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Suppression of band crossing in the neutron-rich nuclei ^{172,173}Yb due to the absence of a static pair field

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Abstract. High-spin states in the neutron-rich nuclei ^{172,173}Yb have been populated in a ^{170}Er(^{7}Li,(p,d,t)xn) incomplete-fusion reaction and the emitted γ-radiation was detected with the GASP array. The signature partners of the $7/2^+[633]$ rotational band of the odd-N ^{173}Yb isotope have been newly established and were observed up to spin values of $(45/2^+)$ and $(43/2^+)$, respectively. The ground-state band of the even-even nucleus ^{172}Yb has been observed up to a spin value of (22^+). No band crossings were found in these bands. To explain this observation, it is proposed that the static pair field is absent, considering that the neutron odd-even mass differences reach for these nuclei very small values and that the band crossing is absent in cranked shell modell calculations without pairing. The results indicate, however, that strong dynamic correlations are still present.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 21.10.Re Collective levels – 23.20.Lv γ transitions and level energies – 27.70.+q $150 \leq A \leq 189$

1 Introduction

The $Z = 70$ Yb nuclei represent probably one of the best studied isotopic chains in the $A \approx 160$ region of the rare-earth nuclei, for which high-spin data ranging from $A = 152$ to 178 have been measured. Considerable experimental information about high-spin states is now available for the neutron-deficient nuclei in this region. However, the investigation of high-spin states in the heavier neutron-rich Yb isotopes, in particular in ^{172,173}Yb is limited by their inaccessibility with fusion-evaporation type of reactions. The studies of these nuclei were restricted to (α,2n), (n,γ), (d,p), (d,t), and Coulomb excitation reactions [1]. The highest-spin state reached in this region is the 16^+ level of the ground-state band (gsb) of ^{172}Yb. It was populated via the (α,2n) reaction in the work of Walker *et al.* [2]. Since a large angular momentum is also transferred in deep inelastic reactions [3,4], the ground-state bands of the neutron-rich ^{172,173}Yb isotopes have been extended up to spin values of (18^+) and $31/2^-$, respectively. In recent studies of close-lying neutron-rich nuclei, incomplete-fusion reactions have been exploited [5–10], which can also be used to reach high-spin states.

In the present work incomplete-fusion reactions have been used to study high-spin states in ^{172,173}Yb. A new $7/2^+[633]$ band was observed in the odd-N nucleus ^{173}Yb up to a spin value of $(45/2^+)$ and the ground-state bands of ^{172,173}Yb were extended up to 22^+ and $41/2^-$, respectively. The absence of band crossings in these bands and the fact that the neutron odd-even mass differences decrease very strongly for these nuclei suggests that the static pair field has vanished. This proposal is substantiated by cranked shell modell calculations with and without pairing. The results indicate, however, that dynamic pair correlations are still present.

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2 Experimental methods and results

To populate excited states in the nuclei ^{172,173}Yb, the incomplete-fusion reaction ^{170}Er + ^{7}Li at a beam energy of 51 MeV was employed. The beam was provided by the Tandem XTU accelerator of the Legnaro National Laboratory, Italy, and γ-rays emitted by the reaction residues were detected using the GASP array [11] which consisted of 40 Compton-suppressed large-volume Ge detectors, an 80-element BGO inner ball and the charged-particle array ISIS [12] consisting of 40 Si detector telescopes. The ^{170}Er target (enrichment of 99.2%) was a self-supporting metallic foil with a thickness of 3.05 mg/cm^2. Events were recorded when $\geq$ 2 escape-suppressed Ge detectors and $\geq$ 3 BGO scintillators detected γ-rays in coincidence. In total $4 \cdot 10^9$ events have been collected. The data were sorted off-line into a number of reaction-channel selected two- and three-dimensional $\gamma\gamma$ matrices and $\gamma\gamma\gamma$ cubes using the program Ana [13]. Matrices were created for γ-rays in coincidence with a proton, deuteron, triton or α-particle being detected by ISIS. In the reaction ^{170}Er (^{7}Li,(p,d,t,α)xn), a number of Lu, Yb and Tm isotopes were produced. The Lu isotopes are populated after the evaporation of 4–8 neutrons, while the $^{170-174}$Yb and $^{169-171}$Tm isotopes are produced, respectively, via the (p,d,t)xn and αxn incomplete-fusion reaction channels. This reaction mechanism is responsible for the observed high cross-sections of the different charged-particle channels, as has been discussed in detail in ref. [9]. In the present experiment the nucleus ^{172}Yb was populated with different probabilities via the p4n, d3n and t2n channels, whereas for the heavier nucleus ^{173}Yb the p3n channel is the most important one.

