Decay of mass-separated ^{190}Tl and ^{190}Hg†

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Radioactive sources containing ^{190}Tl and ^{190}Hg have been produced and mass separated with the University Isotope Separator on line to the Oak Ridge isochronous cyclotron. Multiscaled spectra of γ rays, x rays, conversion electrons, and positrons were obtained, and γ-γ and γ–x-ray coincidences were measured. Two isomers in ^{190}Tl decay have half-lives of 2.6 ± 0.3 min (2^-) and 3.7 ± 0.3 min (7^+). From β decay endpoint energies the 7^+ and 2^- isomers lie within 0.1 MeV of each other, but which is the ground state was not determined. Both isomers have ground-state Q_{EC} values of approximately 7 MeV. The 2^- level undergoes β decay primarily to the 2^+ states at 416.4 and 1099.9 keV in ^{190}Hg, while the decay of the 7^+ isomer feeds a number of different states with spins ranging from 5 to 9. We observed the 5^-, 7^-, and 9^- members of the previously identified structure of negative-parity states resulting from coupling of a rotation-aligned $i_{13/2}$ neutron with $3p_{3/2}$ and $2f_{5/2}$ neutrons. Some additional states having decays consistent with (6^-) and (8^-) assignments perhaps are candidates for less aligned members of the $13/2^+$ band coupled with $p_{3/2}$ and $f_{5/2}$ neutrons. The 20-min ^{190}Hg isotope decays approximately 65% of the time to a level at 171.5 keV, thus making it difficult to study other levels in ^{190}Au. Four new states in ^{190}Au were definitely established, while several new ones were suggested by the present work. The populated levels are predominantly low spin and are fairly closely spaced. The logft value for the transition to the 171.5 keV level is 5.7, so it is likely that this state has a spin and parity of 1^+.

[RADIOACTIVITY ^{190}Tl, ^{190}Tl^m, ^{190}Hg [from Ta, W(^{16}O, $xp+yn$), E = 143, 124 MeV]; mass-separated radioactivities. Measured $T_{1/2}$, E_γ, I_γ, I_{ce}, E_β, $\gamma\gamma$ coin, γx coin. Deduced logft, Q. ^{190}Hg, ^{190}Au deduced levels, J, π, ICC, Λ.]

I. INTRODUCTION

There has been considerable interest in the very neutron deficient Hg isotopes in the last few years. Part of this interest was stimulated by the anomalous isotope shifts observed[1] in ^{183,185}Hg, indicating rather large deformations in the ground states of these Hg isotopes, and part by the successful application of the intermediate coupling model to fit decoupled rotational bands in odd-A nuclei with rather small deformations.[2] Subsequently, the yrast band of the light even-A Hg isotopes was studied by in-beam γ-ray spectroscopy. Proetel *et al.*[3] showed that the yrast band of ^{186}Hg changed from vibrational character below the 4^+ to rotational character above the 4^+ state. From the lifetimes of the states in ^{184}Hg, Rud *et al.*[4] concluded that the deformation was present in the 2^+ level of that nucleus. The change in deformation at the 4^+ state in ^{186}Hg has been confirmed by lifetime measurements.[5] A more recent study of the decay of ^{188}Tl by the UNISOR consortium[6] has revealed that the changeover in the yrast sequence to deformed states occurs at the 6^+ level in ^{188}Hg. This study revealed another interesting feature, the existence of two bands, one having vibrational character based on a nearly spherical ground state and the other having rotational character based on a well-deformed excited 0^+ state. The two bands cross near the 6^+ member of each, producing the apparent shift in the yrast levels.

In order to understand more fully the onset of deformation in the light Hg isotopes, the UNISOR consortium is conducting a systematic study of the decay of the light Tl ($A \lesssim 193$) isotopes. When this study was initiated, very little was known about the structure of ^{190}Hg. An in-beam spectroscopy experiment[7] had revealed the yrast band of levels up through the 8^+ state. This same study suggested the location of (5^-) and (7^-) states which should be populated in the decay of the high-spin isomer in Tl. Five of the strongest transitions in the decay of ^{190}Tl had been observed,[8] but only three of these were placed in a decay scheme. Since the preliminary reports[9] of this work, internal-conversion electrons have been measured, improved γ-ray data have been obtained, and a few new levels and several spins have been assigned. Also, new in-beam spectroscopic studies have been reported[10] which tend to complement and augment the present results.

The decay of ^{190}Hg has been studied previously but only seven transitions were observed[11] and only two excited levels were firmly established.[12] Hence, this decay was studied simultaneously to the ^{190}Tl decay and the results are contained in this report.

II. EXPERIMENTAL DETAILS

The ^{190}Tl sources were generally prepared by bombarding ^{181}Ta foils in the ion source of the UNISOR isotope separator with 143-MeV $^{16}O^{5+}$ ions from the Oak Ridge isochronous cyclotron. The reaction producing most of the ^{190}Tl activity was ^{181}Ta(^{16}O, 7n), although this apparently was not true for one run. During the experiment a Ta target of ~1.5 mg/cm^2 was used, but during the run, ~3 mg/cm^2 of natural tungsten from the ion-source filament was deposited on the target foil. Hence, for that particular run, much of the ^{190}Tl activity was obtained from the decay of ^{190}Pb produced by W(^{16}O, xn) reactions. One run was also made with a tungsten foil to purposely enhance the production of ^{190}Tl from the ^{190}Pb decay.

A schematic diagram of the UNISOR facility shown in Fig. 1 has been described in other reports.[13] Two configurations were used for the target ion-source arrangement. Both utilized an oscillating electron ion source of the Nielsen type. In the first arrangement, the Ta target also served as the entrance window to the ion source. The ^{16}O beam passed through this window and was stopped in a thicker Ta foil within the ion source. For off-line ^{190}Tl measurements, the beam energy was adjusted to maximize the production of ^{188}Tl in the target (the results for the decay of ^{188}Tl are reported elsewhere[6]). Most of the ^{190}Tl activity was probably produced in the catcher foil. The other configuration utilized a graphite cloth as the window to the ion source with the target foil being ~5 cm upstream in the beam. The latter arrangement is preferable because of higher efficiency and ease of operation.

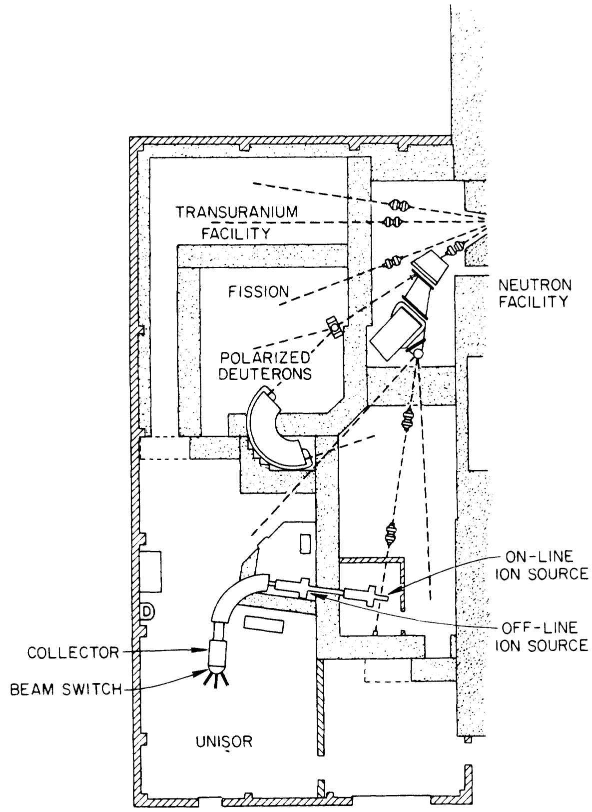

FIG. 1. Schematic diagram of the UNISOR facility. Radioactive nuclei produced by bombarding targets in or near the ion source recoiled or diffused into the ion source. Those that were ionized were mass separated and collected either on foils in the focal plane or on a movable aluminized Mylar tape approximately 3 m behind the focal plane.

