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Signature inversion in semi-decoupled bands: residual interaction between $h_{9/2}$ protons and $i_{13/2}$ neutrons

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Abstract

Semi-decoupled bands based on the $\pi h_{9/2} \otimes \nu i_{13/2}$ configuration are observed in ^{162}Tm,^{164}Tm and ^{174}Ta. Spins assigned to these bands imply an inversion of the expected signature splitting, which is interpreted as being the result of a residual proton-neutron interaction. © 1997 Elsevier Science B.V.

The Cranked Shell Model [1], has been successful in describing the crossing of the ground-state rotational band in even-even rare-earth nuclei by a band of aligned $i_{13/2}$ neutrons. However, in odd-Z nuclei, this crossing is delayed systematically to higher rotational frequencies, (ω_c), when the odd proton occupies the $\pi h_{9/2}(1/2^-[541])$ orbital [2]. This has lead to speculation that residual proton-neutron (p-n) interactions may play a role [3]. Of interest therefore, is the interaction between $i_{13/2}$ neutrons and $h_{9/2}$ protons. This can be studied in odd-odd nuclei, where one well known manifestation of p-n interactions are Gallagher-Moszkowski (GM) splittings [4]. Another observable is the signature splitting [1] Δe, corresponding to the difference in energy $e_{\alpha_u} - e_{\alpha_f}$ between routhians of states in a rotational band with signature α_f and α_u. The energetically favoured and unfavoured branches of a two-quasiparticle rotational band of an odd-odd nucleus are expected to have signatures, α_f and α_u, given by the proton and neutron angular momenta j_p and j_n:

$$\alpha_f = \tfrac{1}{2}\left[(-1)^{j_\text{p}-1/2} + (-1)^{j_\text{n}-1/2}\right];$$
$$\alpha_u = (\alpha_f + 1)\text{mod}2 \qquad (1)$$

In the $A = 130$ and 150 mass regions however, residual interactions have been invoked to explain the observation of rotational bands with α_u favoured in energy [5–7].

Here we present data on three nuclei: ^{162,164}Tm and ^{174}Ta. In each of these nuclei, both signatures of the band based on the $\pi h_{9/2} \otimes \nu i_{13/2}$ configuration, of-

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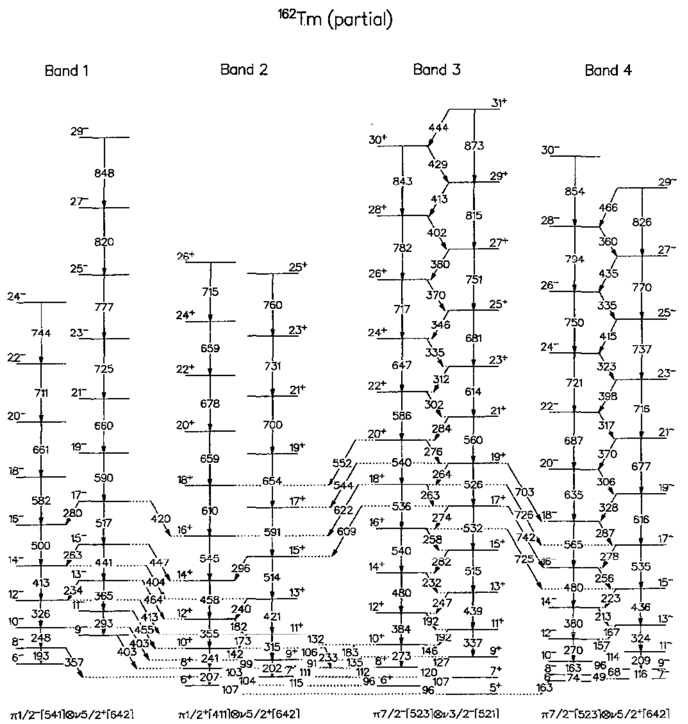

Fig. 1. Partial level scheme of ^{162}Tm, as deduced in the present work. Bands are labelled both numerically and according to their assigned configurations.

ten called semi-decoupled [8], are observed, (for the first time in the case of ^{162,164}Tm). The $\pi h_{9/2} \otimes \nu i_{13/2}$ band has been assigned in many nuclei of the rare-earth region, but firm spin assignments have not been reported. The present work implies new spin assignments which invert the expected signature splitting. It is shown that this is consistent with a residual p-n interaction.

