SUPERDEFORMATION AND PROLATE–OBLATE COMPETITION IN Tl NUCLEI*

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Spectroscopic studies of weakly populated proton $i_{13/2}$ bands in superdeformed Tl nuclei (around mass 190) and in the normally deformed, very light ^{183}Tl nucleus are discussed. Among the results presented, the first measurement of a superdeformed quadrupole moment in an odd-Z nucleus, ^{191}Tl, is reported. The experiments were conducted with the Gammasphere array as "stand-alone" device and coupled with the Argonne Fragment Mass Analyzer.

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1. Introduction

The proton-rich nuclei in the mercury–lead region are well recognized for a multiplicity of shapes [1]. Superdeformed (SD) and well-deformed

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prolate shapes have been observed to coexist with weakly-deformed oblate or spherical shapes, mainly in γ-ray spectroscopic work. Studies of the odd-Z Tl nuclei are important for our understanding of the nuclear structure in that electromagnetic transition rates (*e.g.* B(M1)/B(E2) ratios) and the way an odd proton couples to the deformed even-even core (*e.g.* signature splitting) are fingerprints for the proton orbital at the Fermi level. Whether the nuclear shape is influenced by the odd-particle or not, is also a question of great interest, particularly for the structures in the second minimum.

The most recent finding in superdeformation studies for heavy nuclei are two SD bands in ^{189}Tl [2], the presently lightest SD nucleus in the mercury-lead region (neutron number $N = 108$). This data shed light on the integrity of the second minimum at the edge of the SD island and thus provide an important test for model predictions (*e.g.* those in Ref. [3]). However, the understanding of the underlying nuclear structure will rather advance with a detailed spectroscopy in the SD well — *i.e.* by studying the more strongly populated bands closer to the center of the island. These spectroscopic studies include precision lifetime measurements to investigate the SD shape as a function of N or atomic number Z, measurements of magnetic properties of SD states in odd-mass nuclei to identify the active proton or neutron orbitals, and other topics. As an example, new results for the SD bands in ^{191}Tl are presented in this paper.

An impressive new example for shape-coexistence at low excitation energies is the recent observation of an excited, well-deformed prolate band in ^{184}Pb [4], a nucleus difficult to accesss. Level systematics including the heavier ^{186,188}Pb isotopes indicate that the prolate energy minimum appears at the neutron $i_{13/2}$ midshell ($N = 103$). The corresponding minimum in the Hg isotopes is observed at the same neutron number [1]. This behavior of the even-even nuclei is in accordance with predictions [1], while for their Tl isotones a further drop of the prolate states past midshell is expected [5]. An important test for this picture is the first study of the yrast sequence in ^{183}Tl [6] discussed hereafter.

The measurements presented in this paper required a new-generation array of Compton-suppressed Ge detectors and were carried out with Gammasphere [7] during its stay at the Lawrence Berkeley National Laboratory and most recently at the Argonne National Laboratory. While for the superdeformation studies a high detection sensitivity based on a high-fold γ-ray coincidence measurement was imperative, the far-from-stability study of a very light Tl isotope required reaction channel selection by an external device, namely the Argonne Fragment Mass Analyzer [8]. These results are examples for the type of physics addressed in either the first phase of Gammasphere operation (at Berkeley) or its present phase (at Argonne).

2. Superdeformation studies

Experiments on both ^{189}Tl and ^{191}Tl were performed at the 88-Inch Cyclotron at Berkeley. The nuclei of interest were populated in (HI,xn) reactions. The pertinent information about the experiments is summarized in Table I. Only prompt γ-ray coincidences of fold 4 and higher were collected with the Gammasphere array that comprised between 93 and 102 detectors at the time of the experiments.

TABLE I

Experimental conditions employed in the superdeformation studies

reaction	$E_{\rm beam}$	target foil	no. events[a]
^{156}Gd(^{37}Cl,4n)^{189}Tl	172 MeV	self-supporting	7×10^8
^{174}Yb(^{23}Na,6n)^{191}Tl	132 MeV	self-supporting	1.5×10^9
^{159}Tb(^{36}S,4n)^{191}Tl	165 MeV	with Au backing[b]	5×10^9