At least 20 rotational bands up to 2.6 MeV have previously been identified in the well-deformed even-even nucleus ^{172}Yb [14] studied by a variety of techniques [2–4, 15–17]. However, the different methods do not populate high-spin states in general, with the exception of deep inelastic reactions [4], where the 18$^+$ state of the gsb was tentatively assigned. The most information about the high-spin structure comes so far from the study of ^{172}Yb by Walker *et al.* [2], using the (α,2n) reaction. These authors have identified six bands up to high spins, in particular the gsb was established up to the 16$^+$ state and the octupole band at 1155 keV and the β-band at 1043 keV were populated up to the 14$^-$ and 14$^+$ levels, respectively. In the present work these bands have been extended to higher-spin states of 22$^+$, 19$^-$ and 20$^+$, respectively. Here is reported only about the extension of the gsb in ^{172}Yb. A partial level scheme is shown in fig. 1a. The new (20$^+$) → 18$^+$ 803.9 keV and (22$^+$) → (20$^+$) 857 keV transitions of the gsb can be seen in the $\gamma\gamma$ coincidence spectrum of fig. 2a obtained from a $\gamma\gamma$ matrix gated on protons illustrating the quality of the data. In ref. [4] an energy of 742.4 keV has been assigned to the 18$^+$ → 16$^+$ transition, in agreement with the energy of 743.8 keV deduced from the present data.

In prior work on the nucleus ^{173}Yb the rotational band built on the 5/2$^-$[512] ground state has been populated through Multiple Coulomb Excitation (MCE) [18] up to

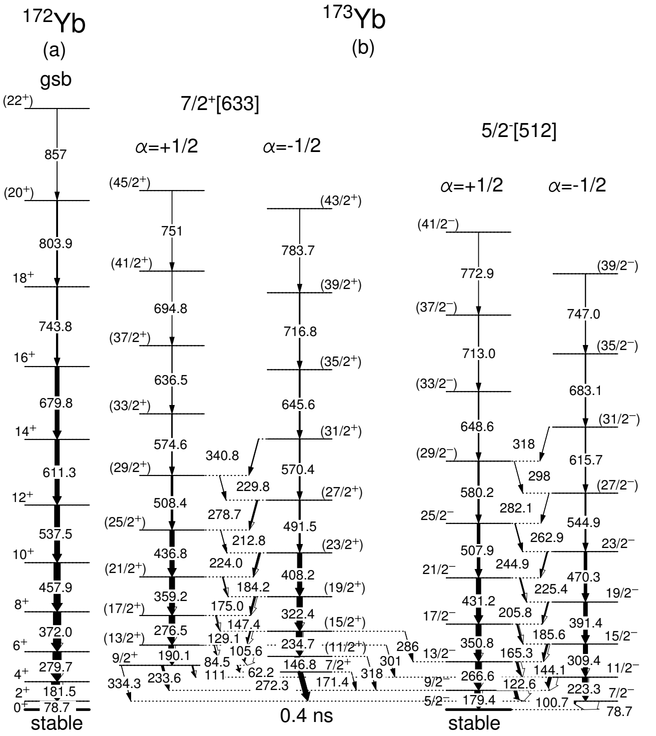

Fig. 1. Partial level schemes of (a) the gsb in ^{172}Yb, and (b) the 5/2$^-$[512] gsb and 7/2$^+$[633] band in ^{173}Yb.