The nuclei were populated in the reactions ^{160}Gd(^{19}F,5n)^{174}Ta, ^{150}Nd(^{19}F,5n)^{164}Tm and ^{130}Te (^{37}Cl,5n)^{162}Tm at 105, 85 and 166 MeV beam energy, respectively. A combination of experiments was performed, employing both thin ($\sim$ 1 mg/cm^2) and backed targets ($\sim$ 10 mg/cm^2 Au backings). The NORDBALL [9] array was equipped with either 20 HpGe detectors, or 18 HpGe and 2 LEP detectors, when unbacked or backed targets, respectively, were employed. Typically, 10^9 $\gamma - \gamma$ coincidences were obtained in each case. Further experimental details for the ^{174}Ta experiment are given in [10], and early results for ^{164}Tm are reported in [11].

Partial level schemes for the three nuclei are shown in Figs. 1 and 2. In Fig. 1, the yrast band, (Band 4), of ^{162}Tm, assigned previously [12–14] to the configuration $K^\pi = 6^-$; $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$, is shown. Its bandhead is depopulated by a transition of 163 keV, which Drissi et al [13] argued feeds a 24.3 s 5^+ isomer, known from β-decay [15]. In this work, the isomer was assigned to the configuration $K^\pi = 5^+$; $\pi 7/2^-[523] \otimes \nu 3/2^-[521]$. We have now observed the band based on this isomer, (Band 3), and tied it to Band 4 near spin $17\hbar$, with transitions of 703,726,742 and 725 keV. DCO ratios for these transitions are consistent with stretched dipole character.

Two near degeneracies between levels of Bands 2 and 3 occur near spins $8\hbar$ and $18\hbar$. The transitions linking the two bands near these spins indicate mixing and fix the spins and parity of Band 2. Band 2 is in turn linked to Band 1 by a series of transitions with energies of around 400 keV. DCO ratios obtained for a number of these transitions are consistent with stretched dipole character.

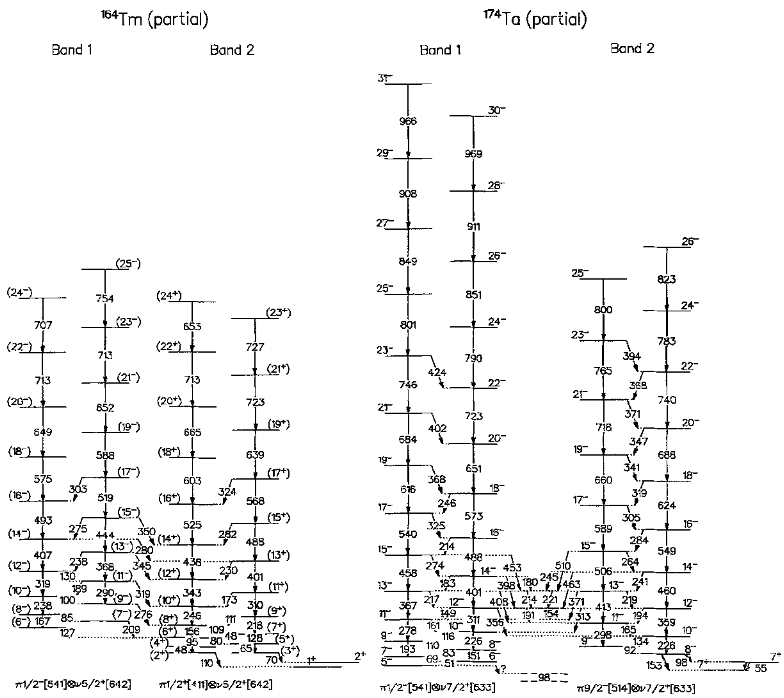

Fig. 2. Partial level schemes of ^{164}Tm and ^{174}Ta, as deduced in the present work.

