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New Results on Superdeformed Bands in Hg and Tl Nuclei

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Abstract

New results have been obtained on superdeformed states in ^{190}Hg, ^{191}Tl and ^{192}Tl. For ^{190}Hg, the previously identified superdeformed band has been extended up to a rotational frequency of $\hbar\omega \geq 0.40$ MeV by combining data from several different experiments. The extracted dynamical moment of inertia $\mathcal{J}^{(2)}$ vs $\hbar\omega$ exhibits a distinct change in slope at $\hbar\omega = 0.32$ MeV. For ^{191}Tl and ^{192}Tl, two and six superdeformed bands have been identified in these nuclei, respectively. Six of these eight bands exhibit a smooth rise in $\mathcal{J}^{(2)}$ with $\hbar\omega$ characteristic of the other superdeformed bands identified in this mass region while the remaining two bands which are in ^{192}Tl show a constant $\mathcal{J}^{(2)}$ with $\hbar\omega$. This new result can be understood in terms of Pauli blocking of quasiparticle alignments in high-N intruder orbitals. The new result for ^{190}Hg is interpreted as evidence of a band interaction at the highest frequencies due to the rotational alignment of a pair of quasiparticles into these same intruder orbitals. These two new features taken together represent the first conclusive evidence that the alignment of intruders is responsible for the smooth rise in $\mathcal{J}^{(2)}$ seen in the other superdeformed bands of this mass region.

1. INTRODUCTION

The evolution of the dynamic moment of inertia as a function of rotational frequency for superdeformed (SD) bands in the mass 150 region is characterized by pronounced isotopic and isotonic variations [1] which have been attributed to differences in the occupation of specific high-N intruder orbitals [2]. In contrast, the vast majority of the SD bands in the mass 190 region display the same smooth and rather pronounced increase of $\mathcal{J}^{(2)}$ with $\hbar\omega$ [1]. The occupation of specific high-N intruders cannot account for this rise [1,3,4] while lifetime measurements [5] rule out the possibility that a change in deformation with $\hbar\omega$ causes this increase. It has been suggested that quasiparticle alignments and the resulting changes in pairing play an essential role [4-8]. Calculations using the cranked Wood-Saxon model with pairing are able to account for the 40% rise in $\mathcal{J}^{(2)}$ observed between $0.12 \leq \hbar\omega \leq 0.35$ MeV in ^{192}Hg. This calculated rise can be directly attributed to the combined alignment of a pair of $N = 6$ ($i_{13/2}$) protons and a pair of $N = 7$ ($j_{15/2}$) neutrons [3]. After these alignments have taken place, the calculations predict a downturn in $\mathcal{J}^{(2)}$ with increasing $\hbar\omega$ until $\mathcal{J}^{(2)}$ approaches the static moment of inertia $\mathcal{J}^{(1)}$.

Until recently, experimental evidence for this alignment picture has been circumstantial. Small differences in the absolute value and the rate of increase of $\mathcal{J}^{(2)}$ with $\hbar\omega$ have been noted when comparing even-even nuclei with the odd-even neighbors. For example, the somewhat steeper slope in $\mathcal{J}^{(2)}$ 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 [4,5,9].

For the remainder of this paper, new results obtained on superdeformed states in ^{190}Hg, ^{191}Tl and ^{192}Tl will be discussed. The data presented were taken at Argonne National Laboratory using the Argonne Notre-Dame BGO γ−ray facility, a spectrometer consisting of twelve Compton suppressed Ge detectors and a 50 element inner array of BGO which provides γ-ray sum energy and multiplicity information for the reaction of interest. The heavy-ion beams utilized were supplied by the Argonne superconducting linear accelerator ATLAS.

NEW RESULTS ON ^{190}Hg

We have recently reported on a new investigation of ^{192}Hg [10] in which the SD band was extended to higher rotational frequencies. As can be seen from fig. 1, $\mathcal{J}^{(2)}$ rises with $\hbar\omega$ over the entire frequency range and there is no sign of the downturn predicted by the calculations. This discrepancy between experiment and theory leads one to question whether the alignment picture discussed above is the correct interpretation of the data.