The atoms ionized in the ion source were mass separated in the Scandinavian-type isotope separator. Some of the measurements were made on line, i.e., mass 190 was collected on an aluminized Mylar tape which was moved periodically to bring a freshly collected source in front of the detectors. Other measurements were made with sources collected on aluminum foils in the focal plane of the separator and periodically removed by means of a vacuum lock.

We recorded three types of experimental data through the use of modular electronics and three computer-based nuclear analyzer systems. γ-ray, positron, and conversion-electron spectra were recorded in a multiscale mode, in order to measure the half-lives of the two isomers in ^{190}Tl and to identify the transitions associated with daughter activities. Large volume Ge(Li) detectors (10–18%) were used in accumulating both singles and coincidence data. The relative efficiencies of these detectors were determined through the use of an NBS calibration source containing several radioactive standards. The elemental assignments of many of the transitions were made by γ–x-ray coincidences. The γ-γ coincidence data aided in the construction of level schemes for ^{190}Hg and ^{190}Au. The energy signals from both Ge(Li) detectors and the time delay between the two energy pulses, were digitized in an 8192 channel analog-to-digital converter and stored on the magnetic tape for each coincident event. The tapes were subsequently scanned to obtain spectra in coincidence with each γ ray. Nearly 5×10^6 events were accumulated in the longest coincidence run made. Conversion electrons were detected in a Si(Li) detector cooled to liquid nitrogen temperature and internal-conversion coefficients were determined, making it possible to assign multipolarities to many of the transitions in ^{190}Hg. Decay Q values were obtained by measuring positron end-point energies using cylindrical NE-110 plastic scintillators 2.5-cm $\times$5.1-cm diam and 9.0-cm$\times$7.6-cm diam coupled to 7.6-cm photomultiplier tubes. On early runs, half-lives were checked by multiscaling the counts in the high-energy portion of the positron spectra, using a single channel analyzer.

III. DECAY OF ^{190}Tl

A. Experimental results

The γ-ray emissions were studied in several experiments. Much of the information relating to measurement of singles rates came from two runs which will be labeled A and B. In run A the older version of the ion source was used. Tungsten was deposited on the target foil during the run and hence, much ^{190}Pb was presumably produced. Since ^{190}Pb is an even-even nucleus with a 0^+ ground state, its decay resulted in enhanced population of the low-spin isomer in ^{190}Tl. For this experiment a ratio of low-spin to high-spin isomer of ~2 was deduced. In run B with the new ion-source design little or no ^{190}Pb was produced. The ratio of low-spin to high-spin isomer was deduced to be ~0.1 for this case. In both of these experiments spectrum multiscaling was used to obtain the half-lives of the two Tl isomers and to identify γ rays associated with their decay. In run B mass-190 sources collected for 8 min were moved in front of an 18% Ge(Li) detector which recorded eight sequential 1-min spectra. New sources were then moved to the detector and the counts were added to the eight spectra. The first of these eight spectra is shown in Fig. 2. γ-ray transitions following the decay of ^{190}Hg and ^{190}Au have been given special labels, while those following the decay of ^{190}Tl have been labeled only with the decay energy. The resolution for 1.33-MeV γ rays was ~2.0 keV.

The best information concerning half-lives of the two Tl isomers came from run A, due to the fact that there was a more favorable ratio of the two. The decay characteristics of some of the transitions are shown in Fig. 3. The 731.1- and 625.4-keV transitions are from 6^+ and 4^+ states, respectively. The decays through these states are largely from the high-spin isomer of ^{190}Tl. The 683.8-keV transition is from the second 2^+ state to the lowest 2^+ state. Very few of the decays of the high-spin isomer cascade through the second 2^+. Hence, the 683.5-keV half-life is more characteristic of the decay of the low-spin isomer. The 416.4-keV transition is from the first 2^+ state to the ground state. It accompanies the decay of both isomers and consequently has a mixture of the two half-lives. Combining the results shown in Fig. 3 with similar results for other transitions, we deduced half-lives of 3.7 ± 0.3 min for the high-spin isomer and 2.6 ± 0.3 min for the low-spin isomer. This differs with the conclusions of Vandlik *et al.*[8] that the low-spin isomer half-life is $\gtrsim3.6$ min and the high-spin isomer half-life is 2.9 ± 0.4 min.

The relative intensities of γ rays observed to follow the decay of ^{190}Tl were measured in four different experiments. The results for runs A and B are given in columns 2 and 3 of Table I. The results for the other two experiments were similar to those of run B. Note that the higher concentrations of the low-spin isomer in experiment A resulted in larger relative intensities of the 416.4-, 683.5-, and 1099.9-keV transitions (those originating from 2^+ states) with respect to the 625.4, 731.1, and other transitions originating from states with spins of 4 or greater.

Conversion electrons were detected in a Si(Li) detector cooled to liquid nitrogen temperature during run B. This detector was positioned on the

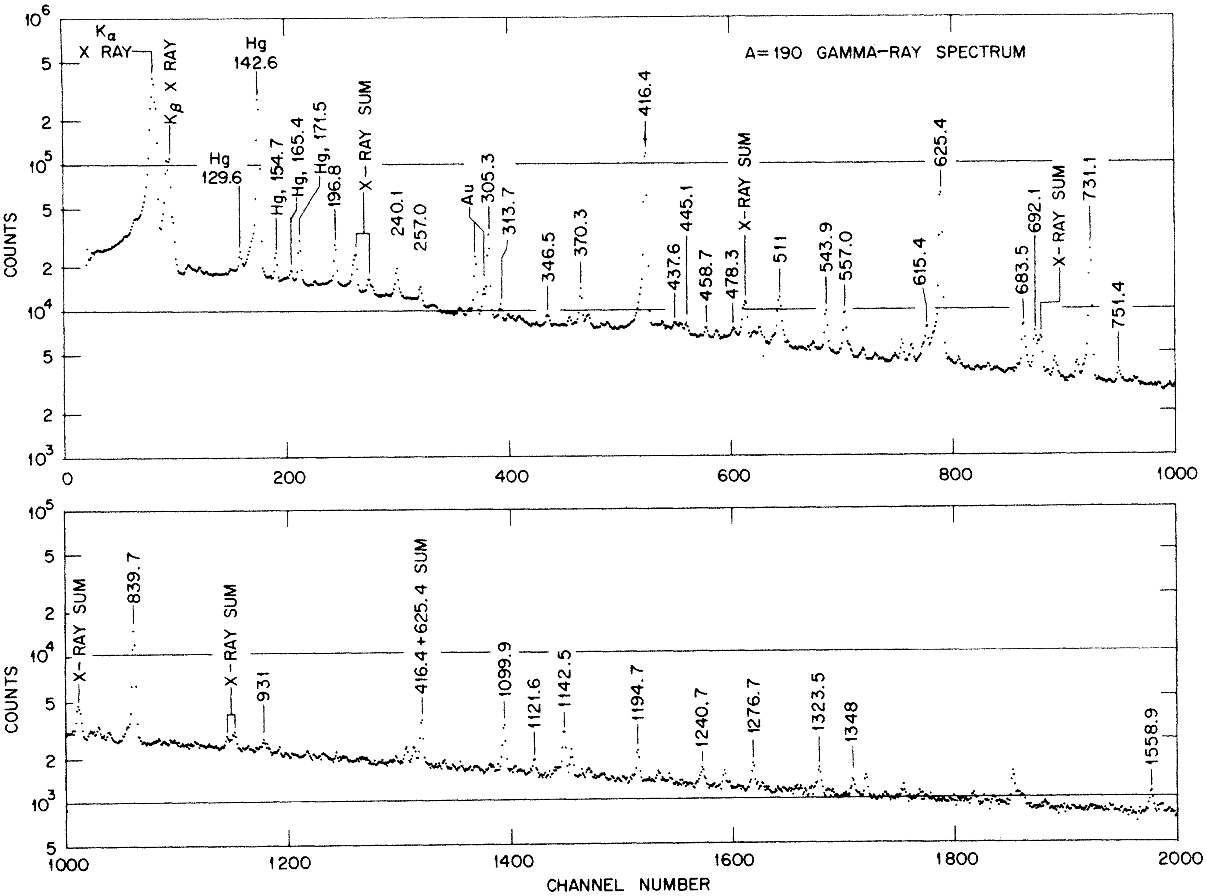

FIG. 2. The first of eight multiscaled γ-ray spectra taken in run B. Those transitions following the decay of ^{190}Hg and ^{190}Au have been given special labels, while those associated with the decay of ^{190}Tl have been labeled only with the decay energy.

opposite side of the source from the γ-ray detector and multiscaled spectra of the conversion electrons and γ rays were obtained simultaneously. The sum of four of the eight sequential spectra is shown in Fig. 4. The full width at half maximum of the K lines is typically 5.5 keV. Using the knowledge that the 2^+ to ground state transition (416.4 keV) must be $E2$, we deduced K and L conversion coefficients for the other transitions, which are listed in columns 6 and 7 of Table I. The ratio of the K to L conversion coefficients for the 416.4-keV transition confirms its $E2$ character.

