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Rotational bands in neutron-rich ^{160,161,162}Ho

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Abstract. High-spin states in ^{160,161,162}Ho have been populated in the reactions ^{158,160}Gd(^{7}Li, xn) at 56 MeV. In all three isotopes the known rotational bands have been extended to significantly higher spin. In ^{160}Ho, the band crossing in the $\pi 7/2^-[523] \otimes \nu 11/2^-[505]$ band has been observed for the first time. The sequences built on the proton $7/2^-[523]$, $7/2^+[404]$, $1/2^+[411]$ and $1/2^-[541]$ states in ^{161}Ho have been extended up to spin $51/2^-$, $35/2^+$, $51/2^+$ and $41/2^-$, respectively, leading to the first observation of upbends in all four cases. In addition, a new band most probably belonging to this nucleus has been identified. In the most neutron-rich isotope ^{162}Ho, the only known rotational band, which is built on the $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ configuration, has been extended up to the 28^- state. The properties of all observed bands are discussed and compared to the neighbouring isotopes.

PACS. 23.20.Lv γ transitions and level energies – 27.70.+q $150 \leq A \leq 189$ – 21.10.Re Collective levels

1 Introduction

With this paper we extend our study of the high-spin properties of neutron-rich nuclei in the rare-earth region, started in the heavy Dy isotopes with $N = 93$–97 [1,2], to the $^{160-162}$Ho isotopes with $N = 93$–95. Whereas a lot of experimental information is available about the high-spin structure of the neutron-deficient nuclei in this region, for the more neutron-rich isotopes it is still rather meager mainly due to the fact that these nuclei cannot easily be populated at high angular momentum in heavy-ion–induced fusion-evaporation reactions. In the present work, the Ho isotopes were produced using the ^{158,160}Gd (^{7}Li, xn) reactions which allowed us to observe excited states with spins as high as $28\hbar$. The aim of the present study was to investigate the properties of the rotational bands in $^{160-162}$Ho and their dependence on the single-particle orbits involved. Information about the performed experiments is given in sect. 2 followed by the presentation of the results concerning the level schemes of $^{160-162}$Ho in sect. 3. The behaviour of the observed rotational bands as well as the signature splitting of the $7/2^-[523]$ bands in the odd isotopes are discussed in sect. 4. Finally, the paper is closed by concluding remarks.

2 Experiments

Excited states in the nuclei $^{159-162}$Ho were populated using the reactions ^{158,160}Gd (^{7}Li, xn), $x = 5$ or 6, at a beam energy of 56 MeV. The beam was delivered by the XTU tandem accelerator of the Laboratori Nazionali di Legnaro and directed onto targets with thicknesses of 3.7 mg/cm^2 (^{158}Gd) and 3.9 mg/cm^2 (^{160}Gd), respectively. The γ-radiation was detected in the 40 Compton-suppressed Ge detectors of the GASP array and the 80-element BGO inner ball. In addition, charged particles emitted in the pxn, dxn and txn reaction channels leading to the Dy isotopes were detected in the Si ball ISIS consisting of 40 Si ΔE-E telescopes arranged in the same geometry as the Ge crystals in GASP, namely in seven rings with $\Theta = 35°$, 59°, 72°, 90°, 108°, 121°, and 145° with respect to the beam. All events with at least three coincident γ-rays in the Ge detectors or two γ in the Ge plus one particle detected in the Si ball were recorded on tape with the additional condition that the γ multiplicity

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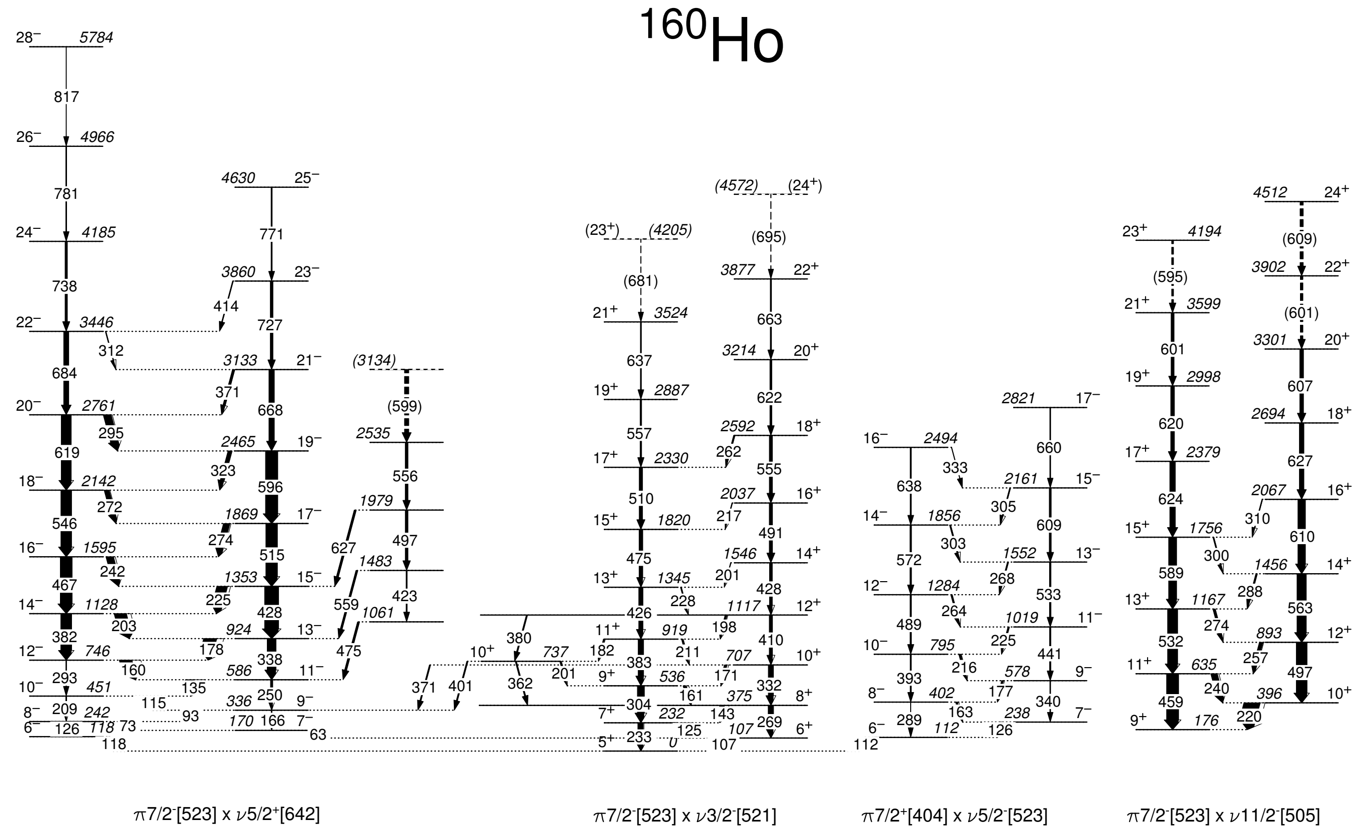