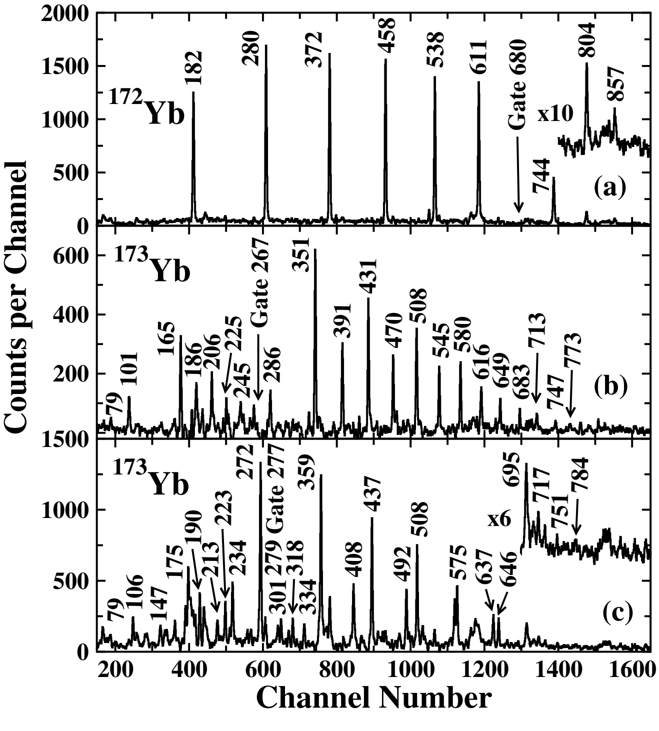

Fig. 2. Three $\gamma\gamma$ coincidence spectra for (a) ^{172}Yb with a gate on the 680 keV 16$^+$ → 14$^+$ member of the gsb, (b) ^{173}Yb with a gate on the 267 keV 13/2$^-$ → 9/2$^-$ transition of the 5/2$^-$[512] band and (c) ^{173}Yb with a gate on the 277 keV 17/2$^+$ → 13/2$^+$ member of the proposed new 7/2$^+$[633] band.

$I^\pi = 27/2^-$ and in deep inelastic reactions up to $29/2^-$ [4]. The low-energy levels in ^{173}Yb have been studied in detail by (d,p), (d,t) reactions [19]. The known position of the $7/2^+$ level at 351 keV and the $9/2^+$ level at 413 keV, their decays to the known levels of the $5/2^-[512]$ gsb through the 171, 272 and 111, 234, 334 keV transitions, respectively, as well as the known position of the $13/2^+$ level at 603 keV, allowed us to establish the new $7/2^+[633]$ band in ^{173}Yb up to spin-parity values of $(45/2^+)$ and $(43/2^+)$ for the $(+,+1/2)$ and $(+,-1/2)$ sequences, respectively. A partial level scheme for ^{173}Yb as deduced from the present experimental data is displayed in fig. 1b. The positive ($\alpha = +1/2$) and negative ($\alpha = -1/2$) signature sequences of the gsb have been extended up to the $(41/2^-)$ and $(39/2^-)$ levels, respectively. The transition energies have an overlap within ≈ 0.3 keV with the energies deduced from the MCE measurement [18], whereas the differences with the values from the deep inelastic experiment [4] are of the order ≈ 2 keV up to the $25/2^-$ level and ≈ 4 keV for the transition energies at higher spin. The γ-ray cascades assigned in ref. [4] to the $5/2^-[512]$ sequence with $\alpha = -1/2$ in ^{173}Yb and the $1/2^+[411]$ sequence with $\alpha = +1/2$ in ^{173}Tm, respectively, have been exchanged in the present work considering the previous knowledge of the level schemes [1]. The placement of the new transitions in the cascades was deduced on the basis of transition intensities in individual and summmed coincidence spectra using the matrix gated on protons, as well as from the individual spectra gated on the $M1$ transitions and the $E2$ crossover lines in the $\gamma\gamma\gamma$ cube, taking into account the sum and intensity correlations. For illustration, fig. 2 shows the coincidence spectra obtained in the proton gated matrix with a gate on (b) the 266.6 keV $13/2^- \to 9/2^-$ member of the gsb and (c) the 276.5 keV $17/2^+ \to 13/2^+$ member of the newly established $7/2^+[633]$ rotational band. The spin assignments are based on the already known spins of the band head, the observation of $\Delta I = 1$ transitions between signature partners, and the analogy with the level structure of the lighter odd-N Yb isotopes. Moreover, the new 286, 301 and 318 keV transitions have been observed (fig. 2b, c) to connect the $15/2^+$, $13/2^+$ and $11/2^+$ levels of the $7/2^+[633]$ band to the $5/2^-[512]$ gsb.