Coincidence data on γ rays from ^{190}Tl decay were obtained in two separate experiments. Three of the gated spectra from the first coincidence experiment are shown in Fig. 5. The second coincidence run had somewhat more counts and extended over a wider energy range than shown here. Similar gated spectra were obtained for every known γ ray originating from ^{190}Tl decay. The results of the coincidence measurements are given in Table II. Since some of the coincidence peaks are weak, a confidence level has been assigned to each coincidence. Note that most of the coincidence relationships are made with high confidence.

Positron spectra were measured on several runs for the $A = 190$ activity produced with a Ta target, and once for the activity from a W target. End-point energies of 4.18 ± 0.30 and 5.70 ± 0.40 MeV were observed in these runs. The only time the positron group with the 5.7-MeV end point was observed to be relatively strong was in the activity produced with the W target, when a relatively large amount of the low-spin isomer of ^{190}Tl was produced. A Fermi-Kurie plot of this spectrum is shown in Fig. 6(a). The activity above 4.3 MeV decayed with a half-life of 2.6 min, and hence we can assign the 5.7-MeV end point to the decay of the low-spin isomer of ^{190}Tl, probably decaying to the 2^+ state of ^{190}Hg at 416.4 keV. The 2.6-min half-life was also observed on run A for all posi-

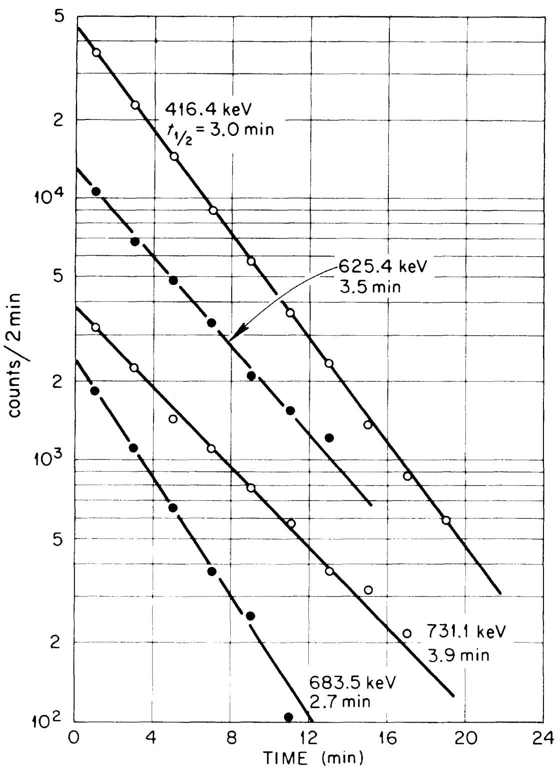

FIG. 3. Decay curves for selected transitions following the decay of ^{190}Tl during run A.

trons above 2.4 MeV.

In run B, when the high-spin isomer of ^{190}Tl was predominant, the spectrum shown in Fig. 6(b) was measured. A small amount of the 5.7-MeV group is present, but its integrated intensity is only 10–15% of the intensity of the group with the next highest end point of 4.18 MeV. Following 5-min collections, 10 time-sequential positron spectra were measured in run B, each for a period of 1 min. The decay curves of the positrons with energies above 2 MeV shown in Fig. 7 are consistent with the high-spin isomer half-life of 3.7 min determined in the γ decay. We are thus able to assign the 4.18-MeV end point to the decay of the 7^+ isomer of ^{190}Tl. The 3.7-min half-life was also measured for the positron decays down to 1 MeV on an early run when the high-spin isomer was predominant.

B. Decay scheme

The decay scheme, shown in Fig. 8, was constructed through use of the coincidence results and accurate energy sums. As is indicated in Fig. 8 most of the transitions are placed by coincidence relationships. The multipolarities given for several transitions were obtained by comparing the experimental conversion coefficients from Table I with the tabulated predictions of Hager and Seltzer.[14] For those transitions appearing to be $M1$-$E2$ admixtures, the dominant component is given first.

The spins were previously known for the 416.4-, 1041.8-, 1772.9-, and 2465.0-keV states, since these are the yrast levels observed by in-beam spectroscopy.[7] The measured multipolarities ($E2$) of the transitions between these states are consistent with these spins. The new level at 1099.9 keV must be a 2^+ state due to the $E2$ nature of the ground-state transition. The level at 1656.9 keV is assigned 3^+ since it decays by $M1$-$E2$ admixed transitions to both 2^+ and 4^+ states. The 5^- and 7^- assignments for states at 1881.5 and 2078.3 keV are based on their $E1$ decays and the fact that $5^-, 7^-, 9^-, \ldots$ bands have been observed in heavier Hg isotopes. The 5^- and 7^- states were placed at incorrect energies in the earlier in-beam work,[7] but were correctly placed in the more recent in-beam work of Beuscher *et al.*[10] The 9^- assignment for the state at 2335.3 keV was made in Ref. 10. The new level at 2318.7 keV depopulates by three transitions to 4^+, 5^-, and 7^- states. The only assignments consistent with these final spins are 5^- or 6^+. A 6^+ level would decay by $E1$ by the 7^- state. The conversion coefficient for the 240.1-keV transition was difficult to obtain due to the presence of contamination peaks, but the approximate value obtained appears to require an $M1$-$E2$ admixture. The L conversion line is also in a region of high line density, but its value is more consistent with $E2$. These approximate conversion coefficients indicate that the 240.1-keV transition is more likely $E2$ than $E1$. Hence, the assignment of 5^- is made. The uncertain (2^+) assignment for the state at 1558.9 keV is based on its decay to 0^+ and 2^+ states. The state at 2200.8 keV is tentatively assigned a spin and parity of 5^+ based on the $E2$ character of the 543.9-keV transition and the fact that it is more strongly populated by the high-spin isomer of Tl. The 2251.8-keV state could be assigned spins of 5^-, 6^-, or 7^- based on the $E2$ character of the 370.3-keV transition to the 5^- level and on the presence of the 478.5-keV transition to the 6^+ level. Nuclear structure arguments will be given later to demonstrate our preference for 6^-. The level at 2392.1 keV is based on the coincident 313.7-keV transition to the 7^- state. Unfortunately, any possible transition to the 5^- 1881.5-keV state would be obscured by the 511-keV annihilation peak. The level at 2424.8 keV is assigned on the basis of a 346.5-keV transition feeding the 7^- state. If it also decays to the 5^- state, the transition would be camouflaged by another γ ray.

As was mentioned above, the different relative

TABLE I. Decay energies, relative γ-ray intensities, and K conversion coefficients for transitions following the decay of ^{190}Tl.

