Evidence for Predicted Level Crossings in $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}i_{13/2}$ Bands in Very Neutron-Deficient, Doubly Odd Tl Isotopes

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Isomeric transitions, of $E3$, $M2$, and $E1/M2$ character, depopulating $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}i_{13/2}$ bands in ^{186,188,190}Tl, respectively, have been found with use of γ-ray spectroscopic techniques. The changes in multipolarity reflect successive changes in the bandhead spin values corresponding to level crossings within the $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}i_{13/2}$ system. These crossings were predicted in the framework of the two-quasiparticle plus rotor model and interpreted as a direct consequence of the depletion of the $i_{13/2}$ shell.

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The study of high-spin states in doubly odd nuclei has so far received little attention in spite of the fact that it may render valuable information concerning the proton-neutron (p-n) residual interaction. Transitional nuclei, because of the nonrigidity of the intrinsic structure, should be particularly suitable systems in which to assess the strength of the p-n force, which in turn could be used as input for the description of multiquasiparticle bands in even-even and odd-mass nuclei. For example, one- and three-quasiparticle band crossings might be affected by residual forces which have so far been neglected.

High-spin bands based on isomeric states ($10 \lesssim t_{1/2} \lesssim 300$ nsec) have been found[1] over the last few years in doubly odd Tl isotopes in the mass range $A = 192-200$ (see Fig. 1). These bands represent the first examples of collective structures based on high-j excitations in doubly odd transitional nuclei, and were successfully described as semidecoupled $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}i_{13/2}$ systems by using a two-quasiparticle plus rotor model.[3] They start with a set of transitions whose energies are small compared to energies in related bands of neighboring odd-mass nuclei, i.e., $\tilde{\pi}h_{9/2}$ and $\tilde{\nu}i_{13/2}$ bands in odd Tl and Hg nuclei, respectively.[4,5] In contrast to high-j bands in odd-mass nuclei, where a single state is associated with vanishing collective angular momentum (the state with $I=j$), in doubly odd nuclei, where the intrinsic spin, J, is built out of two parts ($\vec{J}=\vec{j}_p+\vec{j}_n$), there is a multiplet associated with small core excitation (that with $I=J$ and $I \leqslant j_p + j_n$). The fact that the lowest-lying state within this multiplet has a spin value of around 8 is related to the positions of proton and neutron Fermi levels, λ_p and λ_n, relative to the $h_{9/2}$ and $i_{13/2}$ Nilsson multiplets, respectively. The proton orbital is intruding from the next shell across the $Z=82$ closure and since the deformation is oblate, the Nilsson state with the largest projection on the symmetry axis ($\Omega_p = \frac{9}{2}$) lies nearest to λ_p, giving rise to "normal" $\Delta I = 1$ bands in odd Tl isotopes.[4] On the other hand, for $N \simeq 117$ the $\Omega_n = \frac{1}{2}$ member of the $i_{13/2}$ orbital lies close to λ_n, resulting in decoupled bands[6] in the odd Hg isotopes,[5] in which $\vec{j}_n$ is approximately in a plane perpendicular to the symmetry axis. Hence, the energetically most favorable situation for the heavy doubly odd Tl isotopes

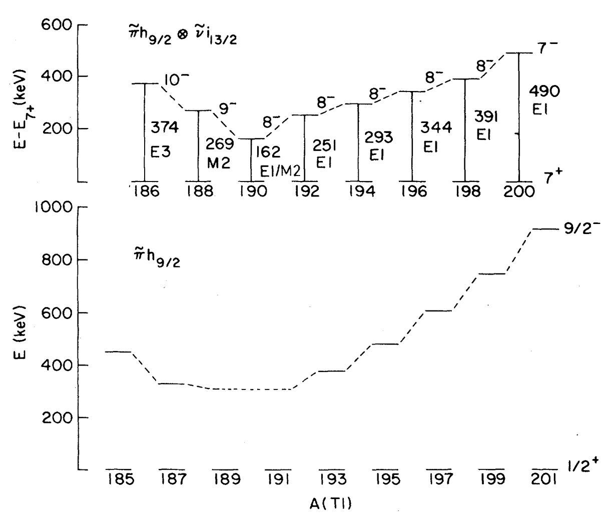

FIG. 1. Systematics of excitation energies of the bandheads of $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}i_{13/2}$ and $\tilde{\pi}h_{9/2}$ structures in odd-odd and odd Tl isotopes, respectively. (Refs. 1 and 2). The excitation energies in ^{189,191}Tl are not precisely known (Ref. 2).

