Z. Phys. A 359, 127–132 (1997)

ZEITSCHRIFT FÜR PHYSIK A
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Loss of alignment gain in the $\pi h_{9/2}[541\ 1/2^-] \otimes (\nu i_{13/2})^2$ band in ^{167}Tm and neighbouring odd-Z N = 98 nuclei

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Received: 7 April 1997
Communicated by B. Herskind

Abstract. The πh$_{9/2}$[541 $1/2^-$] band in ^{167}Tm has been studied through the ^{124}Sn(^{48}Ca$, p4n)^{167}$Tm reaction at E_{beam} = 210 MeV. The favoured signature of the πh$_{9/2}$[541 $1/2^-$] band is observed to spin $61/2\hbar$. A remarkable small gain in aligned angular momentum at the AB-band crossing has been found. The crossing frequency and the gain in aligned angular momentum for ^{167}Tm are compared with data for the N = 98 isotones of Lu, Ta and Re, and contrasted with Cranked Shell Model predictions, based on frequency diabatic configurations. Large deviations are found for the gain in aligned angular momentum.

PACS: 21.10.-k; 21.60.-n; 27.70.+q

1 Introduction

In several odd-Z rare-earth nuclei, with proton numbers between 67 and $\sim$ 75, the πh$_{9/2}$[541 $1/2^-$] Nilsson configuration with α = +1/2 exhibits some anomalous features concerning the crossing frequency, $\hbar\omega_c$, the gain in aligned angular momentum, Δi_x, and the interaction strength at the crossing with the S-band, in which the first pair of $i_{13/2}$ quasineutrons has aligned. While most rotational bands in odd-Z nuclei have crossing features very similar to the corresponding crossing in the even-even neighbours, the crossing in the πh$_{9/2}$[541 $1/2^-$] band is shifted to higher frequencies, with a smaller gain in aligned angular momentum and a larger interaction strength [1-4]. Here we report an exception at N = 98, where the systematic trend for the πh$_{9/2}$[541 $1/2^-$] bands is broken. The Lu, Ta and Re isotones show not a large, but a small shift in the crossing frequency, and depending on Z, a significantly reduced gain in aligned angular momentum. In order to study this new observation at N = 98, we have extended the systematics with a study of ^{167}Tm.

The Cranked Shell Model (CSM) is known to be a rather successful tool for describing the experimental alignment pattern observed for rotational band structures [5-7]. However, this mean field approach seems in general to fail when applied to band structures built on intruder configurations like πh$_{9/2}$[541 $1/2^-$] and $\pi i_{13/2}$[660 $1/2^+$]. In the present paper we introduce a new and improved approach, based on the CSM and frequency diabatic configurations, for calculating both the crossing frequency, $\hbar\omega_c$, and the gain in aligned angular momentum, Δi_x. For the first time a systematic comparison between predictions and data for the N = 98 isotones of Tm, Lu, Ta and Re is presented.

2 Experimental procedure and results

High spin states of ^{167}Tm have been studied at the Nuclear Structure Facility, Daresbury Laboratory, using the EUROGAM array [8-10] consisting of 45 large Compton suppressed Ge detectors. ^{167}Tm was produced in the reaction ^{124}Sn(^{48}Ca$, p4n)^{167}$Tm at a beam energy of 210 MeV. The target consisted of two unbacked stacked ^{124}Sn foils each of thickness 0.5 mg/cm^2. Approximately $8 \cdot 10^8$ coincidence events of suppressed fold $\geq$ 3 were recorded in total. The cross section for the $p4n$ reaction channel leading to ^{167}Tm was less than 1.0% of the total fusion cross section, corresponding to $\approx 5 \cdot 10^6$ events.

The data were gain- matched and sorted into 2D and 3D matrices, using the sorting program “JUGGLER” [11]. Energy dependent time gates on the Ge time signals were used to reduce neutron induced events. Analysis of the matrices was done by means of programs from the RADWARE package [12].