							Theoretical α_K [a]		
E_γ (keV)	I_A	I_B	I_L [b]	I_H [b]	α_K	α_L	$E1$	$M1$	$E2$
196.8		4.7	0.4	5.0	0.192	≤0.128	0.063	1.10	0.180
240.1	2.7	3.7	2.0	3.8	~0.2	0.066	0.039	0.55	0.108
257.0		1.6	0.1	1.7	<0.31		0.033	0.47	0.091
305.3	7.3	16	1.3	17.0	0.019		0.022	0.30	0.060
313.7		1.4	−0.1	1.5	≤0.174		0.021	0.28	0.056
346.5		1.3	−0.1	1.4					
370.3	1.8	4.6	−0.1	4.9	0.037		0.014	0.18	0.038
416.4	100.0	100.0	100	100	0.030	0.0095	0.011	0.13	0.030
437.6		1.0	0.5	1.0					
445.1 [c]		1.1							
458.7		1.0							
478.3		1.2	0.0	1.3					
543.9	2.9	5.8	0.9	6.2	0.0145		0.0061	0.062	0.016
557.0	3.7	6.7	1.6	7.0	0.0198		0.0058	0.059	0.016
615.4	2.4	4.5	1.0	4.7	0.0245		0.0048	0.048	0.013
625.4	43	85.5	13.9	90.2	0.0125	≤0.0034	0.0046	0.044	0.0125
683.8	9.6	8.0	10.6	7.8	0.015		0.0041	0.035	0.0103
692.1	1.9	4.9	−0.2	5.2					
731.1	16	38.3	0.7	40.8	0.0084		0.0034	0.030	0.0088
751.4 [c]		1.2							
839.7	11	24.8	1.6	26.3	0.0023		0.0026	0.020	0.0068
931 [c]		1.1							
1099.9	7.6	5.1	9.3	4.8	0.0033		0.0017	0.0104	0.0041
1121.6 [c]		1.3							
1142.5		3.8							
1194.7 [c]		2.3							
1240.7		1.4	0.3	1.5	≤0.0064		0.0014	0.0081	0.0034
1276.7		1.4	0.8	1.4	≤0.012		0.0013	0.0074	0.0032
1323.5 [c]		1.8							
1348 [c]		0.8							
1558.9		1.0							

[a] Reference 14.

[b] I_L and I_H are deduced relative intensities for the decay of the low-spin and high-spin isomers in ^{190}Tl. See text for details.

[c] Transition not placed in decay scheme.

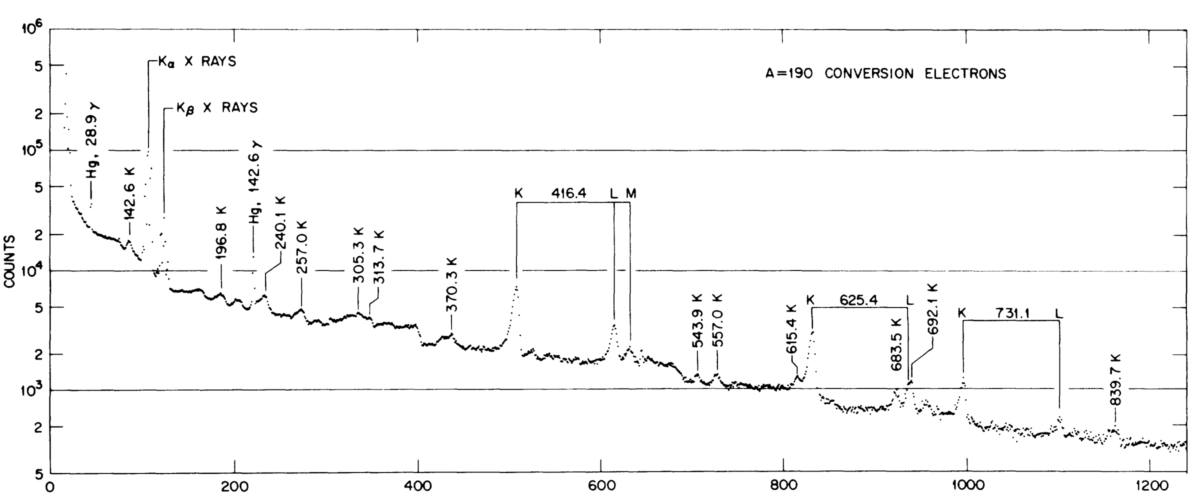

FIG. 4. The sum of four multiscaled conversion-electron spectra taken in run B. The sharp line at 142.6 keV is a γ ray from ^{190}Hg decay.

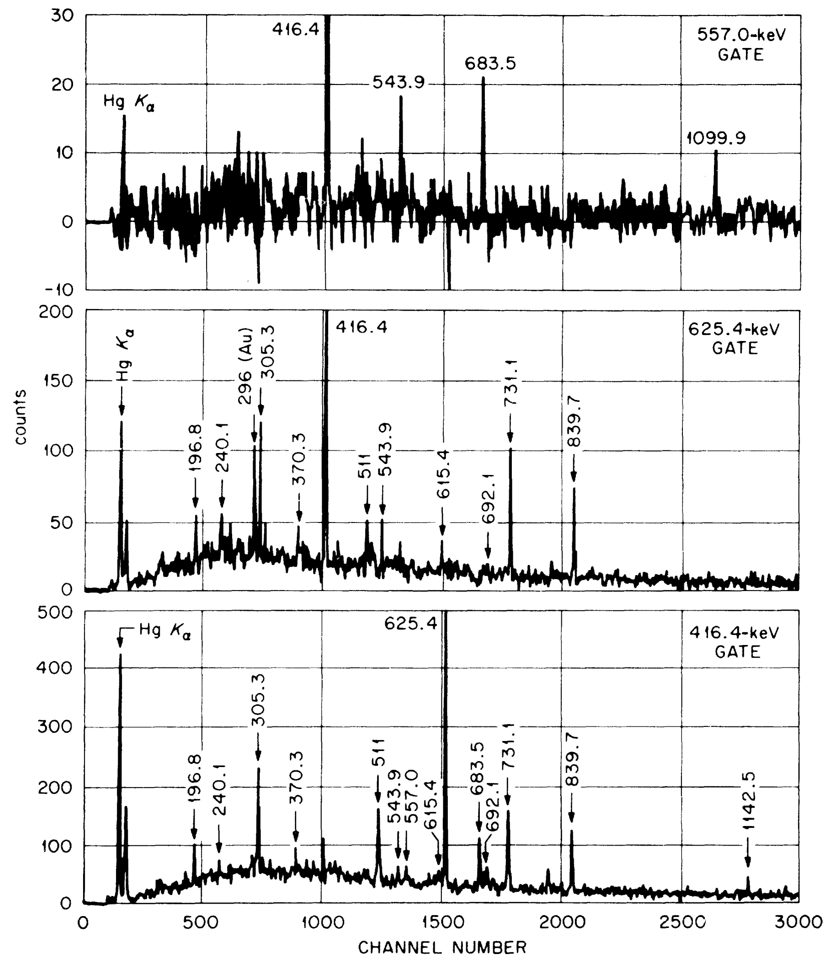

FIG. 5. Three typical gated spectra from the first coincidence run. Spectra from the second coincidence run had somewhat more counts and extended up to approximately 2 MeV.

intensities of runs A and B probably resulted from different ratios of low-spin to high-spin isomers produced during these experiments. From systematics, the most likely spins of these isomers in Tl are 2^- and 7^+, and thus the two isomers will undergo β decay to different states in ^{190}Hg. By assuming that the lowest 2^+ state is directly populated in β decay by only the 2^- isomer and that the states above the 6^+ state are populated directly by only the 7^+ isomer, we were able to deduce the relative abundance of each isomer. The ratio of low-spin to high-spin isomer produced in run B was deduced to be ~0.1 while the same ratio for run A was ~2. Using the relative abundances of high-spin and low-spin isomers in these two runs, coupled algebraic equations were set up, the solutions of which gave the relative intensities one would obtain if the sources were pure isomers. These results are given in columns 4 and 5 of Table I. Because of this reduction process the errors in the relative intensities for the low-spin isomer are large compared to the smaller intensities; intensities less than 3 units are probably consistent with zero. Since the source during run B was essentially pure high-spin isomer (~90%), the errors on the high-spin isomer intensities are largely experimental and are typically ~10%.

From examination of Table I, column 4, and Fig. 8, it is apparent that the low-spin isomer decays directly to the 416-keV, 2^+ state ~70% of the time, to the 2^+ state at 1100 keV with ~17% probability and to all other states with 13% probability. The decay of the high-spin isomer is much less selective; transitions to many different states are apparent. The 7^- state at 2078 keV gets ~14% of the decays; the 6^+ state at 1773 keV, approximately 17%; the 8^+ state at 2465 keV, ~5%; the state at 2252 keV, ~6%; the

TABLE II. Coincidence relationships between transitions following the decay of ^{190}Tl.