In order to further investigate the high frequency behavior of SD bands in this region, we have performed a similar study on ^{190}Hg [11]. Gamma-ray coincidence data were obtained from the ^{160}Gd reaction at three beam energies (159, 162 and 165 MeV), and the experimental details can be found in ref. [12]. In the analysis, a $\gamma - \gamma$ correlation matrix was constructed from the Ge coincidence data. Events corresponding to high-multiplicity cascades in ^{190}Hg were enhanced by taking the appropriate gates on the γ-ray multiplicity and sum-energy. These gating conditions were adjusted at each beam energy in order to take in to account changes in angular momentum and excitation energy brought into the compound nucleus.

The spectrum obtained by adding the cleanest coincidence spectra (gates placed on

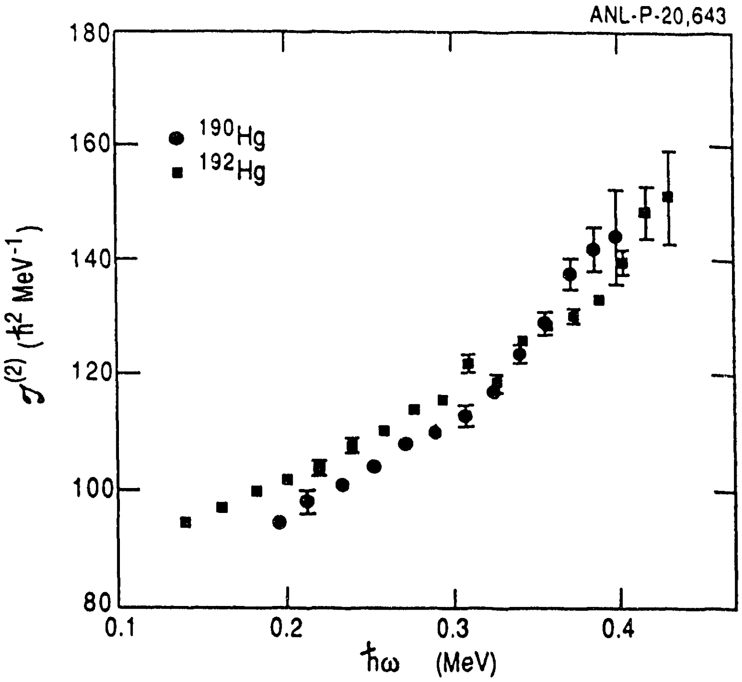

Figure 1: Dynamic moments of inertia $\mathcal{J}^{(2)}$ vs $\hbar\omega$ for the latest data sets on the SD bands in ^{190}Hg and ^{192}Hg.

the 360, 443, 483 and 558 γ rays) is shown in fig. 2. The SD band and yrast transitions reported earlier [12] are clearly visible. From the data, we were able to establish more precisely the energy of the 727 keV transition and add three new γ rays with energies of 756, 784 and 812 keV. These three transitions correspond to intensities of 15, 12 and 5% of the most intense transitions in the SD band.

The behavior of $\mathcal{J}^{(2)}$ for the SD band in ^{190}Hg is also given in fig. 1. With the addition of these new transitions, two markedly different slopes in the $\mathcal{J}^{(2)}$ curve are apparent. At frequencies $\leq$ 0.32 MeV, there is a smooth rise with a slope similar to that of ^{192}Hg. For the higher frequencies, a clear upbend in the data points is observed and as a result, the $\mathcal{J}^{(2)}$ values for ^{190}Hg become even larger than those for ^{192}Hg. Such a change in slope is very similar to those seen in rotational bands at normal deformation and strongly suggests the presence of a crossing between the SD "ground band" and another band.

