Shape coexistence in ^{190}Hg

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Levels in ^{190}Hg were studied by radioactive decay of isotopically separated ^{190}Tl. A new band was observed with spin parity (energy, keV) of 0^+(1279), 2^+(1571), 4^+(1975), and 6^+(2510). Electric monopole transitions were observed between this band and the ground-state band. Relative $B(E2)$ values for intraband transitions in the new band were found to be $\sim$200 times those for interband transitions. Systematics of shape coexistence in the light Hg isotopes and their possible relevance to recent observations of superdeformation in these nuclei are discussed.

The very neutron-deficient mercury isotopes have been a focus of attention ever since the discovery by Bonn *et al.*[1] that there is a large change in the ground-state mean-square radius between ^{187}Hg and ^{185}Hg, and its interpretation as an onset of strong deformation at $A \leq 185$, which contradicted the former view that nuclei near closed shells, such as the Hg isotopes ($Z=80$), are only weakly deformed. Since the work of Bonn *et al.*,[1] strongly deformed ($\beta_2 \simeq 0.27$) bands have been established in ^{180}Hg,[2] ^{182}Hg,[3] ^{184}Hg,[4-6] ^{185}Hg,[7] ^{186}Hg,[6,8-11] ^{187}Hg,[12] and ^{188}Hg.[12-16] These bands in the even-mass Hg isotopes have been shown[5,9,10,13-15] to be built on 0^+ excited states, to exhibit[5,9,10,13-15] deexcitation by electric monopole transitions, and to have intraband $E2$ transitions with large[4,6,8] $B(E2)$ values. Further, measurements of isotope shifts (Ref. 17, and references therein) and an isomer shift in ^{185}Hg (Ref. 18) confirm a picture of weakly deformed ground states in ^{180,182,184,186,187,188,189,190}Hg, strongly deformed ground states in ^{181,183,185}Hg, and a weakly deformed isomer in ^{185}Hg. The empirical systematics suggest that a deformed band built on a 0^+ state should appear in ^{190}Hg at an excitation energy of ≈ 1400 keV. This is predicted[19,20] also by theories based on residual two-body proton-neutron interactions. However, an excited deformed band in ^{190}Hg is not predicted[21] in a recent deformed mean-field calculation. Previous studies of excited states in ^{190}Hg by radioactive decay[22] and in-beam reaction spectroscopy[23] have not observed a deformed excited band. The goal of the present work was to answer the question, is there shape coexistence in ^{190}Hg?

Excited states of ^{190}Hg were studied through the radioactive decay of mass-separated ^{190}Tl^m (3.7 min, $J^\pi=7^+$) and ^{190}Tl^g (2.6 min, $J^\pi=2^-$) by using the UNISOR isotope separator operated on line[24] to the 25-MV folded tandem accelerator at the Holifield Heavy-Ion Research Facility. The activity was obtained through β^+ and electron capture decay of ^{190}Pb (1.2 min, $J^\pi=0^+$) produced *via* (^{16}O,xn) reactions on a ^{nat}W target using 150-MeV ^{16}O ions. Gamma-ray and conversion-electron spectrum multiscaling and γ-γ-t, γ-x-t, γ-ce-t, and ce-x-t coincidence measurements were conducted on line. Conversion-electron spectra were taken with a 200 mm$^2 \times 3$ mm cooled Si(Li) detector. All assignments of γ-ray and internally converted transitions were made on the basis of coincidence information.

Portions of the ^{190}Hg level scheme relevant to the present discussion are shown in Fig. 1. The ground-state band was established previously by studies[22] of the radioactive decay of ^{190}Tl and by in-beam reaction work.[23]

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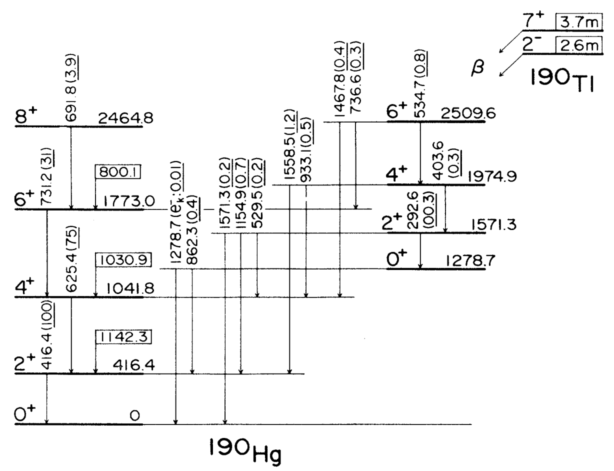