		Coincident lines																															
Energy	Gate (No.)	a	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
196.8	(1)	b		c	c		c			b								b					b										
240.1	(2)	b	c			b				b								b			c		b										
257.0	(3)	c	d			b				b								b			b		b										
305.3	(4)	b		b	b		b	d		b								b			b		c										
313.7	(5)	c	c			c				b								b			b		b										
346.5	(6)	b	b			b				c								b			b		c										
370.3	(7)	c								b								b					b										
416.4	(8)	b	b	c	b	b	c		c						b	c	c	b	b	c	b	d	b				b		c	c	c	c	
437.6	(9)	d																b					c										
445.1	(10)	c	d							c								c															
458.7	(11)	d																	d														
478.3	(12)	d								c								c															
543.9	(13)	b								b						b	b	b	b						b				c				
557.0	(14)	b								b					b				b						b								
615.4	(15)	c								c					b			b															
625.4	(16)	b	b	b	c	b	b		b	b					b		b		c	b	b		b							d			
683.5	(17)	b								b					c	b		b				c	c										
692.1	(18)	c								b								b			b												
731.1	(19)	b		b	c	b	b			b				b				b		c													
751.4	(20)	c																c															
839.7	(21)	b	b						b	b								b															
931	(22)	c								c																							
1099.9	(23)	b													b	b																	
1121.6	(24)	d																															
1142.5	(25)									b																							
1194.7	(26)	c				c				c								c															
1240.7	(27)																	d															
1276.7	(28)	d								b								b															
1323.5	(29)									d								c															
1348	(30)																																
1558.9	(31)	d																															

[a] Hg x rays, other column numbers correspond to numbers shown in column 2.
[b] >90% confidence in coincidence relationship.
[c] >70% confidence in coincidence relationship.
[d] >40% confidence in coincidence relationship.

9^- state, ~2%; the 2393-keV state, ~2%. Surprisingly, the 5^- state at 1882 keV gets (13 ± 6)% of the decays and the 4^+ state (17 ± 14)%. The means by which the 5^- and 4^+ levels are populated is not clear. Since the subtraction of very large numbers is involved in the deduction of the feeding of the 4^+ level, a large error is involved; its feeding could possibly be consistent with zero.

Logft values, tabulated in Table III, were calculated by assuming no direct population of the 0^+ ground state by either isomer, and through the use of logf_0 and logf_1 values of Gove and Martin.[15] Estimated error limits include uncertainties on the experimental relative intensities propagated through the reduction process to the relative intensities of the low-spin and high-spin isomers. They also contain uncertainties in half-life. The error limits have not been increased to account for unobserved γ-ray feeding or depopulation of a state.

The logft values listed in Table III are consistent, within experimental uncertainties, with an assignment of 2^- for the low-spin isomer. However, based upon the guidelines of Raman and Gove,[16] the logft values are too small for four states to be consistent with the 7^+ assignment for the high-spin isomer. To elevate these results to be consistent with the decay of a 7^+ isomer would require 36 ± 16 units of unobserved γ-ray feeding. The total γ-ray strength not placed in the level scheme (see Table I) amounted to less than 10 units. If another 10–40 units were observed it would have to be highly fragmented, i.e., in lines with 1 unit or less of intensity. If one

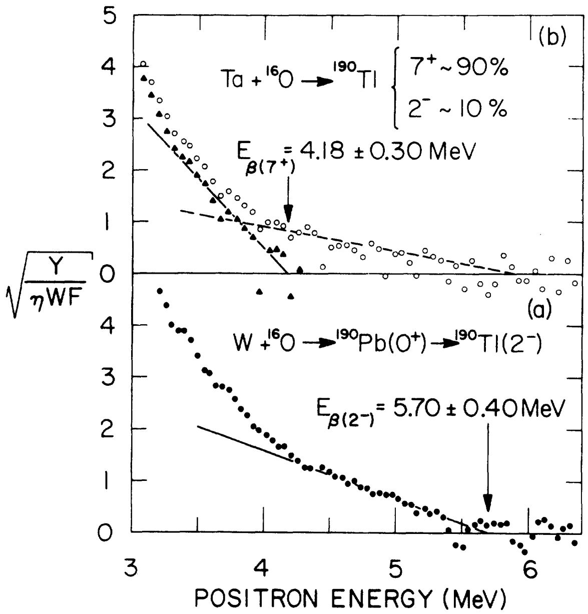

FIG. 6. (a) Fermi-Kurie plot of the positron decay of ^{190}Tl produced by ^{16}O bombardment of a W target. The 2^- isomer was produced in relative abundance and its decay gives the group with the 5.7-MeV end point. Points for which the background exceeded the foreground yield are plotted below the energy axis. The line is a least-squares fit to the data. (b) Fermi-Kurie plot of the positron spectrum measured in run B when the 7^+ isomer of ^{190}Tl was predominant. A weak group from the decay of the 2^- isomer can be seen, but the 4.18-MeV group is 7–10 times more intense and is associated with the decay of the 7^+ isomer. The dashed line is a least-squares fit made to the high energy group solely for the purpose of subtracting out its yield before fitting the stronger low-energy group, and the solid line is a least-squares fit to the difference yield of the inner group.

assumes that the high-spin isomer is 5^+ or 6^-, then many of the discrepancies with these states vanish, but the population of the 9^- state is then unexplained. The possibility of an intermediate-spin isomer, the decays of which were included in the high-spin isomer results, due to the technique of data reduction, could resolve the discrepancies. To investigate this possibility one should consider which neutron and proton orbitals combine to produce these isomers. In the heavier Tl isotopes the 7^+ and 2^- isomers supposedly arise from $(\pi s_{1/2}\nu i_{13/2})_{7+}$ and $(\pi s_{1/2}\nu f_{5/2})_{2-}$ configurations.[17] Another possible contributor to low-energy configurations is the $\pi h_{9/2}$ level which drops with mass number in the Tl isotopes and is probably around 300 keV in ^{191}Tl.[18] The possible contribution of the $\nu p_{3/2}$ level which is the ground state of the light Hg nuclei should also be considered. These single particle orbitals lead to the following possible configurations for

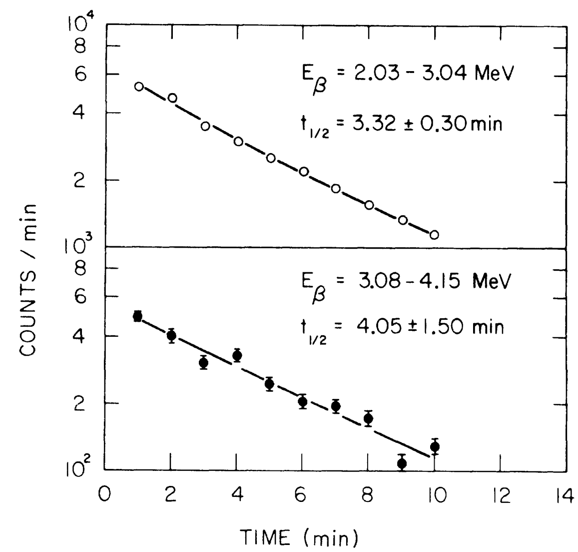

FIG. 7. Decay curves of those positrons in two energy regions in the upper half of the energy spectrum for decay following bombardment of Ta by ^{16}O, in which the 7^+ isomer of ^{190}Tl was produced predominantly. The lines are least-squares fits to the data with a small, time-independent, background activity plus an activity with the half-life given in the figure.

