High-spin structure of ^{189}Tl: Role of $h_{9/2}$ protons in the prolate minimum of light Hg isotopes

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High-spin states in ^{189}Tl have been populated through the ^{165}Ho(^{28}Si,4n) reaction and studied with in-beam γ-ray spectroscopy techniques. Both oblate and prolate structures associated with the $i\frac{13}{2}$ proton orbit are confirmed and extended to higher spins ($\frac{19}{2}$ and $\frac{41}{2}$, respectively). However, only the oblate structure related to the $\pi h\frac{9}{2}$ has been observed meaning that the associated prolate structure is nonyrast contrary to expectation. This experimental result points clearly to a large amplitude of $(\pi h\frac{9}{2})^2$ in the wave function of the prolate minimum of ^{188}Hg.

I. INTRODUCTION

The region of even-A neutron-deficient mercury isotopes ($A \leq 188$) is well known [1,2] for the coexistence of slightly oblate ($\beta \simeq -0.16$) and prolate ($\beta \simeq 0.27$) shapes. This phenomenon shows itself also through the coexistence of oblate and prolate bands in neighboring odd-A Hg nuclei [2–4]. More recently, this behavior has, in addition, been found in odd-Z nuclei such as ^{189}Tl [5] and ^{187}Au [6]. In both cases prolate bands involving the $\pi i\frac{13}{2}$ intruder orbital have been observed, while the band due to the $\pi h\frac{9}{2}$ excitation has only been reported in ^{187}Au. No definite conclusion on the existence of a system of levels related to the prolate $\pi h\frac{9}{2}$ orbit has been reached in ^{189}Tl [5]. With powerful spectroscopic devices available today, such as the "Château de Cristal" [7] utilized here, the high-spin structure of ^{189}Tl has been reinvestigated and this problem reexamined in the present work.

II. EXPERIMENTAL METHODS AND RESULTS

High-spin states of ^{189}Tl have been populated via the ^{165}Ho(^{28}Si,4n) reaction. Excitation functions were measured at four beam energies ranging from 130 to 145 MeV in 5-MeV steps using a target of 600 μg/cm^2 thickness deposited on gold backing. γ-γ coincidences were obtained with a Au-backed target of 1.7 mg/cm^2 thickness at a beam energy of 141 MeV.

All these measurements were performed using the "Château de Cristal" array consisting of 12 Compton-suppressed Ge detectors (20% efficiency) and 38 BaF_2 counters acting as an inner ball, on line with the MP tandem of the Centre de Recherches Nucléaires (CRN), Strasbourg. During the coincidence experiment, at least two Ge and three BaF_2 detectors were required to be in coincidence in order to validate the events. A total of 63×10^6 γ-γ events have been sorted in the final matrix. The coincidences between the 90° and 33°–147° Ge detectors were also used to build a DCO matrix (directional correlation from oriented states). To get more precise information about the spin and parity values of ^{189}Tl levels, angular distribution and polarization measurements were also carried out with a setup on line with the tandem of Institut de Physique Nucléaire (IPN), Orsay. It consisted of (i) two Ge detectors (70% efficiency) positioned successively at θ=0°, 25°, 30°, 45°, 60°, and 90° with respect to the beam line, (ii) a five-coaxial Ge polarimeter placed at $\theta = -90°$ [8], and (iii) a two-segment NaI sum spectrometer (forming a half-cylinder 30 cm in diameter and 30 cm in length) located below the reaction chamber. The Ge and polarimeter spectra were incremented only when one of the two segments of the sum spectrometer fired. This trigger does not lead to any bias in the angular distribution or polarization results, as tested in separate measurements on ^{187}Au γ rays. The data analysis procedures are the same as those already described in detail in Ref. [9].

From this work a total of 37 γ rays has been arranged in four bands constituting the level scheme of ^{189}Tl presented in Fig. 1. Typical coincidence spectra are displayed in Fig. 2. The 502-keV gate spectrum shows all the lines of the band labeled 1. The 395-keV gate spectrum exhibits the lines belonging to the band labeled 4 and its connecting transitions to bands 3 and 1. The results of the DCO, angular distribution, and polarization analyses are given in Table I. The DCO ratios have been extracted from coincidence rates between the γ ray of interest and stretched $E2$ transitions detected at 33° (147°) and 90° with respect to the beam direction. For the angular distribution analysis, the a_4 coefficient was set to zero and a_2 was extracted from a fit over the six data points.

