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Alignment additivity in the two-quasiparticle superdeformed bands of ^{192}Tl

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Four superdeformed bands have been confirmed in ^{192}Tl. Two of these bands have $\mathcal{J}^{(2)}$ dynamic moments of inertia which are nearly constant with rotational frequency $\hbar\omega$. The other two bands show the characteristic rise of $\mathcal{J}^{(2)}$ with increasing $\hbar\omega$ seen in most superdeformed bands of the $A=190$ region of superdeformation. From comparisons with the odd-A neighbors, it was found that the alignments of these bands relative to a ^{192}Hg core can be accounted for from the additive contributions of the assigned quasiproton and quasineutron orbitals. [S0556-2813(96)01605-6]

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I. INTRODUCTION

It is by now generally accepted that the effects of pair correlations at very large deformations can be probed most clearly in nuclei of the $A\sim190$ region of superdeformation. Most superdeformed (SD) bands of this region exhibit the same smooth increase of the dynamic moment of inertia $\mathcal{J}^{(2)}$ with rotational frequency $\hbar\omega$ [1] due to the gradual alignment of quasiparticles occupying high-N intruder orbitals (originating from the $i_{13/2}$ proton and $j_{15/2}$ neutron subshells) in the presence of pair correlations. The fact that the rise in $\mathcal{J}^{(2)}$ is of the same magnitude in most SD bands has made it more difficult to propose firm configuration assignments than in the $A\sim150$ region, for example. In the latter region, variations of $\mathcal{J}^{(2)}$ with $\hbar\omega$ have shown to be a characteristic fingerprint of the active intruder orbitals [2] in the SD band under consideration. Nevertheless, detailed studies such as those performed recently for the SD bands in ^{191,193}Hg [3, 4] have been quite successful in presenting a coherent picture of the various quasiparticle excitations occurring in the SD well. In some instances, these configuration assignments have been confirmed by the direct measurement of $B(M1)/B(E2)$ branching ratios in signature-partner SD bands [5, 6].

It is the purpose of the present paper to examine whether configuration assignments can be made firmer by examining in detail the observed quasiparticle alignments. In particular, we explore here the extent to which the additivity principle of the cranking model [7] remains valid at very large deformations; e.g., whether the alignments observed in a two-quasiparticle SD band can be accounted for by the addition of the alignments measured in the one-quasiparticle bands of neighboring odd-A nuclei. The approach is in many respects similar to that used in the $A\sim150$ region by Ragnarsson [8], although in that case pairing effects were neglected. It should be stressed that the question of additivity of alignments is also important because it provides a crucial test of whether or not the measured alignment gains can be ascribed solely to the alignment of individual nucleons or whether it is the manifestation of a new collective phenomenon such as pseudospin alignment, for example.

Here we focus on new results obtained for the odd-odd ^{192}Tl nucleus. This nucleus has been the subject of an earlier study by Liang *et al.* [9] in which six SD bands were reported. Two of these bands were found to be characterized by a $\mathcal{J}^{(2)}$ moment of inertia constant with $\hbar\omega$, a feature which can be understood in terms of blocking of expected quasiparticle alignments.

II. EXPERIMENT AND RESULTS

In order to study the ^{192}Tl SD bands in more detail, a new measurement has been carried out with the early implementation phase of the Gammasphere spectrometer [10] which consisted, at that time, of 36 Compton-suppressed Ge detectors. High spin states in ^{192}Tl were populated with the ^{160}Gd(^{37}Cl,5n) reaction at 178 MeV. The beam was provided by the 88 in. Cyclotron at the Lawrence Berkeley National Laboratory, and the target consisted of a stack of two thin, 500 μg/cm^2 self-supporting targets of isotopically enriched (97.7%) material. A total of 5×10^8 triple and higher order coincidence events were recorded, and the data were subsequently sorted into a three-dimensional histogram. From the three-dimensional histogram, double-gated one-dimensional spectra were created using full background subtraction and proper error propagation techniques [11].

The four SD bands presented in Figs. 1 and 2 and in Table I are the main results of this analysis. These bands are labeled A–D in the discussion below. The four SD bands can

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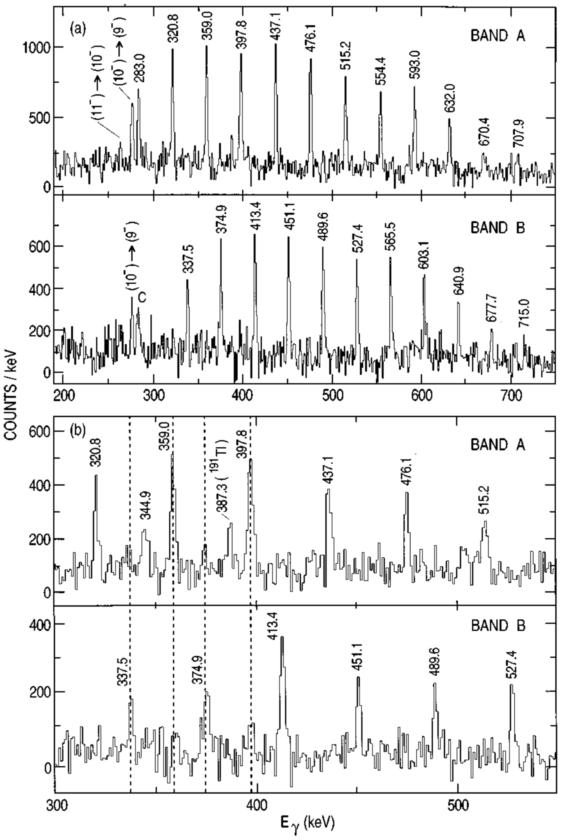

