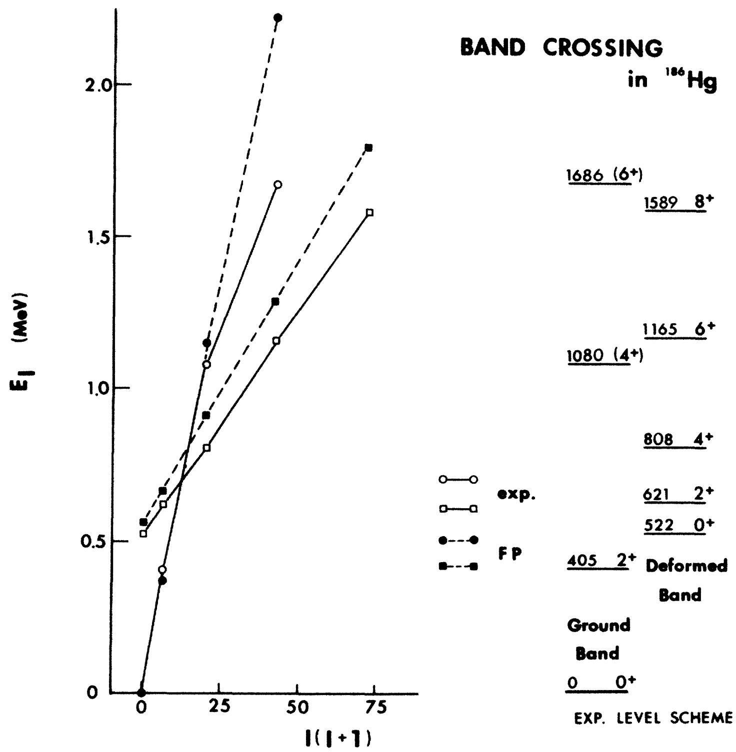

FIG. 5. Levels associated with the near-spherical and deformed bands in ^{186}Hg are shown. On the left the energies of the levels in the two bands are plotted vs $I(I+1)$ and are compared with the calculations of Frauendorf and Pashkevich (Ref. 11).

than that of the other minimum. The successes of these calculations are illustrated in Figs. 5 and 7 which compare the calculations of Frauendorf and Pashkevich[11] and Kolb and Wong[12] with our experimental results. While all of the calculations have two minima, one at an oblate minimum with $\beta \approx 0.15$ and a prolate minimum at $\beta \approx 0.25$, the predicted shape of the ground state is oblate in Refs. 7 and 8 and prolate in Refs. 10–12.

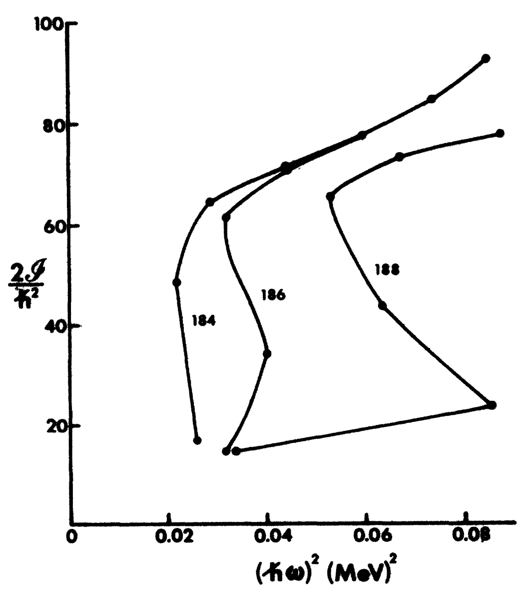

FIG. 6. Plots of the moments of inertia for the yrast cascades in $^{184-188}$Hg are shown for comparison with Fig. 5.

Kolb and Wong[12] have pointed out that the ground-state properties depend sensitively on the single-particle spectra, and this is why earlier calculations[7,8] incorrectly predicted large ground-state deformations in ^{186}Hg. Turning it around, they emphasize that these mercury nuclei provide a good probe of the single-particle spectrum in the deformed region.

The matrix elements for electromagnetic transitions depend on the overlaps of the collective wave functions. Kolb and Wong[12] calculated these overlap integrals which show for ^{186}Hg that as one comes down the yrast cascade from spin 14^+ that there is a crossing from the well deformed band to the near-spherical band around the 4^+ deformed state. As shown in Fig. 7, their calculations reproduce qualitatively our branching ratios.

