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Superdeformed shapes and configurations in thallium nuclei

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Abstract

Superdeformation studies in ^{189,191,192}Tl at Gammasphere are discussed. New results on ^{191}Tl are the observation of interband transitions between the signature partner $E2$ bands and the measurement of an average quadrupole moment ($Q_0 = 18 \pm 1$ eb) for these superdeformed structures. These data enable us to derive absolute $M1$ strengths and confirm that the 81^{st} proton occupies the [642]5/2 orbital. Tentative data for one superdeformed sequence in ^{189}Tl are consistent with the prediction of a decrease in quadrupole deformation for the lightest nuclei at the limit of this island of superdeformation.

1. INTRODUCTION

The superdeformed bands in the mass 190 region are observed at considerably lower spins (down to $\sim 10\hbar$) and smaller transition energies than comparable bands in the mass 80 and mass 150 regions ($> 20\hbar$). This provides a unique opportunity for detailed spectroscopic studies in the second potential well. Focusing on signature partner bands in odd-Z or odd-N nuclei, we may expect that at the bottom of those bands interband $M1$ transitions and inband $E2$ transitions will compete with each other. The magnetic properties ($B(M1)/B(E2)$ ratios) can then be measured and used to identify the active orbitals with medium or high K in the superdeformed nucleus [1]. New results on magnetic properties of the yrast superdeformed bands in ^{191}Tl [2] are presented in this paper. Measured branching ratios and calculated magnetic moments of single proton states [3] are compared for appropriate $B(E2)$ values to verify the proposed [642]5/2 configuration assignment. Similar studies have already been done for the neighboring nuclei ^{193}Tl [4] and ^{195}Tl [5]. However, we are able to base our analysis on measured transition quadrupole moments, Q_0, rather than on an average Q_0 value derived from neighboring nuclei on which the authors of refs. [4,5] had to rely.

A quadrupole moment measurement for ^{191}Tl is also important in itself. So far, no such measurement has been done for an odd-Z superdeformed nucleus in the mass 190 region. It is interesting to see if a proton excitation significantly influences the superdeformed shape by comparing measured Q_0 values for ^{191}Tl with results for even-A neighboring nuclei. Secondly, this measurement should contribute to testing the predicted [6] gradual decrease of the β_2 deformation parameter for the yrast superdeformed bands in the mass 190 region when going towards the light nuclei with neutron number $N < 112$. So far, because there is still a lack of lifetime data for these nuclei, indications for a deformation change were inferred from a comparison of moments of inertia at low frequency within an isotopic chain. Such a comparison for the Tl isotopes is presented in the next chapter.

The data were taken with the Gammasphere spectrometer at the 88" cyclotron of the Lawrence Berkeley National Laboratory. We have performed experiments on ^{189}Tl [7], ^{192}Tl [8], and ^{191}Tl, the most recent data on which we are focusing here. For ^{191}Tl, we measured lifetimes using the Doppler Shift Attenuation Method (DSAM). In all these experiments, only triple and higher fold γ-ray coincidences were collected. With the resolving power of the detector array, the fission background, which represents an equally strong yield as the desired xn evaporation channel, was managable like in previous γ-ray spectroscopic studies in the region.

2. DEFORMATION TREND FOR N $\leq$ 112

The most pronounced variations in the quadrupole deformation are predicted to occur in the lightest isotopes where superdeformed minima might be present, e.g. ^{188}Hg. For the same superdeformed configuration, changes in β_2 and Q_0 of roughly 10% are expected from ^{192}Hg to ^{188}Hg and from ^{193}Tl to ^{189}Tl [6]. The question is whether the trend of a gradually decreasing deformation is supported by the available data and if deformation differences of 10% or less can be measured.

In this context, a tentatively assigned superdeformed band in ^{189}Tl seems to be of importance. Together with the yrast superdeformed bands in ^{191}Tl (this work), ^{193}Tl [4], and ^{195}Tl [5] this might provide a systematic comparison of dynamic moments of inertia, $\mathcal{J}^{(2)}$, along the isotopic chain. The $\mathcal{J}^{(2)}$ moments of these bands are plotted in Fig. 1 versus the square of the rotational frequency. Note that the yrast bands in the heavier isotopes are observed in two signatures.

