High-spin yrast structure of ^{159}Ho

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An investigation of the yrast structure of the odd-Z ^{159}Ho nucleus to high spin has been performed. The ^{159}Ho nucleus was populated by the reaction ^{116}Cd(^{48}Ca,$p4n\gamma$) at a beam energy of 215 MeV, and resulting γ decays were detected by the Gammasphere spectrometer. The $h_{11/2}$ yrast band has been significantly extended up to $I^{\pi} = 75/2^{-}$ (tentatively $79/2^{-}$). A lower frequency limit for the second $(h_{11/2})^2$ proton alignment was extracted consistent with the systematics of this alignment frequency, indicating an increased deformation with neutron number in the Ho isotopes. The energy-level splitting between the signature partners in the $h_{11/2}$ structures of the Ho isotopes and the neighboring $N = 92$ isotones is discussed.

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High-spin spectroscopic studies in the $A \sim 160$ region of the nuclear chart have resulted in the discovery of many new nuclear phenomena. These include the first observation of backbending [1], of triaxial strongly deformed structures [2], of prolate to oblate shape changes via the mechanism of band termination [3], and the more recent discovery of the re-emergence of collectivity beyond band termination at ultrahigh spin ($\sim 60\hbar$) in $^{157-160}$Er [4,5]. Nuclei in this region are deformed prolate rotors at low spin and their yrast structure, with increasing angular momentum, comprises a multitude of rotational bands based on different quasiparticle configurations. In the present work, the $\pi h_{11/2}$ yrast band of $^{159}_{67}$Ho$_{92}$ has been studied up to high spin ($\sim 40\hbar$). The systematics of the crossing frequency of the second and third $(\pi h_{11/2})^2$ alignments in this region are discussed. The energy-level splitting between the signature partners of the yrast band in ^{159}Ho and the systematics of this splitting in the neighboring Ho isotopes and $N = 92$ isotones are presented.

The present experimental work was performed using the ATLAS facility at Argonne National Laboratory. Excited states in ^{159}Ho were populated with the (^{48}Ca,$p4n$) fusion-evaporation reaction using a 215-MeV beam of ^{48}Ca incident upon enriched (98.7%) targets of ^{116}Cd. These targets were comprised of two self-supporting ^{116}Cd foils with a total thickness of 1.3 mg/cm^2. The resulting γ decays were detected using the high-efficiency γ-ray spectrometer, Gammasphere [6,7]. A total of $\sim 1.9 \times 10^9$ events were collected when at least seven of the 101 Compton-suppressed HPGe detectors fired in prompt coincidence. The data were collected over a five-day period. Unfolding the events resulted in approximately 1.4×10^{11} triple and 3.5×10^{10} quadruple coincidence events, which were replayed off-line into RadWare-format three-dimensional (E_γ^3) cubes [8] and four-dimensional (E_γ^4) hypercubes [9] for subsequent analysis. As the nucleus ^{159}Ho was populated through the weak ($\sim 1\%$ of the total reaction cross section) $p4n$ channel, it was observed to high spin only because of the high efficiency and resolving power of the Gammasphere spectrometer. Results from the stronger $5n$ and $4n$ decay channels to ^{159}Er and ^{160}Er are reported in Refs. [5] and [10].

The yrast structure of ^{159}Ho is based on the odd proton occupying the $7/2^{-}[523]$ $h_{11/2}$ orbital. Prior to this work, the signature partners ($\alpha = -1/2$ and $+1/2$) of this $h_{11/2}$ structure had been observed up to $I^{\pi} = (47/2^{-})$ and $(49/2^{-})$, respectively [11], with the spin and parity of the states firmly established up to $35/2^{-}$ and $41/2^{-}$. In the present work, these signature partners have been extended up to $(79/2^{-})$ and $(73/2^{-})$, respectively. A partial level scheme for ^{159}Ho, assuming continuation of rotational structure to higher spin and the intensity measurements from Table I, are presented in Fig. 1.

Spectra produced by using sums of triple coincidence gates set in the E_γ^4 hypercube showing the signature partners of the $\pi h_{11/2}$ yrast band are presented in Fig. 2. For the $\alpha = -1/2$ sequence, seven, possibly eight, new transitions have been established, extending this band by 16 units of spin. Similarly, five, possibly six, new transitions were observed for the $\alpha = +1/2$ sequence, extending this band by twelve units of spin. The low statistics for the ^{159}Ho channel meant that it was not possible to perform an angular correlation analysis for the new transitions; consequently, the spin and parity assignments remain tentative.

