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# Superdeformed bands in $^{189}$Tl

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Two superdeformed bands of 10 transitions each have been found in $^{189}$Tl extending the mass 190 region of superdeformation down to neutron number $N=108$. The new bands can be interpreted as signature partners and are proposed to be based on a proton $i_{13/2}$ ($\Omega=5/2$) configuration, in analogy with the yrast superdeformed band structures in the heavier odd-mass Tl isotopes. The dynamic moments of inertia of all these bands show no noticeable differences as function of $N$, consistent with an essentially constant quadrupole deformation from the center of the island to its edges. [S0556-2813(98)50911-9]

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Rotational bands associated with a superdeformed (SD) shape have been found in 25 nuclei in the mass 190 region, covering isotopic chains from Au to Po [1]. Throughout the whole region, these bands are characterized by a dynamic moment of inertia ($\mathcal{J}^{(2)}$) which rises smoothly with increasing rotational frequency ($\hbar\omega$), in contrast to the SD bands in the mass 150 and 130 regions. This characteristic feature of the $\mathcal{J}^{(2)}$ moment has been explained as resulting from the gradual alignment of $i_{13/2}$ protons and $j_{15/2}$ neutrons, in cranked shell model calculations with pairing [2] and in Hartree-Fock-Bogoliubov calculations [3]. From comparisons between experiment and theory, a detailed picture of proton and neutron excitations with respect to the doubly magic SD nucleus $^{192}$Hg has evolved. Focusing on the SD bands in odd-$Z$ nuclei, the role of the proton $i_{13/2}$ ($\Omega=5/2$) intruder orbital has become particularly clear. It is predicted to be occupied by the 81st proton in a SD configuration, provided that the deformation is stable (see, e.g., Ref. [4]). A prominent feature of this yrast proton configuration is a small but significant signature splitting at rotational frequencies $\hbar\omega>0.2$ MeV [2]. Therefore, two signature partner SD bands are expected. These have been seen first in $^{193}$Tl by Fernandez *et al.* [5] and, subsequently in $^{195}$Tl by Azaiez *et al.* [6] and in $^{191}$Tl by Pilotte *et al.* [7]. In these three SD nuclei, the bands were firmly established as signature partners through the observation of weak interband transitions of $M1$ character connecting both $E2$ sequences [8–10]. Furthermore, the magnetic properties of these SD structures have been inferred from the measured $B(M1)/B(E2)$ branching ratios. These ratios provide direct evidence for the assignment of the SD bands to the proton $i_{13/2}$ ($\Omega=5/2$) orbital. In $^{193}$Tl, Bouneau *et al.* [11] found in addition three excited SD bands and interpreted two of them as signature partners based on a proton configuration [411]1/2, a configuration associated with a large signature splitting.

In this work, proton excitations in the second well are investigated further by studying the next lighter odd-mass isotope $^{189}$Tl. A stable SD minimum is still predicted to occur [4] in this nucleus. However, since it is located at the edge of the island, the secondary minimum is presumably more shallow. The quadrupole deformation for $N=108$ systems is also calculated to be somewhat reduced by 5–10% [4], with respect to the heavier nuclei in the isotopic chain. This could shift other proton orbitals (such as the [411]1/2 or [514]9/2 states) closer to the Fermi surface and, perhaps, change the yrast configuration. A test of this deformation decrease is also important in itself. The SD shapes of the isotopes $^{190-194}$Hg have been shown to be stable with respect to changes in mass (and orbital occupation) [12]. Lifetime measurements in the SD bands of $^{191}$Tl [10] have indicated that the quadrupole moment is similar to those of the adjacent Hg nuclei (agreement within error bars), confirming the stability of the SD shape. Here, first evidence for a change in deformation is being investigated by looking for possible differences in the $\mathcal{J}^{(2)}$ moments and in the signature splitting between $^{189}$Tl and the heavier odd Tl isotopes.

In an earlier study of $^{189}$Tl, one SD band was tentatively assigned [13] to this nucleus, but the expected signature partner could not be observed. In this paper, evidence is presented for two SD bands in $^{189}$Tl. This is the nucleus with lowest neutron number ($N=108$) of the mass 190 region in which superdeformation has now been observed.