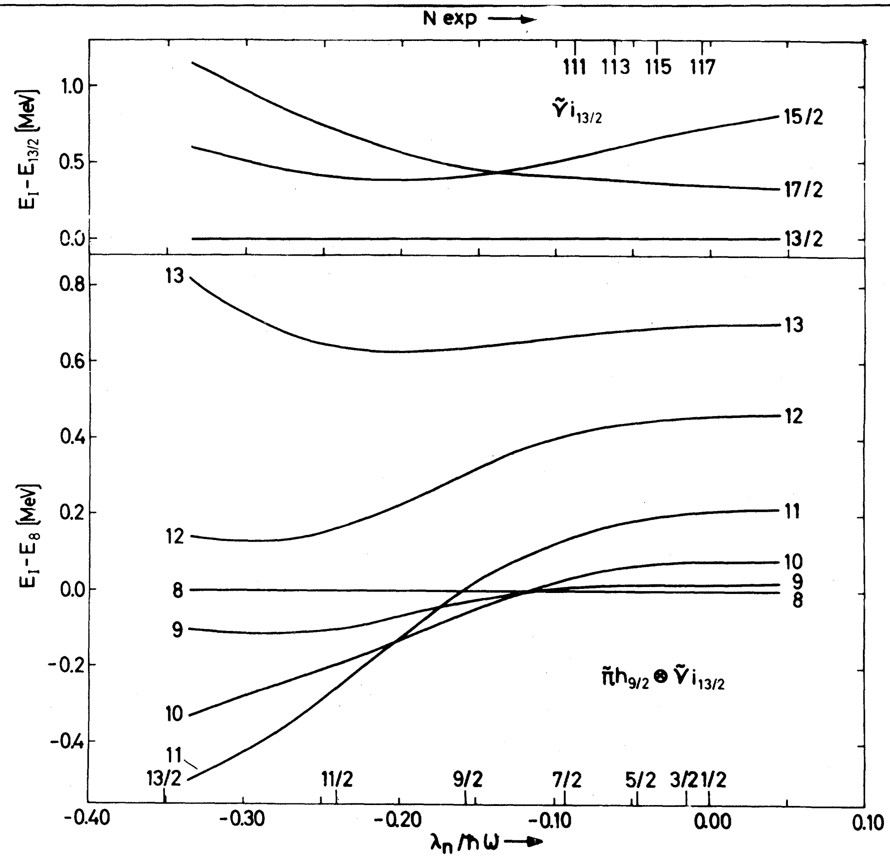

FIG. 2. Calculated energies of some yrast states for the $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}i_{13/2}$ (odd Hg) systems as a function of the neutron Fermi level (λ_n in units of the oscillator constant $\hbar\omega = 41/A^{1/3}$). Positions of single-particle Nilsson energies of the $i_{13/2}$-parentage states are indicated on the λ_n axis. Parameters and method of the calculation are given in Ref. 3. The distance between the first favored (Ref. 6) member $(\frac{17}{2}^+)$ of the $\tilde{\nu}i_{13/2}$ bands in odd Hg nuclei (Ref. 9) and the first unfavored one $(\frac{15}{2}^+)$, which depends very sensitively on λ_n, has been used to establish the correspondence between neutron number ($N_{\rm exp}$) and position of λ_n by comparison with the experimental figures.

is the perpendicular coupling of $\vec{j}_p$ and $\vec{j}_n$ which according to the relation $J(J+1) = \frac{9}{2}(\frac{9}{2}+1) + \frac{13}{2}(\frac{13}{2}+1)$ corresponds to $J \simeq 8$. Higher-spin states in the multiplet (in principle up to $I = \frac{9}{2} + \frac{13}{2} = 11$) are obtained by progressive alignment of $\vec{j}_p$ and $\vec{j}_n$ with respect to each other at the expense of intrinsic energy.[3] In going to the neutron-deficient side, however, λ_n starts penetrating the $i_{13/2}$ subshell and neutron quasiparticle states with larger projections on the symmetry axis ($\Omega_n = \frac{3}{2}, \frac{5}{2}, \ldots$) become successively lower. The implication for the doubly odd system is that states with higher total angular momentum within the multiplet come down in energy. Eventually the state with $I = 9$ will cross below the one with $I = 8$ and subsequently $I = 10$ below $I = 9$, etc.[7,8] This behavior can be observed in Fig. 2, where excitation energies of some yrast states for the $\tilde{\pi}h_{9/2}\otimes\tilde{\nu}i_{13/2}$ system have been calculated as functions of λ_n. For the observed structures in the Tl nuclei, which depopulate into long-lived 7^+ states, this means that the character of the isomeric out-of-band transition will change from $E1$ to $M2$, $E3$, etc., thus giving rise to increasingly longer lifetimes. It should be stressed that the picture outlined above corresponds to a negligible p-n force. The presence of a strong J-dependent force would cause deviations with respect to this behavior, allowing the extraction of the p-n interaction matrix elements $V_J = \langle (j_n j_p)J | V_{p-n} | (j_n j_p)J \rangle$ (Ref. 8).

