Intrinsic proton states around the superdeformed shell closure $Z=80$

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High spin states in ^{193}Tl have been populated by the ^{181}Ta(^{16}O, 6n) reaction at 110 MeV and γ-ray spectroscopy was performed using the EUROGAM II array. In addition to the two known superdeformed (SD) bands, three new superdeformed bands have been identified. The dynamic moments of inertia of two of these new bands display a sudden and opposite change of slope and two of them have identical transition energies within 2 keV. The behavior of their dynamic moments of inertia and their γ transitions allowed us to propose configurations for the proton orbitals involved around the SD shell closure $Z=80$. The intrinsic proton states identified are the two signature partners of the [411]1/2 and the negative signature of the [651]1/2 orbitals. Their properties are compared to the predictions of two theoretical calculations. [S0556-2813(98)04312-X]

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I. INTRODUCTION

An impressive experimental and theoretical effort has been devoted to determine the intrinsic states on which superdeformed (SD) rotational bands are built. For example, in the mass 190 region, the study of several odd-neutron SD nuclei has revealed many excited SD bands which have been interpreted in terms of individual excitations of the valence neutron around the Fermi surface. Thus, the characteristics of the intrinsic neutron states around the SD shell closure at $N=112$ have been experimentally well determined. In ^{191}Hg [1], ^{193}Hg [2], ^{193}Pb [3,4], and ^{195}Pb [5] SD nuclei, the blocking effect of the neutron intruder $N=7$ orbital has been established, causing a flattening of the $\mathfrak{J}^{(2)}$ dynamic moment of inertia of SD bands. Furthermore, from the observation of cross-talk $M1$ transitions between SD bands in ^{193}Hg [6] and ^{193}Pb [4], it has been possible to extract the experimental value of the g_K factor of the single neutron and, by comparison to theoretical calculations [7], the occupancy of the two strongly coupled neutron orbitals [512]5/2 and [624]9/2 has been clearly shown. All these results have provided satisfactory knowledge of intrinsic neutron states in SD nuclei of the mass 190 region, and have brought relevant information to different theoretical models which reproduce the sequence of neutron states very well. However, the sequence of proton states around the SD shell closure at $Z=80$ remains experimentally unknown. From previous studies of odd-proton Tl isotopes, the proton intruder [642]5/2 orbital has been proposed as the lowest excitation above $Z=80$ shell closure [8–11]. This assignment was found to be in agreement with most theoretical calculations [12–14]. Recently, in the ^{193}Tl SD nucleus, the magnetic dipole character of transitions linking the two known signature-partner SD bands (bands 1 and 2) has been established and the experimental value of their g_K factor has been found to be consistent with the proton intruder configuration [642]5/2 [15]. Beyond this intruder orbital, the sequence of the quasiproton orbitals given by different theoretical calculations has never been experimentally identified. In this paper, we report on the observation of three new SD bands in ^{193}Tl. From the behavior of both the $\mathfrak{J}^{(2)}$ moments and the γ transition energies, these bands are interpreted as due to quasiparticle excitations involving the [411]1/2 and [651]1/2 proton orbitals.

II. EXPERIMENTAL PROCEDURE

The nucleus ^{193}Tl has been populated at high spin by the ^{181}Ta(^{16}O, 6n) reaction at a beam energy of 110 MeV. The beam was provided by the Vivitron tandem accelerator at IReS Strasbourg. The target consisted of two stacked 250μg cm^{-2} self-supporting foils of ^{181}Ta. Here γ rays were detected with the multidetector EUROGAM II [16], which comprised 54 Compton-suppressed Ge detectors consisting of 30 large volume Ge detectors at backward and forward angles and 24 ‘‘clovers’’ located around 90° with respect to the beam axis. Approximately 0.8×10^9 γ-ray co-