The aligned angular momentum i_x [12] for the $h_{11/2}$ band of ^{159}Ho, plotted as a function of rotational frequency $\hbar\omega$,

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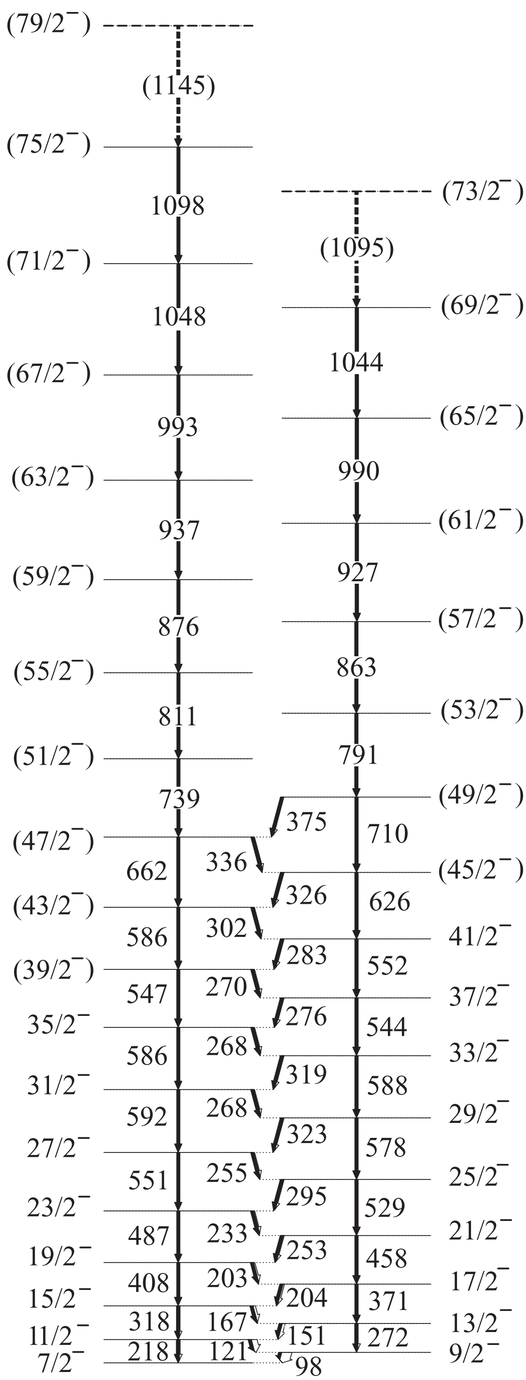

FIG. 1. Partial level scheme for ^{159}Ho of the lowest energy structure based on the $h_{11/2}$ $7/2^-[523]$ proton orbital. Energies are given to the nearest kiloelectronvolt. Parentheses and dotted lines indicate tentative assignments.

is presented in Fig. 3(a) along with that of the yrast band in the neighboring even-Z isotone ^{160}Er [10,13]. The initial alignments for the ^{159}Ho sequences compared with those of ^{160}Er are higher by $\sim 2.5\hbar$, which is consistent with an initial one-quasiproton configuration. A large gain in aligned angular momentum of similar magnitude is observed in all the bands at $\hbar\omega \sim 0.28$ MeV (Fig. 3). This is a result of the alignment of the lowest energy pair of $i_{13/2}$ neutrons.

TABLE I. Measured γ-ray energies E_γ and relative intensities I_γ^{rel} for the new transitions established in the signature partners of the $\pi h_{11/2}$ $7/2^-[523]$ structure of ^{159}Ho. Tentative spin and parity assignments are given. The intensity measurements have been normalized to the 738.9-keV ($51/2^- \rightarrow 47/2^-$) transition. The γ-ray energies are estimated to be accurate to ± 0.3 keV.