In order to verify these predictions, a study of the isotopes ^{186,188,190}Tl was undertaken by using several (HI, xn) reactions: ^{168}Er(^{27}Al, $5n$)^{190}Tl ($E = 130$–160 MeV), ^{169}Tm(^{25}Mg, $4n$)^{190}Tl ($E = 120$ MeV), and ^{176}Hf(^{19}F, $5n$)^{190}Tl ($E = 85$–120 MeV); ^{169}Tm(^{24}Mg, $5n$)^{188}Tl ($E = 115$–135 MeV); and ^{159}Tb(^{32}S, $5n$)^{186}Tl ($E = 160$–165 MeV) and ^{155}Gd(^{35}Cl, $4n$)^{186}Tl ($E = 155$–170 MeV). Heavy-ion beams were accelerated by the tandem Van de Graaff accelerator facility at the Brookhaven National Laboratory. The decays of the residual nuclei were studied with use of in-beam and off-beam γ-ray spectroscopic techniques. The (HI, xn) reaction cross sections become increasingly smaller in going to the neutron-deficient side because of proton emission and fission competition. In addition, since the targets correspond to well-deformed rare-earth nuclei, the prompt spectra are dominated by Coulomb excitation up to $E \simeq 300$ keV. Under these circumstances the use of a Ge(Li) detector surrounded by an anti-Compton shield was essential to obtain an acceptable peak to background ratio. Excitation functions, γ-ray angular distributions, and γ-γ coincidences were measured revealing the existence of bands similar to those found in the heavier Tl isotopes[1] (Fig. 3). The pulsed-beam method was used to search for isomerism in the nanosecond, microsecond, millisecond, and second time regions. γ rays with transition energies of 161.9, 268.8, and 374.0 keV were identified in ^{190}Tl, ^{188}Tl, and ^{186}Tl, respectively. Their decay properties are listed in Table I (see also Fig. 1).

The isotopic assignments of the isomeric transitions were made on the basis of excitation functions, cross bombardments, intensity balances with corresponding Hg activities, and of Tl K x rays decaying with equal half-lives. From these K x-ray intensities it was possible to obtain values for the K-shell conversion coefficient (Table I). This information together with the half-lives and intensity balances with Hg activities leads to $E1/M2$ ($\delta^2 = 0.25 \pm 0.05$), $M2$, and $E3$ assignments for the multipolarities of the isomeric transitions in ^{190,188,186}Tl (see also Ref. 11 for ^{186}Tl). In assigning the multipolarity of the 161.9-keV transition we have assumed that the measured half-life corresponds to the state depopulated by this line. Other possibilities are regarded as very unlikely in view of the extremely regular systematics. Since no other transitions were observed in these nuclei which could account for the intensity of the respective bands, it was concluded that they provide their deexcitation paths. In addition, careful intensity balance with Hg activity rules out the parallel decay of bands and isomeric states for ^{188,190}Tl. In all previously known Tl isotopes the negative-parity bands decay into long-lived 7^+ "effective ground states."[9] In ^{188,190}Tl the spin and parity has been tentatively assigned as $I=7$ and $I^\pi = 7^+$, respectively.[9] A reexamination of the decay of these states to the corresponding Hg isotopes reveals a very similar pattern in all three cases, i.e., ^{186,188,190}Tl, and also to that observed in heavier Tl isotopes.[9] They populate the $I^\pi = 6^+$ and 8^+ ground-band states in ^{186,188,190}Hg with logft values of 6 ± 1 which correspond to allowed or first forbidden transitions, ruling out 6 or 8 for their spin values. Inasmuch as the bands observed here correspond to those found in the heavier Tl isotopes, and since they decay through parity-changing transitions, the high-spin effective ground states have to be of positive par-