FIG. 1. (a) Double-gated coincidence spectra for SD bands *A* and *B*. Yrast transitions in ^{192}Tl are labeled by the spins of the initial and final levels. The transition labeled *C* is a known contaminant. (b) Spectra obtained from sums of all double coincidence gates in band *A* for $E_\gamma \geq 437$ keV or in band *B* for $E_\gamma \geq 451$ keV showing the weak crosstalk between the bands. The lines at 344.9 and 387.3 keV are yrast transitions which are coincident with γ rays of energies nearly identical to those of members of band *A*.

be grouped into two signature partner pairs since, at low transition energies, γ rays of one proposed partner lie almost exactly midway between the energies in the companion sequence. The assignment to ^{192}Tl is based on the observation in the coincidence spectra of yrast transitions assigned to this nucleus [12]. All four bands display energy spacings and intensity patterns characteristic of SD bands in the $A \sim 190$ region [1].

Band *D* is new to this work. While bands *A*, *B*, and *C* correspond to bands 1, 3, and 5 of [9], respectively, there are noticeable differences between the results of the two experiments which need to be addressed briefly. As already pointed out in [9], the SD bands in ^{192}Tl are studied with a (^{37}Cl,5*n*) reaction in which the ^{37}Cl beam brings into the compound nucleus more excitation energy and angular momentum than is truly desirable. As a result, the background due to fission events is larger than is often the case and, consequently, the peak-to-background ratio in the coincidence spectra is not as good as in other superdeformation studies in the $A = 190$ region. To a large degree, the misassignments in [9] were brought about (i) by the lack of knowledge of the yrast and near yrast level structure in ^{192}Tl at that time, (ii) by errors in channel assignment of the observed SD bands, and (iii) by the lack of statistics in some of the coincidence spectra of the previous experiment. For example, bands 1 and 2 of [9] have energies which are rather close to those of the two SD bands which have been discovered recently in ^{191}Tl [13]. In the present work, band 2 was not seen and it is possible that this band was observed in [9] only because in the latter work a long coincidence measurement was performed at a beam energy of 181 MeV where the 6*n* evaporation has a higher cross section. The differences between band 5 of [9] and band *C* at low energies result from contaminants which were removed in the present work through the use of double gating. No strong evidence for bands 4 and 6 could be found in the current data, and it is possible that these sequences belong to another nucleus which is fed at the higher beam energy used in [9].

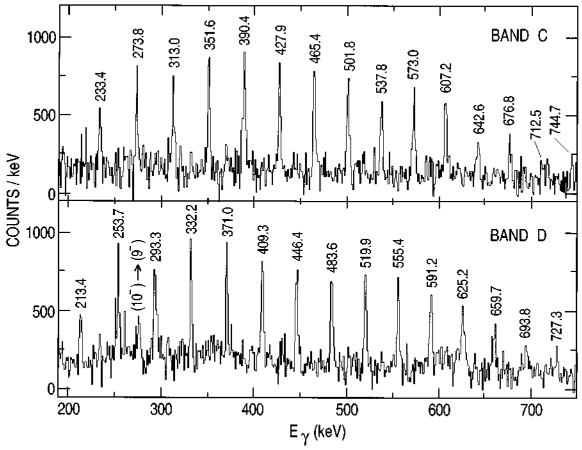

FIG. 2. Double-gated coincidence spectra for SD bands *C* and *D* in ^{192}Tl. An yrast transition in ^{192}Tl is labeled by the spins of the initial and final levels.