The experiment was carried out at the 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory. High-spin states in $^{189}$Tl were populated with the $^{156}$Gd($^{37}$Cl, 4$n$) reaction at a beam energy of 172 MeV. Two self-supporting (0.6 mg/cm$^2$) targets enriched to 94% in $^{156}$Gd were used. The $\gamma$ rays emitted in the reaction were detected by the Gammasphere array [14], which contained 102 Compton-suppressed Ge detectors at the time of the experiment. A total of 700 million events were collected during a one day experiment, with the condition that a minimum of four detectors fired in coincidence. Unpacked 3-fold and 4-fold coincidence events were then analyzed off-line.

The quadruple coincidence events were most useful in establishing the new rotational sequences because of many

 

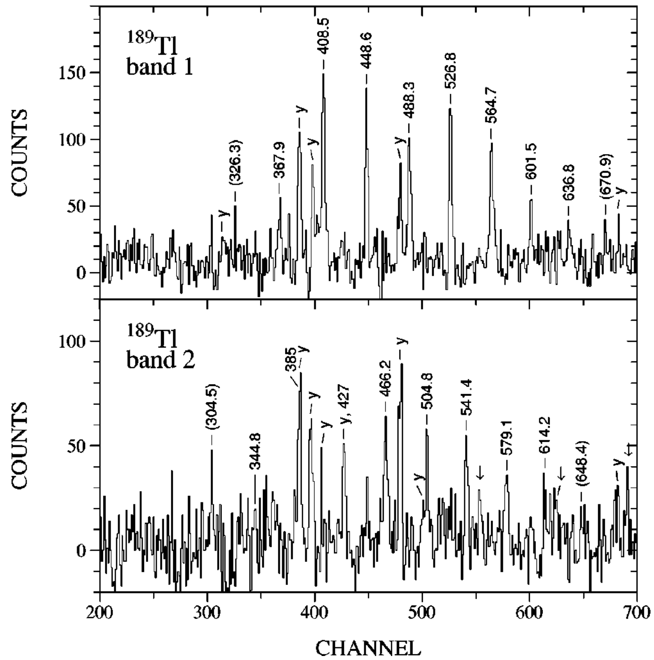


FIG. 1. Spectra of the two SD bands in $^{189}$Tl obtained from sums of triple coincidence gates placed on the inband transitions of interest. All band members are labeled by their transition energies in keV. Known yrast transitions between normal deformed states in $^{189}$Tl are labeled by the symbol y. The highest lying yrast transition observed is $25/2^+ \rightarrow 21/2^+$ (395.0, 398.6 keV doublet [16] in the bottom spectrum). Newly observed near-yrast transitions in $^{189}$Tl are indicated by an arrow (bottom).

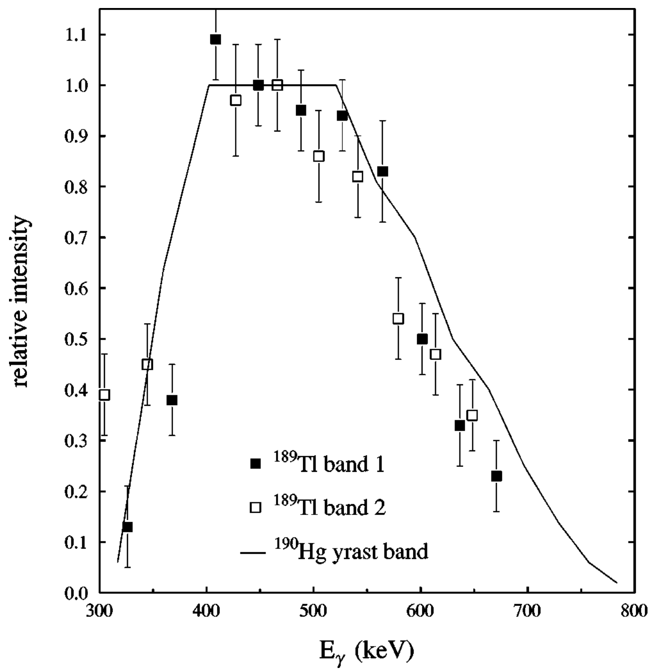


FIG. 2. Relative transition intensities for the two SD bands in $^{189}$Tl. The intensity distribution for the yrast SD band in $^{190}$Hg (Ref. [20]) is given for comparison (solid line). All three bands have been normalized separately. Notice that no result could be obtained for the 385 keV transition in band 2, due to the presence of a close lying yrast transition. See text for details.