With many open reaction channels it was practically impossible to find any clean single gates on transitions belonging to ^{167}Tm in a 2D matrix, whereas most of the double gates in the 3D matrix, on transitions belonging to the favoured signature of the πh$_{9/2}$[541 $1/2^-$] band gave a clean spectrum. The number of counts in the double gates is low, but the

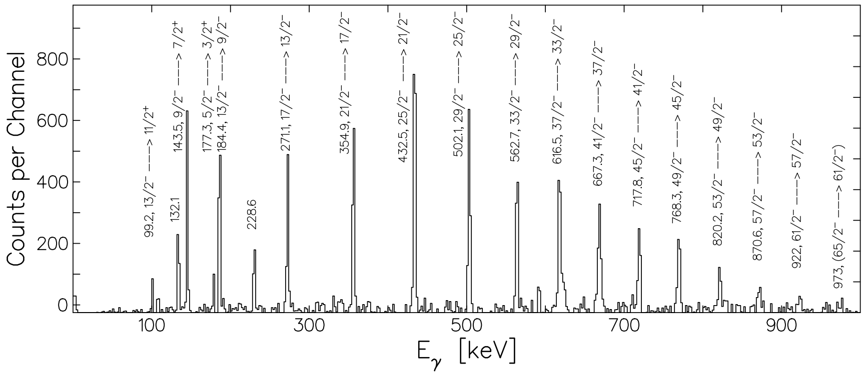

Fig. 1. Sum of 15 double gates on transitions depopulating levels of the positive signature of the $\pi h_{9/2}[541\ 1/2^-]$ band in ^{167}Tm