Figure 3 presents the dynamic moments of inertia $\mathscr{J}^{(2)}$ of

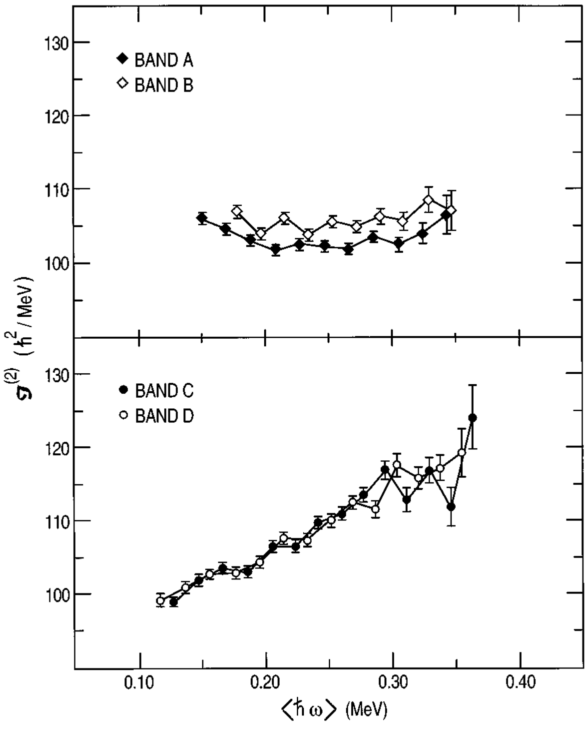

FIG. 3. Dynamic moments of inertia $\mathscr{J}^{(2)}$ for the four SD bands observed in ^{192}Tl.

TABLE I. Measured energies and associated uncertainties (in keV) for the transitions in the four SD bands of ^{192}Tl. The spin values adopted for the final states are given as well — see text for details.

Band *A*	Band *B*	Band *C*	Band *D*
			213.4 (0.3), 9
		233.4 (0.2), 10	253.7 (0.2), 11
283.0 (0.2), 15		273.8 (0.2), 12	293.3 (0.2), 13
320.8 (0.2), 17	337.5 (0.2), 18	313.0 (0.2), 14	332.2 (0.2), 15
359.0 (0.2), 19	374.9 (0.2), 20	351.6 (0.2), 16	371.0 (0.2), 17
397.8 (0.2), 21	413.4 (0.2), 22	390.4 (0.2), 18	409.3 (0.2), 19
437.1 (0.2), 23	451.1 (0.2), 24	427.9 (0.2), 20	446.4 (0.2), 21
476.1 (0.2), 25	489.6 (0.2), 26	465.4 (0.2), 22	483.6 (0.2), 23
515.2 (0.2), 27	527.4 (0.2), 28	501.8 (0.2), 24	519.9 (0.2), 25
554.4 (0.2), 29	565.5 (0.2), 30	537.8 (0.2), 26	555.4 (0.2), 27
593.0 (0.2), 31	603.1 (0.3), 32	573.0 (0.2), 28	591.2 (0.3), 29
632.0 (0.3), 33	640.9 (0.3), 34	607.2 (0.3), 30	625.2 (0.3), 31
670.4 (0.4), 35	677.7 (0.5), 36	642.6 (0.4), 32	659.7 (0.3), 33
707.9 (0.8), 37	715.0 (0.8), 38	676.8 (0.3), 34	693.8 (0.4), 35
		712.5 (0.8), 36	727.3 (0.8), 37
		744.7 (0.8), 38	

the various bands as a function of rotational frequency. The difference in behavior between the two sets of bands is rather striking: while bands *C* and *D* experience a smooth rise in $\mathcal{J}^{(2)}$ with $\hbar\omega$ which is similar to that observed in most bands of the 190 region of superdeformation, bands *A* and *B* are characterized by essentially constant $\mathcal{J}^{(2)}$ values. This difference was already noted in [9] where the ‘‘flat bands’’ were assigned the double intruder configuration $\nu j_{15/2} \otimes \pi i_{13/2}$. This assignment is supported by the results of cranked shell model calculations (CSM’s) which indicate that the constant $\mathcal{J}^{(2)}$ values are brought about by the blocking of the $\nu j_{15/2}$ and $\pi i_{13/2}$ quasiparticle alignments which contribute significantly to the rise in $\mathcal{J}^{(2)}$ seen in neighboring nuclei [1, 14]. These CSM calculations also indicate that the occupancy of the two high-*j* intruder orbitals results in $\mathcal{J}^{(2)}$ values which are larger than those of other configurations at the lowest frequencies, in agreement with the experimental observations.

As indicated above, bands *A* and *B* appear to be signature partners on the basis of the measured transition energies. There is also some evidence for crosstalk between the lowest states of the two bands. Specifically, a spectrum generated from all double-coincidence gates placed on transitions with $E_\gamma \geqslant 451$ keV in band *B* reveals the presence of weak γ rays with energies of 359 and 397 keV assigned to band *A*. Conversely, a similar sum of all clean coincidence spectra with $E_\gamma \geqslant 437$ keV in band *A* exhibits weak coincidence relationships with the 338 and 375 keV γ rays of band *B* (see lower two panels of Fig. 1). Thus, the situation is similar to that reported for some signature-partner SD bands in ^{193}Hg [5, 15] and ^{193,195}Tl [6, 16]. In the configuration of Gammasphere used in the present experiment, only six detectors were located at 90° where the angular distribution of the expected M1 transitions peaks. This observation combined with the lack of detection efficiency at low transition energies explains why the γ transitions linking the two sets of states were not directly observed. It should be noted that a similar analysis was performed for bands *C* and *D* and no evidence for crosstalk was found in this case.