[a] γ^4 and higher fold
[b] DSAM lifetime measurement

In the course of this work, a DSAM lifetime measurement has been carried out for the two SD bands in ^{191}Tl. These bands are viewed as signature partners [9] where each sequence represents about 0.5% of the reaction yield. Sample spectra of these bands are shown in Fig. 1. These histograms are summed spectra for counters at all detector angles. For the transitions with $E_\gamma \geq 456$ keV, the expected line broadening (for picosecond level lifetimes) due to the slowing down of the recoils in the target backing is observed. As is customary for weak γ-ray sequences, a centroid shift analysis has been performed. From the peak centroids measured at five different angle groups of the Gammasphere array, fractions of the full Doppler shift were determined according to the first-order relation $F(\tau) = (\langle E_\gamma\rangle - E_\gamma^0)/E_\gamma^0\beta_0\cos\Theta$. E_γ^0 is the nominal (unshifted) γ-ray energy, and $\langle E_\gamma\rangle$ the corresponding energy measured at an average angle Θ representative for the group of detectors. The factor β_0 refers to the intial velocity of the recoiling nucleus formed in the center of the target and was calculated to be $\beta_0 = 0.0182c$. In Fig. 2, these $F(\tau)$ values are presented as a function of γ-ray energy for the transitions in both bands. The instrinsic quadrupole moments Q_0 of the two SD bands have been extracted using the computer code FITFTAU [10]. In this fitting procedure, two more free parameters have been used: a constant sidefeeding quadrupole moment $Q_{\rm SF}$ representing feeder cascades into each SD state, and a "single" lifetime $T_{\rm SF}$ as a one-step delay at the top of a feeder cascade. The slowing-down times in both the target and the Au backing have

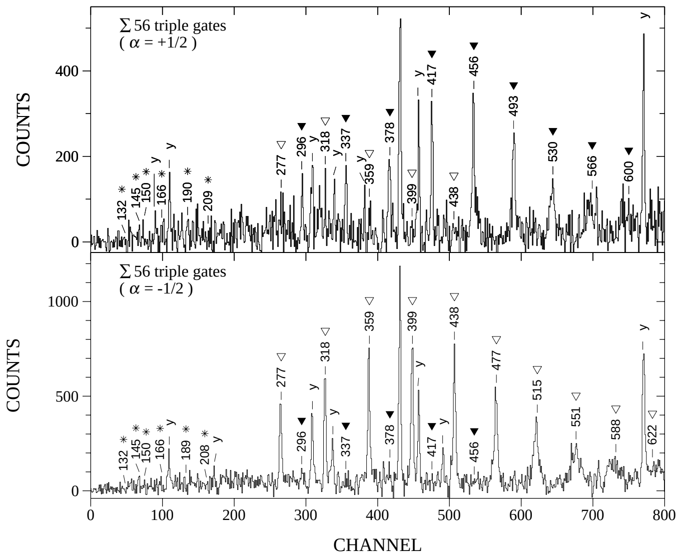

Fig. 1. Sum of triple-gated spectra obtained for the SD bands in ^{191}Tl from the backed target data. Transitions of the $\alpha = +1/2$ and -1/2 band are indicated by filled and open triangles, respectively, and labeled in keV. Prominent transitions between normally deformed states near the yrast line are marked by "y". Candidates for interband transitions linking the two bands are indicated by asterisks.

been calculated with stopping powers provided by the code TRIM [11]. The results of these fits to the $F(\tau)$ data are illustrated by the curves plotted in Fig. 2. The quoted errors for the Q_0 values include the covariance between all three fit parameters, but not the systematic uncertainties associated with the stopping powers.

The quadrupole moments obtained for both bands, $Q_0 = 18.6^{+1.0}_{-0.8}$ eb and $17.7^{+0.8}_{-1.0}$ eb are – as expected – very similar and correspond indeed to a SD rotor with a quadrupole deformation $\beta_2 \sim 0.47$. This is the first measurement of the quadrupole moment in a SD band of an odd-Z nucleus in the mass 190 region [12]. Within the statistical uncertainties, the Q_0 values obtained for ^{191}Tl agree with the quadrupole moments measured in the neigboring nuclei ^{190}Hg [13] and ^{192,194}Hg [10]. For the purpose of a comparison between the Tl and Hg isotopes, one has to ignore the systematic uncertainties in these data associated with different atomic numbers and recoil velocities (in all these experiments Au backing was used). However, these discrepancies in the stopping powers are rather minor since the reactions that have been used are similar, particular those for ^{190}Hg [13] and ^{191}Tl. It is safe to conclude that the SD Hg "core" is not much polarized by the