FIG. 1. Part of the level scheme of ^{190}Hg populated in the β^+/electron capture decay of $^{190}Tl^{m,g}$. Energies are in keV and γ-ray transition intensities are given relative to $I_\gamma(416) \equiv 100$. The 1279-keV transition is pure $E0$, and thus only its K-conversion-electron intensity is given. The 800-, 1031-, and 1142-keV transitions are discussed in the caption to Fig. 2.

The band of states with spin parity (energy, keV) of 0^+ (1279), 2^+ (1571), 4^+ (1975), and 6^+ (2510) is new. Key data supporting this band come from coincidences (see Fig. 2) obtained from gates on γ-ray transitions in the ground-state band. A characteristic feature of the new band in ^{190}Hg and shape coexisting bands in ^{184}Hg,[5] ^{186}Hg,[9,10] and ^{188}Hg (Refs. 13–15) is the electric monopole interband transitions. The very-converted character of the $I^\pi \rightarrow I^\pi$ transitions (737, 933, and 1155 keV) is evident from relative γ-ray and conversion-electron intensities observed in the coincidence gates shown in Fig. 2. The location of these strong electron lines is confirmed by the γ-ray spectra seen in coincidence with them, shown in Fig. 3. The 933- and 1155-keV transitions can be interpreted directly as having low multipolarity because of the prompt coincidence observed at 535 keV [Fig. 3(b)] and 404 keV [Fig. 3(a)], respectively (high multipolarity transitions, e.g., $M2$, $E3$, etc., would be severely retarded). Intraband transitions for the new band are observed in the gates shown in Fig. 3. The mainstay of the 0^+ bandhead is the electron line at 1196 keV, which is not observed to be in coincidence with the 416-keV $2_1^+ \rightarrow 0_1^+$

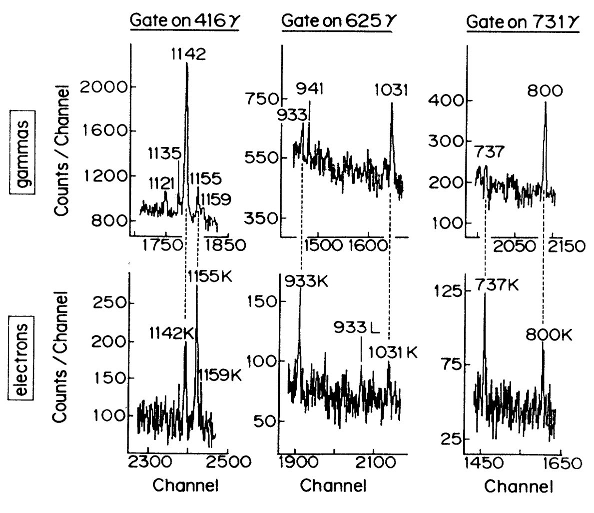

FIG. 2. Gamma-ray and conversion-electron spectra in coincidence with the $2^+ \rightarrow 0^+(416)$, $4^+ \rightarrow 2^+(625)$, and $6^+ \rightarrow 4^+(731)$ γ-ray transitions in the ground-state band. The 800-, 1031-, and 1142-keV transitions ($E2$ or $M1+E2$) are shown for comparison with the very-converted 1155-, 933- and 737-keV transitions. Other lines are not relevant to the present discussion. The data are taken following the $^{190}Pb \rightarrow {}^{190}Tl^{m,g}$ decay and represent a mixture of the 7^+ and 2^- isomers.