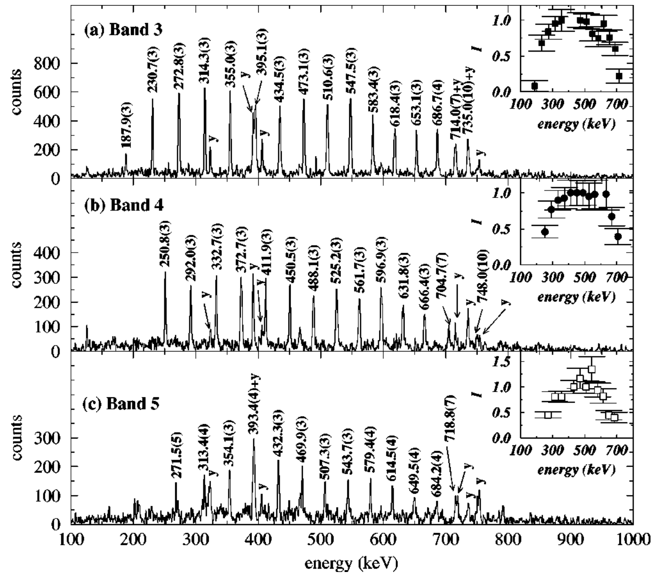

FIG. 1. Spectra of γ rays in coincidence with combinations of three γ rays in (a) band 3, (b) band 4, and (c) band 5 of the superdeformed ^{193}Tl nucleus. The γ transitions connecting low-lying normal deformed states are labeled by the symbol ''y.''

incidence events, in which at least five unsuppressed Ge detectors had fired, were recorded to tape. The search for excited SD bands has been performed by the analysis of spectra from γ-γ matrices as well as multigated spectra.

III. ANALYSIS AND RESULTS

In addition to the two known yrast SD bands [8,15], three new rotational bands have been observed with γ-ray spacings characteristic of superdeformation in this mass region. Sums of triple gated coincidence spectra on the γ-ray transitions of the three new excited SD bands, labeled 3, 4, and 5, are shown in Fig. 1. The assignment of the three new bands to ^{193}Tl was based on the observation of γ rays connecting yrast normal deformed (ND) states in ^{193}Tl [17] in coincidence with the γ sequences of the SD bands (see Fig. 1). The relative intensity of bands 3, 4, and 5, with respect to band 2 (the strongest SD band in this nucleus), is measured to be 60%, 33%, and 16%, respectively.

In Fig. 2, spectra of bands 3 and 4 are displayed in a range of energy between 600 keV and 800 keV. In these figures, one can notice that the spacing between the three highest transitions of band 3 is diminishing while the one between the three highest transitions of band 4 is increasing. The energies of the two highest transitions of band 3, 714.0 keV and 735.0 keV, are very close to the known yrast transitions 716.0 keV ($13/2^- \rightarrow 9/2^-$) and 735.5 keV ($13/2^+ \rightarrow 11/2^-$) in ^{193}Tl [17]. As a consequence, the 715.0 keV and 735.0 keV lines in Fig. 2(a) exhibit different shapes and widths than other neighboring γ lines. In order to firmly establish the doublet structure of these two lines in the spectrum of Fig. 2(a), a spectrum obtained by requiring triple gates including the 716.0 keV transition and any two other transitions from band 3 is shown in Fig. 2(d). The presence of the 716.0 keV γ line in this spectrum can be taken as evidence of its double components. It is worth noting that in a multigated coincidence spectrum where a gate on a noncomposite line is always required, the γ transition used as a gate should be missing, as does the 686.7 keV line in Fig. 2(c). A similar procedure has been used in order to establish the double components of the peaks around 735.0 keV in band 3. Furthermore, using a Gaussian deconvolution, it has been possible to separate the SD components from the known yrast transitions of the two γ lines around 716.0 keV and 735.0 keV and determine the energy of the two highest transitions of band 3.