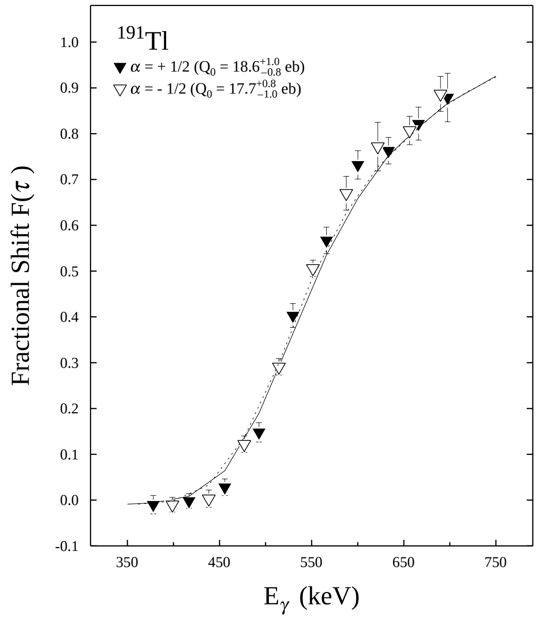

Fig. 2. Measured fractional Doppler shifts $F(\tau)$ for γ-rays in the two SD bands of ^{191}Tl versus transition energies. The solid and dashed curves represent the best fits corresponding to the Q_0 values given for the $\alpha = +1/2$ and -1/2 band, respectively.

additional proton. Interestingly, there is no measurable deformation change between the ^{190,192,194}Hg isotopes either. The SD shapes in the mass 190 region seem to be remarkably constant with respect to variations of both N and Z.

As earlier mentioned in this paper and first reported in Refs. [14, 15], $M1$ linking transitions between signature partner SD bands are observed in several Tl nuclei. The occurrence of $M1$ transitions between SD states is a special feature of the mass 190 region. It is related to the fact that the SD bands there appear at considerably lower spins (down to $\sim 10\hbar$) and smaller transition energies than comparable bands in *e.g.* the mass 150 region ($> 20\hbar$). Thus, for SD structures with medium or high K and large g-factor, $M1$ transitions become nearly competitive with the E2 transitions at the bottom of the sequence. Between the two SD bands in ^{191}Tl cross-talk is observed, like in the heavier Tl isotopes. Some of the corresponding interband transitions, weakly seen in the energy range between 130 and 230 keV [9], are indicated in Fig. 1. The different multipolarities of inband ($\Delta\ I = 1$) and interband transitions ($\Delta\ I = 2$) are inferred from a directional correlation analysis. Assuming for the interband transitions $M1$ character, one may arrange all these transitions in the level scheme shown in Fig. 3. The suggested spins in Fig. 3 are obtained with the fitting procedure described in Ref. [16]. This procedure yields a difference of 1 $\hbar$ between the spins of the levels in both bands, supporting the interpretation of the two SD bands as signature partners. The size of the signature splitting between these bands is near to zero for rotational frequencies $\hbar\omega < 0.2$ MeV and, thus, similar to the splittings of the yrast SD bands in the neighboring nuclei ^{193,195}Tl [14, 15]. By comparison with cranked shell model calculations, only the proton $i_{13/2}$ ($\Omega = 5/2$) orbital matches up with a signature splitting behavior seen in the data.

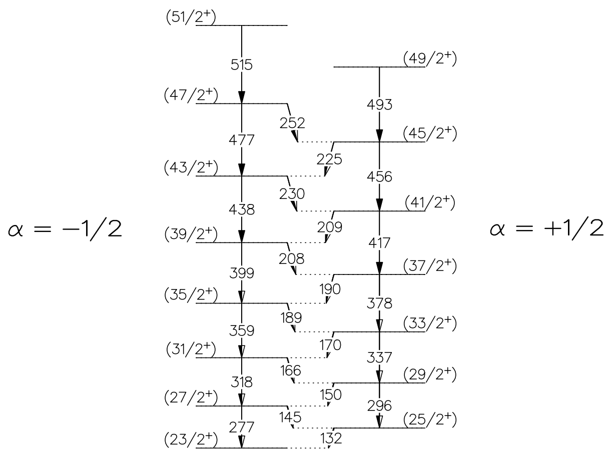

Fig. 3. Part of the proposed level scheme for the SD states in ^{191}Tl. Favored (unfavored) signature is denoted by $\alpha = +1/2$ ($\alpha = -1/2$). The suggested spins are obtained based on a fitting procedure (see text).