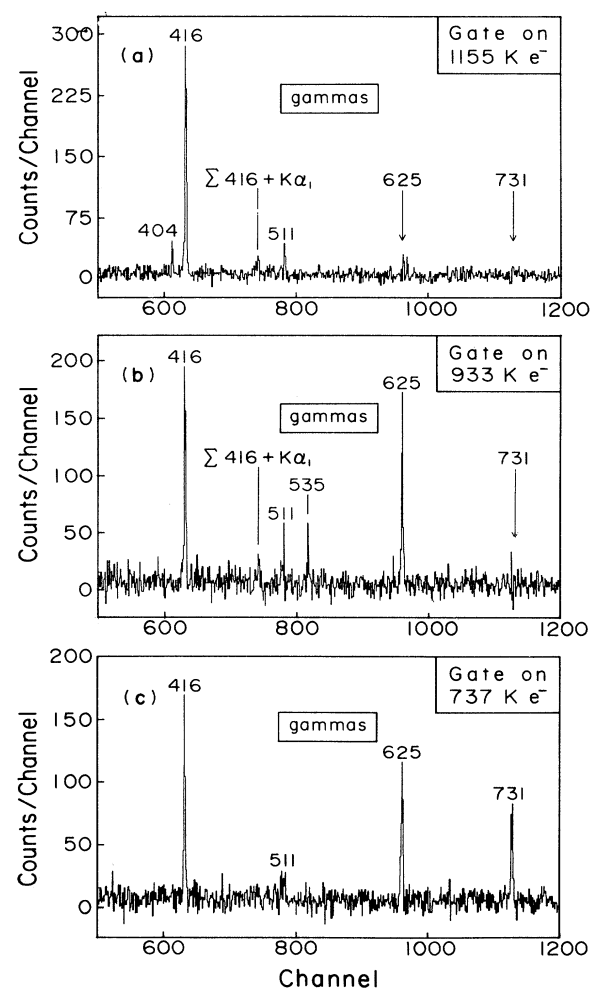

FIG. 3. Gamma-ray spectra in coincidence with K-internal-conversion electrons from the very-converted (a) 1155-keV, (b) 933-keV, and (c) 737-keV transitions. Also shown are the intraband transitions at (a) 404 keV and (b) 535 keV in the deformed band. The data are taken following the $^{190}Pb \rightarrow {}^{190}Tl^{m,g}$ decay and represent a mixture of the 7^+ and 2^- isomers.

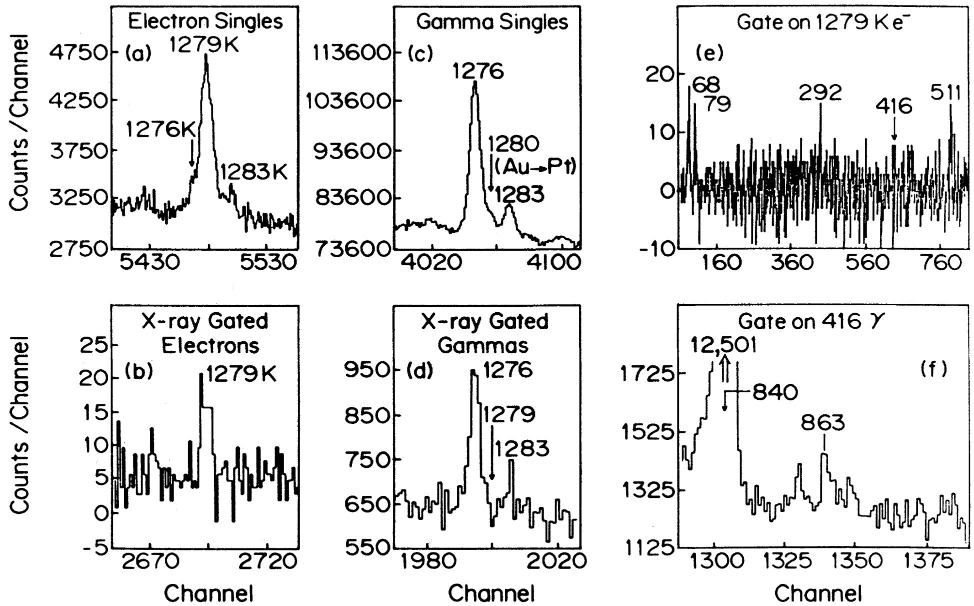

FIG. 4. Evidence that the head of the deformed band is a $J^\pi=0^+$ state at 1279 keV: (a) the 1279 K electron line seen in the singles spectrum, (b) the 1279 electron line seen in coincidence with Hg x rays, (c) γ rays at 1276–1283 keV seen in the singles spectrum [the 1280-keV line is a known (Ref. 25) $E1$ in the $^{190}Au \rightarrow {}^{190}Pt$ decay], (d) γ rays in coincidence with Hg x rays showing $I_\gamma(1279) < 0.04$, (e) γ rays in coincidence with K-internal-conversion electrons from the very-converted 1279-keV transition (the weak 292-keV line fits the 2^+-0^+ deformed band energy difference), and (f) γ rays in coincidence with the $2^+ \rightarrow 0^+$ (416-keV) transition showing the $0_2^+(1279) \rightarrow 2_1^+(416)$ interband transition of 863 keV. The 840-keV transition belongs elsewhere in the scheme (Refs. 22 and 23).