The data on ^{189}Tl were measured with Gammasphere in its Early Implementation phase using a ^{156}Gd(^{37}Cl,4n) reaction [7]. Data analysis has revealed a weak signal of seven transitions in ^{189}Tl ranging from 367 to 603 keV with a constant spacing of about 40 keV and estimated intensities of the order of 0.1 % of the yield of the 4n reaction channel (see also [9]). The statistical accuracy of these data is not sufficient to be sure that all these transitions are in cascade. However, since the features of this weak signal fit with the characteristic rise of $\mathcal{J}^{(2)}$ moments of superdeformed bands in the region [10] we include this candidate for one band in ^{189}Tl in the figure.

The data on ^{191}Tl were taken in two recent experiments with Gammasphere using different reactions. First, a ^{174}Yb(^{23}Na,6n)^{191}Tl reaction at $E_{lab} = 132$ MeV was chosen. In the second run, ^{191}Tl was populated in the ^{159}Tb(^{36}S,4n)^{191}Tl reaction at 165 MeV. The ^{23}Na beam was focused on two thin, self-supporting target foils, while in the ^{36}S-induced reaction, a target foil with Au backing was used to obtain DSAM lifetime information. The new data have enabled us to extend each of the two previously known bands [2] by two additional transitions on the top and at the bottom.

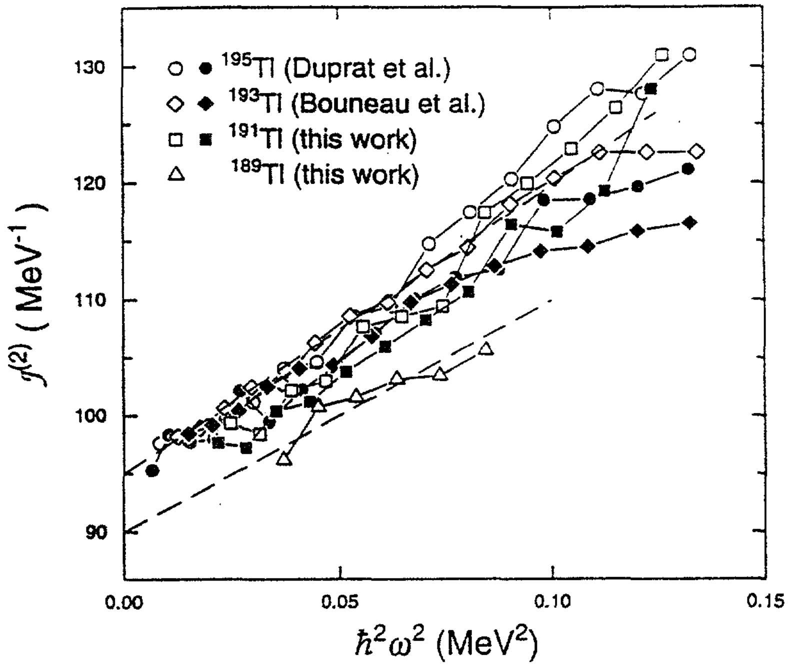

Figure 1. $\mathcal{J}^{(2)}$ moments of inertia as a function of ω^2 for yrast superdeformed bands in odd-A Tl nuclei. The data for ^{189}Tl are tentative.

From Fig. 1 we conclude that the $\mathcal{J}^{(2)}$ moment is somewhat larger for the heavier Tl isotopes. For an estimate of the dependence of these moments of inertia on N, the chosen $\mathcal{J}^{(2)}(\omega^2)$ plot is very useful. Since the dynamic moment of inertia can be written as $\mathcal{J}^{(2)} = \mathcal{J}_0 + 3\mathcal{J}_1\omega^2$, linear fits to the data sets in Fig. 1 lead to values for the Harris parameters $\mathcal{J}_0$ and $\mathcal{J}_1$ where $\mathcal{J}_0$ is proportional to the deformation β_2 [11]. As shown in Fig. 1, a line through the $\mathcal{J}^{(2)}$ values for ^{193}Tl gives $\mathcal{J}_0 \approx 95\ \hbar^2$/MeV, while for ^{189}Tl a value of 90 $\hbar^2$/MeV is obtained. This decrease in $\mathcal{J}_0$ of about 5% is consistent with a similar drop in β_2. The same deformation trend has been suggested for the lighter Hg isotopes ($A = 189 - 192$) from an analysis of their $\mathcal{J}^{(2)}$ moments [12]. A decreased moment of inertia for ^{189}Tl or ^{189}Hg could also be due to increased neutron pairing as one departs from the secondary shell gap at $N = 112$ [6]. However, this departure likely causes also a destabilization of the superdeformed shape with respect to β_2. Clearly, deformation changes need to be considered for the N $<$ 112 systems and quadrupole moment measurements in this part of the superdeformed island are desirable.