overlapping and stronger contaminant peaks. Triple-gated coincidence spectra of the two new rotational bands in $^{189}$Tl are shown in Fig. 1. These spectra represent all combinations of triple coincidence windows placed on the eight strongest transitions in each band, with a generalized background subtracted according to the procedure of Ref. [15]. All band members are labeled by their energies, and transitions assigned to one of the bands with less confidence are given in parentheses (they were not used in the gating procedure). Typical uncertainties for the $\gamma$-ray energies are 0.3–1 keV. The SD rotational character of both bands is inferred from the nearly constant transition-energy spacings ($\Delta E_\gamma \sim 40$ keV). Directional correlations of the $\gamma$ rays of interest are consistent with the proposed $E2$ assignments. The placement of the new transitions in $^{189}$Tl is based on their coincidence relationships with low-lying transitions between normal deformed states in $^{189}$Tl [16] (labeled y in Fig. 1). SD band 1 in $^{189}$Tl is ''isospectral'' to the SD band reported in $^{189}$Hg [17], i.e., the $\gamma$-ray transition energies of both bands agree within three keV over nearly the entire energy range. The intensity in the $p3n$ channel leading to $^{189}$Hg is measured to be only one tenth of the $^{189}$Tl reaction yield. Therefore, possible contributions from $^{189}$Hg to the spectrum of band 1 can be neglected and a misassignment is ruled out. A complication for the study of superdeformation in $^{189}$Tl is the overlap of two prominent transitions in band 2 with the yrast normal deformed transitions of 386.0 keV ($11/2^- \rightarrow 9/2^-$) and 427.3 keV ($15/2^- \rightarrow 13/2^-$) [16], respectively. While there is little doubt about the assignment of the transitions to SD band 2, it is impossible to determine the $\gamma$-ray energies with the accuracy reached for the peak positions of the other band members. Moreover, this situation also results in a higher background to be subtracted from the coincidence spectra and the intensity determination for the two contaminated transitions is also less precise. All other significant peaks in the spectrum of band 2 are identified as transitions in $^{189}$Tl including some non-yrast transitions which have been placed in a new level scheme [18].

The yield of the SD bands as a fraction of the total reaction cross section can be obtained from a comparison of the intensities of yrast transitions in coincidence spectra gated by yrast and SD transitions. It is estimated that the $\gamma$-ray flux through each SD band is about equal and represents 0.1–0.2% of the total $^{189}$Tl yield. This flux is lower by at least a factor of two than the intensities measured in the SD bands of $^{191}$Tl [7] and by an order of magnitude when compared to the strongest bands in the mass 190 region (e.g., the yrast SD band in $^{192}$Hg [19]). Figure 2 presents the intensity distributions along the two bands. For the purpose of comparison, both bands are normalized separately to a relative intensity of 1. Also shown is the decay pattern of the yrast SD band in the neighboring $^{190}$Hg nucleus [20]. Clearly, the intensity distribution is very similar for all three bands and displays a common feature of SD bands in the region: below 600 keV the intensity remains essentially constant until the sudden decay out of the band occurs via a few transitions. This analogy with other SD bands in the mass 190 region further strengthens the conclusion that the newly observed bands correspond to a very deformed structure in the second potential well of $^{189}$Tl.

There is no evidence in the data for cross-talk between the two SD bands, a commonly observed feature in the heavier

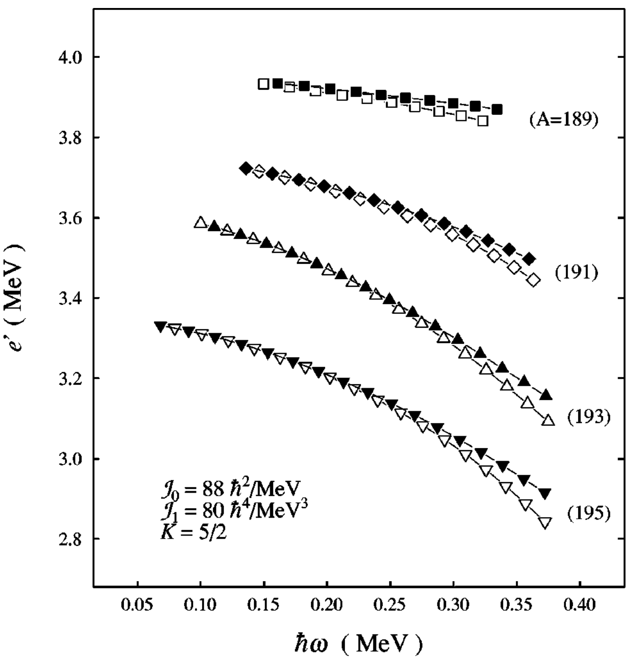


FIG. 3. Comparison between the experimental Routhians $e'$ for the SD bands in the four odd-$A$ Tl isotopes with mass $A=189$, 191, 193, 195. The assumptions made to obtain the Routhians are discussed in the text.