The multipolarity of the ^{189}Tl γ rays and their total intensity (integrated over the angular distribution and corrected for the total electron conversion) have been deduced.

Additional lines (437, 451, 463, 483, 540, 597, and 636 keV) are seen in mutual coincidence (see Fig. 3), but their attribution to ^{189}Tl is uncertain since their coincidences with the known lines are too weak.

III. LEVEL SCHEME

All the high-spin levels observed in this work are built on the $\frac{9}{2}^-$ isomeric state rather than the $\frac{1}{2}^+$ ground state. The isomeric state energy has been determined to be 281 ± 7 keV [10] by means of the α decay of ^{193g,193m}Bi. However, the level energies are given with respect to the $\frac{9}{2}^-$ bandhead energy (Fig. 1). In the following only the particular points contributed by the present data as compared to the previous set [5] will be discussed. Besides the two strongly coupled bands (i.e., $\Delta I=1$ sequences) already seen in the heavier odd-mass Tl isotopes, we confirm the existence of a decoupled $\Delta I=2$ sequence (built on the 1714-keV level).

The $E1$ character of the 480-keV γ ray has been inferred from the angular distribution and polarization measurements (see Table I), thus confirming the positive parity proposed for the 866-keV level from systematics considerations. The new level at 2026 keV, added to band 3, has been established through the detection of the 479-keV γ ray and its associated crossover of 762 keV. The 691-keV line possibly defines a second $\frac{17}{2}$ state at 1955 keV, analogous to the second $\frac{13}{2}$ state of the $\pi h\frac{9}{2}$ oblate band, which has been taken as an indication of nonaxiality. Actually, this proposition relies mainly on a theoretical interpretation [11].

The 407-keV γ ray linking the $\Delta I=1$ positive-parity band (band 3, interpreted as a $\pi i\frac{13}{2}$ excitation coupled to an oblate core [5]) to the $\Delta I=2$ sequence (band 4) has an $E2$ stretched character (see Table I), which implies positive parity for band 4. This work has also revealed the existence of a 242-keV γ ray, this first transition of band 4, which deexcites through a 449-keV transition to band 3. At high spins two new lines (603 and 664 keV) have

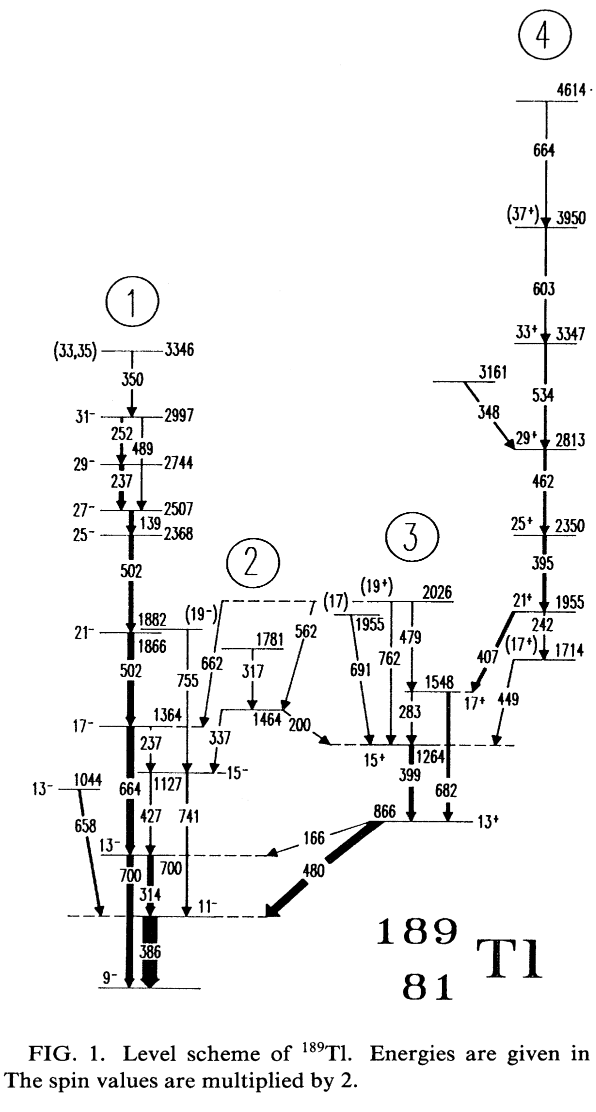

FIG. 1. Level scheme of ^{189}Tl. Energies are given in keV. The spin values are multiplied by 2.