Fig. 1. The level scheme of ^{160}Ho as obtained in the present work.

in the BGO ball was three or higher. More details about this experiment are given in [1,2].

3 Data analysis and results

In the reactions ^{7}Li + ^{158,160}Gd, a number of Ho and Dy isotopes are produced. Whereas the Ho nuclei are populated after the emission of 4 to 7 neutrons, the emission of a charged particle, *i.e.* either a proton, a deuteron or a triton, goes along with the population of the Dy isotopes. The experimental cross-sections for the different reaction products are given in fig. 1 of ref. [1]. As discussed in detail in that work, the reaction mechanism responsible for the observed high cross-sections for the charged-particle channels is incomplete fusion. Whereas charged-particle gated γ-γ matrices were used for the analysis of the Dy isotopes (see [1,2]), the γ-γ matrices sorted in anti-coincidence with the charged particles detected in ISIS were not clean enough to allow for a detailed analysis of the pure neutron channels leading to the Ho isotopes. Therefore, for each of the two runs (targets of ^{158}Gd and ^{160}Gd), γ-γ-γ cubes have been sorted and the extension of the Ho level schemes is based on these cubes. We would like to mention that we observed the nucleus ^{159}Ho in the reaction ^{158}Gd(^{7}Li, 6n) up to spin $43/2^-$, $37/2^+$, $43/2^+$ and $45/2^-$ for the $7/2^-[523]$, $7/2^+[404]$, $1/2^+[411]$ and $1/2^-[541]$ bands, respectively. However, since except for the energy of the $35/2^+ \to 31/2^+$ transition within the $1/2^+[411]$ band (555 instead of 543 keV), no discrepancies have been found with respect to a recent work by Ying-Jun *et al.* [3], we do not present here the level scheme obtained for this isotope.

In the following subsections, the data analysis and the resulting extensions of the level schemes for $^{160-162}$Ho will be discussed for each of the isotopes separately.

3.1 The level scheme of ^{160}Ho

The so far most extensive study of the high-spin properties of ^{160}Ho has been presented by Drissi *et al.* [4] where the reaction ^{154}Sm(^{11}B, 5n) has been used. In that work, four rotational bands have been identified up to spin values of 26^-, 10^+, 12^- and 16^+ and assigned as being built on the proton-neutron configurations $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$, $\pi 7/2^-[523] \otimes \nu 3/2^-[521]$, $\pi 7/2^+[404] \otimes \nu 5/2^-[523]$ and $\pi 7/2^-[523] \otimes \nu 11/2^-[505]$, respectively. The level scheme of ^{160}Ho obtained in the present work is shown in fig. 1, where the bands are labeled by their Nilsson configurations [4]. Within the $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ yrast band, the energy of the $26^- \to 24^-$ transition has been changed from 801 keV in [4] to 781 keV and an additional 817 keV $28^- \to 26^-$ γ-ray has been placed on top of it. The sequence of odd-spin states has been extended by a 771 keV transition up to the 25^- state. We observed a number

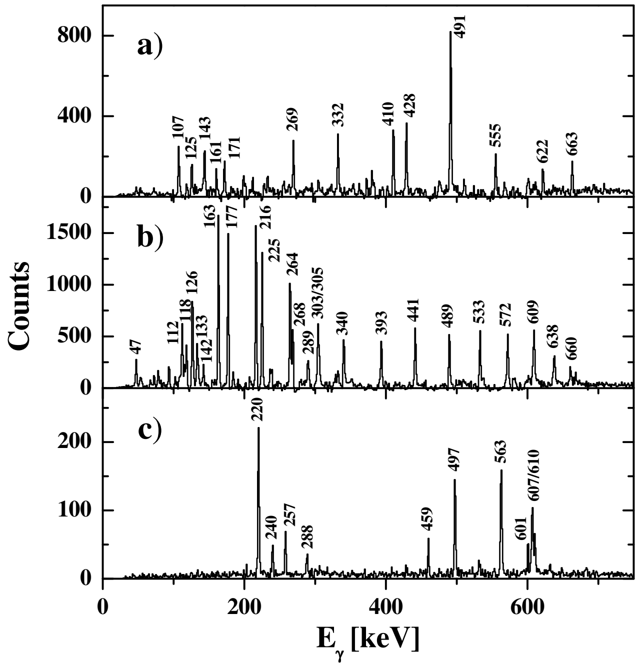

Fig. 2. Examples of double-gated coincidence spectra in ^{160}Ho. Shown are the sums of the spectra obtained in coincidence with two out of the following γ transitions: a) 269, 332, 410, 428, 555 and 622 keV transitions within the $\pi 7/2^-[523] \otimes \nu 3/2^-[521]$ band, b) 126, 163, 177, 216, 225, 264, 268, 303/305 keV transitions within the $\pi 7/2^+[404] \otimes \nu 5/2^-[523]$ band and c) 610, 627 keV within the $\pi 7/2^-[523] \otimes \nu 11/2^-[505]$ band.