Tl isotopes (see discussion above). This is attributed, at least in part, to the low intensity of the SD bands in $^{189}$Tl. Likewise, transitions linking the two bands with the yrast states in $^{189}$Tl are not observed: no $\gamma$ ray with an intensity $>5\%$ of the 448.6-keV transition (band 1) and an energy 1.5 MeV $<E_\gamma<5$ MeV is observed in the present data. The decay intensity is presumably spread over many different pathways. Spin assignments to the new SD bands are proposed on the basis of a fitting procedure for the measured $\mathcal{J}^{(2)}$ moment as a function of $\hbar\omega$ [21], using a Harris parametrization. The spins at the bottom of the bands are suggested to be 27/2 (band 1) and 25/2 (band 2). These values are consistent with the observation that the SD bands feed the normal deformed states at and below spin 25/2, as can also be seen in Fig. 1. More importantly, the fitting procedure indicates a difference of $1\hbar$ between the spins of the levels in both bands. This supports the interpretation of the two SD bands as signature partners.

From cranked shell model (CSM) calculations (e.g., those shown in Fig. 4 of Ref. [2], and Fig. 10 of Ref. [11]) and from calculations using the cranked Hartree-Fock-Bogoliubov method [3], it is clear that the 81st proton is likely to occupy the $i_{13/2}$ ($\Omega=5/2$) orbital in all SD Tl nuclei. To ease the present discussion, we refer to the relevant single-proton Routhians in Ref. [2]. Figure 3 presents the experimental single-particle Routhians $e'$ vs $\hbar\omega$ for the two bands in $^{189}$Tl as well as for the signature partner SD bands in the heavier odd-mass Tl isotopes. The Routhians for the bands in $^{189}$Tl have been computed assuming that both sequences are strongly coupled at low rotational frequency (i.e., the 27/2 level of band 1 has been adjusted midway between the 25/2 and 29/2 levels of band 2). The splitting between the bands in the other isotopes is known [8–10]. For all sets of bands, the spins were obtained from the fitting procedure described above, and $K=5/2$ was assumed according to Refs. [8–10]. In the figure, the excitation energies are chosen arbitrarily. A common rotational core is used, represented by the Harris parameters $\mathcal{J}_0=88\,\hbar^2$/MeV and $\mathcal{J}_1=80\,\hbar^4$/MeV$^3$ (cf. Ref. [7]). It can be seen from Fig. 3 that the bands in $^{189}$Tl follow the same general slope as a function of $\hbar\omega$, suggesting again that they are indeed signature partners. Based on the energy splitting observed at higher frequencies, band 2 (open symbols) is viewed as the favored signature. All sets of bands exhibit increasing signature splitting for $\hbar\omega>0.2$ MeV. The increase is of similar magnitude (10–20 keV at, e.g., $\hbar\omega=0.25$ MeV). Based on the CSM calculations, the proton $i_{13/2}$ ($\Omega=5/2$) orbital is the only active orbital with a behavior similar to that seen in the data. While a Routhian with a similar dependence on $\hbar\omega$ should also be observed for the favored signature of the [411]1/2 orbital, the large signature splitting of this orbital ($\Delta e'>200$ keV) rules out an assignment of the SD bands of $^{189}$Tl to this state. A [514]9/2 assignment is ruled out by the fact that this orbital does not exhibit signature splitting (for $\hbar\omega<0.4$ MeV). Furthermore, in this case the Routhian is calculated to be an upsloping function with $\hbar\omega$.