Bands 1 and 2 have large signature splittings, requiring that both the odd proton and neutron reside in low-Ω orbitals or orbitals subject to strong Coriolis effects. The $\pi 1/2^-[541]$, $\pi 1/2^+[411]$ and $\nu 5/2^+[642]$ orbitals are the only orbitals near the fermi surface that satisfy these criteria. As Band 2 must have positive parity, (due to mixing with Band 3), it is assigned to the configuration $\pi 1/2^+[411] \otimes \nu 5/2^+[642]$. Band 1 must therefore have the configuration $\pi 1/2^-[541] \otimes \nu 5/2^+[642]$. Note that the favoured signature of Band 2 was assigned by Drissi et al. [13] to the $\pi 1/2^-[541] \otimes \nu 5/2^+[642]$ configuration. However, this is inconsistent with the present assignment of parity. With our assignments, the transitions linking Bands 1 and 2 are stretched E1 transitions, and the two bands resemble the $1/2^+[411]$ and $1/2^-[541]$ bands of the odd-proton neighbours, ^{163}Tm [16] and ^{165}Tm [17]. In these nuclei, the $1/2^+[411]$ and $1/2^-[541]$ bands are also linked by stretched E1 transitions. Enhanced electric dipole transitions between these bands are a general feature in the rare-earth region [18].

Bands 1 and 2 in ^{164}Tm are extended to both higher and lower spins compared to the earlier work [12,13] (cf Fig. 2a). Their structure is analogous to that of Bands 1 and 2 of ^{162}Tm. They have similar transition energies and relative excitation energies and are also linked to each other by transitions with DCO ratios consistent with stretched E1 character. Tentative dipole transitions of 70 and 110 keV connect Band 2 to the 1^+ ground state. However, these lines are contaminated by lines from Au X-rays and ^{19}F Coulomb excitation, respectively. Likely spins and configurations, based on this evidence, and comparison with ^{162}Tm, are shown in Fig. 2a.

In Fig. 2b, two bands in ^{174}Ta, assigned by Hojman et al. [19] to the $K^\pi = 4^-$; $\pi 1/2^-[541] \otimes \nu 7/2^+[633]$ and $K^\pi = 8^-$; $\pi 9/2^-[514] \otimes \nu 7/2^+[633]$ configurations, are shown. These bands are extended to higher spins and are now linked to each other by transitions due to mixing from the near degeneracy of levels at spins $12\hbar$ and $13\hbar$. With the observation of two new transitions of 69 and 51 keV, Band 1 is extended to lower spins as well. The band is depopulated promptly, (< 2 ns), by a 98 keV transition, but the possibility of further levels in the band, separated by energies < 40 keV cannot be ruled out. A 92 keV transition had been assigned [19] as an out-of-band transition, depopulating Band 2, but due to the observation of a weak and therefore tentative 226 keV transition in Band 2, it is now placed in-band. An estimate of the expected E2/M1 branching ratio from the 10^- state implies that the intensity of the 226 keV transition should be just on the detection limit of the experiment. Alternatively, if the 298 keV transition were identified with the decay of the 10^- state, as in the earlier work, its intensity would be a factor of ~ 3 higher than expected. The identification of the 92 keV γ-ray with the $9^- \rightarrow 8^-$ transition is also supported by the observation of delayed ($T_{1/2}$ = 250ns [19]) transitions of 98 and 153 keV, depopulating the 8^- level. These feed bandheads newly assigned [20] to the $K^\pi = 7^+$; $\pi 9/2^-[514] \otimes \nu 5/2^-[512]$ and $K^\pi = 7^+$; $\pi 7/2^+[404] \otimes \nu 7/2^+[633]$ configurations. The transitions linking Bands 1 and 2 fix their relative spins. With the new bandhead assignment for Band 2, the spins of the levels of both bands are raised by one unit compared to the previous assignment [19].