A comparison between the data and the results of cranking calculations using the Warsaw-Woods Saxon code [13] with the parameters given in ref. [14] are presented in fig. 3. The solid line in the figure represents the results from the calculations when the appropriate deformation parameters are used and the pairing is allowed to vary self-consistently using a particle-number projection procedure (see ref. [12] for details). For this calculation, the dynamic moment of inertia shows a sharp rise brought about by the weak interaction strength ($\sim$ 100 keV compared to $\sim$ 500 keV in ^{192,194}Hg) between the ground band and the aligned $\nu(j_{15/2})^2$ band. As the figure shows, this sharp increase

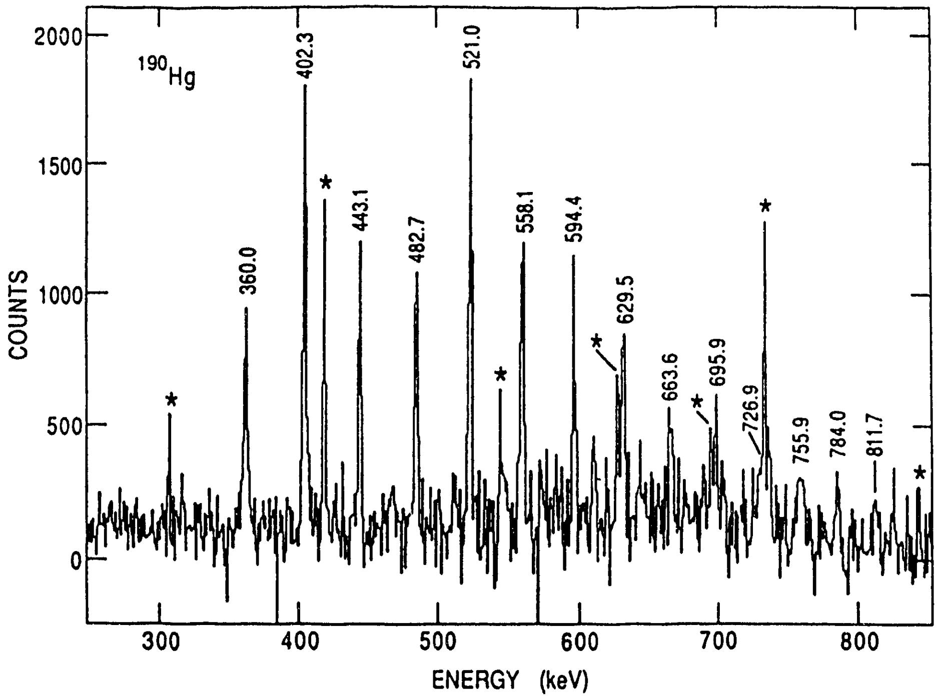

Figure 2: Spectrum of the SD band in ^{190}Hg. Known yrast transitions associated with the decay out of the SD band are marked with a *.

is not present in the data. In fig. 3b, the calculations and the data are presented with a reference subtracted. At the highest spins (or frequencies) the data exhibit a downward slope which can be interpreted as a crossing with a configuration having larger aligned angular momentum. The comparison between data and calculations then suggests that the alignment process is (1) delayed in frequency and (2) occurs with a larger interaction strength than predicted.

The dashed lines in fig. 3a and b are a result of a calculation where the aligned $\nu(j_{15/2})^2$ band has been shifted 350 keV higher in energy relative to the ground band while keeping the interaction strength between the two bands at 300 keV. Clearly, the calculation comes closer to the data. It should be noted that delays in expected crossing frequencies as well as changes in interaction strengths are known to occur in nuclei with normal deformation when intruder configurations are involved. It has been suggested that these delays might result from a strong residual proton-neutron (pn) interaction which would result in a lowering in energy of the vacuum configuration relative to the aligned quasiparticle states [15]. In the SD bands of the mass 190 region, the pn interaction could be enhanced since the protons and neutrons in many instances occupy the same number of intruder orbitals.

Another possible reason for the discrepancy between the calculations and the experimental data could be the simplified treatment of the pairing interaction. In the cranking calculations discussed thus far, only monopole pairing has been considered.