3 Discussion

Evidence for the quenching of static neutron pair correlations has been searched for in many investigations. In ref. [20] it has been suggested that the systematic appearance of band crossings is due to the existence of the pair field, and that the absence of these crossings indicates that the static pair correlations have disappeared. In the study of $^{167-169}$Yb evidence for the disappearance of static neutron pair correlations has been found for the odd-N nuclei at rotational frequencies $\hbar\omega \geq 0.38$ MeV [21]. An unpaired proton crossing has been identified in a more recent investigation of ^{167,168}Yb [22]. A study of neutron-rich Yb nuclei using deep inelastic reactions has been carried out by Lee *et al.* [3]. In a systematics of experimental quasiparticle Routhians for ^{168,170}Yb, ^{174,176}Hf and ^{176,178}Yb it has been shown that the expected band crossing caused by the alignment of an $i_{13/2}$ quasineutron pair cannot be seen [3]. This has been explained by a rather low neutron pairing gap [3]. It is much smaller than the spacing between the $i_{13/2}$ neutron levels with $\Omega = 7/2$ and $9/2$, being 1.3 MeV [3]. This has the consequence, that the band crossings due to the $\nu i^2_{13/2}$ alignment cannot be discerned anymore. In this systematics of experimental Routhians the nuclei ^{172,174}Yb have been replaced by ^{174,176}Hf because the $i_{13/2}$ band in ^{173}Yb was not known. Now the Yb systematics can be completed using the experimental results obtained in the present work.

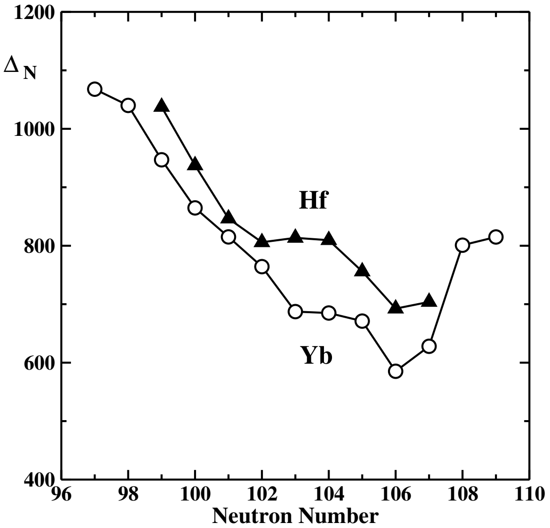

Fig. 3. Neutron odd-even mass differences for Yb and Hf nuclei.

For the interpretation of the band crossings in ^{172,173}Yb the dependence of the neutron odd-even mass difference on the neutron number N is considered as discussed by Lee *et al.* [3]. The neutron odd-even mass difference is derived from the neutron separation energy $S(N)$ as $\Delta_N = \pm 1/4(2S(N) - S(N-1) - S(N+1)$ for even and odd neutron numbers, respectively. The Δ_N values are shown as function of N in fig. 3 for Yb and Hf nuclei derived from the mass tables of Audi *et al.* [23]. It can be seen, that the neutron odd-even mass difference decreases strongly with increasing neutron number indicating that the pair correlations become small. The experimental odd-even mass difference is to be compared with the odd-even mass difference in the absence of pair correlations, which are caused by the twofold degeneracy of the single-particle levels given by one half of the distance between the last occupied and the first empty level [24]. The value estimated from the Nilsson diagram at the appropriate deformation is about 500 keV, which means that the static pair field does not contribute much to the odd-even mass difference when it reaches values of about 600 keV as for the heavy Yb nuclei.