While a rather consistent interpretation of bands *A* and *B* appears to emerge, some questions remain. For example, the intensity of band *A* is roughly twice that of bands *B*, a feature which is not expected for signature partner bands which show small signature splitting.[1] In a similar situation in ^{193}Hg, it was shown that two bands with essentially identical transition energies were present [5]. As in Ref. [5], the widths of γ-ray peaks in the spectra of all SD bands were compared: they were found to be identical within the experimental resolution. Based on this observation, it is concluded that band *A* most likely corresponds to a single SD band and the reason for the large intensity difference remains unclear. This prompted us to seek for further confirmation of the proposed $\nu j_{15/2} \otimes \pi i_{13/2}$ configuration by following the approach presented below.

III. ALIGNMENTS AND ADDITIVITY

A. Bands *A* and *B*

In order to facilitate the interpretation of SD bands in this mass region, the data can be transformed into the intrinsic, rotating frame where they can be compared with quasiparticle Routhians and alignments calculated within the framework of the CSM, for example. Such a transformation requires knowledge of spins and excitation energies associated with the bands of interest. These quantities have not been established experimentally in SD nuclei with the exception of band 1 in ^{194}Hg [17], but it has been shown that it is often possible to obtain a self-consistent picture of *all* SD bands in a given nucleus using assigned spins and arbitrary excitation energies [3, 4].

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[1] Any contribution to the band *A* yields quoted here from a ^{191}Tl SD band (band 1) with approximately the same transition energies is less than 8% of the measured strength. This limit was derived from the measured intensity of the signature partner SD band, ^{191}Tl band 2, which is seen in the data set.

Spin assignments to SD bands have been made (i) by directly identifying primary, high-energy transitions linking the SD states to the yrast levels as was done recently for the first time in ^{194}Hg [17], (ii) by analyzing the decay spectrum associated with an SD band [18] and by establishing the average entry spins into the yrast states following the decay-out of a SD band [3], and/or (iii) by performing a fit with a Harris parametrization to the measured $\mathscr{T}^{(2)}$ values as a function of frequency [19, 20]. In the case of ^{192}Tl, methods (i) and (ii) could not be applied because of the statistical accuracy of the data and method (iii) proved useful only for bands C and D as this technique is known to be unreliable for SD bands built on configurations with a single intruder orbital such as $\nu j_{15/2}$ occupied. The spins adopted for bands A and B are given in Table I. We return to our choice of these spin values later in the discussion.

To compute Routhians and alignments for the four SD bands in ^{192}Tl as well as for some of the SD bands in the odd-even neighbors ^{191}Hg and ^{193}Tl, a reference needs to be chosen. In the present work, the yrast SD band of ^{192}Hg was adopted since there is ample experimental [1, 21] and theoretical [22–25] evidence that this nucleus can be considered as a doubly magic SD nucleus because of the presence of large shell gaps at $Z=80$ and $N=112$ at large deformations. This choice of the full set of experimental data is not without questions, however. The $\mathscr{T}^{(2)}$ moment of inertia changes with frequency in this reference band because of the subsequent gradual alignments of a pair of $j_{15/2}$ neutrons and a pair of $i_{13/2}$ protons [1, 14, 26]. Thus, this reference represents more than the rotating core which is commonly used to compute these quantities, as the effects of alignments and the resulting changes in pairing and/or in deformation with frequency are included. The Routhians for the four SD bands in ^{192}Tl are presented in Fig. 4 together with those for the two SD bands of ^{193}Tl which are built on the $\pi i_{13/2}$ intruder configuration (bands 1 and 2 in [16]). The absolute energy scale on the figure is arbitrary and the relative excitation energies of signature partner bands have been fixed by requiring that there be no energy splitting ($\Delta e'=0$) at the lowest frequencies. As the figure indicates, bands A and B exhibit signature splitting at higher rotational frequencies while bands C and D are strongly coupled over the entire range of the bands.

As discussed above, the double intruder configuration assigned to bands A and B is based primarily on the constancy of the $\mathscr{T}^{(2)}$ moments of inertia with $\hbar\omega$. However, a strong confirmation of the assignment for each band can be inferred from the Routhians in the following way. From Fig. 4 it is clear that the splitting seen in bands A and B mirrors that displayed by the ^{193}Tl $\pi i_{13/2}$ excitations [16]. In addition, the fact that the unfavored signature of the $j_{15/2}$ intruder orbital in ^{191}Hg is populated only at the 10% level relative to the favored one[2] [3] implies that the associated neutron configuration for bands A and B must be the yrast, favored signature of the $j_{15/2}$ orbital (band 1 in [3]). Then, from the Routhian diagram of Fig. 4, band B can be associated with the favored signature resulting from the coupling of the favored $j_{15/2}$ neutron to the favored $i_{13/2}$ proton, giving the signature quantum number $\alpha=0$. Correspondingly, band A results from the coupling of the favored $j_{15/2}$ neutron to the unfavored $i_{13/2}$ proton resulting in $\alpha=1$. It follows from this coupling scheme that bands A and B have odd and even spins, respectively.