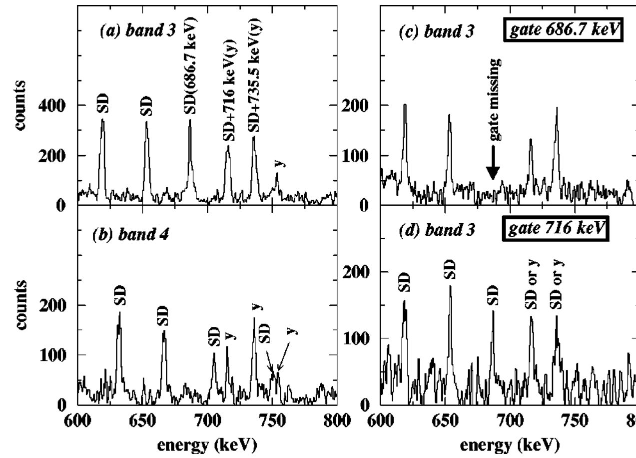

FIG. 2. (a) High energy part of the triple gated coincidence spectrum on the γ-ray transitions of band 3 (excluding the 714.0 keV and 735.0 keV transitions). (b) High energy part of the triple gated coincidence spectrum on all the γ-ray transitions of band 4. (c) High energy part of the spectrum of γ rays in coincidence with combinations of the 686.7 keV transition and two other transitions of the SD band 3. The arrow indicates the missing 686.7 keV transition used as a gate. (d) Spectrum of γ rays in coincidence with combinations of the 716.0 keV transition and two other transitions of the SD band 3 (excluding the 735.0 keV transition). Transitions of SD bands in spectra (a), (b), and (d) are labeled by ''SD'' and the ones connecting low-lying normal deformed states are labeled by ''y.''

The $\mathfrak{I}^{(2)}$ dynamic moments of inertia of the three new SD bands in ^{193}Tl are shown in Fig. 3(a), as a function of the rotational frequency $\hbar\omega$. Up to $\hbar\omega \sim 0.35$ MeV, they behave as the majority of SD bands in the mass 190 region and their smooth increase is similar to the one of the yrast SD band of ^{194}Pb. Above $\hbar\omega \sim 0.35$ MeV, the $\mathfrak{I}^{(2)}$ moment of band 5 continues to increase smoothly; however, those of bands 3 and 4 display a sudden and opposite change of slope. Indeed, the $\mathfrak{I}^{(2)}$ moment of band 3 displays a large increase of about $75\hbar^2$ MeV^{-1} while the $\mathfrak{I}^{(2)}$ moment of band 4 decreases by approximately $23\hbar^2$ MeV^{-1} as compared to the $\mathfrak{I}^{(2)}$ moment of the unperturbed band 5, at the same rotational frequency. This is interpreted as being due to interactions between the SD states in band 3 and band 4. In order to determine the crossing frequency accurately, we have plotted the alignment of bands 3, 4, and 5 with respect to both the yrast SD band of ^{192}Hg [18] and ^{194}Pb [19]. From these plots, shown in Figs. 3(b) and 3(c), one can draw the following conclusions: (i) The alignment of the three excited SD bands (3, 4, and 5) is more constant as a function of rotational frequency when the ^{194}Pb yrast SD band is taken as the reference. (ii) At the crossing frequency, $\hbar\omega_{\mathrm{expt}} = 0.36$ MeV, the relative alignment between the interacting orbitals is $i_{\mathrm{expt}} = (1.23 \pm 0.2)\hbar$.