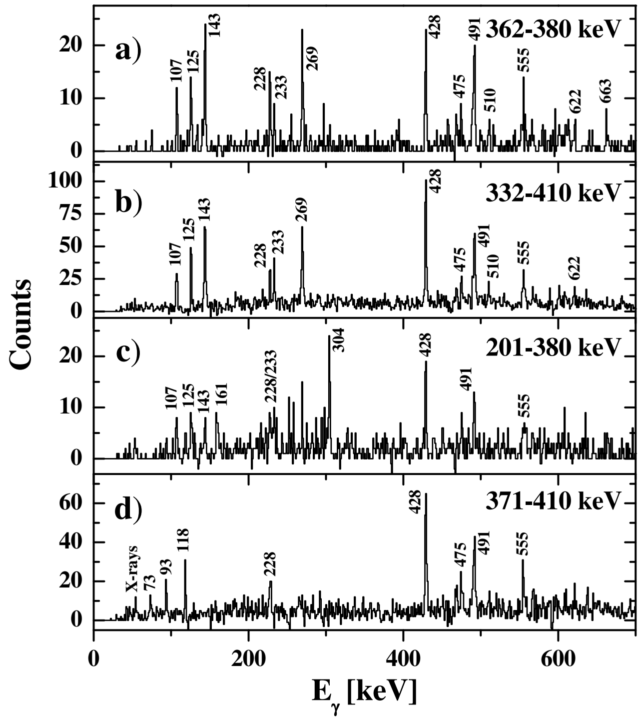

Fig. 3. Double-gated coincidence spectra giving evidence for the newly identified third 10^+ state at 737 keV in ^{160}Ho and the decay of the second 10^+ level at 707 keV to the 9^- yrast state.

of weak γ-rays in coincidence with transitions within this band. Some of them could be arranged in a rotational-like sequence (423-497-556 keV) which is connected to the odd-spin members of the $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ band via transitions of 475, 559 and 627 keV. No spin assignment for the new states was possible due to the weakness of the γ-rays involved.

The $\pi 7/2^-[523] \otimes \nu 3/2^-[521]$ ground-state band has been extended considerably from 10^+ up to the (24^+) state on the basis of the present $\gamma\gamma\gamma$ data. As an example the sum of double-gated coincidence spectra with gates on transitions between the even-spin members of this band is shown in fig. 2a). In addition, a new level at an excitation energy of 737 keV has been identified. Since it is populated from the 12^+ and 11^+ members of the $\pi 7/2^-[523] \otimes \nu 3/2^-[521]$ band and decays to the 9^+ and 8^+ levels of this band, the new state most probably has spin and parity 10^+ and therefore is the third 10^+ level, lying only 30 keV above the second. The similarity between the two double-gated coincidence spectra shown in figs. 3a) and b) demonstrates very nicely that the 362-380 and 332-410 keV transitions form parallel pathways connecting the 12^+ and 8^+ levels (see fig. 1). The spectrum with double gate on the 201 and 380 keV transitions (fig. 3c)) is shown as evidence for the existence of the $M1$ transition connecting the new level to the 9^+ state. Both 10^+ states at 707 and 737 keV decay to the 9^- level of the $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ band via γ-rays of 371 respectively 401 keV. In the gate on the 371 and 410 keV transitions, shown in fig. 3d), the low-energy 73, 93 and 118 keV γ-rays from the decay of the 9^- level are clearly seen in addition to the lines at 228, 428, 475, 491 and 555 keV corresponding to transitions above the 12^+ state within the $\pi 7/2^-[523] \otimes \nu 3/2^-[521]$ band. Unfortunately, due to limited statistics, we were not able to identify any members of a band built on the 10_3^+ state.

Five new $E2$ transitions have been added on top of the two signature sequences of the known $\pi 7/2^+[404] \otimes \nu 5/2^-[523]$ band. A sum spectrum for this band is shown in fig. 2b). Up to the highest spin, relatively strong $M1$ crossover transitions have been observed. This band has been assigned as $\pi 7/2^+[404] \otimes \nu 5/2^-[523]$, $K = 6^-$ band in [4] on the basis of rotational parameters, band head energy predictions, possible K-values and the branching ratios between cascade and crossover transitions within the band. The determination of the band head energy has to be considered tentative since in ref. [4] only a weak prompt 112 keV transition has been observed in coincidence with some band members. Although the authors of ref. [4] conclude that it is most probable that this band decays to the isomeric 6^- band head of the $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ band at $E_x = 118$ keV ($T_{1/2} = 56(6)$ ns), they exclude this possibility because of the absence of the 112 keV line in coincidence with the delayed 118 keV transition and instead assumed a decay to the 5^+ ground state. In our data, we clearly observe the 112 keV line but in addition, we also