For all three nuclei, the new spin assignments are consistent with the addition of aligned angular momenta from the corresponding one-quasiparticle bands in the neighbouring nuclei, and delayed crossings are observed in all configurations proposed to include an $i_{13/2}$ neutron.

However, a consequence of these spin assignments, for all three nuclei, is that the favoured signature of the $\pi h_{9/2} \otimes \nu i_{13/2}$ bands has $\alpha = 0$ over substantial ranges of spin, while $\alpha_f = 1$ is expected according to (1). The signature inversion is illustrated in the sensitive energy-staggering plots of Fig. 3. In the two Tm isotopes, the signature splitting eventually reverts to the normal ordering at high spin, while in ^{174}Ta, the disappearance of signature splitting is due partly, if not wholly, to a bandcrossing (BC) in the $\alpha = 1$ branch.

Signature inversions at low spin are common features in other bands of odd-odd nuclei. For example, the configuration $\pi h_{11/2} \otimes \nu i_{13/2}$ is inverted at low spins in a chain of Tb, Ho and Tm nuclei. Several effects are often invoked to explain such observations. These include Coriolis effects [21,22] for spins $I \lesssim j_\pi + j_\nu$, triaxial shapes [23], and p-n interactions [5,24]. To investigate such possibilities here, we use the particle-rotor model code of Ref. [5]. The model Hamiltonian includes the rotational energy of

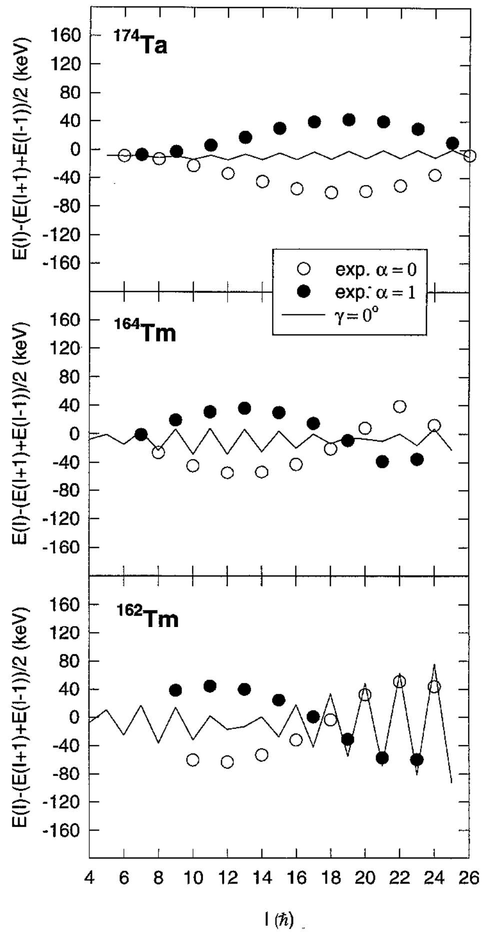

Fig. 3. The staggering function $E(I) - 1/2[E(I-1) + E(I+1)]$, which compares the energy of a level $E(I)$ at spin I with energy of levels above and below it in spin, for the $\pi h_{9/2} \otimes \nu i_{13/2}$ bands in the three nuclei compared with the results of the particle-rotor calculations.