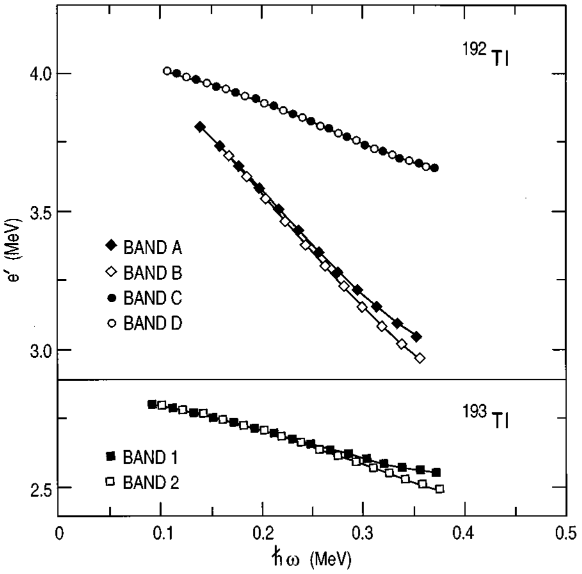

FIG. 4. Experimental Routhians for the four SD bands in ^{192}Tl obtained under the assumptions described in the text. Also shown are the two SD bands of ^{193}Tl corresponding to the $\pi i_{13/2}$ excitations. In all cases the reference is the yrast SD band of ^{192}Hg.

The alignments calculated with the same ^{192}Hg reference are presented in Fig. 5 for the SD bands of ^{192}Tl, the favored $j_{15/2}$ band in ^{191}Hg and the two $i_{13/2}$ signature partner excitations in ^{193}Tl. Before discussing the alignments observed in the SD bands of ^{192}Tl, it is important to understand the behavior seen in the two odd-even neighbors. In contrast to what might be expected for intruder bands, the $\nu j_{15/2}$ band of ^{191}Hg begins to lose alignment almost immediately with respect to the core. This can be understood by realizing that the $j_{15/2}$ neutrons are predicted to align below $\hbar\omega=0.35$ MeV in ^{192}Hg [1, 14] and their contribution to the angular momentum is included in the reference. The alignment of this quasiparticle pair is blocked in band 1 of ^{191}Hg, and a negative contribution to the alignment should be expected when the neutrons begin to align in the core. This process starts at $\hbar\omega=0.2$ MeV (see Fig. 5) and continues over the entire frequency range of band 1. In fact, by examining the data in this way, one is able (i) to determine experimentally the frequency at which the $j_{15/2}$ neutrons begin to add significantly to the angular momentum of the core, and (ii) to show that the alignment process is gradual, taking place over a wide frequency range. In contrast, the alignment curves for bands 1 and 2 in ^{193}Tl show a small increase in alignment between $\hbar\omega=0.1$ and 0.2 MeV. This difference in behavior is not unexpected since the alignment of $j_{15/2}$ neutrons is not blocked in these bands. The observed alignment ($i\sim 1\hbar$ at $\hbar\omega=0.25$ MeV) represents intrinsic contributions to the alignment from the favored and unfavored $i_{13/2}$ protons with

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[2] This is in agreement with the results of CSM calculations which place this orbital quite high in excitation energy above the Fermi surface for $\hbar\omega \geqslant 0.2$ MeV [3].

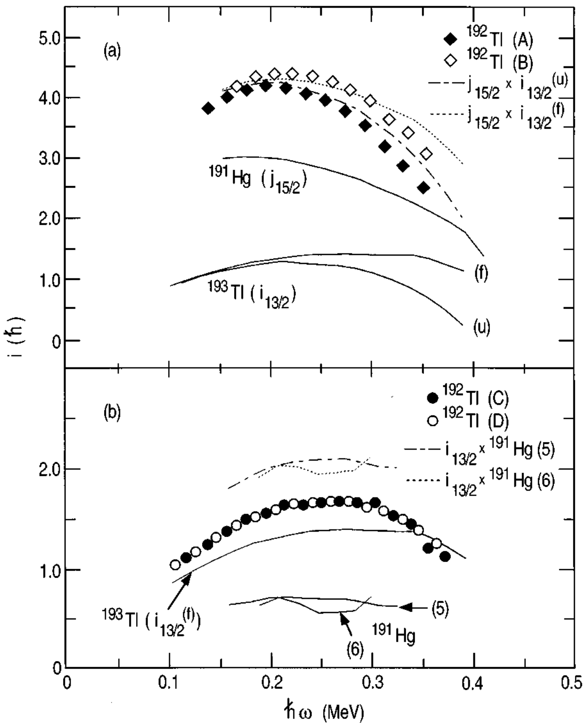

FIG. 5. (a) the solid curves show the experimental alignments for the $\nu j_{15/2}$ band of ^{191}Hg (band 1) and the favored (band 2) and unfavored (band 1) $\pi i_{13/2}$ bands of ^{193}Tl. The dotted and dot-dashed curves show the sums of these alignments for the configurations where the $\nu j_{15/2}$ favored configuration is coupled to the two signatures of the $\pi i_{13/2}$ configuration. The experimental alignments derived from the data for bands *A* and *B* compare well with the curves and indicate that alignments are additive in the SD well. (b) same as (a) for alignments in bands *C* and *D*. In this case the data are compared to configurations involving SD bands 5 and 6 of ^{191}Hg — see text for details.

respect to the ^{192}Hg reference. The decrease in alignment at the highest frequencies seen in the favored signature may be due to the blocking of the $i_{13/2}$ proton alignment. Confirmation of this interpretation requires the extension of this band to higher spins as it is difficult to address the blocking issue from the inspection of the alignment in the unfavored partner because of the signature splitting.