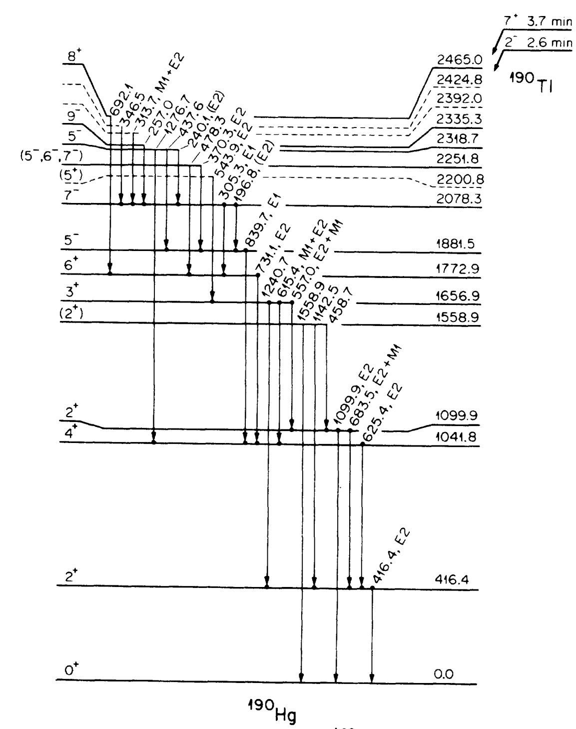

FIG. 8. The decay scheme for ^{190}Tl. Transitions seen in coincidence with other transitions below it are indicated with dots on the tip of the arrow; those in coincidence with transitions above have dots on the tail of the arrow. Transition energies and multipolarities determined by conversion coefficient measurements are given for each transition.

TABLE III. Logft values for states populated in ^{190}Hg by high-spin and low-spin isomers in ^{190}Tl. It is assumed that there is no direct population of the ground state by either isomer. Logf_0 and logf_1 values were taken from Ref. 15. Upper and lower limits of each logft value are given in parentheses.

State		High-spin isomer		Low-spin isomer	
E	I^π	Logf_0t [a]	Logf_1t [b]	Logf_0t [a]	Logf_1t [b]
416.4	2^+	∞ (∞ / 6.67)	∞ (∞ / 8.69)	6.05 (6.18 / 5.90)	8.07 (8.20 / 7.92)
1041.8	4^+	6.60 (7.37 / 6.22)	8.54 (9.31 / 8.16) [c]	6.72 (∞ / 6.35)	8.65 (∞ / 8.29)
1099.9	2^+	7.17 (8.23 / 6.89)	9.10 (10.16 / 8.82) [c]	6.50 (6.68 / 6.35)	8.43 (8.61 / 8.28)
1656.9	3^+	6.81 (7.17 / 6.50)	8.70 (9.06 / 8.39) [c]	7.23 (∞ / 6.86)	9.12 (∞ / 8.75)
1772.9	6^+	6.40 (6.76 / 6.11)	8.27 (8.63 / 7.98)	∞ (∞ / 7.07)	∞ (∞ / 8.94)
1881.5	5^-	6.44 (6.83 / 6.15)	8.29 (8.68 / 8.00)	7.62 (∞ / 6.82)	9.47 (∞ / 8.67)
2078.3	7^-	6.40 (6.71 / 6.14)	8.24 (8.55 / 7.98)	∞ (∞ / 6.92)	∞ (∞ / 8.76)
2200.8	(5^+)	6.71 (6.98 / 6.45)	8.53 (8.80 / 8.28)	7.42 (∞ / 7.04)	9.24 (∞ / 8.86)
2251.8	$(5^-, 6^-, 7^-)$	6.67 (7.07 / 6.38)	8.48 (8.88 / 8.19)	...	...
2318.7	5^-	6.61 (6.98 / 6.32)	8.41 (8.78 / 8.12)	6.75 (7.47 / 6.45)	8.55 (9.27 / 8.25) [d]
2335.3	9^-	7.18 (7.59 / 6.97)	8.98 (9.39 / 8.77)	...	...
2392.0		7.20 (7.76 / 6.93)	8.99 (9.55 / 8.72)	∞ (∞ / 7.28)	∞ (∞ / 9.07)
2424.8		7.27 (7.85 / 7.00)	9.05 (9.63 / 8.77)	∞ (∞ / 7.27)	∞ (∞ / 9.05)
2465.0	8^+	6.68 (7.08 / 6.44)	8.46 (8.66 / 8.22)	...	...

[a] Logft if the transition is allowed.
[b] Logft if the transition is first forbidden unique.
[c] Values inconsistent with decay of a 7^+ isomer. To elevate these three values to consistency with a 7^+ isomer would require 36 ± 16 units of missed γ feeding.
[d] Value inconsistent with $2 \to 5$ transition. However, less than 1 unit of missing γ-ray feeding could produce this discrepancy.

^{190}Tl: $(\pi s_{1/2}\nu f_{5/2})_{2^-}$, $(\pi s_{1/2}\nu i_{13/2})_{7^+}$, $(\pi h_{9/2}\nu f_{5/2})_{7^+}$, $(\pi h_{9/2}\nu i_{13/2})_{2^-}$, $(\pi s_{1/2}\nu p_{3/2})_{2^-}$, and $(\pi h_{9/2}\nu p_{3/2})_{3^-}$. It seems that, even if the $\pi h_{9/2}$ and $\nu p_{3/2}$ states are contributing, there would be only two isomers, one a 7^+ and the other a 2^- or 3^-. The most probable combination is still 2^- and 7^+. There is evidence[20] that the 5^- level at 1881 keV is a two-quasiparticle state composed of $i_{13/2}$ and $p_{3/2}$ neutrons. The $7^+ \to 5^-$ transition is surely not retarded and hence the most favored configuration for the 7^+ isomer in Tl is the $(\pi s_{1/2}\nu i_{13/2})_{7^+}$.

C. Discussion

Turning now to the structure of ^{190}Hg, the low-lying levels appear to be of a vibrational nature with the first excited state resulting from a quadrupole phonon, and the 2^+ and 4^+ states near 1

MeV being members of the two-phonon triplet. The 0^+ member of this triplet has never been observed. The positive-parity levels around 1.6 MeV are at the correct excitation to be three-phonon states but decay of the 3^+ state to the first excited state and decay of the (2^+) to the two lowest states indicates that the states are not predominantly collective. The vibrational model predicts that transitions from two-phonon states to one-phonon states are $E2$ transitions. In the present case the 683.5-keV transition is 81% $E2$ and 19% $M1$, yielding a mixing ratio $\delta^2 = E2/M1$ of 4.3. This compares with values 3.2, 0.7, 3.4, and 1.8 obtained for $^{192,194,196,198}Hg$, respectively.[19] This significant $M1$ admixture shows a shortcoming of the simple vibrational model in describing the structure of Hg.

The negative-parity states are believed to result from the coupling of two neutrons, one in an $i_{13/2}$ orbital and the other in a $p_{3/2}$ or $f_{5/2}$ orbital, to different rotation states of a slightly deformed core.[20] In the odd Hg isotopes (e.g., ^{191}Hg) the $i_{13/2}$ band appears to exhibit a Coriolis alignment of the $i_{13/2}$ neutron along the rotation axis since the $\frac{13}{2}^+$, $\frac{17}{2}^+$, $\frac{21}{2}^+$, ... members have essentially the same spacings as the 0^+, 2^+, 4^+, ... sequence of the even-A core.[10] The other states of this band, i.e., $\frac{15}{2}^+$, $\frac{19}{2}^+$, ..., appear at higher energies and again have spacings similar to the spacings between the $\frac{13}{2}^+$, $\frac{17}{2}^+$, $\frac{21}{2}^+$, ... levels. The 5^-, 7^-, 9^-, ... levels in the even Hg nuclei, which have also been populated in (α, xn) experiments,[10] probably result from the coupling of a $p_{3/2}$ neutron with the core-decoupled $\frac{13}{2}^+$, $\frac{17}{2}^+$, $\frac{21}{2}^+$, ... members of the $\frac{13}{2}^+$ band. Hence, one would expect 6^-, 8^-, 10^-, ... states resulting from the less favored $\frac{15}{2}^+$, $\frac{19}{2}^+$, $\frac{23}{2}^+$, ... members. These qualitative arguments are verified by the calculations of Neergard, Vogel, and Radomski, the results of which are shown in Fig. 9.