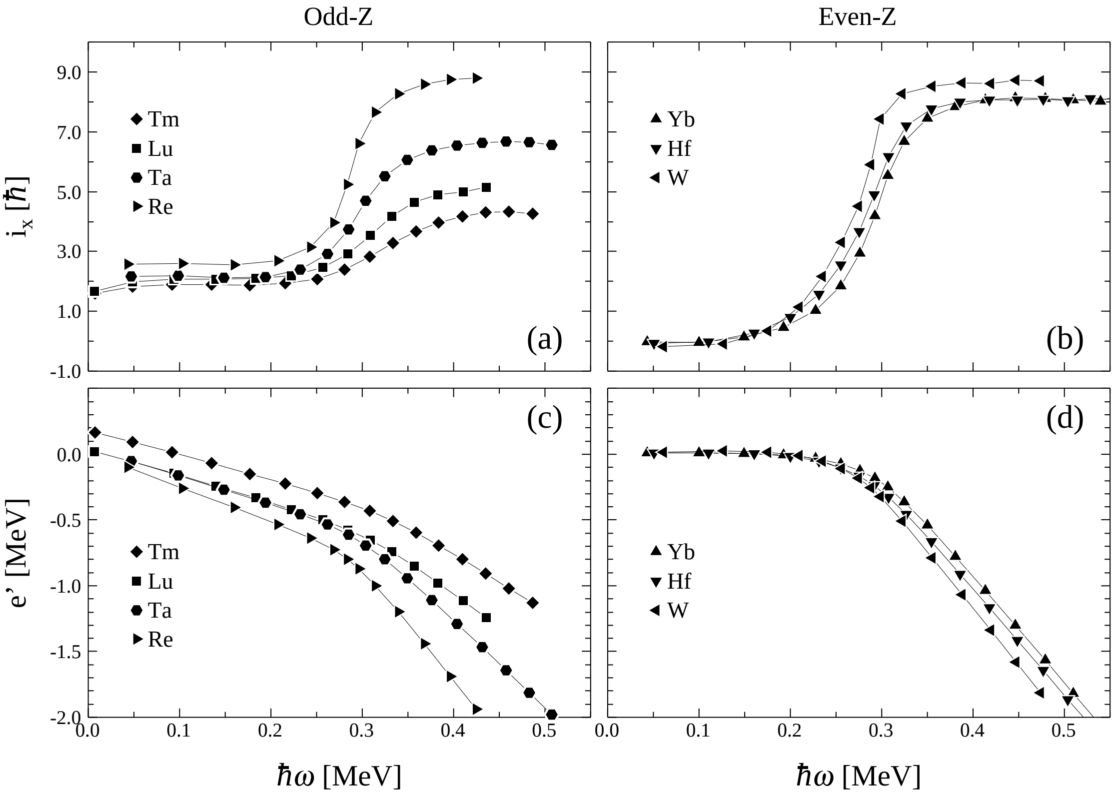

Fig. 2. Illustrative plots of experimental alignments (*top*) and routhians (*bottom*) plots for the $\pi h_{9/2}[541\ 1/2^-]$ band in the N = 98 isotones of Tm, Lu, Ta and Re, and for the (0,+) yrast configuration in the intermediate even-even nuclei. Data are shown relative to a reference configuration with a moment of inertia, $\mathcal{J}^{(2)}$, parameterized by a different set of Harris [14] parameters ($\mathcal{J}_0$, $\mathcal{J}_1$) in each case. Data for Z = 70, 71, …, 75 are from [15,4,16-19]

background is considerably reduced. The favoured signature partner was extended from spin $33/2^-$ to $61/2^-$ (tentatively $65/2^-$). Figure 1 shows the background corrected sum of the 15 strongest and most clean double gates on transitions depopulating levels of the favoured signature of the $\pi h_{9/2}[541\ 1/2^-]$ band. All established transitions in the band, including the E_γ = 922 keV, $61/2^- \rightarrow 57/2^-$ transition (and tentatively the 973 keV, $65/2^- \rightarrow 61/2^-$ transition), are clearly seen. The lower part of the $\pi d_{3/2}[411\ 1/2^+]$ band is also seen [13]. This includes the 132.1 and 228.6 keV transitions from states populated by the three cross-band E1- transitions of 99.2, 143.5 and 177.3 keV. Energies for the assigned transitions are indicated in Fig. 1.

With the present data, it was not possible to add new transitions to the unfavoured signature of the $\pi h_{9/2}[541\ 1/2^-]$ band. This is presumably due to the large signature splitting $\Delta e'$, (e.g. $\Delta e'$ = 480 keV at $\hbar\omega$ = 200 keV) resulting in a weak population. Olbrich et al. [13] observed a 20-30 times weaker population of the unfavoured signature at low spins. None of the other 16 known bands [13] in ^{167}Tm could be extended, presumably also due to the low population within the weakly populated reaction channel.

The routhians, e', and aligned angular momenta, i_x, for the favoured $\pi h_{9/2}[541\ 1/2^-]$ band in ^{167}Tm are shown in Fig. 2a,c together with corresponding data for the N = 98 isotones of Lu, Ta and Re. Values of e' and i_x for the yrast band of the intermediate even-even isotones Yb, Hf and W are shown in Fig. 2b,d. All these N = 98 nuclei show the characteristic features of a band crossing with a large interaction, and also a distinct difference in alignment gain, Δi_x, between the