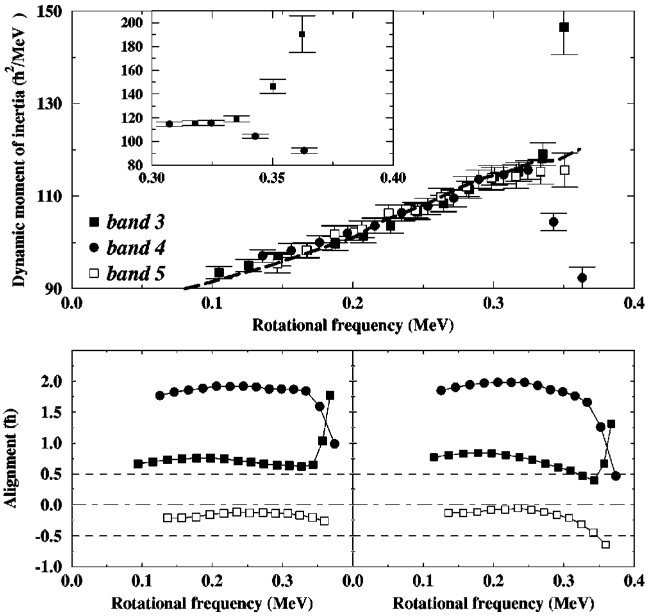

FIG. 3. (a) Dynamic moments of inertia $\Im^{(2)}$ as function of rotational frequency $\hbar\omega$ for band 3 (solid square), band 4 (solid circle), and band 5 (open square) in ^{193}Tl and the yrast SD band in ^{194}Pb (dashed line). (b) Experimental alignments for SD bands 3 (solid square), 4 (solid circle), and 5 (open square) in ^{193}Tl. The yrast SD band of ^{194}Pb is taken as the reference. (c) Experimental alignment for SD bands 3 (solid square), 4 (solid circle), and 5 (open square) in ^{193}Tl with the yrast SD band of ^{192}Hg taken as the reference.

From a simple two-level mixing scenario [20], one can extract the experimental value of the strength of this interaction, $|V|_{\rm expt}=(8\pm1)$ keV. This value corresponds to a weak interaction influencing only three transitions. This is in marked contrast to the strong interaction ($\sim$26 keV) observed for bands 1 and 4 in ^{193}Hg, which has a measurable effect over seven transitions [2,21].

The γ-ray energies of bands 3 and 5 are identical within 2 keV up to 450 keV (see Fig. 1). In the strong coupling limit of the particle-rotor model, this is expected to happen for two signature partners built on a $K=1/2$ orbital with a decoupling parameter $a=\pm1$ [22]. Moreover, the comparison of the γ-ray energies in the odd-A nucleus and in the even-even core determines the sign of the decoupling parameter (if they are as midpoint, it is negative [23]). For each pair of transition energies of bands 3 and 5, the values of the a decoupling parameter have been extracted. Up to $E_\gamma\approx450$ keV, where the transition energies of bands 3 and 5 are identical within 2 keV, the experimental decoupling parameter values were found to be roughly constant and equal to an average value of $a_{\rm expt}=-0.93\pm0.03$. Above $E_\gamma\approx450$ keV, the decoupling parameter is no longer constant. This seems to indicate that a Coriolis mixing with different effects on the two signature partners is taking place at the highest values of rotational frequency.

The experimental Routhians of the five SD bands of ^{193}Tl, where the yrast SD band of ^{194}Pb is taken as the reference, are shown in Fig. 4. They have been calculated using $(15/2)\hbar$, $(23/2)\hbar$, and $(21/2)\hbar$ as the spin values of the lowest level of bands 3, 4, and 5, respectively. Only such values give a sequence of the Routhians, at high rotational

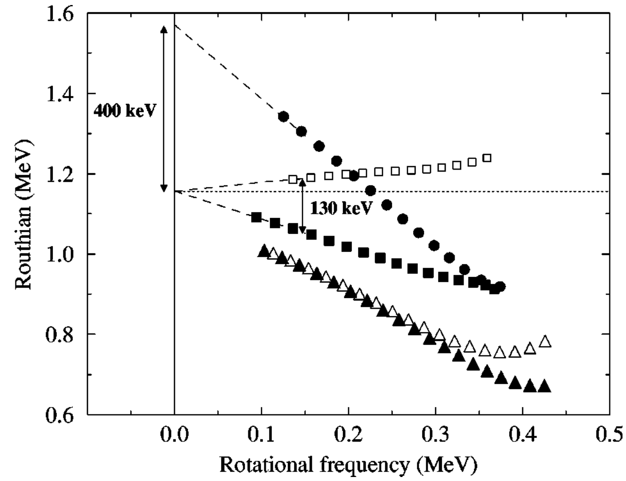

FIG. 4. Experimental Routhians of bands 3 (solid square), 4 (solid circle), and 5 (open square) in ^{193}Tl. Their relative positions are fixed (see text). Experimental Routhians of bands 1 (open triangle) and 2 (solid triangle) in ^{193}Tl for which the single proton is occupying the [642]5/2 intruder proton orbital [15]. Their positions, with respect to the Routhians of bands 3, 4, and 5, are arbitrary. Dashed lines represent their extrapolation back to zero frequency.

frequency, which is consistent with the measured relative intensities of the three SD bands. It is worth noting that the usual spin assignment procedure for the SD bands in this mass region is not suitable in our case mainly because of the nature of the orbitals involved [24]. The relative energies of bands 3 and 5 can be fixed, assuming that they are signature partners and, therefore, coincide at zero frequency whereas the relative energies of bands 3 and 4 are determined by the fact that they exhibit a crossing at $\hbar\omega_{\rm expt}=0.36$ MeV. A linear extrapolation of the experimental Routhians to zero frequency (see Fig. 4) suggests a 400 keV energy gap between the orbitals involved in these three new SD bands.

