RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 46, NUMBER 6 DECEMBER 1992

Double blocking in the superdeformed ^{192}Tl nucleus

Y. Liang,(1) M. P. Carpenter,(1) R. V. F. Janssens,(1) I. Ahmad,(1) R. G. Henry,(1) T. L. Khoo,(1) T. Lauritsen,(1) F. Soramel,(1),* S. Pilotte,(2) J. M. Lewis,(3) L. L. Riedinger,(3) C.-H. Yu,(3) U. Garg,(4) W. Reviol,(4) and I. G. Bearden(1,5)

(1)*Argonne National Laboratory, Argonne, Illinois 60439*
(2)*University of Ottawa, Ottawa, Canada K1N 6N5*
(3)*University of Tennessee, Knoxville, Tennessee 37831*
(4)*University of Notre Dame, Notre Dame, Indiana 46556*
(5)*Purdue University, West Lafayette, Indiana 47907*

(Received 26 August 1992)

Six superdeformed bands have been found in the nucleus ^{192}Tl. For two of the bands, the dynamic moment of inertia $J^{(2)}$ is found to be constant with the rotational frequency $\hbar\omega$. This result can be understood in terms of Pauli blocking of quasiparticle alignments in intruder orbitals, and represents strong experimental evidence that the alignment of these intruders is responsible for the smooth rise in $J^{(2)}$ seen in other superdeformed nuclei of this mass region.

PACS number(s): 21.10.Re, 23.20.En, 23.20.Lv, 27.80.+w

One of the most intriguing differences between the properties of superdeformed (SD) nuclei in the $A=150$ and $A=190$ regions is the behavior of the dynamic moments of inertia $J^{(2)}$ as a function of the rotational frequency $\hbar\omega$. The pronounced isotopic and isotonic variations of $J^{(2)}$ with $\hbar\omega$ seen in the SD bands near $A=150$ have been attributed to a large extent to differences in the occupation of specific high-N intruder orbitals [1,2]. In contrast, the vast majority of SD bands near $A=190$ displays the same smooth pronounced increase of $J^{(2)}$ with $\hbar\omega$. Here, we present new data which provide insight into the origin of this behavior of $J^{(2)}$. It has been shown that the occupation of specific high-N intruders cannot account for this observed rise [1,3–5]. An explanation in terms of changes in deformation with $\hbar\omega$ has also been ruled out from the available lifetime measurements [6]. It has been suggested that quasiparticle alignments and the resulting changes in pairing play an essential role [4–8]. For example, calculations using the cranked Woods-Saxon Strutinsky model with pairing are able to account for the 40% rise in $J^{(2)}$ observed for $0.12 \leq \hbar\omega \leq 0.40$ MeV in ^{192}Hg. The rise is ascribed to the combined alignment of protons and neutrons occupying intruder orbitals, i.e., $N=6$ ($i_{13/2}$) protons and $N=7$ ($j_{15/2}$) neutrons [6].

Experimental evidence for this alignment picture is at present circumstantial. Small differences in the absolute value and the rate of increase of $J^{(2)}$ with $\hbar\omega$ have been noted when comparing even-even nuclei with the odd-even neighbors. For example, the somewhat steeper slope in $J^{(2)}$ of the SD band of ^{192}Hg, when compared with that of the SD bands in ^{193}Tl and ^{191}Hg (band 1), has been interpreted in terms of the blocking of either the proton or the neutron alignment in the odd-even neighbor [1,5,9]. On the other hand, the expected downbend of $J^{(2)}$ at frequencies where the high-N intruder alignments are calculated to be completed has not been observed in either ^{192}Hg (Ref. [10]) or ^{190}Hg (Ref. [11]). Clearly, the study of the behavior of $J^{(2)}$ in the SD bands of an odd-odd nucleus should be particularly revealing. If both the odd proton and the odd neutron occupy the high-N intruder orbitals, the alignments should be blocked and, as a result, the moments of inertia should be constant with frequency. Here, we report on a study of ^{192}Tl where six SD bands have been located. Two of these bands are characterized by constant moments of inertia, thereby providing the first strong evidence that the alignment of quasiparticles occupying the high-N intruder orbitals plays an essential role in the evolution of $J^{(2)}$ with $\hbar\omega$. Finally, the comparison of the properties of the six SD bands with those of the neighboring nuclei and, in particular, with those of ^{194}Tl (Ref. [12]) allows one to propose quasiparticle configurations for all the bands. It should be noted that ^{194}Tl is the only other odd-odd SD nucleus known in this region: six SD bands have been observed in this nucleus by Azaiez *et al.* [12].