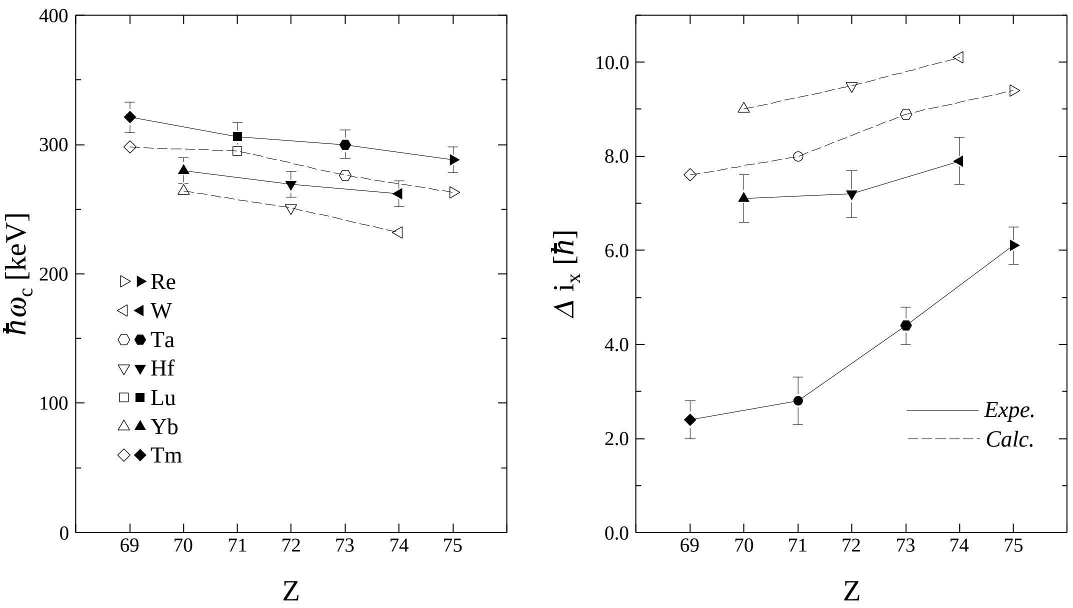

Fig. 3. Experimental (*filled symbols*) and calculated (*open symbols*) values of $\hbar\omega_c$ (left) and Δi_x (right) for the $\pi h_{9/2}[541\ 1/2^-]$ - and the (0,+) yrast band in the N = 98 isotones of Tm through Re

even-even core-nuclei and the odd-Z isotones with a quasiproton occupying the $h_{9/2}[541\ 1/2^-]$ orbital. This difference is strongly increasing with decreasing Z.

Values of the crossing frequency, $\hbar\omega_c$, and alignment gain, Δi_x, are extracted for the N = 98 isotones and presented in Fig. 3. In the determination of $\hbar\omega_c$, and Δi_x, for crossings with large interactions, special precautions must be taken [5]. For all the bands presented in Fig. 3, the dynamic moment of inertia $\mathcal{J}^{(2)}$ has been inspected to ensure appropriate references which produce a constant value of i_x before the crossing and a linear relation between i_x and $\hbar\omega$ after the crossing. These are used for extracting $\hbar\omega_c$ from plots of routhians, and Δi_x from plots of i_x vs $\hbar\omega$. The procedure used for extracting Δi_x is illustrated in Fig. 4 for ^{167}Tm and ^{171}Ta. All data are treated in the same way, and the estimated errors shown in Fig. 3 include the ambiguity in the choice of references. A loss of alignment gain as a function of decreasing Z, and for ^{167}Tm almost a quenching, is clearly seen.

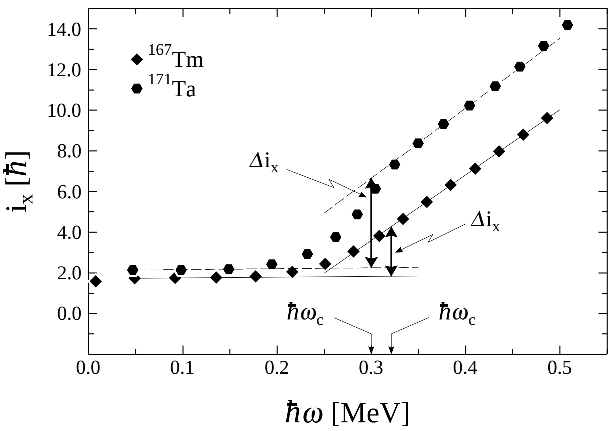

Fig. 4. Illustrative plot of the extraction of alignments for ^{167}Tm and ^{171}Ta. Harris parameters $(\mathcal{J}_0, \mathcal{J}_1)$ = $(46\hbar^2/MeV, 0\hbar^4/MeV^3)$ and $(\mathcal{J}_0, \mathcal{J}_1)$ = $(39\hbar^2/MeV, 0\hbar^4/MeV^3)$ have been used for ^{167}Tm and ^{171}Ta respectively

3 Calculations

In the CSM, the alignment pattern for the quasineutron pair is intimately related to both the neutron pairing gap, Δ_ν, and the position of the neutron Fermi level, λ_ν, relative to the $\nu i_{13/2}$ intruder shell. A configuration dependence for the alignment pattern in an odd-Z nucleus is consequently expected, if a difference in the pairing and/or the relative position of the Fermi level is caused by the occupation of different quasiproton configurations. Both Δ_ν and λ_ν depend on the shape parameters. For proton numbers below $Z \sim 75$, the $\pi h_{9/2}[541\ 1/2^-]$ configuration is expected to drive the nucleus towards larger prolate deformations (see Fig. 5a) and is therefore expected to influence $\hbar\omega_c$ and Δi_x. CSM calculations [5-7] using frequency adiabatic configurations based on both experimentally determined [2,4] and expected changes in equilibrium deformations [20] are able to explain a fraction varying from 20-60% of the observed shift in crossing frequency, in the cases where these shifts are large [1-4].

