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High-spin band structure of ^{192}Tl

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High-spin states in ^{192}Tl, excited through the ^{181}Ta(^{18}O,7n) and ^{181}Ta(^{16}O,5n) reactions, were studied using in-beam γ-ray spectroscopic techniques. Excitation functions, activity spectra, γ-ray angular distributions, and multidimensional coincidences were measured. The strongly Coriolis-distorted $\tilde{\pi} h_{9/2} \times \tilde{\nu} i_{13/2}$ two-quasiparticle band already known in the heavier ^{194,196,198}Tl isotopes has also been found in this case based on an $I^{\pi} = 8^{-}$ isomeric state at 250.6 keV above the known long-lived 7^{+} level. Trends already noted in the other Tl isotopes and also predicted by two-quasiparticle plus-rotor model calculations are confirmed thus reinforcing such a theoretical description.

[NUCLEAR REACTIONS ^{181}Ta(^{18}O,$xn\gamma$), E=105–125 MeV; ^{181}Ta(^{16}O,$xn\gamma$), E=95–105 MeV; measured E_{γ}, I_{γ}, $\sigma(E, E_{\gamma}, \theta_{\gamma})$, γ-γ coin.; ^{192}Tl levels deduced, J, π, $T_{1/2}$. Natural target. Ge(Li) detectors.]

I. INTRODUCTION

States of ^{192}Tl have been studied by several authors in the past.[1] As a result of these investigations two isomers with $I^{\pi} = (2^{-})$, $T_{1/2} = 9.5$ min and $I^{\pi} = (7^{+})$, $T_{1/2} = 11$ min, and their subsequent EC/β^{+} decay to ^{192}Hg are known. No in-beam measurements of the prompt radiation following the production of ^{192}Tl have been performed so far. In contrast, the heavier doubly odd isotopes ^{194,196,198}Tl have been recently studied on line, using the (α or HI, xn) reactions.[2-4] These studies revealed the existence of a collective two-quasiparticle band of $\tilde{\pi} h_{9/2} \otimes \tilde{\nu} i_{13/2}$ parentage,[2-5] which displays a smooth neutron-number dependence. Furthermore, this behavior is well reproduced by two-quasiparticle plus-rotor model (TQRM) calculations,[6] which also allow for definite predictions for the lighter Tl isotopes, such as the further compression of the first excited states of the band, leading eventually to the occurrence of level crossings. Hence, the purpose of the present work was to obtain additional information in order to test the validity of the theoretical description.

II. EXPERIMENTAL PROCEDURES AND RESULTS

A. Singles measurements

The two reactions ^{181}Ta(^{18}O, 7n) (bombarding energies E =105–125 MeV) and ^{181}Ta(^{16}O, 5n) (E =95–105 MeV) were studied and were found to peak at ≈120 and ≈100 MeV, respectively. The spectra obtained from both reactions are very similar. However, the peak to background ratio is more favorable in the 5n reaction case because of the fewer open channels. Figure 1 shows an angle integrated singles spectrum obtained with a relatively thin (1.2 mg/cm^2) tantalum foil. No target backing was used to avoid the production of unwanted radiations. From an analysis of the singles on- and off-line spectra one concludes that, in addition to Coulomb excitation, only reactions involving neutrons in the exit channel are observed. The decay into ^{192}Hg is very similar to those observed previously[2-4] for $^{194-198}$Tl, indicating that only the high-spin isomer is reached in the reaction, confirming its 7^{+} assignment. No transition was found connecting the 2^{-} and 7^{+} isomers in ^{192}Tl so that the relative location of both states remains uncertain.

In order to gain information on transition multipolarities the angular distribution of the γ radiation was measured between 20 and 90°. Table I summarizes the results obtained from singles measurements. Lines of ^{192}Tl are listed along with two of the strongest γ rays of the neighboring odd Tl isotopes[7] of 387.6 and 392.2 keV for comparison purposes. The isotopic assignment of the strongest transitions in ^{192}Tl was made on the basis of the excitation functions, while the weaker ones were mainly assigned utilizing the γ-γ coincidence data. Due to the relatively high velocity of the recoiling residual nuclei some of them come out of the 1.2 mg/cm^2 thick target.[8] This fact introduces some distortion in the angular distribution of γ rays depopulating isomeric