TABLE I. Tabulation of transitions in the $^{190}Tl^{m,g} \rightarrow Hg$ decay scheme relevant to the present discussion. These data come from spectra taken following the $^{nat}W(^{16}O,xn)^{190}Pb$ reaction. No attempt has been made to separate $^{190}Tl^m(J^\pi=7^+)$ and $^{190}Tl^g(J^\pi=2^-)$ feeding intensities. This can be done for stronger lines by comparison with data in Ref. 22. Errors in the last significant figures of I_γ and α_K are given in parentheses. All energies (E) are in keV.

E_γ	I_γ [a]	$\alpha_K \times 10^2$	Multipolarity	$\frac{B(E2;I_d \rightarrow (I-2)_d)}{B(E2;I_d \rightarrow (I-2)_g)}$	Location $I^\pi(E_i) \rightarrow I^\pi(E_f)$
292	0.03(2)			600(400)	$2^+(1571) \rightarrow 0^+(1279)$
404	0.28(8)	3.0(4)		190(60)	$4^+(1975) \rightarrow 2^+(1571)$
416	100(7)	3.0(3)[b]	$E2$		$2^+(416) \rightarrow 0^+(0)$
529	0.18(7)				$2^+(1571) \rightarrow 4^+(1042)$
535	0.75(6)			307(35)	$6^+(2510) \rightarrow 4^+(1975)$
626	75(5)	1.30(13)	$E2$		$4^+(1042) \rightarrow 2^+(416)$
692	3.9(3)	0.94(10)	$E2$		$8^+(2465) \rightarrow 6^+(1773)$
731	31(2)	0.92(9)	$E2$		$6^+(1773) \rightarrow 4^+(1042)$
737	0.34(11)	6.7(7)	$E0+M1+E2$		$6^+(2510) \rightarrow 6^+(1773)$
800	1.63(14)	0.69(14)	$E2$		$(2573) \rightarrow 6^+(1773)$
863	0.42(3)				$0^+(1279) \rightarrow 2^+(416)$
933	0.48(15)	5.5(6)	$E0+M1+E2$		$4^+(1975) \rightarrow 4^+(1042)$
1031	1.35(10)	0.78(12)	$M1+E2$		$(2073) \rightarrow 4^+(1042)$
1142	4.24(30)	0.43(6)	$E2(+M1)$		$2^+(1558) \rightarrow 2^+(416)$
1155	0.69(6)	4.3(6)	$E0+M1+E2$		$2^+(1571) \rightarrow 2^+(416)$
1279	<0.04	>30	$E0$		$0^+(1279) \rightarrow 0^+(0)$
1468	0.38(3)				$6^+(2510) \rightarrow 4^+(1042)$
1559	1.22(9)				$4^+(1975) \rightarrow 2^+(416)$
1571	0.21(12)				$2^+(1571) \rightarrow 0^+(0)$

[a]Normalized to 100 for the 416-keV transition.
[b]Normalized to α_K ($E2$; theory).