We observed a level at 2251.8 keV which must have spin and parity of 5^-, 6^-, or 7^-, as discussed earlier. This state lies above the 7^- level of this 5^- band and thus is a candidate for the 6^- member by analogy to the fact that the $\frac{15}{2}^+$ member of the $i_{13/2}$ band lies above the $\frac{17}{2}^+$ state. In a similar way the 8^- should be at a slightly higher energy than the 9^- band member; levels observed at 2392.1 and 2424.9 keV are candidates for this state. The second 5^- state at 2318.5 keV could represent the coupling of an $f_{5/2}$ neutron with the $\frac{15}{2}^+$ state. The levels observed by Lieder *et al.*[22] through in-beam spectroscopy are also shown in Fig. 9. They do not report a 6^- state, but do place an 8^- state feeding the 7^- state with a 239.9-keV transition. The second 5^- state observed in this work decays to the 7^- state with a 240.1-keV

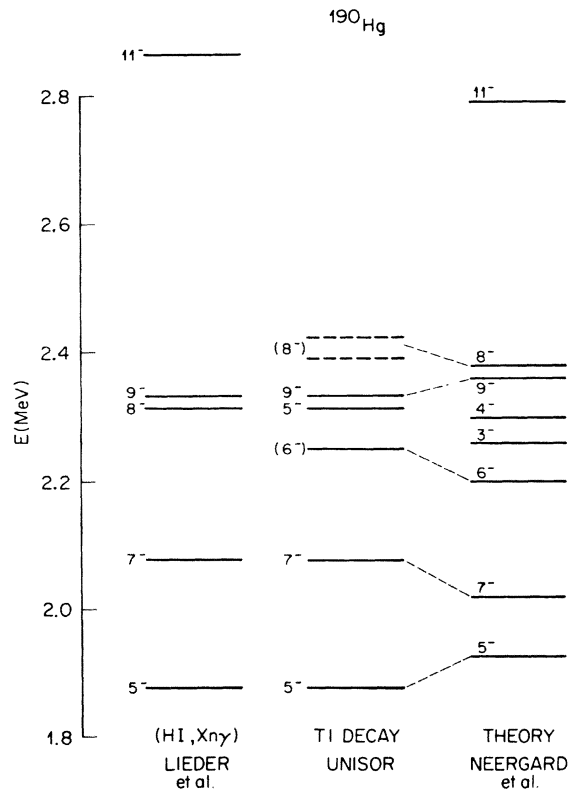

FIG. 9. Comparison of negative-parity levels of ^{190}Hg in experiment and theory. The in-beam results of the first column came from Ref. 22, while the theoretical calculations are contained in Ref. 21.

transition, and must be 5^- since it also decays to 5^- and 4^+ levels. It is difficult to understand the different assignments in our work and that of Lieder *et al.*; it is possible that there are two close-lying states near 2318.7 keV.

From the β^+ end-point energies and knowledge of the decay schemes, electron capture Q values were deduced. The group with the (5.7 ± 0.4)-MeV end point from decay of the 2^- isomer almost certainly is due to decay to the 2^+ state at 0.416 MeV, giving an experimental mass difference of the 2^- isomer and the ^{190}Hg ground state of 7.1 ± 0.4 MeV. Since the decay of the 7^+ isomer strongly feeds three levels in the range of excitation, $E_x = 1.77-2.08$ MeV, and the resolution of the positron detector is poor, it is difficult to say exactly how much energy should be added to the observed 4.2 ± 0.3-MeV end point to obtain the total decay energy of the 7^+ isomer. Assuming the observed end point corresponds to decay to the 6^+ state at 1.773 MeV, we find that the 7^+ isomer in Tl has a decay energy of 7.0 ± 0.3 MeV, placing it 0.1 ± 0.3 MeV below the 2^- isomer. If a weighted mean of the 1.773-, 1.881-, and 2.078-MeV excitations is used, the 7^+ is calculated to lie slightly higher ($\lesssim$100 keV) then the 2^- isomer. This is consistent with the systematic trend of the 7^+ isomers seen in the heavier Tl isotopes where this energy difference is 544 keV for ^{198}Tl and 395 keV for ^{196}Tl.[17] From this trend it is likely that the ground state of ^{188}Tl would be 7^+. The experimental values of Q_{ec} for both isomers agree well with the values of 7.00 MeV predicted by systematics[23] and 7.03 MeV predicted by the Garvey-Kelson mass formula,[24] but not with the value of 6.5 MeV predicted by Seeger and Howard[25] or the Myers-Swiatecki prediction[26] of 5.99 MeV.

IV. DECAY OF ^{190}Hg

The decay of the 20-min ^{190}Hg was observed simultaneously with the measurement of ^{190}Tl decay. Transitions associated with the ^{190}Hg decay were identified by half-life and through coincidence relationships with Au x rays and γ rays. In addition, the low-energy transitions were observed both in singles and coincidence measurements with a Ge(Li) x-ray detector. The spectrum obtained with the x-ray detector is shown in Fig. 10.

The energies, relative intensities, and coincident photons for 24 transitions associated with the Hg decay are given in Table IV. The transition energies in parentheses resulted from our data in both x-ray and γ-ray detectors, but due to the presence of the giant peak at 142.6 keV, there is some uncertainty in these transitions. The relative intensities of the strongest transitions agree fairly well with the previous results of Kilcher[11] which are also displayed in the table for comparison. Most of the γ-ray strength is the 142.6-keV transition, with the next largest one being the 171.5-keV line. While the confidence level is low for many coincidence relationships, note that it is high for Au x rays, confirming the association of these transitions with the decay of Hg.

To get an estimate of the ground-state feeding by electron capture the relative intensities of the Au $K\alpha_1$ and $K\alpha_2$ x rays were measured. By using the formulas and tables of Martin and Blichert-Toft,[27] corrections were made for capture from higher shells and for Auger conversion of K-shell vacancies. Measured internal conversion coefficients[11] were used to account for K-shell vacancies due to that process. Dionisio *et al.*[28] reported a Q_{ec} of 2100 ± 80 keV for ^{190}Hg decay, but recently revised the value to 3070 ± 300 keV.[29] Using the more recent value the intensity due to β^+ decay was calculated by use of a table in Ref. 15. In making these corrections the transitions were assumed to be allowed. The result of this exercise is that the 171.5-keV state is populated by 65^{+20}_{-10}% of the Hg decays. Other excited states may receive 10% of the feeding, so the ground state is fed 25% of the time or less.

The decay scheme for ^{190}Hg is shown in Fig. 11. Of the levels shown, only the 28.9- and 171.5-keV levels were previously established.[12] Solid lines represent those levels established in the present work by high confidence γ-γ coincidence results or by more than one intermediate confidence coincidence result. Levels suggested by single intermediate or lower confidence coincidence results are shown as dotted lines. The spin assignments are partially the results of previous work. A spin of 1 for the ground state was established through the atomic beam experiments of Chan, Ehlers, and Nierenberg.[30] The 1^+ assignment for the 171.5-keV state is based on the strong (~65%) electron-capture feeding of this state. Using the Q_{ec} measured by Dionisio *et al.*,[29] we find that the decay to this state has a $\log f_0 t$ value of 5.7, which means it is an allowed Gamow-Teller transition, according to the strong rule of Raman and Gove.[16] Since 0^+ to 0^+ transitions are isospin forbidden, the 1^+ assignment is established. Suggested spins of other levels result from previously measured conversion coefficients.[11] The $E1$ character of the 171.5- and 142.6-keV transitions then establishes that the ground state is a 1^- state and the 28.9-keV level has negative parity. Assuming a 25% branch the $\log f_0 t$ for the ground-state transition is 6.2 which is consistent with the first-forbidden nonunique character of a $0^+ \to 1^-$ transition. The 28.9-keV transition is mainly $M1$, but with a small admixture of $E2$. This restricts the spin of this level to either 1 or 2. Due to the $M1$ character of the 129.6- and 154.7-keV transitions, the levels at 129.6 and 284.2 keV are likely $(0,1,2)^-$ and $(0,1,2,3)^-$ states, respectively.