E_γ (keV)	I_γ^{rel}	I^π_{initial}	I^π_{final}
	$\alpha = -1/2$		
738.9	100	($51/2^-$)	($47/2^-$)
810.7	73.9(2.0)	($55/2^-$)	($51/2^-$)
876.1	53.7(2.2)	($59/2^-$)	($55/2^-$)
937.3	22.6(1.9)	($63/2^-$)	($59/2^-$)
993.3	20.8(1.6)	($67/2^-$)	($63/2^-$)
1048.4	16.8(2.1)	($71/2^-$)	($67/2^-$)
1098.0	16.3(2.9)	($75/2^-$)	($71/2^-$)
(1145)		($79/2^-$)	($75/2^-$)
	$\alpha = +1/2$		
791.3	62.5(1.5)	($53/2^-$)	($49/2^-$)
862.6	40.4(1.7)	($57/2^-$)	($53/2^-$)
927.2	17.4(1.7)	($61/2^-$)	($57/2^-$)
989.9	15.5(1.9)	($65/2^-$)	($61/2^-$)
1043.7	11.4(2.7)	($69/2^-$)	($65/2^-$)
(1095)		($73/2^-$)	($69/2^-$)

The first $(h_{11/2})^2$ proton alignment is established in ^{160}Er at $\hbar\omega \sim 0.48$ MeV. The new data in ^{159}Ho pushes both signatures well above this frequency and this alignment is not observed, as expected since the odd $h_{11/2}$ quasiproton blocks this in both signature sequences. At even higher frequency, the second and third $(h_{11/2})^2$ proton alignments are expected since they are not blocked in the $\alpha = -1/2$ and $\alpha = +1/2$ sequences, respectively. The second $(h_{11/2})^2$

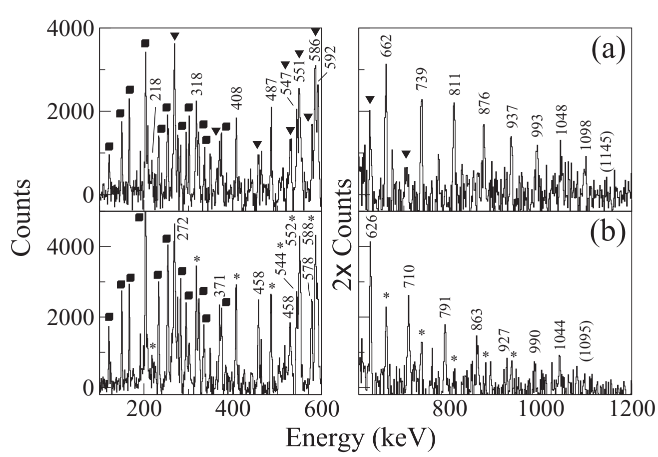

FIG. 2. γ-ray spectra obtained from sums of triple gates set on the low-spin interband and intraband transitions and (a) the $\alpha = -1/2$ transitions above ($43/2^-$) and (b) the $\alpha = +1/2$ transitions above ($41/2^-$) in ^{159}Ho. Photopeaks labeled with squares correspond to the low-energy interband transitions. Photopeaks labeled with triangles in (a) correspond to transitions associated with the $\alpha = +1/2$ signature partner, and photopeaks labeled with asterisks in (b) correspond to transitions associated with the $\alpha = -1/2$ signature partner. Energies labeled in parentheses indicate tentative transitions.

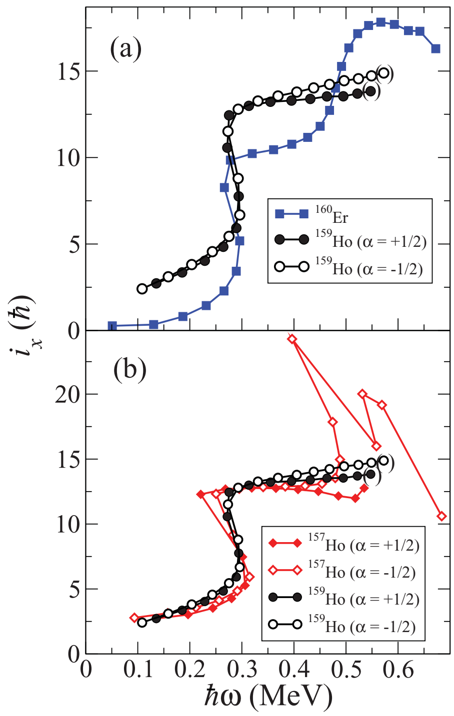

FIG. 3. (Color online) Aligned angular momentum i_x as a function of rotational frequency $\hbar\omega$ for (a) the $h_{11/2}$ band in ^{159}Ho and the yrast band in ^{160}Er, and (b) the $h_{11/2}$ band in ^{157}Ho and ^{159}Ho. A common reference [14] was extracted through a variable moment-of-inertia fit to the ground-state band of ^{160}Er with Harris parameters [15,16] of $\mathcal{J}_0 = 23\hbar^2$ MeV^{-1} and $\mathcal{J}_1 = 58\hbar^4$ MeV^{-3}.