The analysis of the magnetic properties of the signature partner bands in ^{191}Tl verifies that the 81^{st} proton occupies the $i_{13/2}[642]5/2$ Nilsson level. Under the assumption that for these SD bands the strong coupling limit is valid, $(g_K - g_R)K/Q_0$ values have been extracted for several of their states where $M1$-to-E2 branching ratios could be measured (for details see Ref. [9]). These values can be compared with calculations by Semmes *et al.* [17] in the following way. Taking a quadrupole moment 16.7 eb $\leq Q_0 \leq$ 19.6 eb, which is the range of the quadrupole moments measured for both bands, and the g_R-factor equal to Z/A, the theoretical $(g_K - g_R)K/Q_0$ values for $g_K = 1.45$ ([642]5/2) [17] agree with the data, while the alternative high-K configuration ([514]9/2) is ruled out. The same proton $i_{13/2}$ configuration assignment has been reported for the signature partner SD bands in ^{193,195}Tl [14, 15]. However, with the measured quadrupole moments of the bands in ^{191}Tl the present result is obtained with a minimum of assumptions.

3. Study of ^{183}Tl — spectroscopy beyond the neutron midshell

The yrast band in the lighter odd-mass Tl isotopes ($A \leq 189$) is based on the $i_{13/2}[660]1/2$ proton intruder state (see *e.g.* Ref. [5]). This low-K structure is typically observed in one signature only, consistent with an expected large signature splitting. Due to its large downward slope in the prolate sector of the Nilsson diagram, the [660]1/2 is expected to drive the quadrupole deformation ($\beta_2 \sim 0.25$). The $i_{13/2}$ yrast band feeds into a lower-lying structure based on a $h_{9/2}[505]9/2$ isomeric state that is associated with a weakly-deformed oblate shape ($\beta_2 \sim -0.15$). Thus, the yrast line in the Tl isotopes above the $9/2^-$ state resembles the yrast spectrum observed the neighboring Hg isotopes. Previous to this work, ^{185}Tl has been the lightest Tl isotope measured in-beam [5]. Studies of the next lighter isotopes become increasingly difficult as the HI-induced reactions required to produce them are overwhelmed by the fission process that introduces a large background in the γ-ray spectra.

In a recent experiment with Gammasphere at the Fragment Mass Analyzer (FMA), the ^{108}Pd(^{78}Kr,$p2n$) reaction at 340 MeV was used to study ^{183}Tl. Prompt γ radiation from the target was detected with 97 Compton-suppressed Ge detectors four of which were of planar type. The FMA was used to separate the evaporation residues from fission products and primary beam. These recoils were then mass-analyzed and subsequently implanted in a double-sided Si strip detector. A total of $\sim 10^8$ events was recorded under the trigger conditions, recoil-γ^n ($n \geq 1$) or decay event in the strip detector. From the measured α decay yield, the cross section of the chosen reaction was estimated to be in the 100 μb range.

It should be pointed out that the strongest line in the α decay of ^{183}Tl ($E_\alpha = 6.38$ MeV) [18] represents a branch of only 1.5%. Thus, the present result is mainly based on the spectroscopy of ^{183}Tl with mass identification and Z-identification by the X-ray yield. In Fig. 4 (top), a sample γ-ray coincidence spectrum attributed to ^{183}Tl is shown. The level spacings of the new sequence in ^{183}Tl resemble the well-deformed (prolate) excited bands in adjacent nuclei of Hg, Tl, and Pb, but its decay-out properties are different from those cases in two respects.

(1) The rotational-like sequence is observed from medium spin to the $13/2^+$ state, as indicated by the level scheme inserted in the figure, *i.e.* the population intensity stays within the band down to the bandhead.

(2) Unlike in heavier Tl nuclei, a strong γ-decay branch from the prolate band to a lower-lying-oblate structure is not observed. To highlight these differences, a spectrum of ^{185}Tl [5] is shown in the bottom part of Fig. 4 for comparison. These features of the yrast spectrum of ^{183}Tl indicate that the well-deformed band must be lower-lying with respect to the $9/2^-$ isomeric state than in the heavier isotopes.