For the $N = 103$ nucleus ^{173}Yb Δ_N is 126 keV smaller than for the isotone ^{175}Hf. Therefore, the effect of a

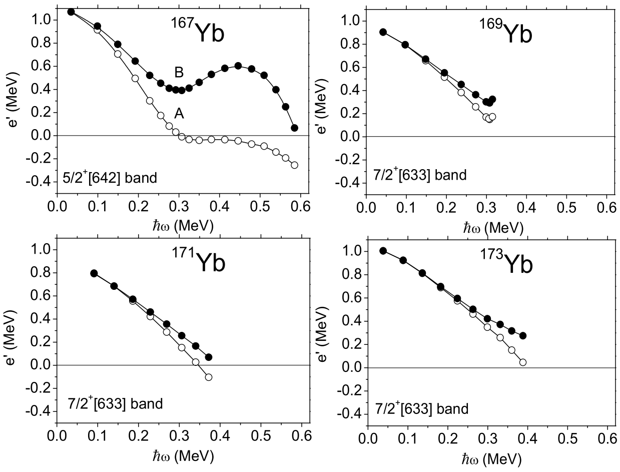

Fig. 4. Experimental Routhians for the $i_{13/2}$ neutron bands in ^{167,169,171,173}Yb. States of signature $\alpha = +1/2$ (A) are shown as open symbols and the ones with $\alpha = -1/2$ (B) as filled symbols.

corresponding small neutron pairing gap should be more pronounced in the former nucleus. The best cases should be ^{175,177}Yb; however in ^{175}Yb the $i_{13/2}$ neutron band is only known up to the $13/2^+$ level and in ^{177}Yb only until a rotational frequency of $\hbar\omega \approx 0.3$ MeV [4] and hence not through the band crossing region. The $i_{13/2}$ neutron band in ^{173}Yb has been established in the present work until $\hbar\omega \approx 0.4$ MeV.

In fig. 4 the experimental quasiparticle Routhians are shown for the $i_{13/2}$ neutron bands in ^{167,169,171,173}Yb using the yrast bands of ^{168,170,172,174}Yb as reference [2, 4, 21, 22, 25, 26]. They were obtained by subtracting from the experimental Routhians E'_N of the $i_{13/2}$ band in the odd-N nucleus the experimental Routhian E'_{N+1} of the yrast band of the even-mass neighbour and adding the experimental neutron odd-even mass difference. The use of the experimental Routhian as reference is different from the commonly used reference obtained by a fit of a fourth-order curve (Harris fit) to the low-spin part of the experimental Routhian. For the heavy Yb isotopes it is more appropriate to use the experimental yrast bands as reference since the pairing correlations are weak and the structural changes are very gradual, as discussed in ref. [27]. In the same fashion the experimental aligned angular momenta have been derived, which are shown for ^{167,169,171,173}Yb in the middle column of fig. 5. It can be seen in figs. 4, 5 that pronounced structural effects exist in ^{167,169}Yb resulting from band crossings, whereas the quasiparticle energies and the aligned angular momenta of ^{171,173}Yb vary smoothly with the rotational frequency. For ^{171}Yb the neutron odd-even mass difference is already very much reduced and reaches a value of 687 keV for ^{173}Yb.