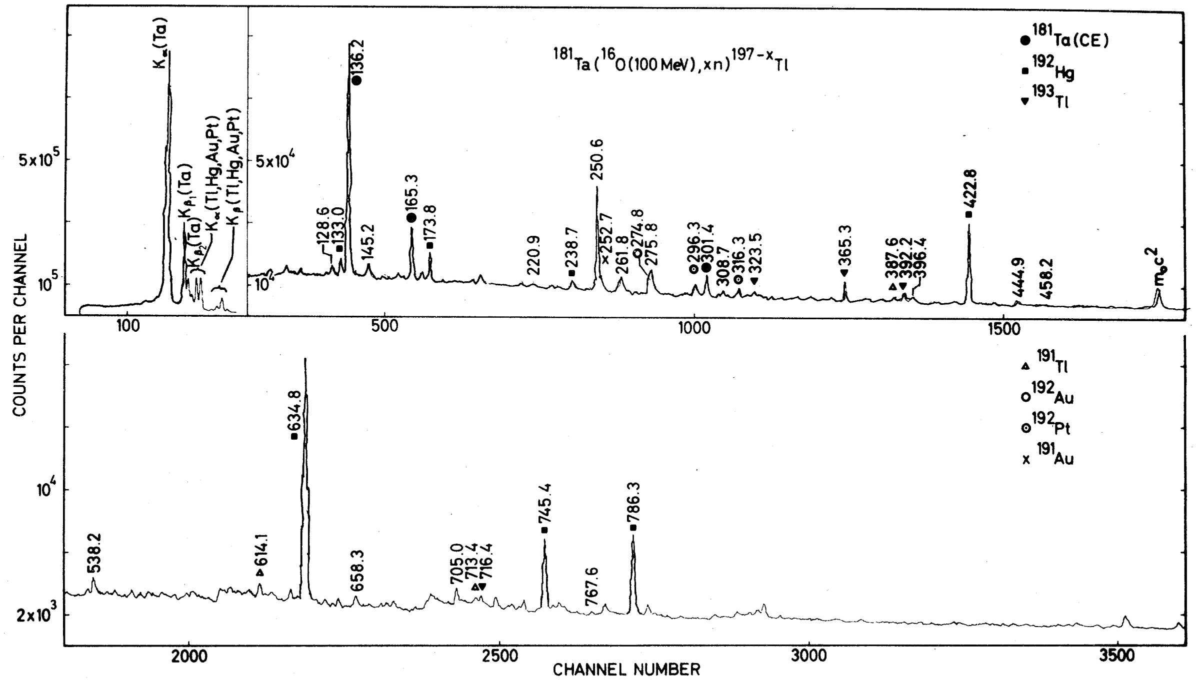

FIG. 1. Angle integrated γ-ray singles spectrum for the ^{181}Ta(^{16}O,xn) reaction at 100 MeV. Lines labeled only by their energies correspond to transitions in the nucleus ^{192}Tl. CE denotes Coulomb excitation of the target.

states such that the counting rate is enhanced for forward angles. For instance, the 365.3 keV transition from the $\frac{9}{2}^-$, 2.1 min state in ^{193}Tl (Ref. 7) should be isotropic but displays a positive anisotropy. The same effect, then, should occur for the 250.6 keV γ ray which has (as will be discussed below) a half-life of 272 ns. (In both cases most of the recoils leaving the target will stop at the back wall of the chamber before decaying.) The first set of angular distribution coefficients given in Table I for the 250.6 keV line are obtained by normalizing to the angular distribution of the 365.3 keV γ ray in order to approximately correct for the spurious asymmetry. The second set of coefficients was obtained by using a target thick enough to stop all the recoils, thus eliminating the need for this correction.

B. Coincidence measurements

Two conventional fast-slow coincidence experiments were performed: a γ-γ-x five parameter ($E_{\gamma_1}, E_{\gamma_2}, E_X, t_{\gamma_1\gamma_2}, t_{\gamma_1 x}$) measurement using the ^{181}Ta(^{18}O, 7n) reaction and γ-γ three parameter run with the ^{181}Ta(^{16}O, 5n) reaction at 120 and 100 MeV, respectively. The data obtained from both experiments are comparable even though, as already mentioned, the second reaction is cleaner.