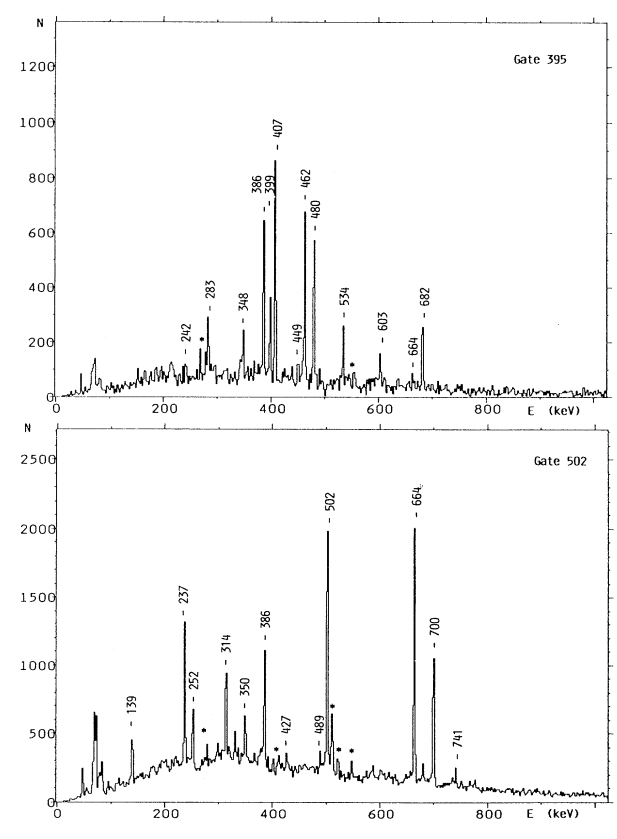

FIG. 2. Examples of background corrected γ-γ coincidence spectra. Energies are given in keV. The lines marked by asterisks are identified contaminants.

been added to this decoupled band. Its previous interpretation as a $\pi i\frac{13}{2}$ excitation coupled to a prolate core [5] is strongly supported by the positive-parity assignation.

The main difference with the previous results [5] appears on band 1. The analysis of the coincidence spectra revealed the existence of a 237-keV γ line deexciting the 1364-keV level. Thus the 664-keV $E2$ γ ray is the crossover if this new line and the 427-keV transition. In addition, the character of the 502-keV self-coincident doublet is measured to be stretched $E2$ and the nature of the 139-, 237-, and 252-keV lines is established here to be mainly $M1$. All these findings lead to a consistent interpretation of band 1 in terms of the coupling of the $h\frac{9}{2}$ proton to the oblate ground-state band of ^{188}Hg as discussed now.

IV. DISCUSSION

Figure 4 shows a comparison between the oblate $\pi h\frac{9}{2}$ structure in ^{189}Tl (band 1), the ground-oblate and excited-prolate bands in ^{188}Hg [2], and the oblate and prolate $\pi i\frac{13}{2}$ bands (bands 3 and 4) in ^{189}Tl (the level energies being referred to the $I^{\pi}=\frac{13}{2}^{+}$ bandhead at 866 keV).

TABLE I. Energy, location, DCO ratio R, angular distribution coefficient a_2, linear polarization P, and total intensity I_{tot} of the ^{189}Tl γ rays.