The nature of the levels in ^{190}Au are poorly understood, perhaps due to the complication of odd-odd nuclei in a transition region and to the scarcity of experimental data. The low-lying negative-parity states probably result from the combination of $s_{1/2}$ and $d_{3/2}$ protons with $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ neutrons. The allowed Gamow-Teller transition between ^{190}Hg and the ^{190}Au 1^+ state at 171.5 keV does not change l; so the odd proton must have the same l value as the odd neutron. Only the $l = 5$ orbital lends itself to this type of transition in this region. This then suggests that the 1^+ state has a large component of $(\pi h_{11/2}, \nu h_{9/2})$.

We note that the observed $\log f_0 t$ value of 5.7 lies between the lower limits of 5.1 and 5.9 given in the Raman and Gove[16] strong rules on first-forbidden, nonunique β decay for $Z \geq 80$ and $Z < 80$, respec-

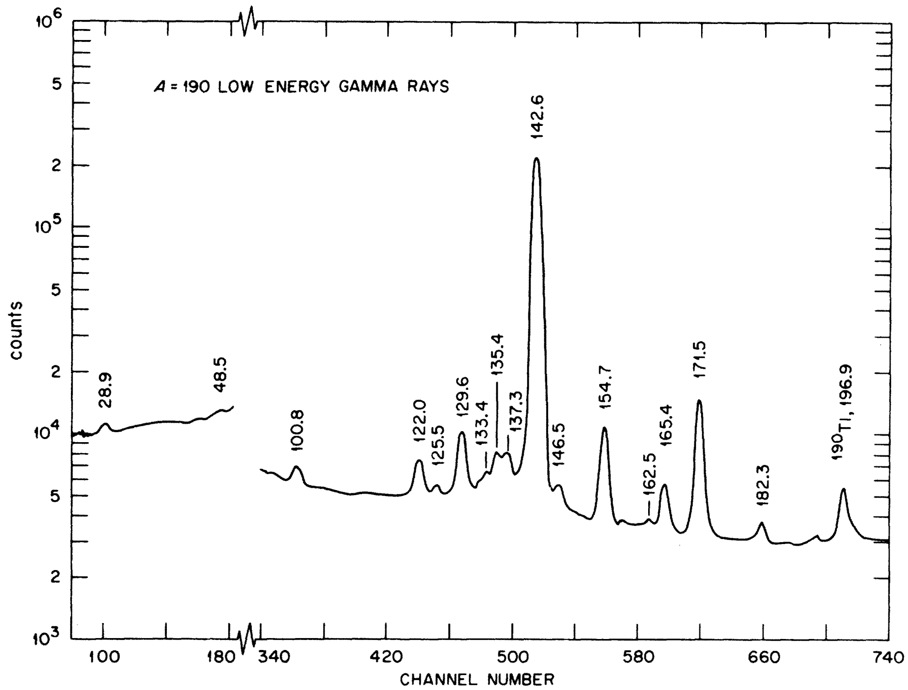

FIG. 10. The low-energy γ-ray spectrum showing primarily peaks due to decay of ^{190}Hg.

TABLE IV. Energies, relative intensities, and coincident photons from the decay of 20-m ^{190}Hg.

Photon	$E\gamma$ (keV)	Relative intensity	Coincident photons
1	Au $K\alpha$		Many (see below)
2	28.9	14	$1^a, 12^a$
3	48.5	4	$1^a, 12^c$
4	100.8	6 (7) [d]	$1^a, 9^c, 14^b$
5	112.6		$12^c, 18^c$
6	(122.0)	4	1^b
7	(125.5)	< 1	
8	129.6	23 (19) [d]	$1^a, 8^b, 9^b$, $10/11^b, 14^a$
9	(133.4)	~5	$1^a, 8^b, 14^b$
10	(135.4)	~10	$1^a, 4^b, 8^b, 12^b, 14^b$
11	(137.3)	~8	$1^a, 8^b, 14^b$
12	142.6	1000 (1000) [d]	$1^a, 2^a, 5^c, 7^c, 8^a, 9^c, 10^c, 20^a$
13	146.5	5	$1^a, 8^b, 14^b$
14	154.7	37 (40) [d]	$1^a, 4^a, 8^a, 9^c, 10^b, 11^c$
15	162.5	1	$1^b, 6^c$
16	165.4	14 (8) [d]	$1^a, 18^c$
17	171.5	70 (50) [d]	$1^a, 6^c$
18	182.3	4	1^b
19	(255.3)		1^b
20	242.6		$1^b, 12^b$
21	284.8	9	1^a
22	373.8	4	$1^b, 12^b$
23	384.5	3	
24	(637.9)	9	

[a] High confidence ($\gtrsim 90\%$).
[b] Medium confidence ($\gtrsim 70\%$).
[c] Low confidence ($\gtrsim 40\%$).
[d] Previous results, see Ref. 11.

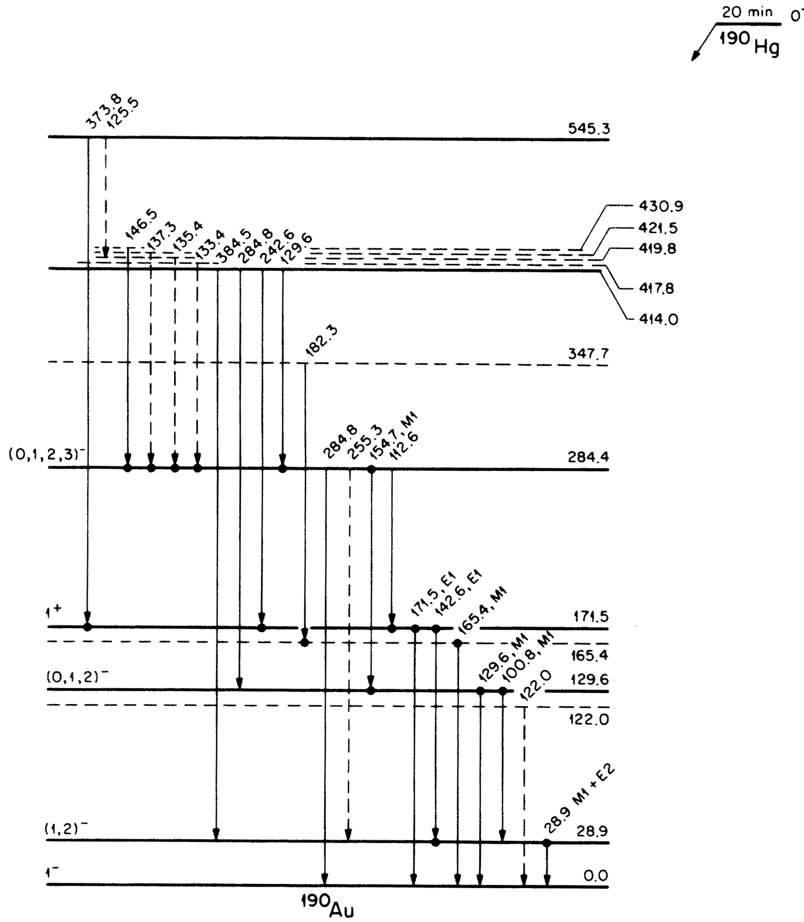

FIG. 11. The decay scheme for ^{190}Hg. See caption for Fig. 8.

tively. If one conjectures that 5.7 is a new lower limit for $Z = 79$, a different level structure may be possible for ^{190}Au which could also be consistent with the known information on valence orbitals in neighboring nuclei. A first-forbidden, nonunique decay would require a 0^- or 1^- assignment to the 171.5-keV level. Such a decay could occur by $(\pi s_{1/2}{}^2)_{0^+} \rightarrow (\pi s_{1/2} \nu p_{1/2})_{0^-}$, implying a 0^- assignment. All the spin assignments or limits for other levels would be the same as shown in Fig. 11, but all the parities would be reversed. This then would require explaining many low-lying positive-parity states (including the ground state) as couplings involving the $h_{9/2}$ or $h_{11/2}$ proton. It seems more plausible to use the lowest-lying stated in odd-Au nuclei, $d_{3/2}$ and $s_{1/2}$, to explain the lowest states in ^{190}Au, and thus to revert to the 1^+ $(\pi h_{11/2}, \nu h_{9/2})$ assignment for the 171.5-keV state.

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