The decrease of the neutron odd-even mass difference suggests a decrease of pairing. It is proposed that above $N = 100$, the static pair correlations become unimportant. This is demonstrated by the quasiparticle energies and aligned angular momenta (cf. figs. 4, 5) since for ^{171,173}Yb they do not show the characteristic behaviour indicating a band crossing. Since band crossings are seen in the lighter Yb nuclei it is suggested that for them the static pair field still exists. To substantiate this notion, cranked shell model (CSM) calculations [27] have been carried out. The used pairing gap parameters are 75% of the odd-even mass differences shown in fig. 3. The deformation parameters $(\varepsilon_2, \varepsilon_4)$ are (0.255, 0.014) for ^{168}Yb, (0.265, 0.024) for ^{170}Yb, (0.269, 0.036) for ^{172}Yb and (0.266, 0.048) for ^{174}Yb, which are taken from [27]. The deformation parameters of the odd-A Yb isotopes are the averages of those of the neighbouring even-A Yb isotopes. In the left column of fig. 5 the aligned angular momenta obtained in the CSM calculations with pairing are shown and in the right column those without pairing. A comparision with the experimental aligned angular momenta shows clearly that in ^{167}Yb static pair correlations exist but that they are absent for ^{171,173}Yb. The nucleus ^{169}Yb can be described in both calculations. The reason is that in the unpaired CSM calculation for $N = 100$ two configurations exist near the Fermi surface, *viz* a $\nu i_{13/2}$ and a negative-parity neutron $(\nu h_{9/2})$ configuration. The corresponding orbitals can be seen in fig. 6. At a frequency of $\hbar\omega = 0$ MeV the $\nu i^2_{13/2}$ orbitals lie lowest und are occupied by the last pair of neutrons. Above a frequency of $\hbar\omega = 0.18$ MeV it becomes more favourable for the neutron pair to occupy the negative-parity orbitals. The relative alignments for ^{169}Yb corresponding to these two configurations are shown in the right column of fig. 5. The vertical line at $\hbar\omega = 0.18$ MeV indicates where the neutron pair jumps from one configuration to the other. This jump leads to a sudden decrease in the aligned angular momentum as observed experimentally. Therefore, ^{169}Yb can be considered as a transitional case. For ^{173}Yb the crossing in the CSM calculation with static pair correlations is pushed to higher frequencies with respect to those in the lighter Yb isotopes. The reason is that the energy difference between the single-particle states is larger than the pairing gap.

The validity of the calculations resulting in the single-neutron orbital diagram shown in fig. 6 is confirmed by the fact that the lowest-lying negative-parity band lies energetically lower in ^{170}Yb than in ^{168,172}Yb. In fact the negative-parity band in ^{170}Yb approaches rapidly the yrast line and comes close to it at $\hbar\omega \approx 0.3$ MeV. This behaviour corresponds to the crossing of the $\nu i_{13/2}$ and $\nu h_{9/2}$ orbitals with signatures $+1/2$ and $-1/2$ at rotational frequencies of $\hbar\omega = 0.15$ and 0.24 MeV, respectively, as can be seen in fig. 6.

It is proposed that above $N = 100$, the pair correlations are of dynamic nature (fluctuations around a mean value of zero). That substantial pair correlations still exist for ^{171,173}Yb can be concluded from the following facts: i) The neutron odd-even mass differences are larger than expected from a pure single-particle spectrum. ii) The aligned angular momenta of ^{171,173}Yb have always positive values (*i.e.* the aligned angular momenta of the odd-N nuclei are always larger than those of the neighbouring even-N nuclei). If pair correlations were absent the aligned angular momenta should be sometimes positive,