E_γ [a] (keV)	Location from	Location to	Band number	$R(\Delta R)$	$a_2(\Delta a_2)$	$P(\Delta P)$	Multipolarity	I_{tot} [b]
139.5	2507.5	2368.0	1		−0.3(1)		$M1$[c]	20
165.9	865.8	700.0	3-1					
199.6	1464.0	1264.4	2-3					
236.9	1364.1	1127.2	1					
236.9	2744.4	2507.5	1	0.3(1)	−0.25(12)		$M1(+E2)$	22
241.6	1955.0	1713.6	4					
252.2	2996.6	2744.4	1	0.3(1)	−0.31(14)		$M1(+E2)$	11
283.3	1547.6	1264.4	3	0.3(1)	−0.28(5)		$M1(+E2)$	7
314.0	700.0	386.0	1	0.20(5)	−0.32(5)	−0.08(4)	$M1(+E2)$	30
317.0	1781.0	1464.0	2					
336.7	1464.0	1127.2	2-1					
348.0	3160.7	2812.7	4					
349.7	3346.3	2996.6	1					
386.0	386.0	0	1	0.15(5)	−0.68(7)	0.05(5)	$M1+E2$[d]	70
395.2	2350.2	1955.0	4	1.0(2)	0.31(14)	0.09(5)	$E2$	16
398.6	1264.4	865.8	3	0.2(1)	−0.68(9)	0.06(6)	$M1+E2$[d]	20
407.3	1955.0	1547.6	4-3	1.0(2)	0.20(14)	0.11(5)	$E2$	15
427.3	1127.2	700.0	1	0.3(1)		−0.06(3)	$M1(+E2)$	5
449.2	1713.6	1264.4	4-3					
462.5	2812.7	2350.2	4	1.1(2)		0.15(5)	$E2$	12
479	2026.1	1547.6	3					10
479.8	865.8	386.0	3-1	0.40(11)	−0.19(5)	0.25(7)	$E1$	40
489.2	2996.2	2507.5	1					
501.9	2368.0	1866.1	1	1.3(3)	0.15(4)	0.29(8)	$E2$	20
501.9	1866.1	1364.2	1				$E2$	30
534.4	3347.1	2812.7	4	1.0(3)		0.13(5)	$E2$	8
562.0	2026.1	1464.0	3-2					
603.1	3950.2	3347.1	4					
657.6	1043.6	386.0	1		−0.17(8)	−0.18(6)	$M1(+E2)$	10
662	2026.1	1364.1	3-1					
664	4614	3950.2	4					
664.2	1364.1	700.0	1	0.9(2)	0.26(3)	0.17(5)	$E2$	35
681.8	1547.6	865.8	3	1.0(3)	0.41(17)	0.13(5)	$E2$	15
690.7	1955.1	1264.4	3					
700.0	700.0	0	1	1.0(2)	0.26(9)	0.27(11)	$E2$	30
741.1	1127.2	386.0	1	0.9(3)			$E2$	7
754.7	1881.9	1127.2	1					
761.7	2026.1	1264.4	3					

[a]Errors are 0.2–0.5 keV, depending on γ-ray intensity.
[b]Normalized to 100 for the sum of the 386- and 700-keV γ-line intensities. Uncertainties are 10–30 %.
[c]An $E2$ component is excluded by total intensity balance.
[d]The a_2 coefficient value implies a large δ mixing ratio.

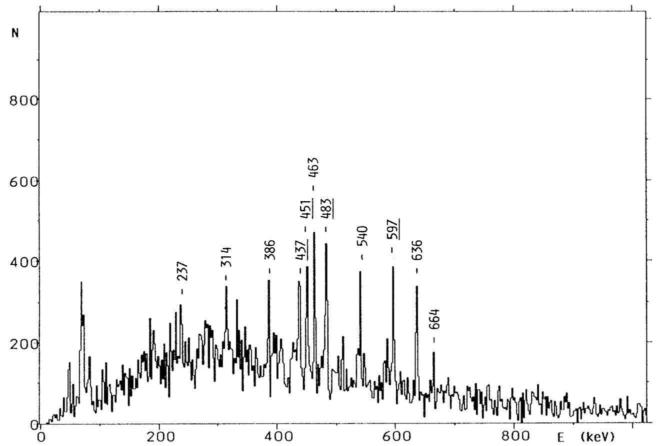

FIG. 3. Added background corrected γ-γ coincidence spectra for an unplaced cascade. The gate energies used are underlined.