Fig. 2 shows representative spectra of the two superdeformed bands in ^{191}Tl [2] from our recent measurement using a Au backed target. The histograms are summed coincidence spectra for counters at all detector angles generated from the cleanest double gates. For the transitions with $E_\gamma \geq 477$ keV, the expected line broadening associated with picosecond level lifetimes (similar to the slowing down times of the recoiling nuclei in the target backing) is observed. Many of the gating transitions at lower E_γ are compromised by stronger yrast γ-ray transitions of ^{191}Tl [7] close in energy, and the fission background is rather high. Accordingly, the spectra of Fig. 2 contain a number of contaminants. Nevertheless, it is possible to perform a DSAM analysis and successfully search for interband transitions.

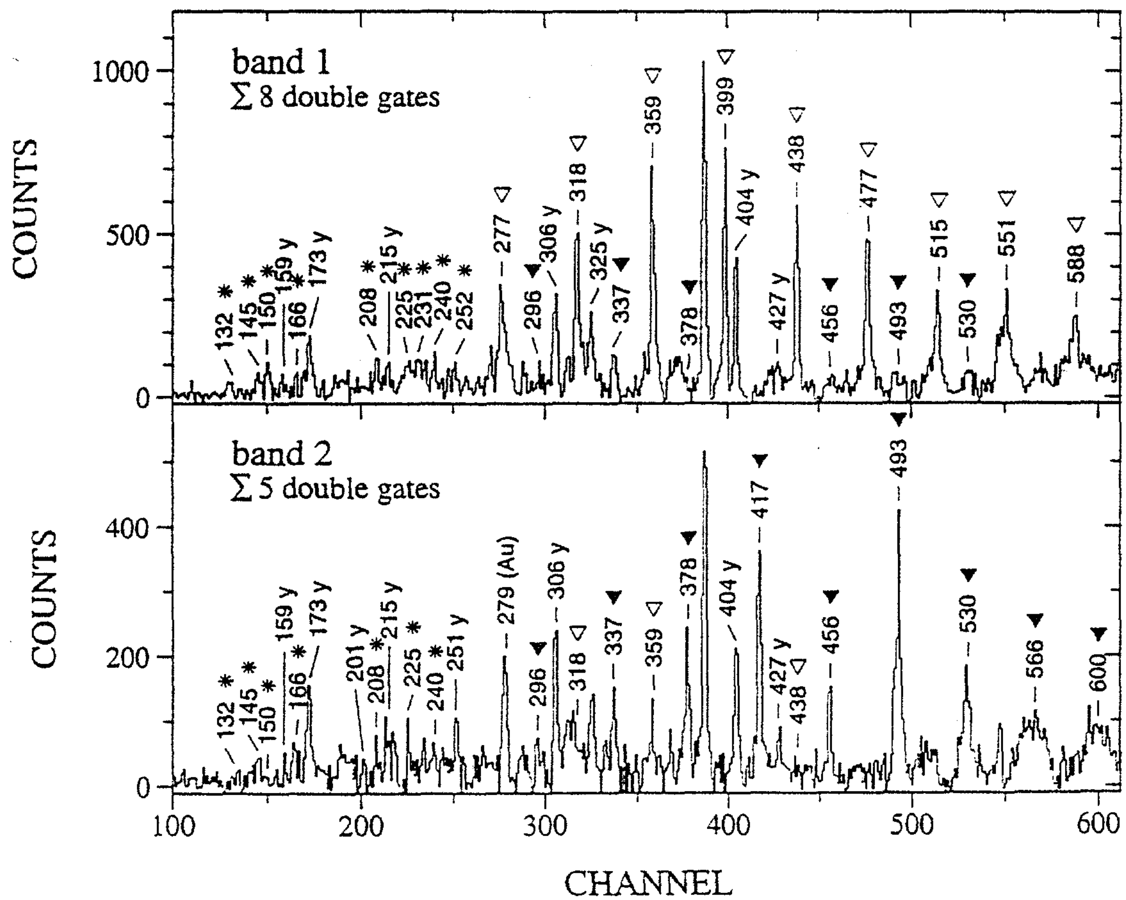

Figure 2. Gamma-ray spectra obtained for the superdeformed bands in ^{191}Tl from the backed-target data. The spectra result from summing up the cleanest double gates in the band of interest. Transitions of band 1 and 2 are indicated by open and filled triangles, respectively. Candidates for interband transitions linking the two bands are indicated by asterisks. Prominent transitions between normally deformed states near the yrast line are labeled by "y".