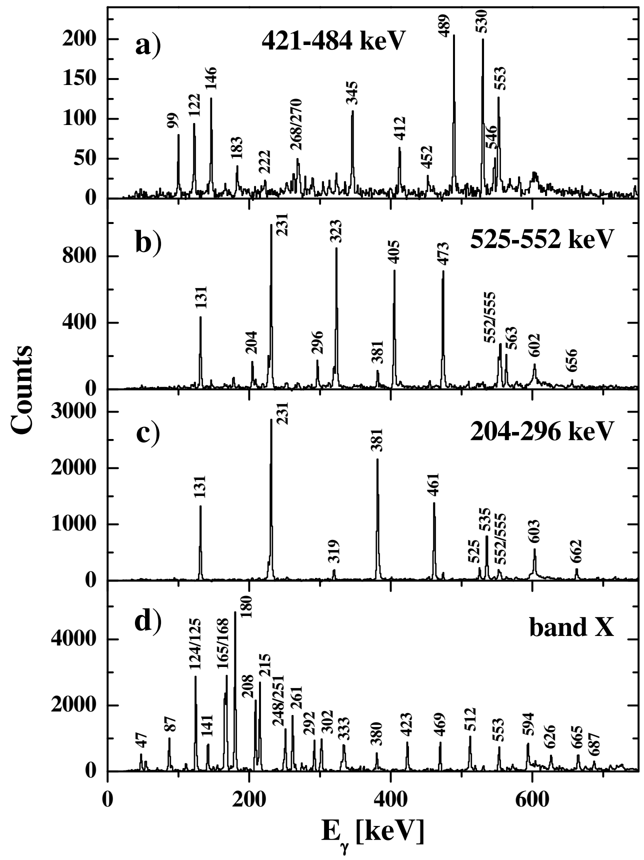

Fig. 4. Examples of double-gated coincidence spectra in ^{161}Ho. Gates are set on a) the 421 and 484 keV transitions within the $7/2^+[404]$ band, b) the 525 and 552 keV transitions within the $1/2^+[411]$ band and c) the 204 and 296 keV transitions within the $1/2^-[541]$ band. The sum of the spectra obtained in coincidence with two of the 87, 124/125, 168, 165, 215, 208, 261, 251 and 302 keV γ-rays within the new band X is shown in panel d).

observe γ-rays with 118, 133, and 142 keV in many coincidence spectra with gates on band members (see fig. 2b)). However, due to their weakness we were not able to place them and therefore the question of the band head energy of this band still remains open.

The $\pi 7/2^-[523] \otimes \nu 11/2^-[505]$ band built on the 9^+ isomeric state ($T_{1/2} \approx 3$ s) at $E_x = 176$ keV has been extended from 16^+ up to 24^+ by four new $E2$ transitions for each of the two signatures. As example, the double-gated spectrum with gates on the 610 and 627 keV transitions is plotted in fig. 2c). Due to the doublet structure of the 609/610 keV line, the order of the two highest transitions (601 and 609 keV) could not be fixed unambiguously.

3.2 The level scheme of ^{161}Ho

Most information about high-spin states in ^{161}Ho comes from the work by L. Funke *et al.* [5]. In that work, the ^{159}Tb(α, 2n) reaction was employed and five rotational bands were observed up to a maximum spin value of 29/2. In a later study by E. Grosse *et al.* [6], the ^{154}Sm (^{11}B, 4n) reaction was used to extend the ground-state band up to the $(39/2^-)$ level; this work has been at that time the first proof "that backbending can occur in rotational bands in odd-A nuclei" leading to the important conclusion "that the $h_{11/2}$ proton is not strongly involved in the mechanism producing the backbending in this region". In the present experiment this band was observed up to spin $51/2^-$, well above the band crossing region and thus allowing the determination of the total angular-momentum gain (see sect. 4.1). The extension of the $7/2^+[404]$ band up to the $35/2^+$ state is illustrated in fig. 4a), which shows the double-gated coincidence spectrum with gates set on the 484 and 421 keV $23/2^+ \to 19/2^+ \to 15/2^+$ transitions within this band. Figure 4b) shows the spectrum with gates on the 525 and 552 keV γ-rays to testify the extension of the positive-signature sequence of the $1/2^+[411]$ band by six new $E2$ transitions up to spin $51/2^+$ well above the band crossing region. Finally, a spectrum with gates set on two transitions within the $1/2^-[541]$ band is given in fig. 4c). The complete level scheme of ^{161}Ho obtained in the present work is shown in fig. 5. In addition to these extensions, a new band (called band X in the following) consisting of cascade as well as crossover transitions has been observed for the first time (fig. 6). The sum of the coincidence spectra obtained with gates on two of the crossover transitions at a time is shown in fig. 4d). The observation of two lines at 47 and 54 keV suggests that this band belongs to one of the Ho isotopes since these are the energies of the Ho X-rays. Although three additional unknown transitions with 87, 141 and 180 keV are observed in coincidence with many of the inband transitions (compare also fig. 4d)), it was not possible to connect this band to any of the known rotational bands in the Ho isotopes and to fix its excitation energy and spin. Since ^{161}Ho is the by far strongest populated Ho isotope in the ^{160}Gd + ^{7}Li reaction at 56 MeV, it is most probable that this band belongs to this nucleus, although this tentative assignment cannot be proven on the basis of the present data.

3.3 The level scheme of ^{162}Ho

The high-spin information for the odd-odd isotope ^{162}Ho is scarce. Only one rotational band has been observed up to intermediate spins of 15^- in the ^{160}Gd (^{7}Li, 5n) reaction by J.R. Leigh *et al.* [7] and assigned to the $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ configuration. In the present work, this band could be considerably extended up to the 28^- state at 5881 keV. As for the band based on the same configuration in ^{160}Ho (see sect. 3.1), additional weak transitions feeding some of the odd-spin members of this band have been observed as shown in the level scheme in fig. 7. Examples of coincidence spectra for the two sequences corresponding to the two signatures are given in fig. 8.