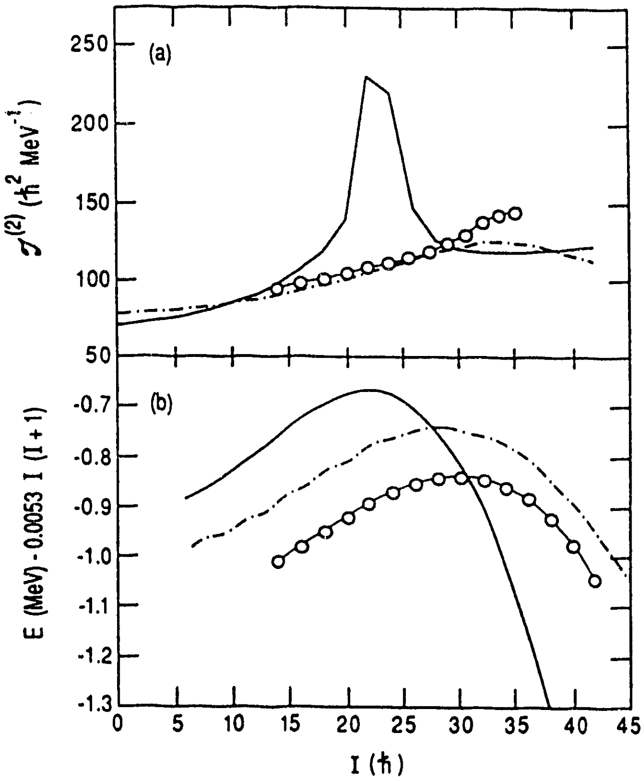

Figure 3: Comparison of the dynamic moments of inertia (a) and the energies with respect to a reference (b) between the data (open circles) and the cranking calculations with (i) an unshifted (solid line) and (ii) a shifted (dashed line) in energy $\nu(j_{15/2})^2$ configuration.

At very large deformation, states originating from different shells approach the Fermi surface, and these states should have a reduced pairing interaction. If the monopole pairing strength is reduced significantly, higher order corrections, which are configuration dependent, may become important. Efforts to explore this possibility are currently under way for SD nuclei [16,17] and preliminary calculations which include quadrupole pairing result in higher crossing frequencies for the intruder orbitals.

3. NEW RESULTS ON ^{191}Tl AND ^{192}TL

Previously, multiple superdeformed bands have been identified in ^{193}Tl (2 bands) [9], ^{194}Tl (6 bands) [18] and ^{195}Tl (2 bands) [19]. In ref. [9], the two bands observed have been associated with the $[642]\frac{5}{2}^+$ intruder orbital which is calculated to lie between the $Z = 80$ and $Z = 82$ gaps at large deformations ($\beta_2 \sim 0.47$) when using a Wood-Saxon potential. Recently, we have identified for the first time multiple superdeformed bands in ^{191}Tl (2 bands) [20] and ^{192}Tl (6 bands) [21].

The bands in ^{191}Tl were populated using the ^{159}Tb(^{36}S,4n) reaction at 165 MeV (see ref. [20] for the experimental details). The two bands consist of 8 and 10 transitions, respectively with and average spacing between consecutive γ rays of 38 keV. The intensity of these transitions was estimated to represent $\sim 0.4\%$ of all 4n reaction products. The characteristics of these two bands agree well with what is observed in other SD bands identified in this mass region. First, the dynamical moment of inertia for both bands (see fig. 5) rises with increasing $\hbar\omega$. Secondly, the two bands appear to be signature partners built on the same intrinsic configuration. Evidence for this comes from the fact that over a wide energy range, the energy of a γ ray in one of the two bands lies almost exactly midway between the energies of two consecutive transitions in the other band. A similar relationship between SD bands is observed in ^{193}Tl and ^{195}Tl and is consistent with the suggested intrinsic configuration of $\pi i_{13/2}$ $[642]\frac{5}{2}^{+}$ for these bands. Thus, the same configuration is proposed for the two SD bands in ^{191}Tl.