the core (which can be either axially symmetric or triaxial), the quasiparticle energies of the odd proton and neutron, and a residual p-n interaction. The Hamiltonian is diagonalized within the space of low lying 1-quasiproton, 1-quasineutron states; all neutron orbitals originating from the $i_{13/2}$ subshell and the six lowest proton orbitals with main components from the $f_{7/2}$ and $h_{9/2}$ subshells were included. The κ, μ parameters of the Modified Oscillator Potential were taken from ref [25], and a common deformation $(\varepsilon_2, \varepsilon_4) = (0.27, 0.00)$ was used for all three cases. This deformation is a reasonable average of values calculated using the code Ultimate Cranker [26]; these same calculations also predict that the triaxiality parameter γ be restricted within a range $|\gamma| < 4°$. A Coriolis attenuation factor of 0.80 and a VMI [27] description of the rotational cores were used. The VMI parameters were obtained from an average of the values fitted to the ground bands of the neighbouring $Z \pm 1, N \pm 1$ even-even nuclei. Energy staggerings, calculated without a residual interaction, are summarized in Fig. 3. These calculations show a favoured signature of $\alpha = 1$ (odd spins favoured), in accord with the CSM, and in agreement with the data for ^{162,164}Tm above a spin of $20\hbar$. However, the prominent signature inversion, or change in phase of the staggering, observed experimentally below spin $\sim 20\hbar$ for ^{162,164}Tm and below spin $\sim 26\hbar$ for ^{174}Ta, is not present in these calculations. Furthermore, the inversion cannot be obtained by including triaxiality with γ between $\pm 10°$; sample triaxial calculations are shown for ^{174}Ta (where $\gamma > 0$ is simulated by interchanging the x and y moments of inertia [28]). These triaxial calculations also show a favoured signature of $\alpha = 1$, in disagreement with the data.

Since triaxiality and Coriolis effects alone are insufficient to explain the data, we consider a residual p-n interaction of the form

$$V_{pn} = \sqrt{8\pi^3}\left(\frac{\hbar}{m\omega}\right)^{\frac{3}{2}} \delta\left(r_p - r_n\right)\left(u_0 + u_1 \sigma_p . \sigma_n\right) \quad (2)$$

This interaction has been employed [5–7] to describe signature splitting effects in the $A = 130$ and 150 regions, in connection with $\pi h_{11/2} \otimes \nu h_{11/2}$ and $\pi h_{11/2} \otimes \nu i_{13/2}$ bands. Reasonable values for the parameters u_0 and u_1 were found to be $u_0 = -7.2$ MeV and $u_1 = -0.80$ MeV. The spin-spin strength parameter u_1 has been estimated from a fit to available GM splittings [29,30], and a relative strength of the two terms $u_0 : u_1 = 9 : 1$ is suggested from an analysis of p-n multiplets in spherical odd-odd nuclei [31,32]. For the bands considered here, which have wavefunctions of about 65% $\pi h_{9/2} \otimes \nu i_{13/2}$ character, u_0 and u_1 can also be estimated directly from the splitting of the spherical $\pi h_{9/2} \otimes \nu i_{13/2}$ multiplet in ^{208}Bi [33], which leads to values about half as large as cited above. The overall strength of V_{pn} was adjusted to give approximately the correct inversion spin for ^{164}Tm, while keeping the 9 : 1 ratio of $u_0 : u_1$ fixed; the parameters