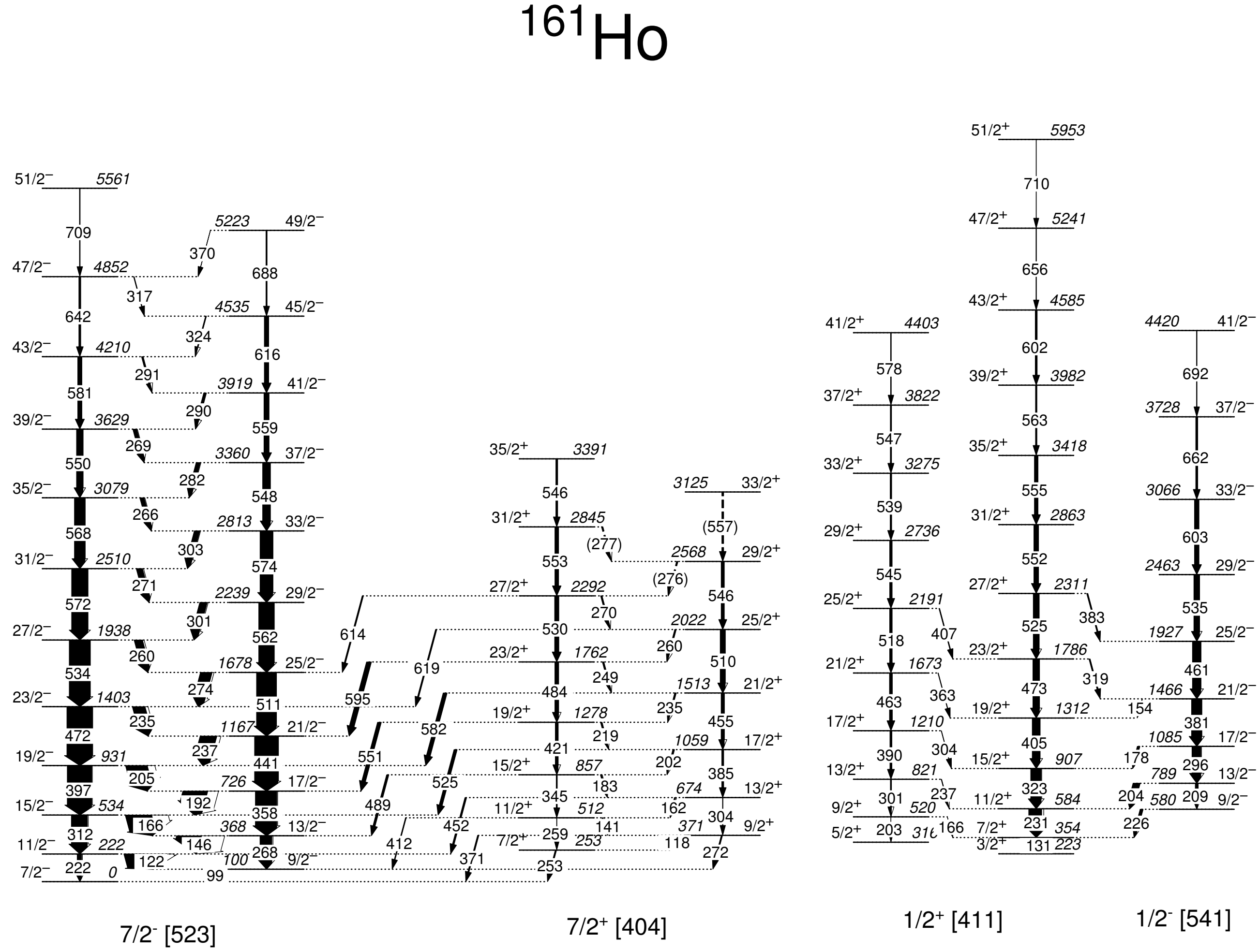

Fig. 5. The level scheme of ^{161}Ho as obtained in the present work.

4 Discussion

4.1 The odd-even isotopes ^{157,159,161}Ho

As discussed in the previous section, all rotational bands known in ^{161}Ho were extended up to spin values significantly higher than known before. In order to discuss the properties of these bands at high spin and compare them to the neighbouring ^{157}Ho and ^{159}Ho isotopes, plots of the aligned angular momentum *versus* the rotational frequency $\hbar\omega$ are shown in fig. 9. For further comparison the alignments for the yrast bands of the even-even neighbour isotopes ^{156,158,160}Dy are included in the figure as well. To determine the aligned angular momenta, a reference rotor with $I_{\mathrm{ref}} = (\mathcal{J}_0 + \mathcal{J}_1\omega^2)\frac{\omega}{\hbar}$ has been subtracted using the Harris parameters $\mathcal{J}_0 = 28\hbar^2/\mathrm{MeV}$ and $\mathcal{J}_1 = 110\hbar^4/\mathrm{MeV}^3$ (same as used in [1,2]).

The ground-state bands, which are based on the $7/2^-$ [523] $h_{11/2}$ proton single-particle orbital, show for all three isotopes ^{157,159,161}Ho a behaviour very similar to that of the respective neighbouring even-even Dy isotope (see left column of fig. 9). This agrees with the expectations since the energy of this single-particle orbit is rather independent of the deformation parameter and its occupation by the odd proton therefore does not lead to any significant change in the nuclear deformation. As a consequence, the neutron pair correlations remain unchanged and the band crossing due to the breaking of an $i_{13/2}$ neutron pair occurs at the same frequency of about $\hbar\omega \approx 0.28$ MeV as in the corresponding Dy isotope. The interaction strength between the two bands involved in this crossing is much larger in ^{159}Ho and ^{161}Ho than in ^{157}Ho as indicated by the upbend rather than a backbend for the $7/2^-$[523] band in these isotopes. This means that the maximum of the oscillating interaction strength observed within the chain of Dy isotopes for $N = 92$, 94 in ref. [1] is also found here for the Ho isotopes.