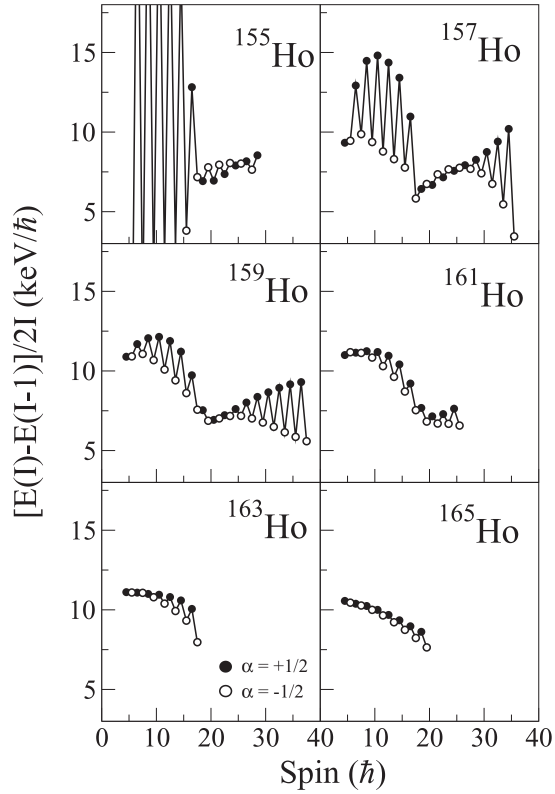

FIG. 4. Energy-level splitting as a function of spin for the $7/2^-[523]$ signature partner bands in ^{155}Ho [24], ^{157}Ho [17,18], ^{159}Ho, ^{161}Ho [25], ^{163}Ho [26], and ^{165}Ho [27].

proton alignment has been observed at $\hbar\omega \sim 0.48$ MeV in the $\alpha = -1/2$ sequence in ^{157}Ho [17,18] [see Fig. 3(b)]. The new data for ^{159}Ho place a lower frequency limit for this second proton alignment at $\hbar\omega > 0.55$ MeV. The increase in alignment frequency is consistent with the predictions from cranked shell-model calculations based on the Woods-Saxon potential [19,20], using the equilibrium deformations (β_2, β_4) for the lowest proton configurations taken from Ref. [21], where a shift of ∼0.05 MeV is predicted between ^{157}Ho and ^{159}Ho. This behavior of increasing proton alignment frequency with increasing neutron number is observed for the first $(h_{11/2})^2$ proton alignment in the neighboring even-Z erbium isotopes and is interpreted as evidence for a gradual increase in deformation as valence neutrons are added [22]. The same trend in the second proton alignment is also found in the odd-Z Tm isotopes [23]. The third proton alignment, which may start at $\hbar\omega \sim 0.54$ MeV in the $\alpha = +1/2$ sequence in ^{157}Ho, also appears to be delayed in ^{159}Ho [see Fig. 3(b)].

The energy-level splitting of the signature partners in the $h_{11/2}$ band in ^{159}Ho up to the first $(i_{13/2})^2$ neutron alignment is similar to that of the other odd-Z nuclei in this region (see Ref. [11] and references therein). This splitting has been interpreted as being caused by the shape-driving effect of the high-K $h_{11/2}$ quasiprotons [32] (where K is the projection of the total angular momentum on the symmetry axis). This causes the nucleus to deviate from axial symmetry toward triaxial shapes with negative γ values [33]. The splitting is reduced after the first alignment, as the aligning $i_{13/2}$ neutrons drive the nucleus back toward axial symmetry. Figure 4 presents the energy-level splitting for the $h_{11/2}$ signature partners of ^{159}Ho and the neighboring odd-A Ho isotopes. At spins below the first $(i_{13/2})^2$ neutron alignment, the splitting reduces in magnitude with increasing neutron number. After the first alignment, all the Ho isotopes established to high enough spin, showing a dramatic reduction in splitting, with some showing signature inversion. This inversion effect occurs when the initially energetically unfavored $\alpha = +1/2$ states (solid circles in Fig. 4) fall in energy to become lower than the favored $\alpha = -1/2$ states (open circles in Fig. 4). This is evident in ^{157}Ho [17,18] and more so in ^{155}Ho [24]. This has been interpreted as a shape change from negative to positive γ triaxial deformation [34]. Signature inversion is not seen in ^{161,163,165}Ho, and in ^{159}Ho there is almost zero signature splitting directly after the first alignment, which would indicate $\gamma \sim 0^\circ$. The signature splitting re-emerges after the $(i_{13/2})^2$ neutron alignment earlier in spin with increasing neutron number for the Ho isotopes.