The major drawback of these calculations is that constant deformation parameters and pairing strength have been used. Furthermore most effort has been concentrated on the understanding of the crossing frequencies for specific nuclei, and only little attention has been paid to other observables. In addition systematic comparisons between data and predictions should be performed for all available data.

In a new and improved approach, using a new version [21] of the *Ultimate Cranker* [22], based on a modified oscillator potential with Nilsson parameters from [23], we have attempted to eliminate these problems by:

– Calculating frequency diabatic quasiparticle configurations for both the $\pi h_{9/2}[541\ 1/2^-]$ g- and S- configuration in

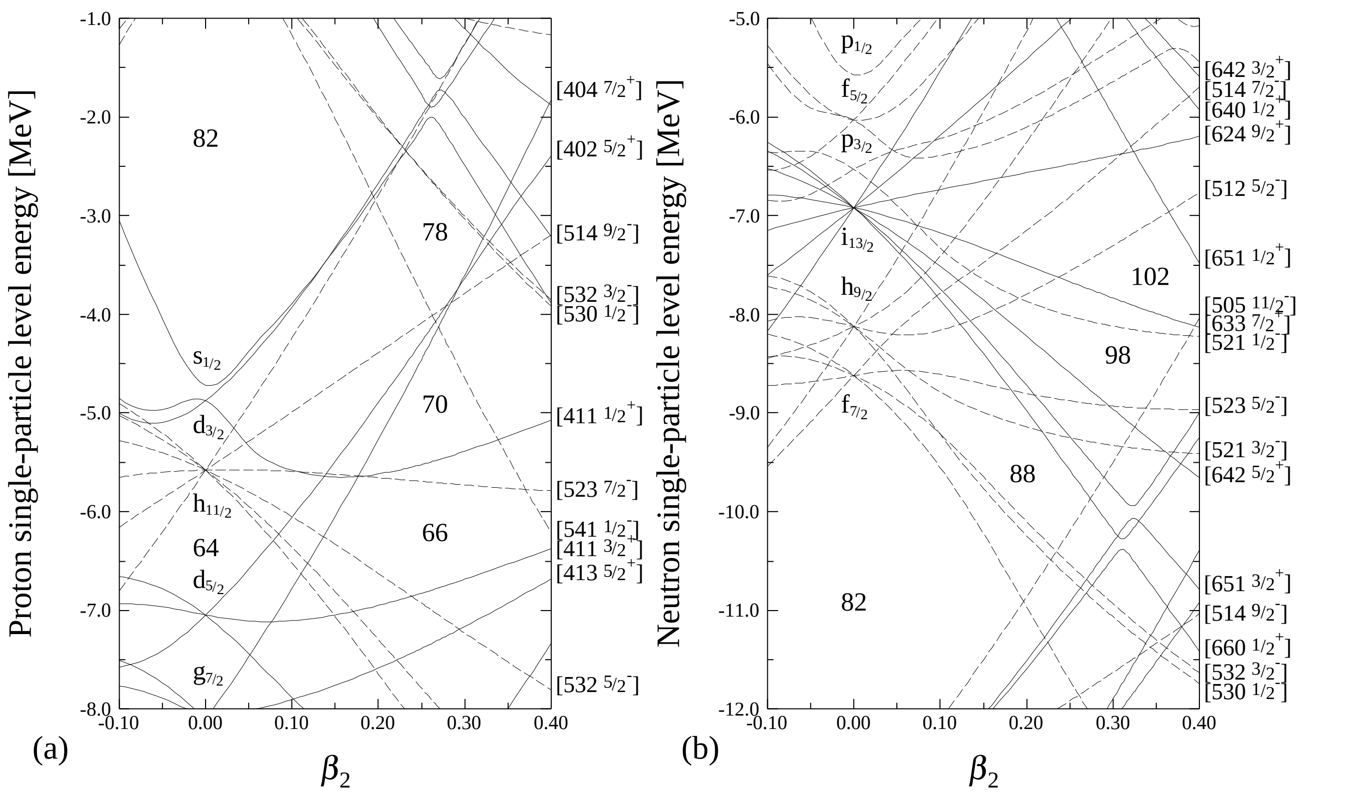

Fig. 5. Proton **a** and neutron **b** single-particle level energies versus quadrupole deformation β_2 (β_4 = 0.0, $\gamma = 0.0°$) calculated for Z = 70 and N = 98 using a Woods-Saxon potential. At β_2 = 0.0 the levels are labelled by the spherical quantum numbers l_j, while at large deformation the asymptotic Nilsson quantum numbers $[Nn_z\Lambda\ \Omega^\pi]$ are given for some configurations

odd-Z nuclei with N = 98 and the yrast (0,+) g- and S-configurations in the neighbouring even-even nuclei.

– Performing systematic particle-number projection and appropriate blocking.
– Applying frequency independent monopole pairing gaps at each $(\varepsilon_2, \varepsilon_4, \gamma)$ mesh point, expressed as a fraction of the BCS pairing gap at $\hbar\omega = 0$, for the proton one-quasiparticle configuration (Δ^g_π), the neutron zero-quasiparticle (Δ^g_ν) and the neutron two-quasiparticle configurations (Δ^S_ν):

$$\Delta^{g/S}_{\pi/\nu}(\varepsilon_2, \varepsilon_4, \gamma, \omega) = R^{g/S}_{\pi/\nu} \cdot \Delta^{BCS}_{\pi/\nu}(\varepsilon_2, \varepsilon_4, \gamma, \omega = 0)$$

Self-consistent calculations of the three pairing gaps, for a few nuclei at deformations which are appropriate at the band crossing, were used to determine an average set of reduction factors $R^{g/S}_{\pi/\nu}$ for all the nuclei studied.