For the DSAM analysis, angle sorted spectra were generated by double-gating on stopped and nearly stopped transitions at the bottom of each of the two superdeformed bands. From these spectra, fractions of full Doppler shift $F(\tau)$ were obtained over a range of recoil velocities $0.0 \leq v/c \leq 0.9$. Fits to the $F(\tau)(E_\gamma)$ curves for both bands using the code FITFTAU have revealed very similar intrinsic quadrupole moments Q_0 between 17 and 19 eb (including uncertainties). For the remainder of this paper, we will use for the two superdeformed bands in ^{191}Tl a preliminary average value $Q_0 = 18 \pm 1$ eb.

In Table 1, a comparison between measured and calculated Q_0 values for superdeformed bands in Hg and Tl nuclei with even N is presented. The theoretical values are from recent cranked Wood-Saxon calculations with monopole and quadrupole pairing terms by Satula et al. [13]. These values are taken at a representative frequency of 0.24 MeV and it should be noted that in the frequency range of interest variations are at most 0.3 eb. According to Table 1, experiment and theory are in agreement. Moreover, the following observations can be made. (i) The quadrupole moments of the superdeformed bands in Tl nuclei are, perhaps, 0.5 eb larger than the Q_0 values obtained for their Hg isotones, but the superdeformed core is certainly not much polarized by the additional proton. (ii) There is no measurable deformation change between the ^{190,192,194}Hg isotopes. For the purpose of this comparison, systematic uncertainties in the stopping powers associated with different atomic numbers and recoil velocities have been ignored. Nevertheless, it can be concluded that the superdeformed shapes in the mass 190 region are essentially constant. In order to observe deviations from these constant shapes, one needs to study the lightest nuclei at the expected edge of the superdeformed island, *i.e.* nuclei with $N < 110$. This is also suggested by the $\mathcal{J}^{(2)}$ data discussed above.

Table 1
Measured (top) and calculated [13] (bottom) instrinsic quadrupole moments Q_0 (eb) of yrast superdeformed bands in Hg and Tl nuclei. References for the measurements in Hg nuclei: ^{a} ref. [14], ^{b} ref. [15], ^{c} ref. [16].

^{188}Hg	^{190}Hg	^{192}Hg	^{194}Hg
–	17.6 ± 1 ^{a}	17.7 ± 1 ^{b}	17.2 ± 0.2 ^{c}
16.4	17.3	18.0	17.7
^{189}Tl	^{191}Tl	^{193}Tl	^{195}Tl
–	18.0 ± 1	–	–
16.9	18.0	18.5	18.1

3. TRANSITIONS BETWEEN SIGNATURE PARTNER BANDS IN ^{191}Tl

As seen in Fig. 2, cross-talk between the two bands in ^{191}Tl is observed. The corresponding interband transitions are weakly seen in the energy range between 130 and 270 keV. In Fig. 3, the low energy part of the level scheme proposed for the yrast superdeformed states in ^{191}Tl is shown. The identification of linking transitions and their placement in this scheme is based on energy sums *and*, in some cases, on coincidence relationships. The different multipolarities of inband ($\Delta I = 2$) and interband transitions ($\Delta I = 1$) are inferred from a directional correlation analysis of the γ-ray intensities. Since both bands are viewed as signature partners [2], the cross-talk transitions are most likely of the $M1$ type. The suggested spins in Fig. 3 are obtained with the methods described in refs. [17,18]. It should be mentioned that the signature splitting between these bands in ^{191}Tl is near to zero (~ 5 keV at $\hbar\omega = 0.15$ MeV) and, thus, similar to the splittings of the yrast superdeformed bands in the neigboring nuclei ^{193}Tl (~ 12 keV) and ^{195}Tl (~ 2 keV).