The six SD bands observed in ^{192}Tl were populated with the ^{160}Gd(^{37}Cl,5n) reaction at beam energies of 178 and 181 MeV (see ref. [21] for experimental details). Fig. 4 presents spectra for these bands which are the sum spectra generated from the cleanest gates. All the bands presented here are rather weak and most of the transitions are contaminated by other γ-ray transitions of stronger intensity. Accordingly, the spectra of fig. 4 contain a number of contaminants. Nevertheless, the coincidence relationships between the various band members were verified from the individual gates as well as from a two-dimensional γ-ray correlation analysis using the code BANDAID [22], and the γ rays for which the assignment was judged not to be entirely certain are given in parenthesis in fig. 4. 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 of all bands to ^{192}Tl is correct by checking that (1) the relative variation of the γ-ray intensities between the beam energies and (2) the fold distributions at each beam energy follow the patterns exhibited by the ^{192}Tl transitions. Finally, in analogy for grouping the two SD bands in ^{191}Tl as signature partners, these six bands can be grouped into three sets of signature pairs, i.e. bands 1-2, 3-4 and 5-6.

The dynamic moments of inertia for the six bands as a function of $\hbar\omega$ are presented in fig. 5. From the figure, it is clear that $\mathcal{J}^{(2)}$ remains constant with $\hbar\omega$ for bands 3 and 4 while the other four SD bands display the more characteristic rise with $\hbar\omega$. In fact, the data on bands 3 and 4 represent the first case where constant values of $\mathcal{J}^{(2)}$ have been observed in SD bands near A=190. A comparison between the $\mathcal{J}^{(2)}$ values for bands 3 and 4 and those of the odd-even neighboring nuclei ^{191}Hg (band 1) [4] and ^{191}Tl indicates that, at the lowest frequencies, the value of $\mathcal{J}^{(2)}$ is lower in the odd-even neighbors than in the two new SD bands. This same conclusion holds when bands 3 and 4 are compared to the four other SD bands identified in ^{192}Tl.

In order to understand these results, we have performed cranking calculations similar to those described above for ^{190}Hg to calculate quasiparticle routhians and $\mathcal{J}^{(2)}$ values for the superdeformed ^{192}Tl nucleus and its neighbors. 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 ^{190}Hg) within $0.15< \hbar\omega <0.25$ MeV, is blocked in ^{192}Tl (and ^{191}Hg) when an odd