The main result of these experiments shows a prompt cascade of γ rays in delayed coincidence with a 250.6 keV transition. This cascade is very similar to those previously found in the heavier doubly odd Tl isotopes.[2-4] In addition some other transitions weakly connected with this cascade were found but their place in the level scheme could not be established.

Figure 2 shows three gated spectra corresponding to the ^{181}Ta(^{16}O, 5n) reaction. The upper one corresponds to the second strongest transition in ^{192}Tl of 275.8 keV, the γ intensity of which represents about 10% of the total production cross section of ^{192}Tl. This gate is contaminated with the strongest 274.8 keV activity line in ^{192}Au (Ref. 9); 40% of the ^{192}Hg decay goes directly through this transition. This intensity subsequently cascades down into the ground state through a single $M1$ 31.6 keV transition which is clearly seen in the coincidence spectrum. The identification of this line was further corroborated by setting a gate on the low energy tail of the 274.8 +275.8 keV doublet. A spectrum with a very low background is obtained in this case which displays only the 31.6 keV γ ray apart from the large Au K-x-ray intensity originated in the electron capture process. The plot in the center of Fig. 2 shows the spectrum in coincidence with another

TABLE I. Energies, angle integrated γ-ray intensities, angular distribution coefficients, and total intensities for transitions in ^{192}Tl following the ^{181}Ta(^{16}O,5n) reaction at 100 MeV. (Two lines of ^{191}Tl and ^{193}Tl are also included for comparison.)

E_γ (keV) [a]	I_γ [b]	A_2/A_0 [c]	A_4/A_0	I_{tot} [d]	Multip.
83 ± 1 [e]	22 ± 7			81 ± 24	$M1/E2$
128.6	8.3	−0.09 ± 0.10	−0.12 ± 0.16		
145.2	12.8	−0.30 ± 0.04	−0.04 ± 0.07		
161.4	1.7				
220.9	5.1	−0.73 ± 0.24	0.28 ± 0.35	9.8	$M1/E2$
250.6	100.0	(−0.10 ± 0.06) [f]	(0.02 ± 0.09) [f]	104.0	$E1$
		−0.12 ± 0.03 [g]	0.01 ± 0.06		
260.1	7.7	−0.59 ± 0.08	0.12 ± 0.12		
261.8	19.0	−0.73 ± 0.08	−0.11 ± 0.12	30.2	$M1/E2$
275.8	27.2	−0.66 ± 0.04	−0.06 ± 0.05	41.0	$M1/E2$
308.7 [h]	8.9	−0.52 ± 0.09	−0.09 ± 0.14	12.3	$M1/E2$
359.0	5.5			6.0	
396.4	11.0	−0.41 ± 0.07	0.18 ± 0.14	13.1	$M1/E2$
444.9	14.9				
458.2	5.2	−0.89 ± 0.19	−0.10 ± 0.27	5.8	$M1/E2$
538.2	8.7			8.9	$E2$
658.3	7.8			7.9	$E2$
705.0	23.8	0.32 ± 0.05	−0.07 ± 0.07	24.2	$E2$
387.6 [i]	12.9	−0.77 ± 0.04	0.02 ± 0.06		$M1/E2$
392.2 [j]	18.9	−0.57 ± 0.01	0.06 ± 0.04		$M1/E2$

[a] Energies accurate to ± 0.2 keV unless otherwise stated.
[b] Errors range from 5 to 15% (for weak lines).
[c] Given only for those lines where the fit to the data gives useful results.
[d] Listed only for those transitions where arguments are available regarding the parity.
[e] Derived from coincidence data (see text).
[f] Obtained by normalizing to the 365.3 keV ^{193}Tl transition. See text.
[g] Obtained by using a thicker target. See text.
[h] Contaminated with the 308.5 keV, $3_1^+ \rightarrow 2_2^+$ activity line in ^{192}Pt (Ref. 7).
[i] $(\frac{11}{2}^-) \rightarrow \frac{9}{2}^-$ transition in ^{191}Tl (Ref. 7).
[j] $\frac{11}{2}^- \rightarrow \frac{9}{2}^-$ transition in ^{193}Tl (Ref. 7).