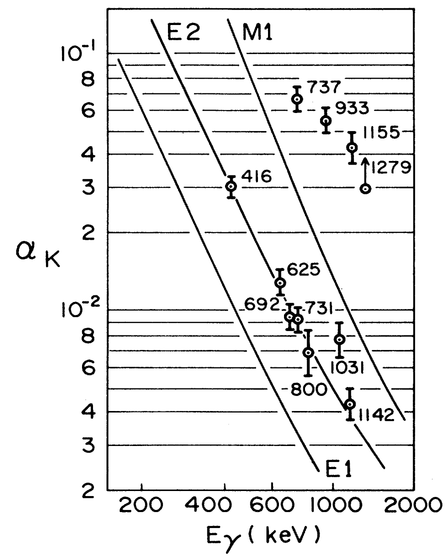

FIG. 5. A plot of α_K values observed for transitions shown in Fig. 1. The plotted values are given in Table I. The value for the 1279-keV transition is a lower limit. The solid lines are theoretical values for $E1$, $E2$, and $M1$ multipolarities. The 416-keV $E2$ ($2^+ \rightarrow 0^+$) transition was used to normalize the experimental conversion-electron and γ-ray intensities. The transitions with $\alpha_K(\text{expt}) > \alpha_K(M1, \text{theory})$ are interpreted to have $E0$ components. For the 1155- and 933-keV transitions, high multipolarities are excluded by the prompt feeding coincidences of 404 and 535 keV, respectively (see Fig. 3).

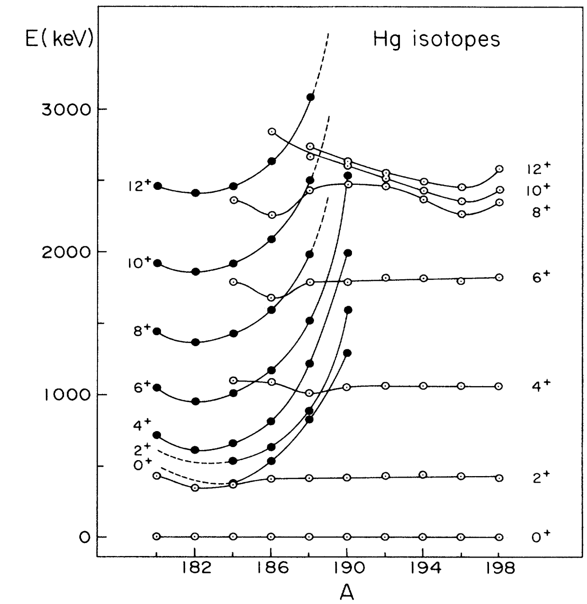

FIG. 6. Systematics of strongly deformed bands (solid circles) and weakly deformed bands (open circles) in the even-mass Hg isotopes. The data are taken from Ref. 2 (^{180}Hg), Ref. 3 (^{182}Hg), Refs. 4–6 (^{184}Hg), Refs. 8–11 (^{186}Hg), Refs. 12–16 (^{188}Hg), Refs. 22, 23, and the present work (^{190}Hg), Ref. 23 (^{192,194}Hg), Ref. 26 (^{196}Hg), and Ref. 27 (^{198}Hg).

γ-ray and is thus interpreted as coming from K conversion of a 1279-keV transition feeding the ground state. If it has a γ-ray partner, the intensity is limited to a value that results in $\alpha_K(1279) > 0.3$. Coincidence data supporting this location are shown in Fig. 4. The α_K values obtained for this transition and some of the other transitions in Fig. 1 are shown in Fig. 5. Full information on these transitions is given in Table I. From the present data, relative $B(E2)$ values can be obtained for the intraband transitions of the deformed band. These are also shown in Table I and are seen to be much larger than the interband $B(E2)$ values.

The present work supports a band built on a 0^+ state at 1279 keV with a much closer energy spacing than the ground-state band, interband $E0$ transitions between all band members and states of the same spin in the ground-state band, and $B(E2)$ values for intraband transitions which are much larger than for interband transitions. This parallels similar bands established in ^{180,182,184,186,188}Hg. The systematics of these bands are shown in Fig. 6.

The recent observation[28,29] of superdeformation at low spin (8–10 units) in ^{192}Hg adds an important dimension to these results and their theoretical interpretation. An extrapolation of the systematics shown in Fig. 6 predicts the 0_2^+ bandhead to occur near 2 MeV in ^{192}Hg. Connecting transitions between the superdeformed band and the ground-state band were not found in the in-beam data.[28,29] Thus it is critical to determine the extent of the deformed configurations in these Hg isotopes and to understand the mechanisms which produce them. Our results are consistent with the theoretical predictions of shape coexistence models[19,20] based on a proton-neutron interaction, but disagree with the prediction of a deformed mean-field model[21] which did not predict the deformed band for $A > 188$. Such states can be produced in that model, however, by introducing diabatic configurations.[30] This is an important theoretical development which is supported by these results and which bears directly on the theoretical understanding of shape coexistence (including superdeformation) in nuclei.

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