The first point to be noted is that the compression of the $\pi h\frac{9}{2}$ oblate band is clearly correlated with the compression of the oblate ground band of the ^{188}Hg core: The states cluster from $I^{\pi}=\frac{25}{2}^{-}$ on, reflecting the 8^{+},10^{+},12^{+} clustering in ^{188}Hg (due to the alignment of a pair of $i\frac{13}{2}$ neutrons [2]). This behavior is analogous to the one already described in ^{195,197}Tl [12], which is stressed by the systematics shown in Fig. 5. The only peculiarity is the inversion of the $\frac{21}{2}^{-}$ and $\frac{19}{2}^{-}$ states in ^{189}Tl, and we shall come back to this issue below.

A second striking feature apparent in Fig. 4 is the close similarity between the level energies of the prolate band in ^{188}Hg and the prolate $\pi i\frac{13}{2}$ structure in ^{189}Tl (aside from some perturbations near the bandhead [5]): This $\pi i\frac{13}{2}$ structure appears in fact as a nice example of a decoupled band. Particularly noteworthy is the agreement between the excitation energy of the prolate minimum in ^{188}Hg and the relative excitation energy of the prolate $i\frac{13}{2}$ band with respect to the oblate $i\frac{13}{2}$ bandhead. Note that the $\frac{13}{2}^{+}$ prolate bandhead is not observed in this work, but it is expected to lie just below the $\frac{17}{2}^{+}$ states; this resembles the situation in ^{188}Hg where the prolate 0^{+} state has only been observed in radioactivity experiments [2].

Thus the $i\frac{13}{2}$ proton acts as a spectator without disturbing the supposedly prolate core structure in ^{188}Hg. This seems to indicate [5] that the occupation probability of the $\frac{1}{2}^{+}$ [660] state (and higher-lying related $i\frac{13}{2}$ prolate Nilsson orbits) is small in the wave function of the prolate minimum of the core.

The remaining question is why one does not observe the prolate $h\frac{9}{2}$ band. If the $\pi h\frac{9}{2}$ excitation would behave as the $\pi i\frac{13}{2}$ one, we would expect the members of the prolate $\pi h\frac{9}{2}$ decoupled band to lie approximately as indicated in Fig. 4 where we have labeled (in brackets) the levels of the prolate band in ^{188}Hg with the expected spins ($\frac{9}{2}^{-}$, $\frac{13}{2}^{-}$, . . .). This band would clearly be yrast (taking into account the excitation energies of the $\pi i\frac{13}{2}$ bands) and thus would receive a strong feeding. This is not ob-

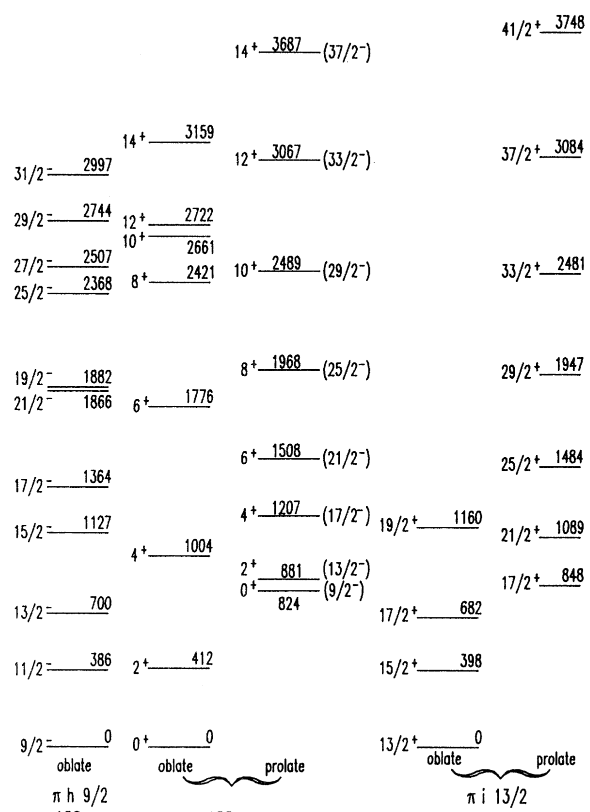

FIG. 4. Comparison between bands 1, 3, and 4 in ^{189}Tl (this work) and the oblate and prolate bands in ^{188}Hg [2].