– Calculating the corresponding spin diabatic quasiparticle configurations and diabatic energy surfaces (for a constant spin) for both the g- and S- configurations.
– Minimizing energy with respect to deformation parameters ε_2, ε_4 and γ as a function of rotational frequency for both the g- and S- configurations.

More details of the applied procedure can be found in ref. [24].

Predicted spins and excitation energies for the calculated spin diabatic rotational bands were used to extract values for $\hbar\omega_c$ and Δi_x, using the same procedure as for the experimental bands. Calculated values of $\hbar\omega_c$ and Δi_x for the ground bands of even-even nuclei, and $\pi h_{9/2}[541\ 1/2^-]$ bands of odd-Z nuclei, with N = 98, are compared with experimental values in Fig. 3.

4 Discussion

For both the odd-Z and even-even N = 98 nuclei, the Z-dependence of $\hbar\omega_c$ is well reproduced by the calculations, with the small, fairly constant difference of $\sim$ 20 keV between the experimental and calculated values amounting to a $\sim$ 6 % discrepancy. For Δi_x, the experimental Z-dependence is also well reproduced for the even-even N = 98 isotones, where the calculated values are systematically $\sim 2\hbar$ higher. In contrast, there is a wide discrepancy between the calculations and the data for the $\pi h_{9/2}[541\ 1/2^-]$ band. The discrepancy widens with decreasing Z, and is largest at the new data point for ^{167}Tm, where the experimental alignment gain is almost quenched. A strong influence of the occupation of a $\pi h_{9/2}[541\ 1/2^-]$ intruder orbital is demonstrated.

It should be stressed that the diabatic treatment of crossings could cause an overestimate of the calculated alignment gain in the case of strong interaction. A comparison of the present calculations with predictions based on a frequency adiabatic treatment of crossings gives an estimate of a possible systematic error of at most 1.0 $\hbar$. There is, on the other hand, no reason for this effect to be different for the even-even cases and the odd-Z nuclei with the proton $[541\ 1/2^-]$ configuration occupied.