The experiments were carried out at the Argonne superconducting linear accelerator ATLAS using the Argonne–Notre Dame BGO γ-ray facility which consists of 12 Compton-suppressed Ge detectors and an inner array of 50 BGO elements. The states in ^{192}Tl were populated with the ^{160}Gd(^{37}Cl,$5n$) reaction at beam energies of 178 and 181 MeV. With this choice of beam energies, the ^{192}Tl nuclei are produced under conditions of angular momentum ($l_{max} \sim 50\hbar$) and excitation energy ($E^* \sim 22$ MeV) similar to those where the SD bands in Hg and Tl isotopes were populated with the highest intensities using $5n$ fusion-evaporation reactions [3,9]. The target consisted of a stack of two isotopically enriched self-supporting 500 μg/cm^2 thick foils. With a threshold of four on the number of array elements firing in coincidence with at least two Compton-suppressed Ge detectors, a total of $\sim 10^8$ events were collected event by event

*On leave from Padova University, I-35131 Padova, Italy.

at each beam energy. In addition to the energy and time information measured by the Compton-suppressed Ge detectors, the γ-ray sum energy, the prompt and delayed multiplicities, and the hit pattern of the array were stored on magnetic tape.

For each beam energy, several E_γ-E_γ coincidence matrices were produced where high-multiplicity cascades in ^{192}Tl were enhanced by appropriate gating on the multiplicity distributions measured in the array. In this way, matrices were obtained at each beam energy where at least 60% of all events belonged to ^{192}Tl. The data presented below were extracted from the sum of these matrices and contained 7.5×10^7 events. The detailed analysis revealed the presence of six rotational bands with average energy differences between consecutive transitions of $\sim$38 keV. This value is very similar to those reported for other SD bands in this region and is consistent with the spacing expected for a SD shape [1]. Figure 1 presents spectra for these bands which are the sum of spectra generated from the cleanest gates. All the bands presented here are rather weak (see below) and most of the transitions are contaminated by other lines of stronger intensity. Accordingly, the spectra of Fig. 1 contain a number of contaminants. Nevertheless, the coincidence relationships between the various band members were verified from the individual gates, and the γ rays for which the assignment was judged to be plausible, but not certain, are given in parentheses. As the bands are very weak, and in some cases difficult to separate from the contaminants, the coincidence relationships between the γ rays were also studied carefully from the observation of regular grid patterns in the two-dimensional $\gamma\gamma$ matrix using the code BANDAID [13], thereby taking advantage of the enhanced resolving power provided by the inspection of the two-dimensional space. This technique was pioneered by Johansson *et al.* [14] for identifying weak multiple SD bands. Another useful feature in uncovering some of the SD bands in ^{192}Tl is the fact that, in analogy with the neighboring ^{191,193,194}Tl isotopes [15,9,12], bands appear in pairs that can be interpreted as signature partners. Over a wide energy range, the transition energies in the first band of any given pair are almost exactly midway between the energies of the transitions in the partner.

Bands 1, 3, and 5 in Fig. 1 are estimated to carry respective intensities of 0.9%, 1.1% and 0.5% of the total flow through the ^{192}Tl nucleus under the multiplicity condition outlined above. Their partners (bands 2, 4, 6) appear to carry only about 50–70% of the respective amounts. Because of these low intensities and the fact that there are very few clean gates, multipolarity information could be obtained only for the strongest transitions in each band. The correlation data derived from angle-sorted matrices [16] indicate that the transitions involved are of stretched $E2$ character. Finally, as some of the γ rays discussed here are close in energy to SD transitions in ^{191}Tl, care was taken to ensure that the assignment into ^{192}Tl is correct by checking that (1) the relative variation of the γ-ray intensities with the beam energy and (2) the fold distributions at each beam energy follow the pattern exhibited by the ^{192}Tl transitions. Furthermore, in many cases coincidence relationships between ^{192}Tl yrast transitions and the strongest SD lines could be verified, even though the precise yrast feeding pattern could not be determined. The relative intensities of the transitions in these SD bands show a behavior similar to that seen in all other bands in the region. A slow increase in intensity is observed with decreasing transition energy, followed by a region where the intensities remain constant before a rapid depopulation within one or two tran-