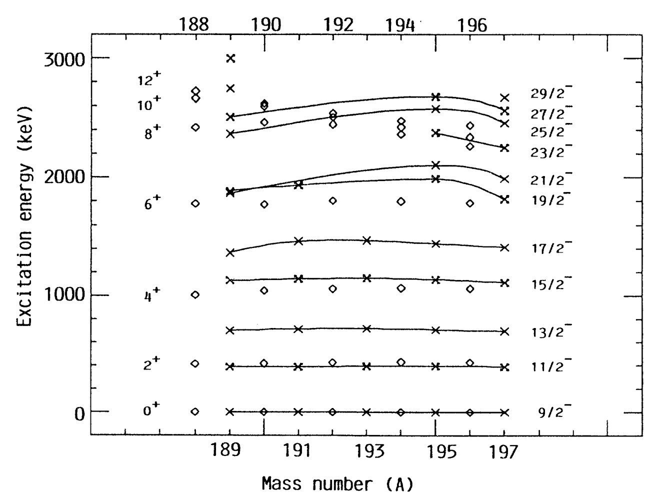

FIG. 5. Systematics of the oblate $h\frac{9}{2}$ bands in odd-A Tl nuclei ($A=189-197$) and the ground-state bands in even-A Hg cores ($A=188-196$). Odd-A Tl data are from this work and Refs. [12,13] and Hg data from Refs. [2,14,15].

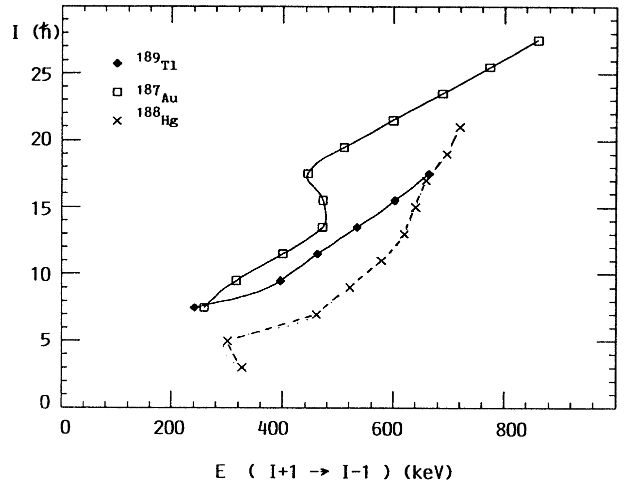

FIG. 6. Spin I vs transition energy E_γ for the $\pi i_{\frac{13}{2}}$ bands in ^{187}Au [6] and ^{189}Tl (this work), compared to the prolate band in ^{188}Hg [2].

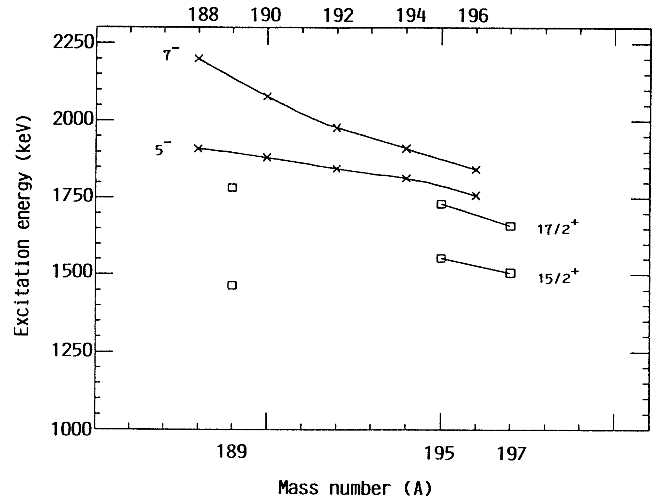

FIG. 7. Excitation energy comparison between the two levels of band 2 (^{189}Tl), the $\frac{15}{2}^+$, $\frac{17}{2}^+$ states in ^{195,197}Tl [12,13], and the 5^-, 7^- states in even-A Hg cores [2,14,15].

served experimentally, which implies that the band is shifted to higher energy. The shift must be at least of the order of 400 keV because the prolate $\frac{21}{2}^-$ state (which would nominally lie at 1508 keV) has to lie above the $\frac{21}{2}^-$ oblate one (which is actually identified at 1866 keV).