strong transition in ^{192}Tl. This gate actually contains part of the intensity of the 260.1 keV line (see Fig. 1 and Table I), which is seen to be weakly connected with the 261.8 keV γ ray itself. The 161.4 keV line appearing in the spectrum is in coincidence mainly with the 260.1 keV transition, as may be concluded from inspecting the spectrum gated with a window placed on the left shoulder of the 260.1 +261.8 keV doublet. The spectrum in coincidence with the 261.8 keV line shows furthermore, that the K-x-ray peaks exhibit an $I(K\beta)/I(K\alpha)$ intensity ratio which is greatly enhanced as compared to the theoretical value[9] (0.62 ± 0.04 against 0.28). This implies the existence of a γ line hidden under the $K\beta$ distribution. The same enhancement may be observed in all spectra gated with the transitions in the band (see for instance the upper plot in Fig. 2). In order to assure that the $I(K\beta)/I(K\alpha)$ ratio is not modified by some other effect, this quantity was directly measured in a spectrum gated by the 392.2 keV ^{193}Tl line, obtaining a value consistent with the theoretical one. The hidden line is even unresolved in singles because of the large amount of internal conversion $K\beta$-x rays present, and most likely lies inbetween the $K\beta_1$ and $K\beta_2$ lines so that its intensity had to be derived from coincidence measurements (see Table I).

The gated spectrum shown at the bottom of Fig. 2 corresponds to the $7^- \rightarrow 6^+$ transition in ^{192}Hg (Ref. 9), whose γ-intensity represents about 20% of the total ^{192}Tl cross section. The statistics and the peak to background ratio are in general better for activity than for in-beam gates because of the much larger fragmentation of the intensity in the latter case. Also in this spectrum the $I(K_\beta)/I(K_\alpha)$ ratio corresponds to the theoretical one which has practically the same value for Hg as for Tl.

Table II gives the results of a quantitative evaluation of coincidence intensities for the set

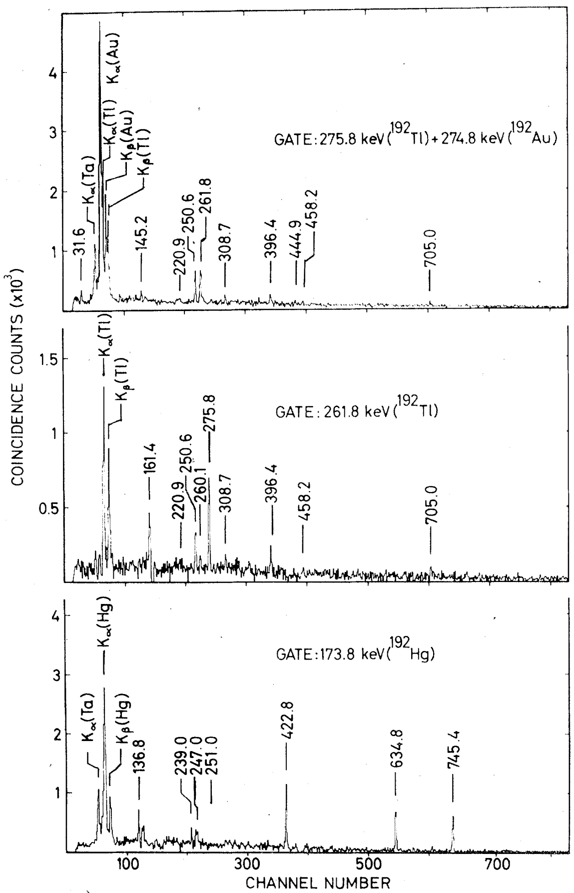

FIG. 2. Background-corrected γ-γ coincidence spectra gated with two of the strongest transitions in ^{192}Tl and one activity line in ^{192}Hg.

of lines in delayed coincidence with the 250.6 keV transition, whose intensity is lower as expected (see Sec. II C) because it lies partially outside the accepted time-to-amplitude converter range. The intensities corresponding to the 83 keV line were obtained subtracting the true $K\beta$ intensity, as deduced from the theoretical $I(K\beta)/I(K\alpha)$ ratio, from the peak at the $K\beta$ position.