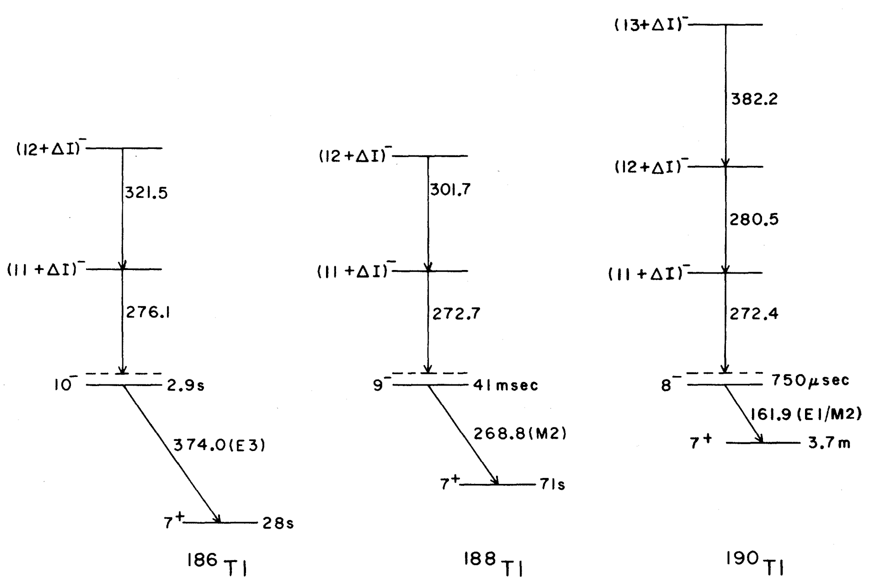

FIG. 3. $\pi h_{9/2} \otimes \nu i_{13/2}$ bands determined in the present work. There is an uncertainty in the spin values of the band members (ΔI most likely 0 or 1, see Ref. 8).

TABLE I. Properties of isomeric transitions in $^{186-190}$Tl.

A	Energy (keV)	$T_{1/2}$	α_k	$\alpha_k^{\text{theor a}}$	K/L	$K/L^{\text{theor a}}$	Multipolarity
190	161.9 ± 0.2	750 ± 40 μsec	1.9 ± 0.3	0.1 ($E1$) 9.1 ($M2$)			$E1/M2$
188	268.8 ± 0.2	41 ± 4 msec	1.5 ± 0.2	1.7 ($M2$)			$M2$
186	374.0 ± 0.2	2.9 ± 0.2 sec	0.07 ± 0.04	0.10 ($E3$)			
		$3\ \pm1$ sec	0.095 ± 0.02 [b]		≈1 [b]	0.9 ($E3$)	$E3$
		4.5 ± 1.3 sec	0.17 ± 0.07 [c]		1.5 ± 0.9 [c]		

[a]Ref. 10.
[b]From Béraud *et al.* (Ref. 11).
[c]From Cole *et al.* (Ref. 11).

ity. In addition, negative parity for these states is very unlikely in view of the available proton and neutron orbitals, $\pi(s_{1/2}, d_{3/2})$ and $\nu(p_{1/2}, p_{3/2}, f_{5/2})$, found near the Fermi levels in neighboring odd-mass Tl and Hg nuclei.[9]

It is worth noting that the excitation energies of the $\tilde{\pi} h_{9/2} \otimes \tilde{\nu} i_{13/2}$ bandhead states (Fig. 1) show the same neutron-number dependence as the $\tilde{\pi} h_{9/2}$ bandheads in neighboring odd Tl isotopes,[2] reaching a minimum at mass 190 and rising again beyond that point, lending additional support for the present interpretation. (The structure of the 7^+ states has been interpreted as the spherical $[\pi s_{1/2} \otimes \nu i_{13/2}]_{7^+}$ configuration and the $\frac{1}{2}^+$ ground states of the odd Tl isotopes are given by $\pi s_{1/2}$.[12])

In conclusion, the present data provide strong evidence for the occurrence of predicted level crossings in ^{188}Tl and ^{186}Tl. The behavior of the $I^\pi = 8^- - 10^-$ multiplet of states appears to be dictated only by the binding to the quadrupole field of the core. As far as these states are concerned, the p-n force does not seem to play an important role in determining their structure. This is consistent with the force known from ^{208}Bi which is small for these states and should be further quenched by the pairing correlations.[8] However, no information is contained in the present data about the force acting in the $J=11$ state for which a positive identification of the $I=11$ state would be needed.

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