In the same context we can now explain the above-mentioned inversion of the $\frac{21}{2}^-$ and $\frac{19}{2}^-$ oblate state. If the prolate $\frac{21}{2}^-$ state lies above but not very far from the oblate one, it will push it down through their mutual interaction. On the other hand, the $\frac{19}{2}^-$ oblate state will remain rather unaffected since the $\frac{19}{2}^-$ prolate level (being unfavored in the decoupled band) would lie much higher in energy. A similar behavior is also expected for the oblate $\frac{25}{2}^-$ state, which is pushed below the oblate $\frac{23}{2}^-$ one. Thus, unlike the situation in ^{195,197}Tl (see Fig. 5), the $\frac{23}{2}^-$ state of ^{189}Tl is not fed by the deexcitation of the $\frac{25}{2}^-$ level and then is not observed.

If we admit that the amplitude of $(\pi h_{\frac{9}{2}})^2$ in the structure of the prolate minimum of ^{188}Hg is large, the shift in ^{189}Tl would be caused by Pauli blocking of the $h_{\frac{9}{2}}$ orbit: The occupation of this orbit by the odd proton of ^{189}Tl would lead to a significant loss in pairing correlation energy of the core (which can be correlated to the quoted shift of 400 keV). On the other hand, such an effect is clearly smaller in ^{187}Au (where the prolate $\pi h_{\frac{9}{2}}$ is observed [6]) because the space available for scattering pairs across the Fermi surface is larger. Also, the deformation is expected to be larger in ^{187}Au than in ^{189}Tl, meaning that it is a more collective phenomenon less dependent on the occupancy of a particular orbit.

The same arguments can be developed to explain the alignment picture in the prolate $\pi i_{\frac{13}{2}}$ band of these nuclei. Figure 6 shows an I-vs-E_γ plot for the $i_{\frac{13}{2}}$ prolate bands in ^{189}Tl and ^{187}Au. The pronounced back bending in the $\pi i_{\frac{13}{2}}$ band of ^{187}Au can be mainly explained as an alignment of a pair of $h_{\frac{9}{2}}$ protons [6,16]. On the other hand, the absence of back bending in the $\pi i_{\frac{13}{2}}$ band in ^{189}Tl can be understood along the lines discussed above. The large loss of pairing energy due to the breaking of a pair of $h_{\frac{9}{2}}$ protons in ^{189}Tl should lead to a very delayed crossing, above the upper rotational frequency value observed in this work. Figure 6 also shows the behavior of the ^{188}Hg prolate band. The lack of sharp back bending in this case is also consistent with the same picture.

The last point to be mentioned concerns the two states at 1464 and 1781 keV excitation energy. These states may be three-quasiparticle states due to the coupling of $\pi h_{\frac{9}{2}}$ to the 5^--7^- oblate states of the Hg cores, as those observed in ^{195,197}Tl [12] (See Fig. 7.)

V. SUMMARY AND CONCLUSION

Shape coexistence in ^{189}Tl is firmly established through the existence of a prolate $\pi i_{\frac{13}{2}}$ and both oblate $\pi h_{\frac{9}{2}}$ and $\pi i_{\frac{13}{2}}$ structures. The oblate $\pi h_{\frac{9}{2}}$ band reflects the irregularities of the oblate ground-state band of ^{188}Hg, but also the distortions likely due to the presence of the higher-lying nonobserved prolate $\pi h_{\frac{9}{2}}$ structure. It is proposed that this structure is pushed up in energy as a result of the decrease in the pairing correlation energy caused by Pauli blocking when the odd proton occupies the $h_{\frac{9}{2}}$ orbit. This implies that the wave function of the prolate minimum in ^{188}Hg has a significant $(\pi h_{\frac{9}{2}})^2$ component.

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