The systematics of energy-level splitting between signature partners in the neighboring $N = 92$ isotones is presented in Fig. 5. Before the $(i_{13/2})^2$ neutron alignment, signature splitting is minimum in ^{159}Ho. After the first neutron alignment, as the number of protons increases the re-emergence of signature splitting is delayed and signature inversion becomes more prevalent. More data at high spin is sought for the

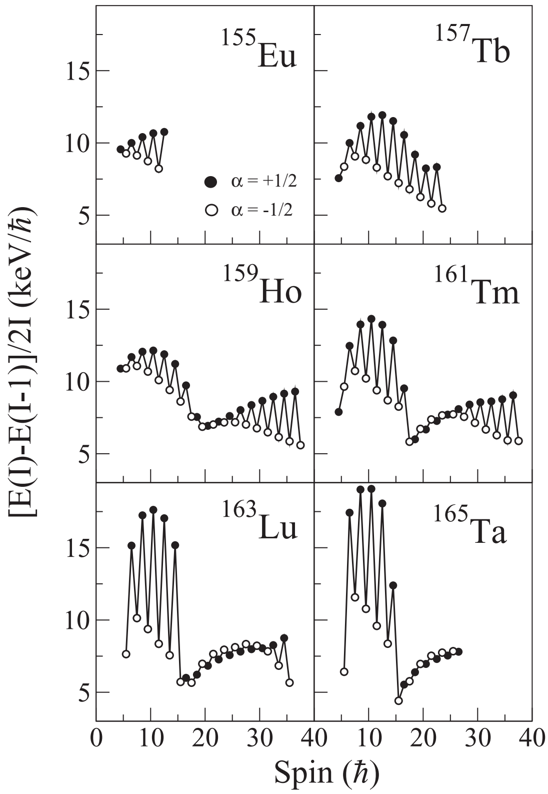

FIG. 5. Energy-level splitting as a function of spin for the $\pi h_{11/2}$ signature partner bands in the $N = 92$ isotones ^{155}Eu [28], ^{157}Tb [28], ^{159}Ho, ^{161}Tm [29], ^{163}Lu [30], and ^{165}Ta [31].

heavier isotones to verify whether this trend continues. The return of signature splitting at high rotational frequency may be a consequence of the negative-γ driving influence of the high-K $\pi h_{11/2}$ quasiprotons dictating the nuclear shape once more or the influence of low-Ω $\pi h_{9/2}$ orbitals approaching the Fermi surface with increasing frequency. The spin at which significant signature splitting re-emerges has been discussed [35] to have a large dependency on the quadrupole deformation and on the placement of the proton and neutron Fermi surfaces (λ), although a consistent theoretical picture has not yet fully emerged. It has also been proposed to be caused by the second proton alignment itself in some cases [35]; however, the present work in ^{159}Ho establishes energy-level splitting of the signature partners at high spin, even though there is no evidence of this alignment.

In summary, the signature partners of the yrast band in ^{159}Ho, which is based on the $7/2^-[523]$ $\pi h_{11/2}$ orbital, have been extended up to $I^\pi = (79/2^-)$ and $(73/2^-)$. A lower limit of $\hbar\omega > 0.55$ MeV for the rotational frequency at which the second $(h_{11/2})^2$ proton alignment occurs is established. This increase in alignment frequency with neutron number is associated with the systematic increase in deformation. The trends in the signature splitting of the neighboring Ho isotopes and $N = 92$ isotones are discussed.

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