One difference in branching ratios to be noted in ^{186}Hg compared with the heavier Hg isotopes is the absence of a strong ground-state transition from the 2^+ member of the deformed band. There could be a relatively weak 621-keV transition that is

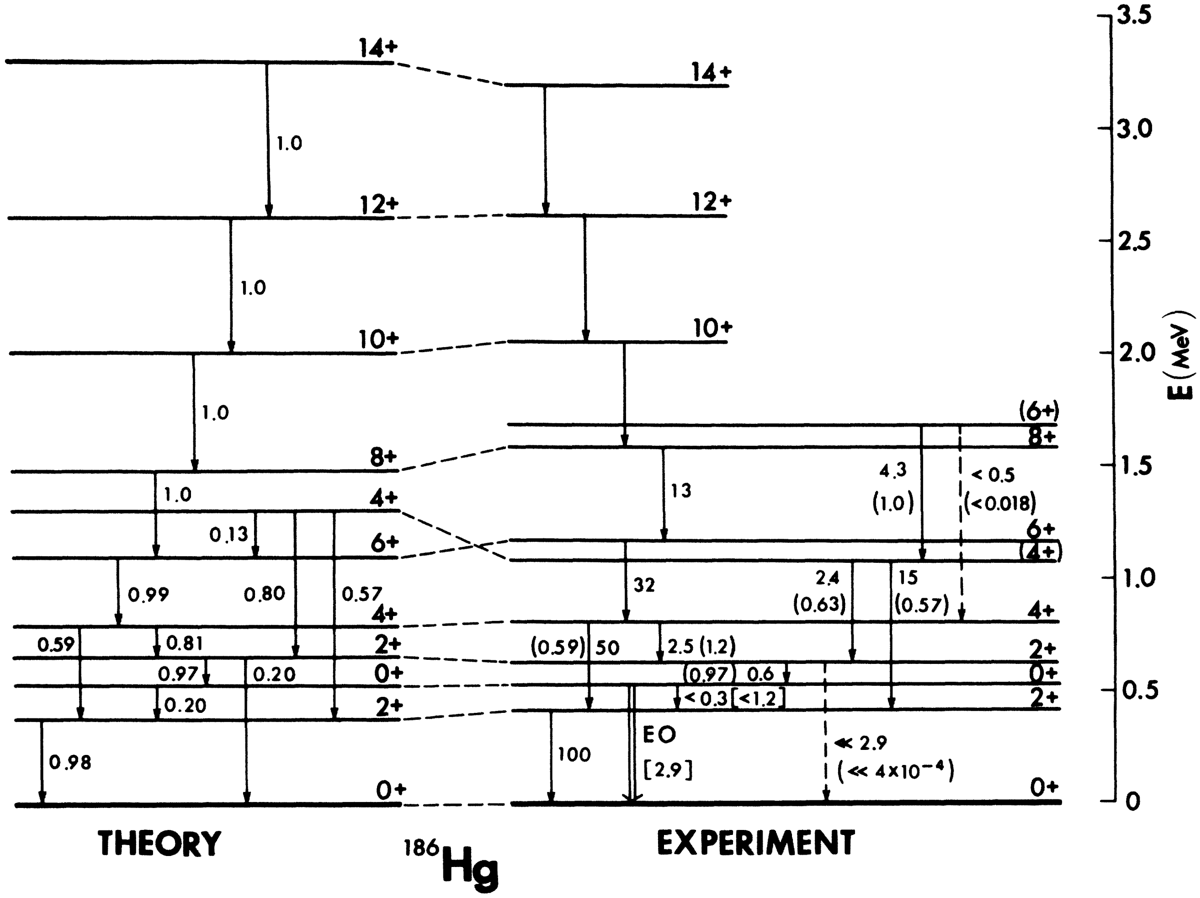

FIG. 7. The energy levels predicted by Kolb and Wong (Ref. 12) are compared with our experimental results. Below our γ-ray intensities in parentheses are given $B(E2)$ values normalized to one of the overlap integrals of Kolb and Wong (Ref. 12) since these are roughly comparable.

masked by a rather strong, longer lived transition of that energy in our spectrum. The longer lived 621-keV transition is much weaker in the spectrum of Beraud *et al.*,[3] but a weak 621-keV transition of uncertain half-life is still seen.

Beraud *et al.*[3] have presented a table of $X(E0/E2;\ 2_2^+ \to 2_1^+)$ values for ^{186,188}Hg. These results may be misleading, however, since $M1$ admixtures are possible, and these have not been measured. Finally the systematics of the behavior of the near-spherical and deformed bands in $^{184-188}$Hg have been represented elsewhere recently.[13,14]

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