For the $1/2^+$[411] $d_{3/2}$ bands in ^{159,161}Ho (see right column of fig. 9), upbends are observed at about the same frequency as for the $7/2^-$[523] bands, namely around $\hbar\omega \approx 0.28$ MeV. Not only the frequency but also the shape of the alignment curve is very similar to that of the ground-state band, although the total alignment gain is a bit larger. Since the $1/2^+$[411] proton single-particle orbit is rather flat as a function of the deformation, the similarity between both bands is not too surprising. However,

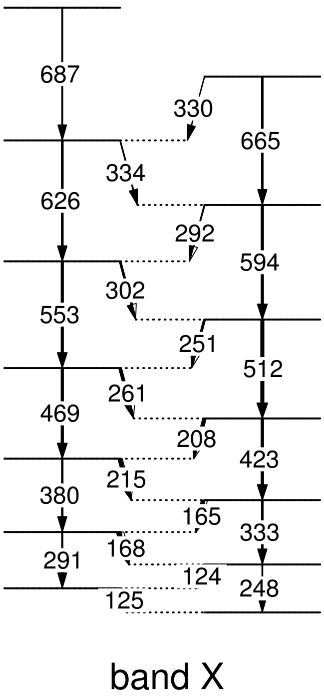

Fig. 6. The new band tentatively assigned to belong to ^{161}Ho.

the $1/2^+[411]$ band in ^{161}Ho shows a rather large signature splitting before the band crossing which is not observed in the case of the $7/2^-[523]$ band in this nucleus.

The alignment curves for the $1/2^-[541]$ $h_{9/2}$ bands in all three isotopes discussed are also displayed in the right column of fig. 9. All three bands show upbends around $\hbar\omega \approx 0.35$ MeV, a frequency much higher than that observed for the two bands discussed above. Part of this delay can be attributed to the large negative slope of this single-particle orbital which drives the nuclei into larger deformation. However, as noted already by Ying-Jun *et al.* [3], the observed delay is much larger than what can be expected due to the known 10% increase of β_2. There must be an additional reason for this large delay which, however, has not yet been found.

Finally, the alignment curves for the $7/2^+[404]$ $g_{7/2}$ bands in ^{157,159,161}Ho are shown in the middle column of fig. 9. They look again very similar to the ones for the $7/2^-[523]$ ground-state bands all showing band crossings around $\hbar\omega \approx 0.28$ MeV. This similarity is somewhat unexpected since the $7/2^+[404]$ proton single-particle orbit has a positive slope with increasing deformation. Therefore, one would expect a reduced deformation and a sharper backbending.

In all three odd Ho isotopes discussed, an energy splitting between the levels of different signature is observed for the negative-parity ground-state band in which the odd proton occupies the $7/2^-[523]$ Nilsson orbit. In fig. 10, the

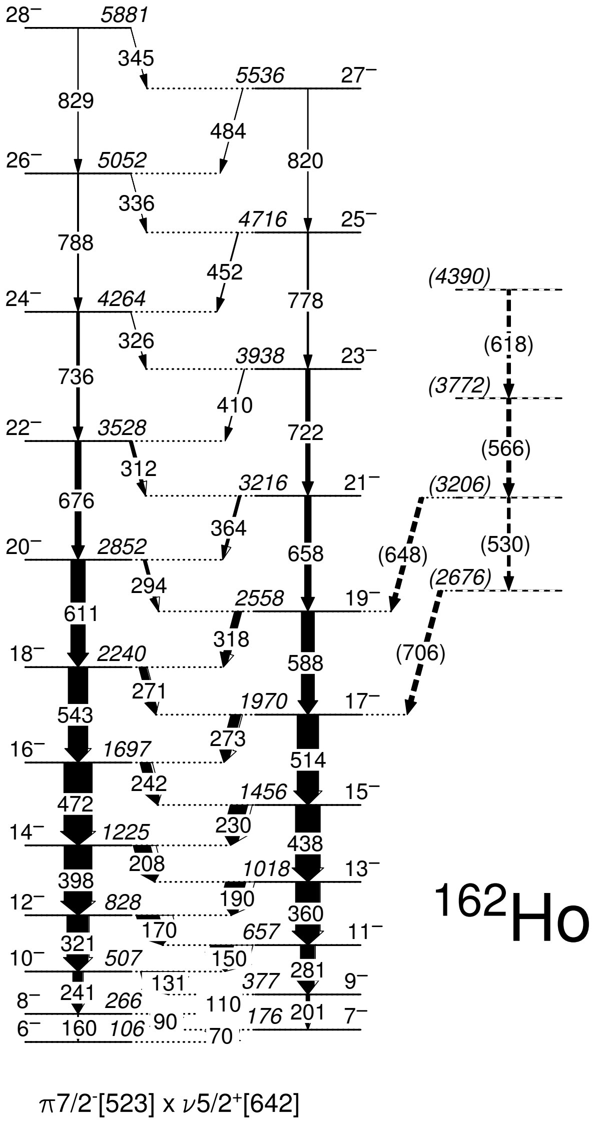

Fig. 7. The level scheme of ^{162}Ho as obtained in the present work.

quantity

$$S(I) = E(I) - E(I-1) - \Big[E(I+1) - E(I) + E(I-1) - E(I-2)\Big]/2 \qquad (1)$$

is shown as a function of the spin I. In all three isotopes, a very regular signature splitting is found before the first band crossing which is largest in ^{157}Ho (about 150 keV around spin 29/2), much smaller in ^{159}Ho (about 60 keV) and smallest in ^{161}Ho (about 30 keV). This enhanced splitting has been interpreted as evidence for a sizable negative γ deformation. The deviation from the axial symmetry might be due to the shape driving effect of the high-K $h_{11/2}$ proton orbital. As can be seen in fig. 10, the signature splitting in the $7/2^-[523]$ band reduces in all three isotopes immediately after the alignment of the