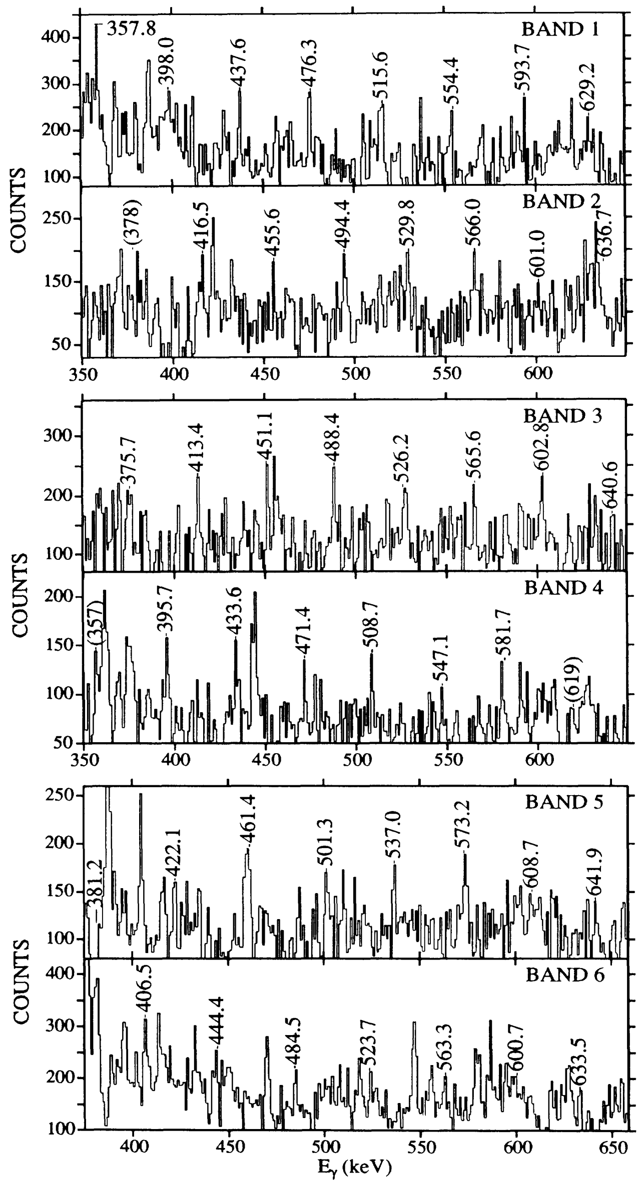

FIG. 1. γ-ray spectra obtained for the six SD bands in ^{192}Tl by summing coincidence gates. The SD band energies are indicated. The errors are on the order of 0.5 keV for the strongest transitions and up to 1 keV for the weakest γ rays. Transitions for which the placement is not certain are given under parentheses (see text for details). As discussed in the text, the intensity in the SD bands is small and several contaminants are also present in the spectra. The spectra are grouped into pairs according to the interpretation of the bands as signature partners (see text).

sitions at the low-energy end.

The dynamic moments of inertia for the six bands are presented as a function of the rotational frequency $\hbar\omega$ in Fig. 2. From this figure, several observations can be made. First, it is clear that $J^{(2)}$ remains constant with $\hbar\omega$ for bands 3 and 4 [Fig. 2(a)], while it displays the more typical rise with $\hbar\omega$ for the other four SD bands [Figs. 2(b) and 2(c)]. In fact, the data on bands 3 and 4 represent the first case where constant values of $J^{(2)}$ have been observed in SD bands near $A = 190$. Second, a comparison between the $J^{(2)}$ values for bands 3 and 4 and those of the odd-even neighboring nuclei ^{191}Hg (band 1) [5] and ^{191}Tl [15] [Fig. 2(a)] indicates that, at the lowest frequencies, the value of $J^{(2)}$ is lower in the odd-even neighbors than in the two new SD bands. Finally, a similar conclusion holds when bands 3 and 4 are compared to the four other ^{192}Tl SD bands: at the lowest frequencies, bands 3 and 4 again have the larger $J^{(2)}$ value.