The effect of occupying the $\pi h_{9/2}[541\ 1/2^-]$ orbital may be related to its excitation above the Fermi level. For the

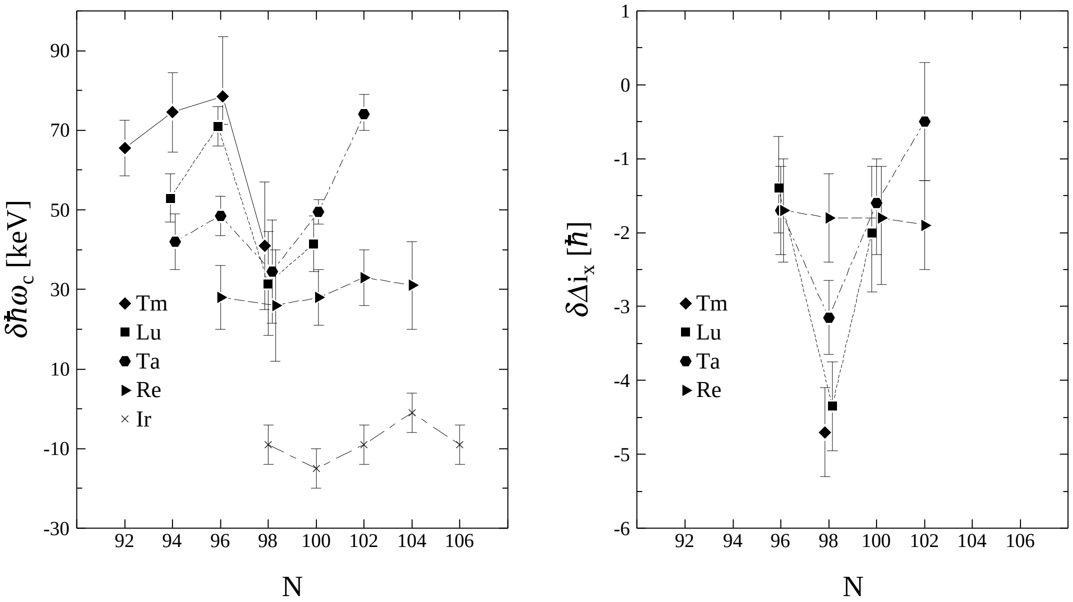

Fig. 6. Systematics of the experimental values of $\delta\hbar\omega_c$ (*left*) and $\delta\Delta i_x$ (*right*) for a number of odd-Z nuclei plotted as a function of neutron number N. Data for $^{160-164}$Er are from [25-27], $^{161-165}$Tm from [28,3,29], ^{167}Tm from the present work, $^{160-170}$Yb from [30-33,15,34], $^{165-171}$Lu from [35,1,4,36], $^{162-176}$Hf from [37-40,16,41-43], $^{167-177}$Ta from [44,45,17,46-48], $^{166-180}$W from [49-51,18,52,53], $^{171-181}$Re from [54,19,55-58], $^{172-182}$Os from [59-63], and $^{173-185}$Ir from [64-69]

N = 98 isotones of Re, Ta, Lu and Tm, the excitation energy of the $\pi h_{9/2}$[541 $1/2^-$] orbital varies from 0 to 170 keV, which is still a modest excitation, see Fig. 2c, and the band is in all cases yrast for $I \geq 13/2$. The alignment pattern for the $\pi h_{9/2}$[541 $1/2^-$] configuration is very similar to the alignment pattern for the (0,+) yrast band in the neighbouring even-even nuclei for nuclei with $Z > 75$, emphasizing the effect of the position of the Fermi level.

It should be noted that for bands built on other low lying quasiproton orbitals, like for example $h_{11/2}$[514 $9/2^-$] or $g_{7/2}$[404 $7/2^+$] in these N = 98 nuclei, both experiment and calculations show values of $\hbar\omega_c$, and Δi_x, which resemble the even-even neighbours. Therefore, the reduction in Δi_x at N = 98 is a unique feature of the $\pi h_{9/2}$[541 $1/2^-$] intruder orbital.

The crossing behaviour of the $\pi h_{9/2}$[541 $1/2^-$] intruder orbital is demonstrated in a broader context in Fig. 6, where the experimental crossing frequencies and alignment gain relative to the even-even neighbours, $\delta\hbar\omega_c$ and $\delta\Delta i_x$ respectively, are shown as a function of neutron number N for odd-Z nuclei with $69 \leq Z \leq 77$. There are much larger observed shifts in $\hbar\omega_c$ for nuclei with $Z \leq 73$ (Ta) and $N \neq 98$, than observed for the N = 98 isotones, which clearly represents a different physical situation. For the other observable, Δi_x, an almost opposite situation is observed, with the largest observed discrepancy between the odd-Z nuclei and the even-even neighbours found at N = 98.