Through appropriate scanning of the events stored during the three parameter experiment, relative time distributions of the γ rays were obtained. At the left-hand side of Fig. 3 we show the time distribution of the 250.6 keV γ ray with respect to the whole spectrum in the other detector. The prompt component arises from a contaminating 252.7 keV activity line in ^{191}Au (Ref. 9). As mentioned above, some of the recoiling residues come out of the thin target and this may distort the observed decay curve. However, the correlation coefficient in the exponential fit was very close to -1 ($\rho = -0.98$) giving a value of $T_{1/2} = (272 \pm 10)$ ns. The right-hand side of the figure illustrates the time resolution of the timing set up.

C. The level scheme

The 250.6 keV γ ray is the strongest line of those assigned to ^{192}Tl (see Table I) and should therefore populate directly the 7^+ "effective" ground state. In addition, this transition displays a half-life of 272 ns and is in delayed coincidence with a whole set of γ rays. Dipole character is implied by the angular distribution measurement and, in addition, such a half-life most likely corresponds to an $E1$ transition with a hindrance of $\simeq 0.5 \times 10^{-7}$ (a value which lies within the systematics; see for instance Ref. 10). This assignment is also supported by consideration of the intensity balance between the 250.6 keV transition and the decay into ^{192}Hg. The total transition intensity of the $2^+ \to 0^+$, 422.8 keV γ ray in ^{192}Hg (Ref. 9) is in this case a good measure for the total formation cross section of ^{192}Tl. We obtain I_{tot} (422.8 keV)/I_γ (250.6 keV) = 2.6 $\pm$ 0.4. This ratio is incompatible with an $M2$ character because of the large conversion coefficient for such a multipolarity [$\alpha_{tot}(M2) \simeq 2.8$,

TABLE II. Coincidence γ intensities for the set of lines strongly time related to the 250.6 keV transition in the ^{181}Ta(^{16}O,5n) reaction.[a]

Gate (keV) \ E_γ (keV)	83[c]	220.9	250.6	261.8	275.8	308.7	396.4	458.2	538.2	705.0
250.6[b]	167			99	206				106	
261.8	250	32	278		696	101	293	148		234
275.8	630	65	533	747		138	264	137		146
308.7	51		87	54	113		89			
396.4	64		66	226	119	43				
538.2	69		38							

[a]Errors range from 15 up to 50% for weak lines in small gates.
[b]Isomeric transition.
[c]Intensities derived from $I^{exp}(K\beta) - [I^{theor}(K\beta)/I^{theor}(K\alpha)]\, I^{exp}(K\alpha)$, where $I^{exp}(K\beta)$ indicates the measured intensity of the peak at the Tl $K\beta$-x ray energy.

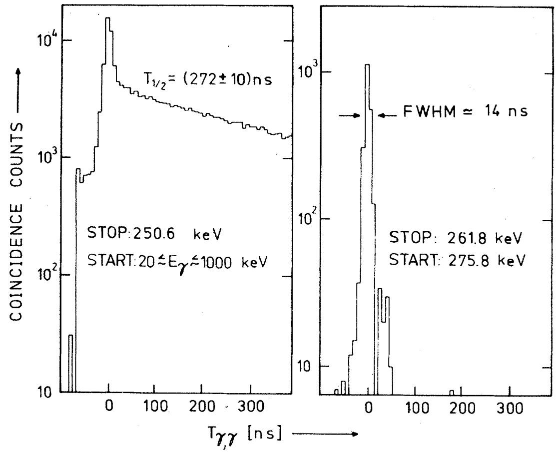

FIG. 3. Time distributions for the 250.6 keV transition and of the 261.8 and 275.8 keV γ rays with respect to each other.

Ref. 11].

The level scheme presented in Fig. 4 was constructed on the basis of the singles and coincidence data given above. The fact that the band in delayed coincidence with the 250.6 keV γ ray is drawn as not ending directly on the 8^- state is related with the possibility that other highly converted low-energy transitions (≤ 40 keV) may exist through which the band depopulates into the isomer. This presumption is based both on experimental evidence obtained for ^{196}Tl, in which an additional transition has been observed, and on theoretical arguments, as will be discussed in Sec. III. From a purely experimental standpoint the spins of the band members are indicated as $(9+I_0)$, $(10+I_0)\cdots$, with $I_0 \geq 0$ undetermined.