In order to understand these results, we have performed cranking calculations with the Warsaw Wood-Saxon code [17] with parameters given in Ref. [18] to calculate quasiparticle routhians and $J^{(2)}$ values for the superdeformed ^{192}Tl nucleus and its neighbors. These calculations are similar to those presented in Refs. [4–7] and [9] where the relevant single-particle energy diagrams and quasiparticle routhians can be found. While specific results depend on the deformation and the pairing gaps used, the following general conclusions can be drawn. (i) An alignment of a $N = 7$ neutron pair, which is calculated to occur in ^{191}Tl (and ^{192}Hg) within $0.15 < \hbar\omega < 0.3$ MeV, is blocked in ^{192}Tl (and ^{191}Hg) when the odd neutron occupies a $j_{15/2}$ orbital involved. (ii) An alignment of a pair of $N = 6$ protons is calculated to occur in the range $0.25 < \hbar\omega < 0.4$ MeV in ^{191}Hg (and ^{192}Hg). This alignment is also blocked in ^{192}Tl (and ^{191}Tl) when the proton occupies an $i_{13/2}$ orbital. (iii) At low values of $\hbar\omega$, our calculations show that the occupation of both the $\pi i_{13/2}$ and $\nu j_{15/2}$ orbitals will result in an additional contribution to $J^{(2)}$ with respect to the odd-even neighboring nuclei. The calculated $J^{(2)}$ value ($107\hbar^2$ MeV^{-1}) for this double-intruder configuration, which is also shown in Fig. 2(a), agrees well with the data. On the basis of this discussion, we propose that bands 3 and 4 correspond to a configuration built on the favored ($r = +i$) signature of the $\nu j_{15/2}$ orbital coupled to the two signatures ($r = \pm i$) of the $\pi i_{13/2}$ orbital. [It has been shown in Ref. [5] that the unfavored ($r = -i$) signature of the $\nu j_{15/2}$ orbital is located too high in energy to be observed experimentally.] Adopting the nomenclature proposed originally in Ref. [2], which reflects the number of occupied intruder orbitals in a SD configuration, bands 3 and 4 are labeled as $\pi 6^5(r = \pm i) \otimes \nu 7^3(r = +i)$.

The discussion above also serves as a starting point for the interpretation of the four other SD bands in ^{192}Tl. From Figs. 2(b) and 2(c) it is apparent that the four bands all exhibit a rise in $J^{(2)}$ with $\hbar\omega$. Furthermore, this rise is similar to that seen over the same frequency range in the odd-even neighbors and is significantly smaller than that observed in the even-even ^{192,190}Hg nuclei. This suggests that only one pair of high-N intruders is aligning in these four ^{192}Tl bands. (This argument is also consistent with the observation that the $J^{(2)}$ values at the lowest frequencies are smaller here than in bands 3 and 4, as discussed above.) The question then becomes whether it is possible to identify the odd intruder particle as a proton or a neutron.

We propose that the four bands are associated with the intruder $\pi(i_{13/2})^5$ (i.e., $\pi 6^5$) configuration coupled to the lowest neutron excitation identified in ^{191}Hg (bands 2 and 3 in Ref. [5]), i.e., the $\nu[642]\frac{3}{2}$ orbital. Our assignment is based on the following considerations. (1) Both pairs of SD bands can be interpreted as signature partners which show increasing signature splitting as a function of $\hbar\omega$. In the framework of our cranking calculations, both the $\pi i_{13/2}$ and $\nu[642]\frac{3}{2}$ orbitals are calculated to exhibit splitting for $\hbar\omega \geq 0.2$ MeV, and these splittings are thought to have been observed experimentally in the SD bands of ^{191,193}Tl (Refs. [9,15]) and ^{191}Hg (bands 2 and 3 in Ref. [5]). (2) Recently, Stephens *et al.* [19] have proposed to compare SD bands near $A = 190$ by examining the evolution with $\hbar\omega$ of the incremental alignment Δi. This value depends only on the relationship between the γ-ray ener-