The analogies between experimental and calculated Routhians strongly support an $i_{13/2}$ ($\Omega=5/2$) configuration assignment for the new sequences in $^{189}$Tl. However, the possible changes in quadrupole deformation discussed above deserve further attention, since the most pronounced drop in $\beta_2$ deformation ($\leqslant 10\%$) is predicted to occur within an isotopic chain between $N=112$ and the lightest isotope. Even with lifetime data for the bands in $^{189}$Tl, it would be difficult to demonstrate the presence of such a small deformation effect. However, a deformation difference can, perhaps, be verified by a careful inspection of the signature splitting of the proton $i_{13/2}$ bands between the various Tl isotopes. This dependence of signature splitting on deformation has been shown in a study of the signature splitting in neutron $i_{13/2}$ bands at normal deformation [23]. Figure 4 shows a comparison between $\Delta e'$ values extracted from the experimental data for $^{189-195}$Tl (cf. Fig. 3) and calculated signature splitting values. The experimental error bars are determined by the uncertainties of the measured $\gamma$-ray transition energies (additional uncertainties introduced when varying slightly the Harris parameters can be neglected). The calculated values (open symbols) have been obtained from CSM calculations with a Woods-Saxon code with pairing [22]. In these calculations, the quadrupole deformation has been varied within a range of $\leqslant 10\%$ according to theoretical predictions ($\beta_2=0.456$ for $^{189}$Tl, 0.474 for $^{191}$Tl, and 0.483 for $^{193,195}$Tl [4]), while the parameters $\beta_4$ and $\gamma$ have been kept constant. At three representative frequencies the experimental splittings are larger for $^{189}$Tl than for the heavier isotopes. This deviation is in agreement with the calculated trend: the $i_{13/2}$ signature splitting increases as deformation decreases. The ''pure'' $\Delta e'(\beta_2)$ dependence (pairing neglected) [23] for these $K=5/2$ bands is also indicated in the figure by the dotted line. From this comparison between experiment and theory it can be concluded that the bands in $^{189}$Tl may well correspond to a somewhat less (5–10%) deformed shape.

In Fig. 5, the $\mathcal{J}^{(2)}$ moments obtained for $^{189}$Tl are presented together with those of the $i_{13/2}$ SD bands in the

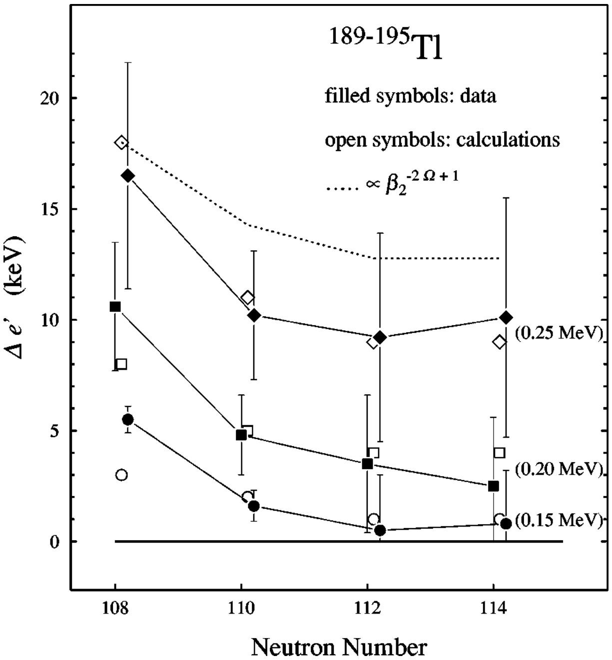


FIG. 4. Experimentally deduced and calculated proton $i_{13/2}$ signature splitting for the SD nuclei $^{189-195}$Tl at the three representative frequencies $\hbar\omega = 0.15$, 0.2, and 0.25 MeV (circles, squares, and diamonds, respectively). The dotted line represents the expected general dependence $\Delta e' \propto \beta_2^{-2\Omega+1}(\Omega = 5/2)$.