The level sequence up to the state labeled as $(14+I_0)$ is almost certain even though the evidence for the 767.6 keV cross-over transition is not conclusive. Such a weak line is present in the singles spectrum but its energy does not fit very well with the energy sum 458.2 + 308.7 = 766.9 keV. The evidence for the 658.3 keV crossover comes not only from its well-fitting energy but also from its presence in a spectrum where the coincidence spectra corresponding to the strongest gates have been added up. The additional assumption of $M1$ character for the intraband $\Delta L = 1$ transitions is necessary in order to achieve consistency for the proposed level scheme, being especially important for the hidden 83 keV line [which has, if $M1$, a total conversion coefficient of $\simeq 2.5$ (Ref. 11)]. This is a plausible assumption not only considering the collective character of the band but also in view of the very similar structures in the heavier Tl isotopes where the $M1$ nature of these transitions has been measured in one case[2] (see Sec. III). It is interesting to point out that the energy of 83 keV for the first cascade transition is exactly what is expected from an extrapolation of the analogous transitions in ^{194,196,198}Tl.

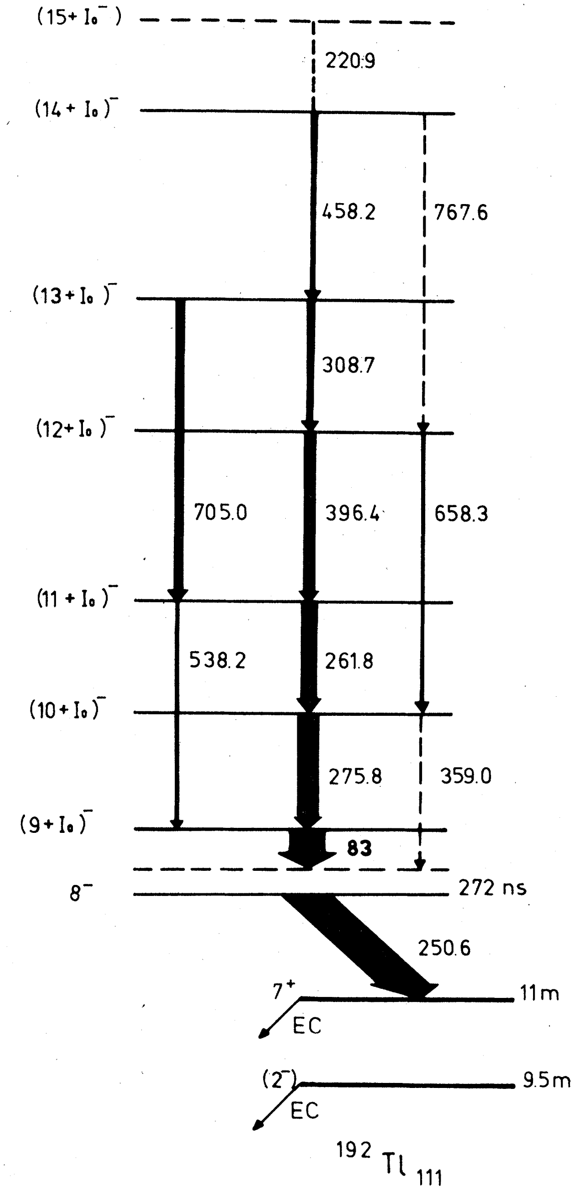

FIG. 4. Level scheme of ^{192}Tl proposed in the present work. Arrow thicknesses indicate total transition intensities. For the meaning of I_0 see text.

III. DISCUSSION

The level scheme proposed in this paper for ^{192}Tl, consisting of a sequence of levels feeding an 8^- isomer, constitutes a new example of a remarkably regular structure already found in the heavier isotopes ^{194}Tl (Ref. 4), ^{196}Tl (Ref. 3), and ^{198}Tl (Ref. 2).

This structure is interpreted in terms of the $\tilde{\pi} h_{9/2} \otimes \tilde{\nu} i_{13/2}$ configuration space and it has been discussed in the framework of the noninteracting TQRM.[5] A simple and unifying picture emerges from this model and its various features relating to the description of these levels have already been given in previous papers.[2-6] It is interesting to briefly review the most important predictions of these calculations in order to compare them with the now available data:

(a) The lowest states of this structure constitute an $I^\pi = 8^- - 11^-$ multiplet which corresponds to different orientations of the proton without involving significant core excitation. The splitting of this multiplet is sensitive to the position of the neutron Fermi level and diminishes as nuclei become more neutron deficient. This trend continues up to a point ($A \sim 190$) where a level crossing is predicted.[6] For $A \gtrsim 190$ the 8^- state is the lowest member of the group and the level ordering follows the sequence of increasing spins.