IV. DISCUSSION

These experimental results can be compared with the predictions of theoretical models in order to assign proton configurations and to evaluate the predictive power of some theoretical approaches already used with success to interpret the SD bands of odd-N nuclei in this mass region.

A. Cranked Woods-Saxon calculations

Theoretical Routhians for protons in the SD ^{193}Tl nucleus obtained with a cranked Strutinsky-Lipkin-Nogami approach, using a Woods-Saxon potential and a quadrupole pairing term [25], are shown in Fig. 5. The two lowest candidates for band crossings are at $\hbar\omega=0.3$ MeV and $\hbar\omega=0.4$ MeV, respectively. The first one involves the two negative signatures of the [770]1/2 and [514]9/2 orbitals and the second the two negative signatures of the [411]1/2 and [651]1/2 orbitals. The first interaction can be ruled out because, if one of the two interacting bands (3 or 4) was built on the [514]9/2 strongly coupled proton orbital, one should observe, at low frequency, cross talk between this band and its signature partner. Indeed, the $M1/E2$ competition for the [514]9/2 orbital is expected (due to the large g_K factor of this orbital [7]) to be even stronger than the one observed in

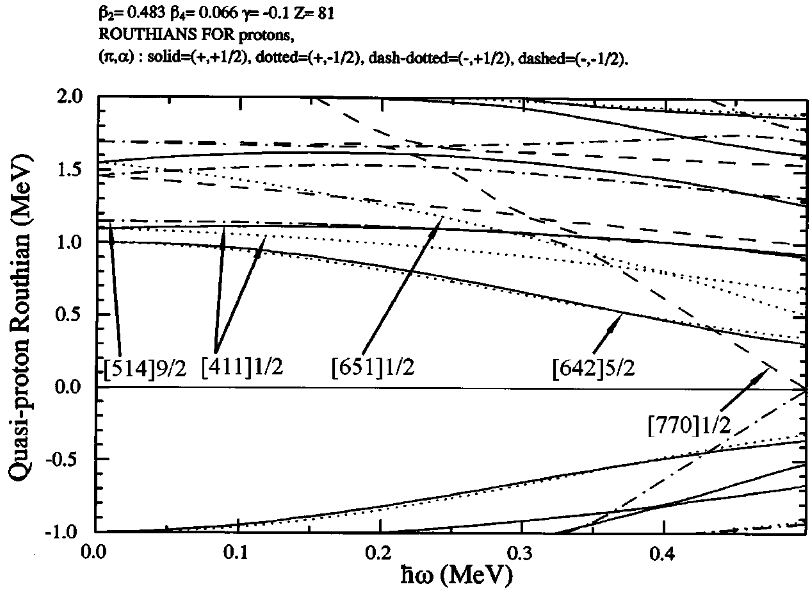

FIG. 5. Theoretical Routhians for protons in the SD ^{193}Tl nucleus. They are obtained by a cranked Strutinsky-Lipkin-Nogami approach, using a Woods-Saxon potential with a quadrupole pairing term [25].

the same experiment between bands 1 and 2 associated with the [642]5/2 state [15]. In the spectra of bands 3 and 4, there is no evidence of such $M1$ transitions (see Fig. 1).