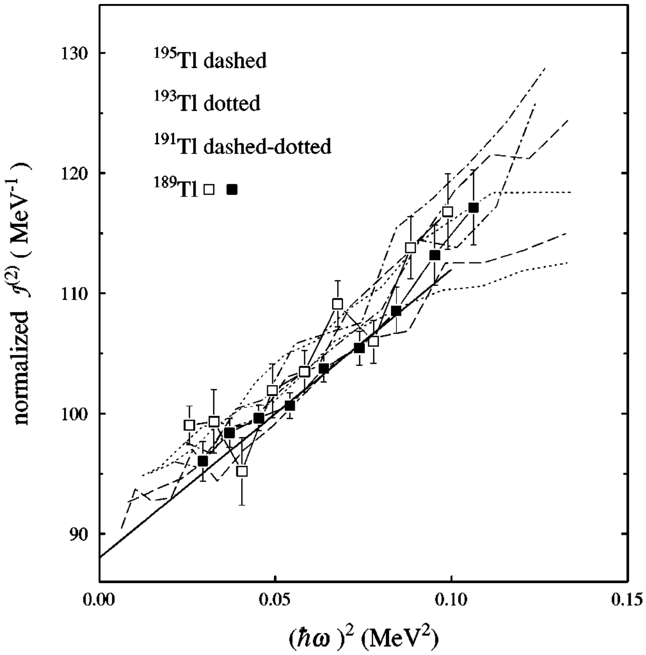


FIG. 5. Dynamic moments of inertia $\mathcal{J}^{(2)}$ as function of $(\hbar\omega)^2$ for the yrast SD bands in odd-$A$ Tl nuclei. The average mass dependence of the $\mathcal{J}^{(2)}$ moments ($\propto A^{5/3}$) has been removed via a normalization to $^{189}$Tl. See text for details.

heavier Tl isotopes. In the figure, a normalization according to the $A^{5/3}$ mass dependence (with respect to $A = 189$) has been applied. The $\mathcal{J}^{(2)}$ moments are plotted as a function of $(\hbar\omega)^2$ (rather than $\hbar\omega$) so that a Harris parametrization ($\mathcal{J}^{(2)} = \mathcal{J}_0 + 3\mathcal{J}_1\omega^2$) can be directly applied to these data. The important parameter in this context is $\mathcal{J}_0$ (obtained at $\hbar\omega = 0$) which is assumed to be proportional to the deformation $\beta_2$ [24]. To guide the eye, a fit to the $^{189}$Tl data yielding $\mathcal{J}_0 = 88\,\hbar/\mathrm{MeV}$ is included in the figure. Even at the small scale of Fig. 5, the SD bands in $^{189}$Tl show the same behavior as the bands in the heavier odd-mass isotopes, and essentially agree within error bars. At low frequencies [$(\hbar\omega)^2 < 0.1$ MeV$^2$], there is perhaps a marginal difference between the unfavored signature in $^{189}$Tl (open symbols) and the bands in $^{193}$Tl (dotted functions). However, this small decrease of the moment of inertia could be due either to a small drop in $\beta_2$ deformation between the nuclei or to an increase of the neutron pairing as one departs from the secondary $N = 112$ shell gap or to both effects together. Interestingly, the values for $^{195}$Tl also seem to be somewhat reduced compared to the behavior of $^{193}$Tl, perhaps due to pairing effects. Thus, a decrease in deformation from $^{193}$Tl to $^{189}$Tl is not conclusively demonstrated from the $\mathcal{J}^{(2)}$ moments. Rather, the agreement between the experimental values can be taken as a confirmation of the choice of a common rotating reference in the analysis presented above.

Finally, it is also striking in Fig. 3 that there is a clear trend with mass for the lowest SD transition observed in the bands: the decay out occurs at the highest transition energy in $^{189}$Tl and evolves towards increasingly lower $\gamma$-ray energy with mass. With the assumption that the rotational frequency is strongly correlated to the spin of the SD state, the differences between isotopes should be viewed as indications of a systematic change of the depth of the SD potential with mass. In fact, for this mass region, the well is predicted (i) to have the largest barrier height for the heaviest SD nucleus in an isotopic chain, and (ii) to become more shallow towards the lighter isotopes [4]. Even though the decay out of the SD bands is governed by more factors than the well depth (SD bandhead energy and level density of the normal entry states, in particular), the decay out features and the low intensity of the bands in $^{189}$Tl follow the expected isotopic trend.

In conclusion, two SD bands in $^{189}$Tl have been found and the isotopic limit for superdeformation in the mass 190 region is shifted to $N = 108$. The weak intensity of these bands and their decay patterns agree with predicted isotopic trends and reflect a shallow second potential well at the edge of the island of superdeformation. The two bands are interpreted as signature partners associated with the proton $i_{13/2}$ ($\Omega = 5/2$) proton configuration. The bands in $^{189}$Tl fit the systematics of yrast SD band structures in the $^{191-195}$Tl isotopes and a consistent picture for proton excitations in the SD well is obtained from the center of the region to its edges. Circumstantial evidence for a slight decrease in quadrupole deformation between $^{189}$Tl and $^{193}$Tl has been obtained from a comparison of the degree of signature splitting with theoretical calculations as a function of the $\beta_2$ deformation parameter.

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