The alignments for bands *A* and *B* in ^{192}Tl are compared in Fig. 5(a) with those obtained by summing the individual contributions of the experimental one-quasineutron and one-quasiproton orbitals which form the appropriate two-quasiparticle bands, i.e., $j_{15/2} \otimes i_{13/2}^{(f)}$ (for band *B*) and $j_{15/2} \otimes i_{13/2}^{(u)}$ (for band *A*). The "*f*" and "*u*" superscripts refer to the favored and unfavored orbitals, respectively. A satisfactory agreement exists both in the magnitude and the variation of the alignment with frequency between the data and the computed values over the entire $\hbar\omega$ range. From this observation it is concluded that the concept of alignment additivity is applicable to SD bands in the $A=190$ region. The approach presented here is model independent in the sense that (i) there is no parametrization for the reference and (ii) the agreement between the experimental alignments in bands *A* and *B* and those computed from the chosen SD bands in the neighboring ^{191}Hg and ^{193}Tl nuclei is completely independent of any *a priori* quasiparticle assignment. As such, this agreement also provides a positive self-consistency check of the proposed configurations for bands *A* and *B*.

A brief comment on the spin assignments for bands *A* and *B* is also in order at this point. As outlined above, there is strong experimental evidence that these two bands are signature partners. This implies that one band will have even spin values and the other odd ones. Based on the observed signature splitting and the comparison with the $i_{13/2}$ proton excitations in ^{193}Tl, bands *A* and *B* have been assigned odd and even spins, respectively, and this coupling scheme appears to be confirmed by the data. It also follows that if the spin assigned to the levels in the two bands are wrong, they must be changed by at least $2\hbar$ to maintain the correct signatures. Such a change would significantly affect the magnitude of the alignment curves but not their trajectories. In this case, a situation would arise in which the response with rotational frequency of the summed alignment curves agrees with the two-quasiparticle bands but differs in magnitude by at least $2\hbar$ (i.e., ± 50%). There seems to be no reasonable explanation to account for such a phenomenon, and the spins assigned to bands *A* and *B* can be viewed as the most probable with some confidence.

Finally, as indicated in the previous section, there is evidence for crosstalk between bands *A* and *B*. As in earlier work [6], limits on $B(M1)/B(E2)$ ratios could be inferred from the measured coincidence intensities. Under the assumption that the deformation of the SD well in ^{192}Tl is the same as that derived from lifetime measurements in the SD band of ^{192}Hg [27, 28], an upper limit to the $B(M1)$ rate of $\sim 1\mu_N^2$ is deduced. This value is consistent with recent particle-rotor calculations by Semmes *et al.* [29] which predict the $B(M1)$ rates for the $\nu j_{15/2} \otimes \pi i_{13/2}$ configuration to be of the order $0.6 - 1.0\mu_N^2$. In these calculations all other two-quasiparticle excitations involving the π [642]5/2 orbital result in $B(M1)$ rates which are either significantly smaller or much larger than $1.0\mu_N^2$.

B. Bands *C* and *D*

Since bands *C* and *D* do not exhibit any signature splitting, guidance about the associated spins could not be obtained from the method used for bands *A* and *B*. Rather, spin assignments were derived from fits to the dynamic moments of inertia as described in [19, 20]. The alignments for the two bands are presented in Fig. 5(b) together with those of the favored signature of the $i_{13/2}$ proton SD band in ^{193}Tl [see also Fig. 5(a)] and of a pair of strongly coupled SD bands in ^{191}Hg (bands 5 and 6 in [30]). It is clear from the figure that the alignments with rotational frequency in bands *C* and *D* closely follow that of the favored $i_{13/2}$ proton band in ^{193}Tl, and it is then suggested that this is the associated proton configuration. A similar type of analysis was performed by Azaiez *et al.* [31] on SD bands in ^{194}Tl to determine the proton configurations involved. Because bands *C* and *D* exhibit no signature splitting, the neutron contributions to these bands must be based on a set of strongly coupled orbitals. Experimentally, two such bands have been identified recently in ^{191}Hg [30] and in the isotone ^{193}Pb [32]. These excitations have been associated with the ν [512]5/2 orbital

[30]. From Fig. 5(b) it can be seen that the spins assigned to this pair of bands imply a gain in alignment of $\Delta i \sim 1/2\hbar$ with respect to ^{192}Hg. The summed alignments resulting from the coupling of bands 5 and 6 in ^{191}Hg to the favored $i_{13/2}$ band in ^{193}Tl reproduce the trends exhibited by bands C and D. Noting that the spin assignments for the ^{192}Tl and ^{191}Hg bands are not as firm as those of the intruder configurations shown in Fig. 5(a) (i.e., no checks based on signature splitting are possible), the agreement between experimental and calculated alignments for bands C and D can be considered as rather satisfactory. It should also be noted that the proposed $\nu[512]5/2 \otimes \pi[642]5/2$ configuration for bands C and D is associated with small $B(M1)$ values $[B(M1) \sim 0.01\mu_N^2]$ for the energetically favored parallel coupling of neutron and proton K quantum numbers [29]. This prediction is consistent with the lack of experimental evidence for M1 crossover transitions between the two signature partner bands.