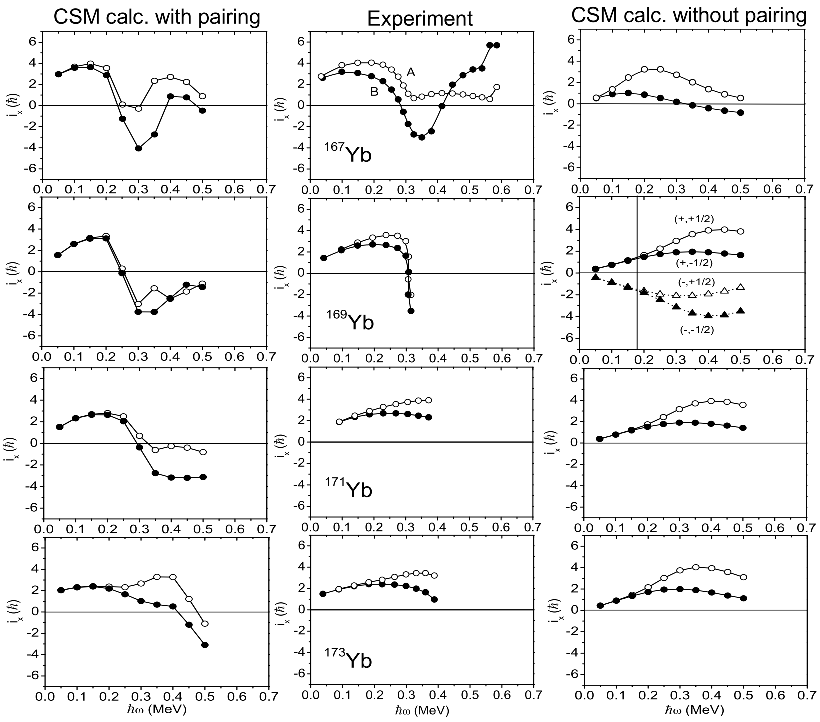

Fig. 5. Middle: Alignment plots for the $i_{13/2}$ neutron bands in ^{167,169,171,173}Yb. States of signature $\alpha = +1/2$ (A) are shown as open symbols and the ones with $\alpha = -1/2$ (B) as filled symbols. Left: Results of CSM calculations with pairing. Right: Same without pairing.

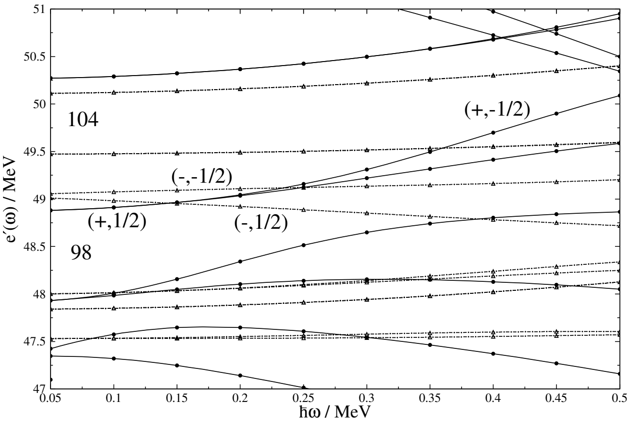

Fig. 6. Single-neutron orbitals for Yb with $N = 100$ as obtained in CSM calculations without pairing. The full lines represent positive-parity states and the dash-dotted curves negative-parity states.

sometimes negative. iii) The experimental aligned angular momenta start for ^{167,169,171,173}Yb at ≈ 2 $\hbar$ as in the CSM calculation with pairing, whereas those without pairing begin at ≈ 0 $\hbar$. The sudden onset of alignment is due to pair correlations and has been explained by Fermi aligned coupling [28]. The comparison of the present data with the results of CSM calculations demonstrates the absence of a static pair field but the presence of strong dynamic correlations.

4 Summary and conclusions

High-spin states of ^{172,173}Yb nuclei have been studied via the incomplete-fusion reaction ^{170}Er(^{7}Li,(p,d,t)xn). The known ground-state rotational bands have been extended up to higher spins and a new rotational band built on the $7/2^+$[633] Nilsson state has been established in ^{173}Yb. No band crossings were found in the $i_{13/2}$ quasineutron band of ^{173}Yb and in the gsb of ^{172}Yb. This observation has been related to the decrease of the neutron odd-even mass difference with increasing neutron number N reaching a value $\Delta_N \leq 0.7$ MeV for ^{173}Yb suggesting a decrease of pairing. It has been concluded that the static pair field is absent for these nuclei but that strong dynamic correlations are still present. Cranked shell model calculations have been performed with and without pairing and a comparison wih the experimental results demonstrates that static pair correlations exist for ^{167}Yb but are absent for ^{171,173}Yb. The nucleus ^{169}Yb is a transitional case since both calculations can explain the experimental data.

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