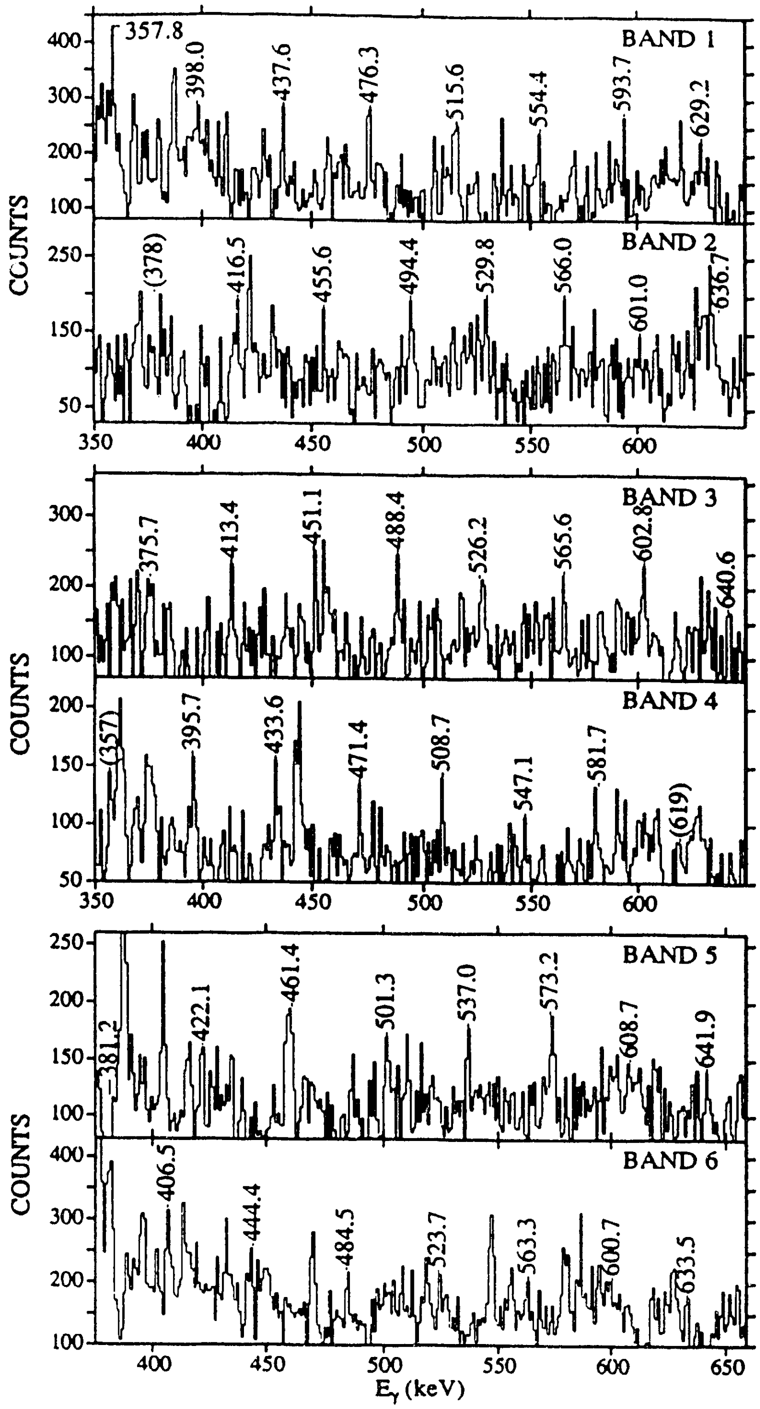

Figure 4: Gamma-ray spectra obtained for the six SD bands in ^{192}Tl. The individual spectrum were constructed from summing up several clean gates in the band of interest. Transitions for which the placement is uncertain are given in parenthesis.