C. Alignments and identical bands

From the above analysis, it is concluded that the alignments of bands A and B relative to the ^{192}Hg SD band can be accounted for by considering the alignment contributions associated with SD bands in the odd-N and odd-Z neighbors. In addition, the alignments in the odd-A bands themselves have been found to agree with the values calculated within the framework of the CSM for the associated quasiparticle configurations; i.e., $\nu j_{15/2}$ [3] and $\pi i_{13/2}$ [30]. Thus, the data and the above analysis indicate that the measured alignments relative to the ^{192}Hg core are associated mostly with single-particle effects in both the one and two-quasiparticle excitations when intruder configurations are involved. This conclusion should be contrasted with the assertion that an apparent $1\hbar$ alignment observed between excited ''identical'' bands in ^{191,193,194}Hg relative to ^{192}Hg results from so-called pseudospin alignment [33].[3] In this picture, the unit of alignment is generated from the decoupling of the intrinsic nucleon spins from the orbital angular momenta where the latter remain strongly coupled to the symmetry axis while the former align with the rotation axis. This phenomenon has been associated with triplet ($S=1$) pairing [31], i.e., the observed alignment results from a collective rather than a single-particle effect. In the present work it has been shown that a more conventional interpretation within the framework of the CSM describes the data quite well and the need for new symmetries or coupling schemes remains an open question.

Integer alignments are not observed in bands C and D of ^{192}Tl with respect to ^{193}Tl. Thus, it does not appear that the pseudospin picture applies in this case either. It should be noted, however, that 11 of the 14 transitions in band C are within 2 keV of the transition energies in ^{191}Hg band 3 [3] implying that both bands C and D have half-integer alignment with respect to this band. However, band 3 is not believed to be involved in the configuration of bands C and D nor does band 3 exhibit integer alignment with respect to ^{192}Hg. It may well be that the similarities in gamma energies are accidental in this case.

IV. ΔI =2 STAGGERING

Because superdeformed nuclei are some of the best rotors available, the characteristic long sequences of in-band transitions provide an opportunity to search for unexpected effects on an energy scale rarely achieved elsewhere in nuclear physics. As reported by Flibotte *et al.* [34], a staggering of the $\mathcal{J}^{(2)}$ moments of inertia was observed above a frequency of 0.5 MeV in the yrast SD band of ^{149}Gd indicating that the SD states are alternatively pushed up and down in energy by ~ 60 eV. Thus, the SD band can be viewed as two sequences of states in which spins differ by $4\hbar$ from level to level and a small energy displacement occurs between the two sets. This $\Delta I=2$ staggering has been referred to as ''ΔI =4 bifurcation'' or as ''C4-oscillation,'' hereby suggesting the presence of a fourfold rotational symmetry term in the SD Hamiltonian. Besides the case of ^{149}Gd, the effect has also been reported in three SD bands of ^{194}Hg [35], and there is also tentative evidence in a SD band in ^{153}Dy [36] as well as in a similar, but shorter SD sequence, in ^{154}Er [37]. While a substantial theoretical effort is taking place to understand this phenomenon [38–45] it is also important to search in all regions of superdeformation for more SD bands where this staggering might occur.

As can be seen from Fig. 3, the $\mathcal{J}^{(2)}$ moments of band B display a staggering pattern similar to that of the SD band in ^{149}Gd over the entire length of the cascade. This is illustrated further in Fig. 6 where the quantities $\Delta^n E_\gamma$ (with $n=3$ and 4) introduced by Flibotte *et al.* [34] and by Cederwall *et al.* [35] are presented as a function of spin. The staggering amplitude is of the same order of magnitude as that seen in the other nuclei mentioned above.

The presence of this oscillation in band B might be particularly significant for the following reasons. Recently, Reviol *et al.* [38] have shown that $\Delta I=2$ staggering arises naturally in any rotational $E2$ cascade as a result of a band interaction. Near the spin where a crossing between two bands occurs, the energy levels are shifted up or down because of the interaction, resulting in a staggering in the $\Delta^3 E_\gamma$ and $\Delta^4 E_\gamma$ plots which will extend over 4 – 6 spin states. Such a band interaction scenario could perhaps account for the ΔI = 2 staggerings in ^{194}Hg. As discussed above, the rise in $\mathcal{J}^{(2)}$ moments with frequency is proposed to be due to the successive alignments of a pair of $j_{15/2}$ neutrons and a pair of $i_{13/2}$ protons with $\hbar\omega$. In terms of a band interaction picture, this interpretation means that the SD ground band first interacts with an aligned neutron band and that a second crossing at higher frequencies with an aligned proton band is present and maintains the oscillatory pattern over a larger number of levels. Both of these interactions are absent in band B because of the blocking effects. Thus, the effect seen in ^{192}Tl cannot be attributed to band interactions in a straightforward way.