Preliminary calculations for even-even nuclei with $68 \leq Z \leq 76$ and $94 \leq N \leq 102$ but with $N \neq 98$ give similar agreement with the data as the results at N = 98. In contrast, for the odd-Z nuclei with a quasiproton occupying the $h_{9/2}$[541 $1/2^-$] orbital, and $N \neq 98$, the dependence on N and Z is relatively well reproduced for Δi_x whereas rather large deviations are found for $\hbar\omega_c$. In these calculations [29] the shape changes between g- and S-band configurations are in general rather moderate. There is, in addition, a good agreement between the predicted shape parameters and measured values in the few cases where they are known. As for N = 98, the low-lying bands built on other quasiproton orbitals show crossing features that resemble the even-even neighbours e.g. very small shifts in both $\hbar\omega_c$ and Δi_x, in agreement with the calculated features.

5 Conclusion

New data for the $\pi h_{9/2}$[541 $1/2^-$] configuration have been presented here for ^{167}Tm together with data for the neighbouring N = 98 isotones, and the systematics of a broader range of odd-Z nuclei. It can be concluded that the behaviour at the $i_{13/2}$ neutron crossing in bands built on the $\pi h_{9/2}$[541 $1/2^-$] orbital cannot be explained by the presented improved CSM approach, including a diabatic treatment of crossings and a configuration dependence in both shape- and monopole pairing parameters. In this connection, the N = 98 isotones provide a unique situation. These nuclei have the largest interaction at the crossing. The observed small shifts in crossing frequency are explainable, in contrast to the severe reduction in alignment gain with decreasing Z, and almost a quenching for ^{167}Tm with Z = 69.

There is in the Nilsson diagram, Fig. 5b, of neutron single particle energies versus quadrupole deformation an energy gap at N = 98, which is reflected in the experimental ground state masses and binding energies. There is no reason for this gap to have a different effect on even-even and odd-Z neighbours with a quasiproton occupying the $h_{9/2}$[541 $1/2^-$] orbital. Neither is it expected to have a different effect on different rotational bands in the same nucleus. Other possible N = 98 effects could be a change in sign of the driving force towards a non-axial shape at the middle of the $i_{13/2}$ neutron sub-shell. Likewise, the expected hexadecapole deformation changes sign around N = 98 [20]. On the other hand, such effects are already included in the present calculations. Relatively small and smooth variations in the triaxiality parameter, γ, and in the hexadecapole deformation were found around N = 98.

One may therefore have to suggest explanations for the severe N = 98 discrepancies beyond the present mean field approach. One possibility is contributions from the higher-multipolarity part of the pairing interaction, e.g. the configuration dependent (quadrupole) pairing, which seems to have an effect on the description of, for example, the signature splitting and the crossing frequency for the $\pi h_{9/2}[541\ 1/2^-]$ band. This has been demonstrated by Sun et al. [70,71] for selected nuclei in the rare-earth region, using the *Projected Shell Model* [72-74]. So far it is an open question if the configuration dependent pairing is able to account for both the N- and Z-dependence of the discrepancies.

Another interesting possibility is residual proton-neutron (n-p) interactions, which are expected to influence the total energies and consequently also several spectroscopic properties. It has been made probable, in various investigations [75-79] using different models, that the n-p interaction can change the alignment processes and cause a shift in, for example, the crossing frequency.[1] The interaction is expected to be strongest when the protons and the aligning neutrons occupy the same (or very similar) high j orbitals. In addition there is a correlation to the filling of the proton- and neutron j shells. It is on the other hand hard to understand how this can account for the unique features observed for the N = 98 isotones, and especially the strong neutron number dependence around N = 98 presented in in Fig. 6.

This project was supported by the Danish Natural Science Foundation.

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[1] It should be emphasized that there are some severe disagreements between the predictions in the different approaches [77].