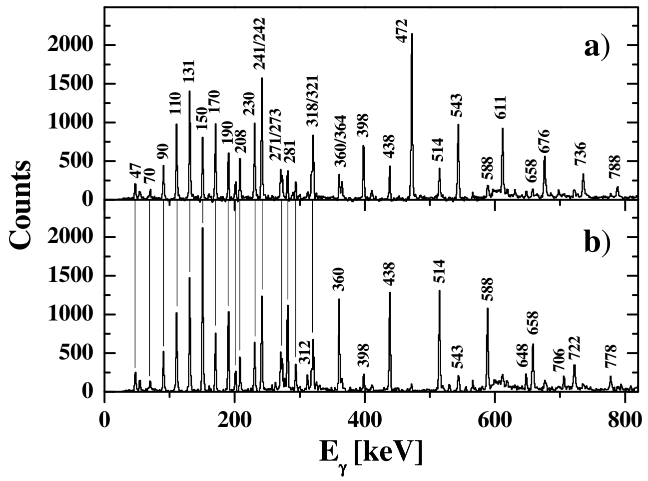

Fig. 8. Examples of double-gated coincidence spectra in ^{162}Ho. Shown are the sums of the spectra obtained in coincidence with two out of the following γ transitions: a) 321, 398, 472, 543, 611, 676, 736 and 788 keV transitions and b) 360, 438, 514, 588, 658, 722 and 778 keV within the $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ band.

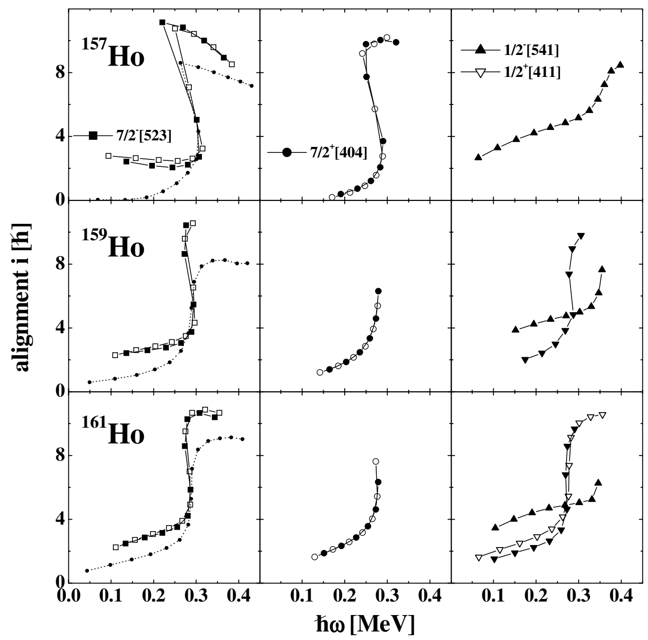

Fig. 9. Alignment plots for the rotational bands in ^{157}Ho (top row), ^{159}Ho (middle row) and ^{161}Ho (bottom row). States of positive and negative signature are shown as filled and open symbols, respectively. The Harris parameters used for the reference are $\mathcal{J}_0 = 28\hbar^2/\text{MeV}$ and $\mathcal{J}_1 = 110\hbar^4/\text{MeV}^3$. The alignments of the yrast bands in the even neighbours ^{156,158,160}Dy are included for comparison as small dots connected by lines in the left column.

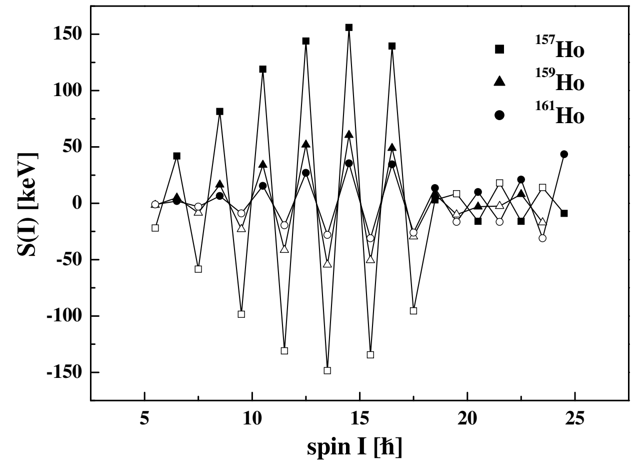

Fig. 10. Experimental energy differences $S(I)$ (see text for the definition) for the levels of the $7/2^-[523]$ bands in ^{157,159,161}Ho.