Flibotte *et al.* [34] argued that the occupation of a single $N=7$ ($j_{15/2}$) neutron and a pair of aligned $N=6$ ($i_{13/2}$) proton intruder orbitals in ^{149}Gd might be important in the present context; i.e., that the staggering might be associated with the polarization of the ^{152}Dy SD core by the three aligned high-

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[3] A similar relationship has been observed when comparing SD bands 1 and 2 in ^{193}Tl with several two-quasiparticle bands in ^{194}Tl [31].

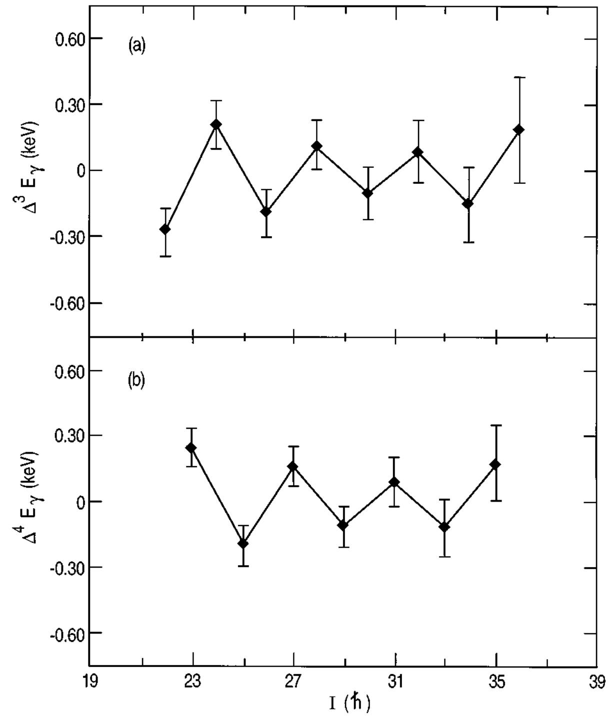

FIG. 6. The $\Delta^3 E_\gamma(I)$ and $\Delta^4 E_\gamma(I)$ staggerings as a function of spin I for band B in ^{192}Tl, with $\Delta^3 E_\gamma(I) = 1/8[E_\gamma(I+3) - 3E_\gamma(I+1) + 3E_\gamma(I-1) - E_\gamma(I-3)]$, and $\Delta^4 E_\gamma(I) = 1/16[E_\gamma(I+4) - 4E_\gamma(I+2) + 6E_\gamma(I) - 4E_\gamma(I-2) + E_\gamma(I-4)]$. The spin axis represents the average value between the spins of the initial and final states.

N holes, and /or by the mutual proton-neutron interaction between the $N=7$ and 6 valence holes. In band B of ^{192}Tl, single $j_{15/2}$ and $i_{13/2}$ orbitals are occupied and it is possible that core polarization by the high-N intruders and/or a proton-neutron interaction manifest themselves through the staggerings seen in Figs. 3 and 6.

A question also arises naturally about the lack of a similar clear effect in the signature partner band A (Fig. 3). As noted above, the intensity of this band is significantly larger than that of band $B$and the possibility that this structure represents the superposition of two SD bands cannot be ruled out. If this were to be the case, effects at the 0.1 keV level might well be smeared out.

V. CONCLUSIONS

Four SD bands in the ^{192}Tl nucleus have been studied with Gammasphere. For reasons explored in the text, three SD bands reported earlier [9] were not seen in the present measurement. Configurations have been assigned to all bands on the basis of the measured variations of the $\mathscr{J}^{(2)}$ moments of inertia with $\hbar\omega$, the extracted Routhians and alignments, and the comparison with the alignments measured in the SD bands of the odd-A neighboring nuclei based on the same configurations. The analysis presented above has demonstrated that additivity of alignments is applicable for SD nuclei in the $A=190$ region, and that these alignments can be accounted for by considering simple quasiparticle excitations. There is no evidence for integer alignments in ^{192}Tl implying that all orbitals probed carry some intrinsic alignment, as calculated within the framework of the cranked shell model. Clearly, further tests of the approach presented here are necessary. These will come from the application of a similar analysis to other SD bands in this region and, more importantly, from the establishment of the spin and parity quantum numbers associated with these SD bands. In view of the recent results on linking transitions in ^{194}Hg [17], such measurements are now possible. Finally, band B was found to display $\Delta I=2$ staggering. It has been argued that in this case, the measured staggering cannot be explained by evoking a band crossing picture [38] as the necessary quasiparticle alignments are blocked in this odd-odd nucleus.

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