Since the $M1$ transitions are weak, we have extracted $I_\gamma(M1)/I_\gamma(E2)$ ratios in two independent ways. From these branching ratios, values of the $(g_K - g_R)K/Q_0$ ratio are

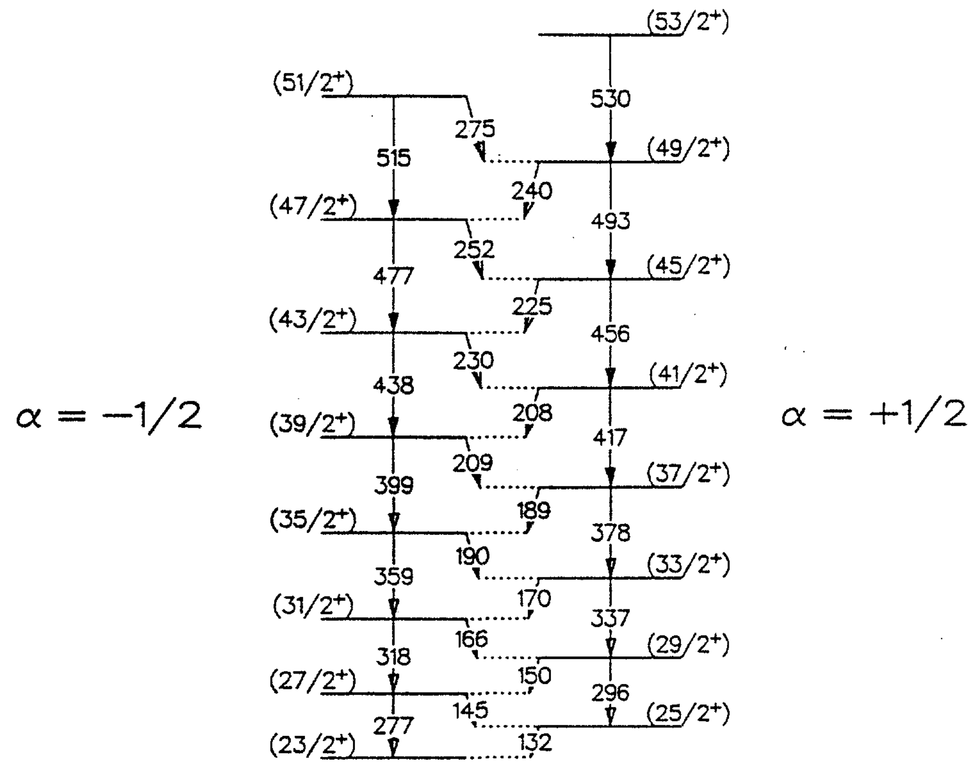

Figure 3. Part of the proposed level scheme for the superdeformed states in ^{191}Tl. Favored (unfavored) signature is denoted by $\alpha = +1/2$ ($\alpha = -1/2$).

deduced assuming that the states of interest are strongly coupled in nature. Figs. 4 (a) and (b) show $(g_K - g_R)K/Q_0$ ratios as a function of spin, sampling the superdeformed transitions which are not contaminated by stronger γ-rays. The data displayed in Fig. 4 (a) are obtained from directly measured branching ratios, while Fig. 4 (b) shows the result obtained for the same spin range when using a procedure based on intensity conservation [5], for which $I_\gamma(M1)$ must not explicitly be known. All data points are consistently scattered between 0.1 and 0.2 eb^{-1}. The agreement between both procedures is also supportive of the proposed $M1$ character of the interband transitions since in procedure (b) internal conversion coefficients [19] for the respective $M1$ and $E2$ transitions are used.

For comparison with theoretical g_K values [3], we have indicated in Fig. 4 calculated limits for the two lowest lying [6] strongly coupled proton configurations, [642]5/2 and [514]9/2, by full and dotted lines, respectively. A g_R value equal to Z/A is assumed. The limits come from the uncertainty on the adopted value $Q_0 = 18 \pm 1$ eb. It is obvious that the experimental ratios are in agreement with the assignment of the [642]5/2 configuration for both signatures. Averaging these $(g_K - g_R)K/Q_0$ ratios over the different states, we obtain values of (a) 0.145 $\pm$0.013 eb^{-1} and (b) 0.125 $\pm$0.015 eb^{-1}, which fit well into the range calculated for a $K = 5/2$ proton $i_{13/2}$ configuration.