Taking into account their relative intensity observed at high rotational frequency, bands 3 and 4 are thus interpreted, respectively, as the negative signature of the [651]1/2 and [411]1/2 proton orbitals. One may extract the interaction strength between these orbitals from the calculated Routhians. The obtained value, $|V|_{\mathrm{theory}}=7.5$ keV, is in nice agreement with the experimental one, $|V|_{\mathrm{expt}}=(8\pm1)$ keV. In addition, the relative energy of the two orbitals ([411]1/2 and [651]1/2) at zero frequency is 450 keV (see Fig. 5) which is in agreement with the one determined from the linear extrapolation of experimental results (see Fig. 4). From the experimental Routhians of bands 3 and 5, a signature splitting of 130 keV can be estimated at $\hbar\omega \sim 0.15$ MeV (see Fig. 4). This value is also in striking agreement with the theoretical value of 100 keV estimated at the same rotational frequency for the [411]1/2 orbital (see Fig. 5). Thus, having in mind that band 3 is built, at low rotational frequency, on the negative signature of the [411]1/2, band 5 has been interpreted as the positive signature of this same orbital.

B. Hartree-Fock-Bogoliubov calculations

The quasi-particle (qp) Routhians obtained from the self-consistent Hartree-Fock-Bogoliubov (HFB) method with the Lipkin-Nogami prescription, Skyrme interaction, and a density-dependent zero-range pairing interaction have been presented for several even-even Hg and Pb isotopes in Ref. [26] and for some odd-N isotopes in Ref. [27]. To go further in the analysis, self-consistent calculations of the ^{193}Tl bands have been performed with two different Skyrme parametrizations: the same Skm* Skyrme parametrization as in Ref. [26] and the more recent one SLy4 [28]. This new interaction has been shown to reproduce dynamic moments of inertia in this mass region with very good accuracy [29]. Six excited bands based on the [411]1/2, [651]1/2, and [514]9/2 proton orbitals have been investigated. At a rotational frequency of 0.3 MeV, the band based on the negative signature of the [651]1/2 orbital is excited by only a few hundred keV with respect to the yrast SD band (bands 1 and 2); three other bands (the positive signature of the [651]1/2 orbital and the two signatures of [411]1/2 orbital) lie all around 1 MeV above the yrast SD band. The [514]9/2 bands, being the most excited, have been disregarded here. Many features support the same configuration assignments as performed on the basis of the Strutinsky method, discussed in the previous paragraph. Whereas, the γ-ray energies calculated for the positive signature band based on the [651]1/2 orbital do not agree with the experimental ones, the ones obtained for the three others ([411]1/2, $\alpha=\pm1/2$ and [651]1/2, $\alpha=-1/2$) agree within a few keV with bands 3, 4, and 5. Moreover, the spin values obtained in this Skyrme HFB calculation, for the lowest states observed in the bands, are exactly the same as those deduced experimentally (see Sec. III). The main discrepancy between the Skyrme calculations and the data is the absence of an interaction between the negative signature of the [411]1/2 and the [651]1/2 orbitals which is proposed to correspond to the observed crossing between bands 3 and 4. Nevertheless, the theoretical dynamic moments of inertia agree with the experiment at low spins (see Fig. 6). The absence of an interaction may be related either to a slightly too large separation between the [651]1/2 and [411]1/2 proton orbitals or to a residual interaction beyond a mean-field approach between bands having the same symmetry. The vacua on which the 1qp bands of ^{193}Tl are constructed are determined fully self-consistently and result directly from the variational calculation. It is interesting to note that these vacua are always very close to ^{194}Pb for bands 3 and 5, which is in agreement with the experimental analysis of the alignments. On the other hand, the vacuum on which band 4 is constructed is always close to ^{192}Hg, which is not clearly reproduced by the data [see Figs. 3(b) and 3(c)].