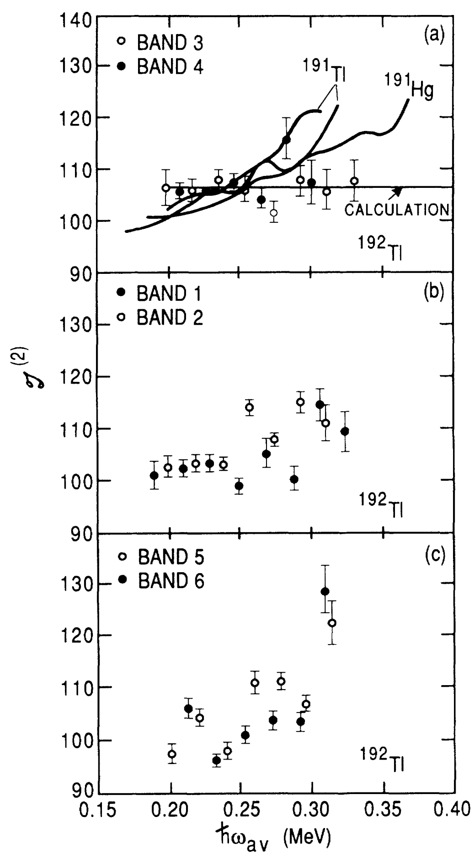

FIG. 2. Dynamic moments of inertia $J^{(2)}$ for the six SD bands in ^{192}Tl. (a) The $J^{(2)}$ values for bands 3 and 4 are compared with those of the two SD bands in ^{191}Tl [15] and with the first SD band in ^{191}Hg [3,5] (thick lines). The result of cranking calculations discussed in the text is given as the thin line. Dynamic moments of inertia for (b) bands 1 and 2 and (c) bands 5 and 6.

gies in a SD band of interest and those of a reference SD band. For example, it was shown that the six SD bands in ^{194}Tl can be related to the ^{193}Tl SD bands and the resulting incremental alignment values cluster around $\Delta i = 1$, ± 0.5, 0 over a wide $\hbar\omega$ range [12]. Striking patterns of this type have been shown to occur mainly when the SD bands being compared are characterized by configurations involving the same number of high-N intruder orbitals [1,9,20]. We have computed Δi values for the ^{192}Tl SD bands using ^{190,191,192}Hg and ^{191,193}Tl as possible references. Only when one of the ^{191}Tl SD bands (band 1 or 2 in Ref. [15]) is the reference does Δi exhibit a behavior analogous to that seen in ^{194}Tl. We obtained Δi(band 2)$\simeq 0$ and Δi(band 5)$\simeq 1$ over the entire $\hbar\omega$ range when the reference is band 1 or band 2 in ^{191}Tl (Ref. [15]), respectively. This suggests that these two bands share the same $\pi 6^5$ intruder content as ^{191}Tl. Furthermore, the two signature partners show smoothly decreasing values of Δi with $\hbar\omega$, as is expected for signature partners with increasing energy splitting. The situation is analogous to that seen in SD bands associated with the $\nu[642]\frac{3}{2}$ orbital in ^{191}Hg (Ref. [5]), where $\Delta i = -0.5$ over the entire $\hbar\omega$ range for band 3 of Ref. [5], while $\Delta i = 0.5$ at low $\hbar\omega$ and decreases smoothly with frequency for the signature partner (band 2). Thus, if the description given above is correct, one of the two pairs of ^{192}Tl SD bands can be labeled as $\pi 6^5(r=+i)\otimes\nu\{7^4\otimes[642]\frac{3}{2}(r=\pm i)\}$, while the other is associated with the unfavored $\pi 6^5$ $(r=-i)$ partner coupled to the same neutron configuration. Unfortunately, the available data do not provide an unambiguous way to determine which of the pairs (bands 1-2 or 5-6) should be associated with the $r=+i$ or the $r=-i$ proton configuration.