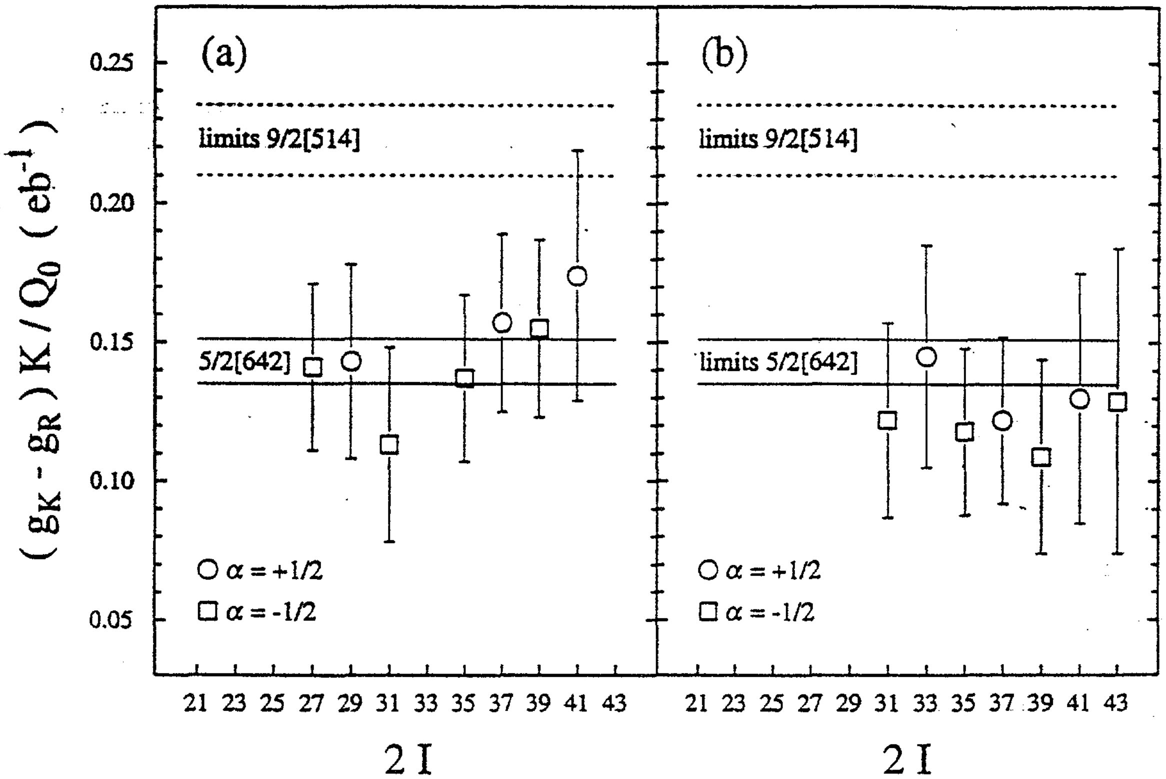

Figure 4. Extracted $(g_K - g_R)K/Q_0$ values for states of the signature partner superdeformed bands in ^{191}Tl and comparison with theoretical predictions. Abscissa values are twice the spins given in Fig. 3. Part (a) and (b) of the figure represent the two different experimental methods used to deduce the data points (see text).

4. CONCLUSIONS

The first measurement of the quadrupole moment in a superdeformed band of an odd-Z nucleus in the mass 190 region has been reported. For the signature partner bands in ^{191}Tl, we obtain as a preliminary result a value of 18 ± 1 eb. Between the same bands we observe cross-talk and find convincing candidates for the corresponding $M1$ interband transitions. Using the strong coupling model, the information on both $B(M1)/B(E2)$ branching ratios and $B(E2)$ values provides evidence that the [642]5/2 intruder orbital is occupied by the odd proton. This conclusion agrees with recent studies of the yrast superdeformed bands in ^{193,195}Tl resulting in a consistent picture for proton excitations.

While medium to high-K orbitals at the superdeformed shell gaps are identfied by their magnetic properties, low-K "intruders" like $j_{15/2}$ neutron orbitals show their presence through the slopes of the $\mathcal{J}^{(2)}$ moments of inertia. An important case for a configuration assignment involving $j_{15/2}$ quasineutrons is the superdeformed bands in ^{192}Tl with constant $\mathcal{J}^{(2)}$, see discussion in ref. [8]. Overall, a complete picture of various excitations in the superdeformed well at mass 190 has been obtained.

The available lifetime data for Hg and Tl nuclei show that the quadrupole deformation in the second well is remarkably rigid with respect to both the addition of a proton and the variation of the neutron number. These results are in agreement with theoretical predictions, however, the predicted deformation decrease for the lightest nuclei at the limit of the mass 190 region of superdeformation ($N = 108$) needs to be verified and remains an unmet experimental challenge. A possible indication for this deformation trend could be differences in the $\mathcal{J}^{(2)}$ moments between different isotopes, as discussed in this paper from the comparison between tentative data on ^{189}Tl and the data on $^{191-195}$Tl. To reach a conclusion on this aspect, we have proposed new experiments on ^{189}Tl and ^{188}Hg.

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