(b) Above this multiplet a typical $\Delta I = 1$ Coriolis distorted band develops which shows a characteristic level staggering of the same origin and similar magnitude as in the odd Tl neighbors.[12] For $A \gtrsim 192$ the spacings among these states are predicted to remain essentially constant as compared with the variations within the multiplet.

Figure 5 summarizes the presently available information on these bands. Data are displayed for the Tl isotopes with $A = 192-198$. Unobserved members of the low-lying multiplet predicted by the TQRM are indicated in dashed lines. Such a situation corresponds to a value $I_0 = 2$ in Fig. 4. So far data regarding transitions within the multiplet are scarce because the detection of such low-energy highly converted lines is very difficult in an on-line experiment. Moreover, as shown by the present experiment, some of these lines are likely to lie in the energy range of the intense x-ray radiation. Only in the case of ^{196}Tl have two transitions within the multiplet been reported.[3]

It is, however, suggestive that the above mentioned predictions of the TQRM would be borne out if the existence of the multiplet is assumed. In the first place, the energy of the $(11)^- \rightarrow (10)^-$ transition (see Fig. 5), being the only one which supposedly belongs to the multiplet and which is also known over the whole mass range $A = 192-198$, is indeed seen to decrease as more neutron deficient nuclei are reached. The results of this paper seem to indicate that level crossing might occur for isotopes lighter than ^{192}Tl so that ^{190}Tl becomes a very attractive case for study. Secondly, above the $(11)^-$ state the predicted constancy with N of the level spacings is supported by the data.

Finally it should be pointed out that an alternative description which introduces a proton-neutron (p-n) residual interaction has been used[13,14] to account for the bands in both ^{196}Tl and ^{198}Tl. In this approach, the staggering phenomenon is ascribed to the p-n force (which in fact gives a contribution to the staggering which is opposite in phase to that caused by the Coriolis interaction[5]). As a consequence of this, however, the staggering in the neighboring odd Tl isotopes,[12] while suggestively similar to the odd-odd cases, appears to have a completely different origin,[5] and a physically very appealing analogy is lost. In view of this situation, it should be of considerable interest to gain more information concerning the multiplet. A suitable experiment is in progress involving the study of the multiplet in the ^{200}Tl isotope whose transition energies are expected to be somewhat larger.

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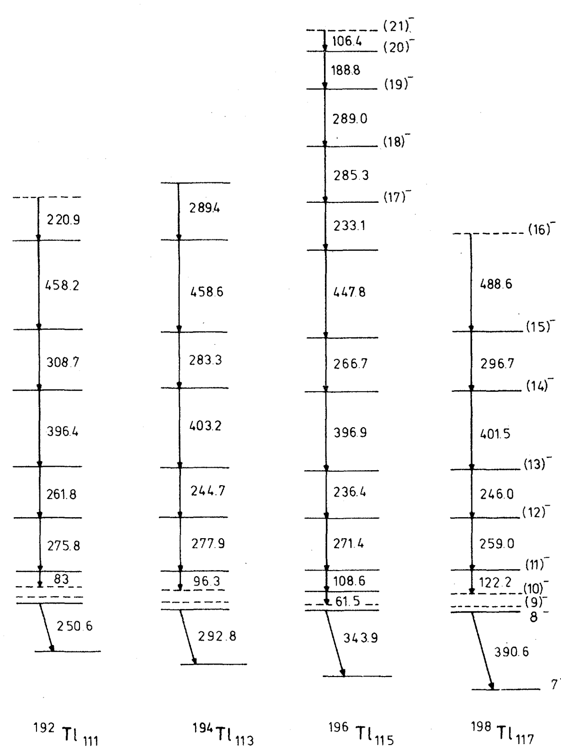

FIG. 5. Systematics of negative parity high-spin bands in doubly odd Tl isotopes.

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