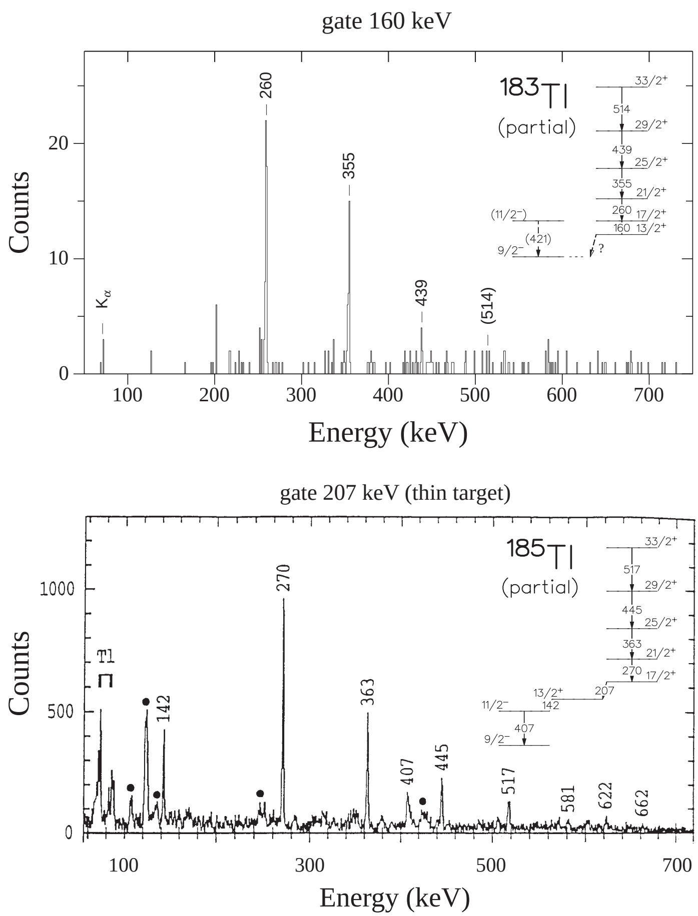

Fig. 4. Top: Sample coincidence spectrum for ^{183}Tl. The spectrum was created from gating on the 160 keV line in the mass 183 selected γ-ray coincidence data. Members of the rotational band are labeled by their energies in keV, Tl X-rays are identified as well. A tentative level scheme for ^{183}Tl is shown where spins and parities are are assigned by analogy with yrast sequences in neighboring isotopes. Bottom: Sample coincidence spectrum for ^{185}Tl reproduced from Ref. [5] and a partial level scheme of this nucleus. The solid circles in this spectrum represent contaminants from Coulomb excitation in the target.

In the present level scheme of ^{183}Tl it is not clear how the $i_{13/2}$ band decays and, therefore, upper and lower-limit estimates for the energy of the $13/2^+$ bandhead relative to the $9/2^-$ isomeric state (oblate) have been made (95 keV $\leq E_{\rm rel} \leq$ 424 keV [6]). However, with the estimated upper limit of 424 keV ($E_{\rm rel} \simeq$ 603 keV in ^{185}Tl [5]), the basic conclusions for the $i_{13/2}$ band in ^{183}Tl are not affected by the uncertainty for the decay out of the band. Possibly, the band in ^{183}Tl decays via α emission to a deformed $13/2^+$ state in the daughter nucleus ^{179}Au; this possibilty is presently under investigation.

From the bandhead systematics, it appears that the prolate minimum in ^{183}Tl drops significantly (by at least 180 keV) compared to ^{185}Tl and minimizes below midshell ($N \leq 102$). This is in contrast to the trend observed for the prolate structures of the neighboring Hg and Pb nuclei at midshell — even though all prolate shapes under consideration are calculated to have a similar elongation and are more deformed than the lower-lying oblate or spherical structures. It is obvious that the odd ($i_{13/2}$) proton has considerable impact on the formation of this ($\beta_2 \sim 0.25$) prolate minimum and, perhaps, it polarizes somewhat the quadrupole core.

4. Conclusions

Experimental studies of SD bands in the mass 190 region have been discussed with emphasis on recent results for Tl nuclei. Detailed spectroscopy in the second well of ^{191}Tl has led to a precise measurement of the quadrupole moment. This result is an important addition to recent DSAM measurements in a series of Hg (and Pb) nuclei. It strongly supports the picture that the SD shape in the mass 190 region is very stiff with respect to proton number, neutron number, and orbital occupation. The magnetic properties for the signature partner SD bands in ^{191}Tl have been measured as well, requiring an $i_{13/2}$ ($\Omega = 5/2$) configuration assignment for these bands. Since the same conclusion has been reached earlier for the yrast SD bands in ^{193,195}Tl, a consistent picture for proton excitations from the center of the mass 190 island to its edges evolves. At normal prolate deformation, the $i_{13/2}$ ($\Omega = 1/2$) intruder state plays a prominent role in the mass 180 to 190 Tl isotopes. The yrast sequence in ^{183}Tl has been studied for the first time and a rotational-like cascade down to the bandhead with spin $13/2^+$ is observed. Because of its "unusual" decay-out features, this cascade represents an extreme case of prolate-oblate shape competition. It seems that the proton $i_{13/2}$ ($\Omega = 1/2$) orbital has a real influence on the normal prolate deformation in this region. In contrast, the $i_{13/2}$ ($\Omega = 5/2$) orbital does not influence much the size of the superdeformation.

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