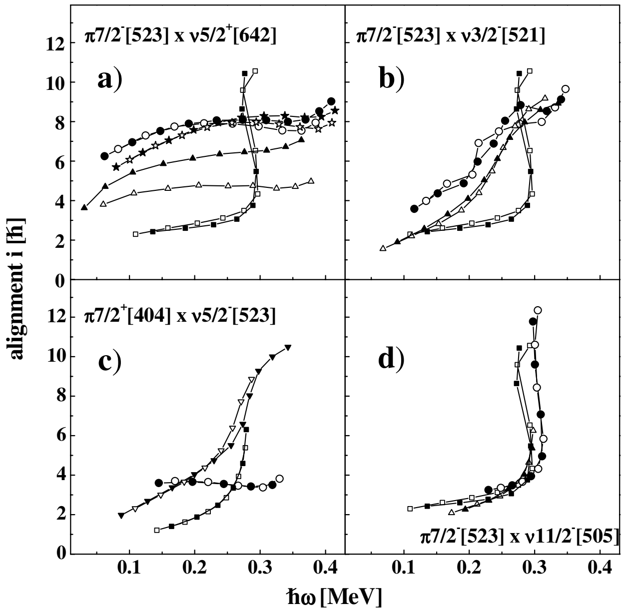

Fig. 11. Alignment plots for the four observed rotational bands in ^{160}Ho (circles) and the $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ band in ^{162}Ho (stars). For comparison, the following bands in the neighbouring odd-proton Ho (squares) and odd-neutron Dy (triangles) isotopes are shown, too: a) $7/2^-[523]$ in ^{159}Ho and $5/2^+[642]$ in ^{159}Dy, b) $7/2^-[523]$ in ^{159}Ho and $3/2^-[521]$ in ^{159}Dy, c) $7/2^+[404]$ in ^{159}Ho and $5/2^-[523]$ in ^{161}Dy and d) $7/2^-[523]$ in ^{159}Ho and $11/2^-[505]$ in ^{159}Dy. For all bands, the states of positive and negative signature are shown as filled and open symbols. The Harris parameters used for the reference are $\mathcal{J}_0 = 28\hbar^2/\text{MeV}$ and $\mathcal{J}_1 = 110\hbar^4/\text{MeV}^3$.

$i_{13/2}$ neutrons, *i.e.* these quasineutrons seem to cancel to a certain extent the negative γ driving effect of the $h_{11/2}$ quasiproton. Whereas the splitting reappears in ^{157}Ho after the band crossing with inverse sign, the phase does not change in ^{159,161}Ho, and in ^{161}Ho the size of the splitting reaches again the maximum value observed before the $i_{13/2}$ band crossing at around 49/2 .

4.2 The odd-odd isotopes ^{160,162}Ho

Plots of the aligned angular momentum as a function of the rotational frequency $\hbar\omega$ are shown in fig. 11 for the observed bands in the odd-odd isotopes ^{160,162}Ho. As mentioned before, all band assignments in ^{160}Ho were adopted from the work of Drissi *et al.* [4].

In fig. 11a), the experimental aligned angular momentum i is shown for the $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ bands in both ^{160}Ho and ^{162}Ho. For comparison, the corresponding curves for the $7/2^-[523]$ proton band and the $5/2^+[642]$ neutron band in the neighbouring odd-mass nuclei ^{159}Ho and ^{159}Dy (the latter taken from [2]) are included in this figure, too. Whereas the alignment curve for the $7/2^-[523]$ proton band in ^{159}Ho shows a clear upbend around $\hbar\omega \approx 0.3$ MeV due to the alignment of an $i_{13/2}$ neutron pair, this orbit is blocked by the unpaired neutron for the $5/2^+[642]$ band in ^{159}Dy and no band crossing is observed below 0.4 MeV for this band. Consequently, also for the $\pi 7/2^-[523] \otimes \nu 5/2^+[642]$ bands in ^{160,162}Ho no crossing is found and only at the highest observed frequencies around $\hbar\omega \approx 0.4$ MeV a slight upbend is visible.

In fig. 11b), the alignment curve for the $\pi 7/2^-[523] \otimes \nu 3/2^-[521]$ band in ^{160}Ho is compared to the $7/2^-[523]$ band in ^{159}Ho and the $3/2^-[521]$ band in ^{159}Dy. Since for this band the uncoupled neutron occupies the $h_{9/2}$ shell and not the $i_{13/2}$ orbit, the $i_{13/2}$ neutron alignment is not blocked and a smooth alignment increase is observed for this band in ^{159}Dy. The newly observed $\pi 7/2^-[523] \otimes \nu 3/2^-[521]$ band in ^{160}Ho shows a rather irregular behaviour not following a smooth curve. On average, however, the shape of the alignment curve for this band is very similar to that of the $3/2^-[521]$ band in ^{159}Dy. The observation of a third 10^+ state only 30 keV above the 10^+ member of the $\pi 7/2^-[523] \otimes \nu 3/2^-[521]$ band indicates the existence of at least one additional positive-parity band close in energy. The observed distortion might therefore probably result from mixing with this unknown band.

For the $\pi 7/2^+[404] \otimes \nu 5/2^-[523]$ band in ^{160}Ho, no upbend has been found up to a frequency of about 0.35 MeV (see fig. 11c)) although both the $7/2^+[404]$ band in ^{159}Ho as well as the $5/2^-[523]$ band in ^{161}Dy (this band was not observed in ^{159}Dy) exhibit band crossings below this frequency. Since the odd nucleons are occupying the $g_{7/2}$ and $f_{7/2}$ shells, respectively, neither an $h_{11/2}$ proton nor an $i_{13/2}$ neutron alignment is blocked and the non-occurence of any band crossing in the $\pi 7/2^+[404] \otimes \nu 5/2^-[523]$ band is rather astonishing. Finally, the $\pi 7/2^-[523] \otimes \nu 11/2^-[505]$ band (fig. 11d)) shows, as expected, a behaviour very similar to the one of both the $7/2^-[523]$ band in ^{159}Ho and the $11/2^-[505]$ band in ^{159}Dy with a pronounced upbend around $\hbar\omega \approx 0.3$ MeV, observed for the first time in the present work.

5 Conclusions

High-spin states in the neutron-rich ^{160,161,162}Ho isotopes have been studied via the reactions ^{158,160}Gd (^{7}Li, xn). In each of these nuclei, known rotational bands have been extended to considerably higher spins and a new band has been observed and tentatively assigned to the nucleus ^{161}Ho. The properties of the bands have been discussed and compared to the neighbouring nuclei. Whereas most bands show the expected behaviour the non-occurence of any band crossing in the $\pi 7/2^+[404] \otimes \nu 5/2^-[523]$ band in ^{160}Ho is surprising and asks for a critical investigation of the Nilsson assignment of this band. Furthermore, to clarify the origin of the very irregular behaviour of the $\pi 7/2^-[523] \otimes \nu 3/2^-[521]$ band in the same nucleus, the observation of a band built on the newly identified 10^+ state at 737 keV would be desirable.

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