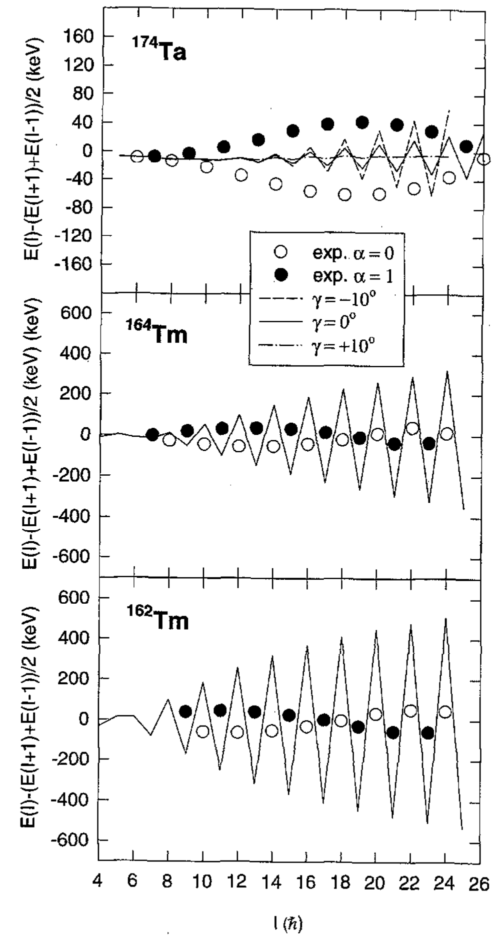

Fig. 4. As for Fig. 3 with a residual p-n interaction V_{pn} included in the particle-rotor calculations. (Note the change in scale compared to Fig. 3.)

adopted here are $u_0 = -4.95$ MeV and $u_1 = -0.55$ MeV.

The effect of including V_{pn} with $\gamma = 0°$ is shown in Fig. 4. Qualitatively the agreement with the data is very good. The inverted staggering pattern is clearly present for all three cases, and the spin at which the inversion occurs increases along the sequence ^{162,164}Tm, ^{174}Ta in both the calculations and the data. The magnitude of the staggering is described fairly well for the Tm isotopes, but is too small for ^{174}Ta. The qualitative agreement with the data is not sensitive to small changes in the calculations (moment of inertia, Coriolis attenuation, etc.), but appears for a wide range of reasonable parameter values.

The wave functions of these semi-decoupled states are complicated, and a simple qualitative understanding of how V_{pn} affects the signature splitting is elusive. The energy eigenfunctions are minimum energy solutions of the total Hamiltonian, and thus represent a balance between the core rotational energy $< E_{rot} >$, the proton and neutron quasiparticle energies $< E_{qp} >$ and $< E_{qn} >$, and the p-n interaction $< V_{pn} >$. The effect of the p-n interaction depends on the particle and hole character of the participating quasiparticles; in a weak coupling basis $|(j_p, j_n) J \otimes R; I\rangle$, the average p-n interaction can be related to the spherical multiplet splittings $\langle (j_p, j_n) J | V_{pn} | (j_p, j_n) J \rangle$. For the $\pi h_{9/2} \otimes \nu i_{13/2}$ configuration, the proton-particle neutron-particle matrix elements are all attractive, while the related proton-particle neutron-hole matrix elements are all repulsive [33]. The largest matrix elements occur for the low spin $J = 2, 3$ states and for the stretched state, $J = J_{max} = 11$.

At high spins, in ^{164}Tm, near e.g. $I \sim 24\hbar$, the situation is relatively transparent. The odd spin states have a larger alignment than the even spin states and therefore the odd-spin states have a dominant $J = 11$ component. This has nearly equal particle-particle and particle-hole amplitudes, while the even spin states have nearly equal $J = 11$ and $J = 10$ components, both mainly of particle-particle character. Consequently, the contribution to the total energy due to the p-n interaction, $< V_{pn} >$ is more attractive for even spins than for odd spins. However, the overall staggering is dominated by $< E_{rot} >$, which favours the normal staggering ($\alpha = 1$ favoured).

At lower spins the wavefunctions are more complex, with $J = 2, 3$ components playing a greater role. Here, the contribution $< V_{pn} >$ is actually at its largest, but it does not oscillate with spin. Instead, the contribution due to $< E_{rot} >$ is forced to change phase, giving rise to the signature inversion.

The present results highlight the importance of considering known residual p-n interactions at medium to high spins. It is hoped that the application of the present residual interaction to $h_{9/2}$ bands in odd-Z nuclei may also shed light on the origin of delayed crossing frequencies.

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