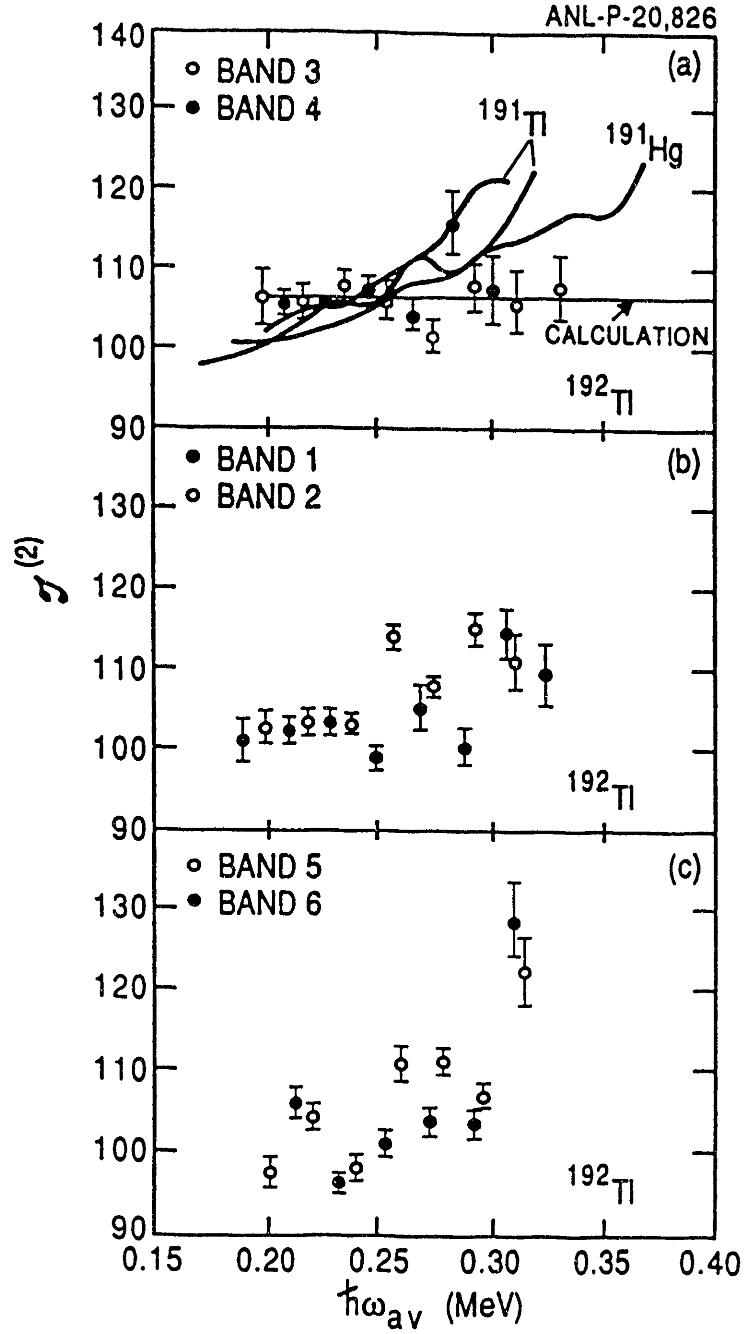

Figure 5: (a) The dynamic moments of inertia $\mathcal{J}^{(2)}$ for bands 3 and 4 are compared with those of the two SD bands in ^{191}Tl and with the first band in ^{191}Hg [3,4] (thick lines). The result of a cranking calculation discussed in the text is given as the thin line. (b) $\mathcal{J}^{(2)}$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

neutron occupies a $j_{15/2}$ orbital. (ii) An alignment of a pair of N=6 protons is calculated to occur between $0.25< \hbar\omega < 0.4$ MeV in ^{191}Hg (and ^{190}Hg). This alignment is blocked in ^{192}Tl (and ^{191}Tl) when the proton occupies an $i_{13/2}$ orbital. (iii) At low values of $\hbar\omega$, the occupation of both the $\pi i_{13/2}$ and $\nu j_{15/2}$ orbitals will result in an additional contribution to $\mathcal{J}^{(2)}$ with respect to the odd-even neighboring nuclei. The calculated $\mathcal{J}^{(2)}$ curve for this double-intruder configuration is shown in fig. 5a and agrees well with the constant dynamic moments of inertia found for bands 3 and 4. On the basis of this discussion, it is proposed that bands 3 and 4 correspond to a configuration built on the favored ($\alpha = +\frac{1}{2}$) signature of a $\nu j_{15/2}$ orbital coupled to the two signatures ($\alpha = \pm\frac{1}{2}$) of the $\pi i_{13/2}$ orbital. 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 labelled as $\pi 6^5(\alpha = \pm\frac{1}{2}) \otimes \nu 7^3(\alpha = +\frac{1}{2})$. It then follows that the remaining four bands are not built upon a double intruder configuration since their moments of inertia rise with frequency. They are most likely associated with the $i_{13/2}$ proton intruder ($[642]\frac{5}{2}^+$) coupled to the configuration associated with bands 2 and 3 in ^{191}Hg [4], i.e. the $\nu i_{11/2}[642]\frac{3}{2}^+$ orbital. The rise in $\mathcal{J}^{(2)}$ then results from the alignment of the neutrons.

4. CONCLUSIONS

We have identified three higher spin levels in the SD band of ^{190}Hg and have identified for the first time SD bands in ^{191}Tl (2 bands) and ^{192}Tl (6 bands). In ^{192}Tl, two of the observed SD bands have dynamical moments of inertia which are constant as a function of rotational frequency. This result can be understood, within the framework of cranking calculations, as being due to Pauli blocking of high-N intruder orbitals. The experimental observation of this double blocking gives strong support to the suggestion that contributions from aligning high-N proton *and* neutron intruder orbitals play an important role in the rise of $\mathcal{J}^{(2)}$ observed in the other SD bands of this mass region. Our new results on ^{190}Hg are consistent with this picture and suggest that the first band crossing occurs around $\hbar\omega = 0.32$ MeV. Cranking calculations are unable to reproduce either the magnitude or frequency at which this band crossing occurs indicating that there are deficiencies in the model.

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