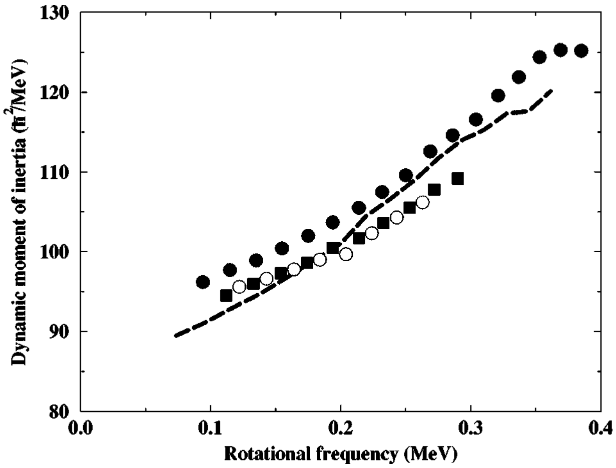

FIG. 6. Theoretical dynamic moment of inertia, as a function of rotational frequency, for the [411]1/2, $\alpha=-1/2$ (band 3) (solid square), [411]1/2, $\alpha=+1/2$ (band 5) (open circle), and [651]1/2, $\alpha=-1/2$ (band 4) (solid circle) orbitals. They are obtained with the self-consistent Hartree-Fock-Bogoliubov (HFB) method with the Lipkin-Nogami prescription, SLy4 interaction, and a density-dependent zero-range pairing interaction. The dashed line represents the experimental dynamic moment of inertia of the yrast SD band in ^{194}Pb.

C. Decoupling parameter

Within the pseudospin scheme [30], the [411]1/2 orbital can be viewed as the $[\tilde{3}\tilde{1}\tilde{0}]1/2$ state leading to a decoupling parameter $a=(-1)^{\tilde{N}}\delta_{\tilde{\Lambda}0}=-1$. This expectation has been confirmed to first order by experimental data at normal deformation where the decoupling parameter of the [411]1/2 orbital was found to be of the order of -0.75 [22]. The decoupling parameter can be calculated from the wave functions of the [411]1/2 proton orbital obtained in the Woods-Saxon potential. The pure single-particle value obtained in this manner corresponds to a value of $a_{\mathrm{theory}}=-0.48$ which is approximately half the experimentally extracted value ($a_{\mathrm{expt}}=-0.93\pm0.03$). This result is somewhat surprising, since we expect the Woods-Saxon wave functions to give a more realistic description than the simple estimate from the pseudospin scheme. In a microscopic model, the near degeneracy of the two signature partner orbitals results from the difference in the effective alignment of the two configurations as a whole. The disagreement between the single-particle expectation value of the decoupling parameter and the experimental value indicates that part of the difference in alignment stems from the dynamical contribution of the system as a whole and that the result from the pseudospin scheme can be considered to be rather fortuitious. These dynamical effects are included in the Skyrme HFB calculations. The decoupling parameter for the three and first γ transitions of the theoretical bands 3 and 5 is -0.96 and does not vary much as a function of the rotational frequency. The fact that it is closer to -1 at the top of the bands than suggested by the experimental data is probably due to the absence of an interaction between bands 3 and 4 in the calculation.

One should note that while bands 3 and 5 behave as ($K=1/2$, $a\sim-1$) signature partners, their transition energies significantly deviate from the midpoint values of the transition energies of the ^{194}Pb yrast SD band. This is illustrated in Fig. 5 where the Routhians of bands 3 and 5 do not exhibit the expected $\pm1/2$ slope. This seems to indicate that the yrast SD band of ^{194}Pb cannot be considered as the effective core of bands 3 and 5 even if from the alignments of Figs. 3(b) and 3(c) ^{194}Pb seems to be a better core than ^{192}Hg for the configurations involved in the excited ^{193}Tl SD bands. Consequently this demonstrates the polarization effect of the [411]1/2 occupancy on the collective rotation of ^{193}Tl.

V. SUMMARY AND CONCLUSION

To summarize, in addition to the two known SD bands, three new SD bands have been identified in ^{193}Tl. All these bands have been interpreted as due to excitations of a single proton around the $Z=80$ SD shell closure. The interaction observed between bands 3 and 4 and the identical energies of transitions in bands 3 and 5 allowed their assignment to proton excitations, involving the [411]1/2, $\alpha=\pm1/2$ and [651]1/2, $\alpha=-1/2$ orbitals. Comparison with two theoretical calculations strongly supports this interpretation.

Despite the general agreement between the experimental results and the theoretical calculations, some specific disagreements concerning the negative parity proton orbitals remain. It is, for instance, not satisfactory that no other excited SD bands could be seen in ^{193}Tl, while the theoretical Routhians indicate fairly low excitation energies for the [770]1/2 and [514]9/2 proton orbitals. The lack of observation of negative parity orbitals can be used as an important guideline to better understand the single-particle structure and residual interactions at superdeformed shapes.

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