It is worth pointing out that a similar classification can be proposed for the SD bands in ^{194}Tl of Ref. [12]. In this case too, a pair of SD bands (bands 3*a* and 3*b* of Ref. [12]) has a higher $J^{(2)}$ value at low $\hbar\omega$ and displays a smaller rise with $\hbar\omega$ than the two other pairs. This pair is most likely associated with a configuration where the two odd particles occupy high-N intruder orbitals as bands 3 and 4 in ^{192}Tl. The small rise in $J^{(2)}$ would then have to be the result of second-order effects (such as small changes in deformation with $\hbar\omega$ and/or small changes in higher order pairing corrections, etc.). The two other signature partner pairs (marked 1*a* and 1*b* and 2*a* and 2*b* in Ref. [12]) can then again be understood as being based on the intruder proton configuration coupled to neutron excitations observed in the ^{193}Hg SD bands [21].

In conclusion, six SD bands have been found in ^{192}Tl. Two of these bands are characterized by a dynamic moment of inertia $J^{(2)}$ which remains constant with rotational frequency. This result can be understood, within the framework of cranking calculations with pairing, as being due to Pauli blocking of high-N intruder orbitals. This is the first strong evidence that the alignment of these intruder orbitals is responsible for the rise in $J^{(2)}$ in the SD nuclei near $A=190$. Configurations have been proposed for all six SD bands. They involve proton and neutron excitations which have been observed in the odd-even neighboring SD nuclei ^{191}Tl and ^{191}Hg.

This work was supported by the Department of Energy, Nuclear Physics Division, under Contracts Nos. W-31-109-ENG-38, DE-FG05-87ER40361 and by the National Science Foundation under Grant No. PHY91-00688.

[1] The topic has recently been reviewed in R. V. F. Janssens and T. L. Khoo, Annu. Rev. Nucl. Part. Sci. **41**, 321 (1991).
[2] T. Bengtsson, I. Ragnarsson, and S. Åberg, Phys. Lett. B **208**, 39 (1988); W. Nazarewicz, R. Wyss, and A. Johnson, Phys. Lett. B **225**, 208 (1989).
[3] E. F. Moore *et al.*, Phys. Rev. Lett. **63**, 360 (1989).
[4] D. Ye *et al.*, Phys. Rev. C **41**, R13 (1990).
[5] M. P. Carpenter *et al.*, Phys. Lett. B **240**, 44 (1990).
[6] E. F. Moore *et al.*, Phys. Rev. Lett. **64**, 3127 (1990).
[7] M. A. Riley *et al.*, Nucl. Phys. **A512**, 178 (1990).
[8] R. R. Chasman, Phys. Lett. B **242**, 317 (1990).
[9] P. B. Fernandez *et al.*, Nucl. Phys. **A517**, 386 (1990).
[10] T. Lauritsen *et al.*, Phys. Lett. B **279**, 239 (1992).
[11] I. G. Bearden *et al.*, to be published.
[12] F. Azaiez *et al.*, Phys. Rev. Lett. **66**, 1030 (1991).
[13] J. A. Kuehner, to be published.
[14] J. K. Johansson *et al.*, Phys. Rev. Lett. **63**, 2200 (1989).
[15] S. Pilotte *et al.*, to be published.
[16] The technique is described in detail for the setup in use here in M. W. Drigert *et al.*, Nucl. Phys. **A530**, 452 (1991).
[17] W. Nazarewicz, J. Dudek, R. Bengtsson, T. Bengtsson, and I. Ragnarsson, Nucl. Phys. **A435**, 397 (1985).
[18] J. Dudek, Z. Szymanski, and T. Werner, Phys. Rev. C **23**, 929 (1981).
[19] F. S. Stephens *et al.*, Phys. Rev. Lett. **64**, 2623 (1990).
[20] W. Satuła, S. Cwiok, W. Nazarewicz, R. Wyss, and A. Johnson, Nucl. Phys. **A529**, 289 (1991).
[21] D. M. Cullen *et al.*, Phys. Rev. Lett. **65**, 1547 (1990).