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Complete valence particle yrast lines in $N=84$ nuclei above gadolinium

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Gamma-ray measurements following fusion-evaporation reactions have identified in the $N=84$ isotones from Ho to Yb the complete yrast lines formed by the configurations $\pi h_{11/2}^{n}\nu f_{7/2}^{2}$ and $\pi h_{11/2}^{n}\nu f_{7/2}h_{9/2}$ from the nuclear ground states up to their highest spins near $25\hbar$ at 5–8 MeV excitation. Their energies are predicted with high accuracy in parameter-free shell model calculations using experimental one- and two-body matrix elements. [S0556-2813(96)50107-X]

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In spherical open-shell nuclei the angular momentum along the yrast line is acquired by the successive alignment of the individual valence nucleons, forming angular momentum coupled multiparticle configurations. Quantitative energy analysis of such multiparticle states requires as input data the nucleon-nucleon residual interactions, but in heavy nuclei these dynamic quantities can rarely be calculated from theory with sufficient accuracy. Instead, shell model analyses that make use of empirical input data, where available, are more successful for the respective region of nuclei. In the present paper, we report experimental investigations of a series of $N=84$ isotones above the $^{146}_{64}\mathrm{Gd}_{82}$ core that have identified all yrast states formed within the two configurations $\pi h_{11/2}^{n}\nu f_{7/2}^{2}$ and $\pi h_{11/2}^{n}\nu f_{7/2}h_{9/2}$ ($n=Z-64$) from the ground states up to their maximum aligned spins in $^{151}_{67}$Ho, $^{152}_{68}$Er, and $^{153}_{69}$Tm, and up to 24 in $^{154}_{70}$Yb. The observed level energies are shown to be in excellent agreement with shell model predictions for which single particle energies and two-body matrix elements were taken from experiment, thus exploiting recent results for the key two-body multiplets located in the three $A=148$ two-valence particle nuclei $^{148}\mathrm{Gd}_{84}$, $^{148}_{65}\mathrm{Tb}_{83}$, and $^{148}_{66}$Dy. For the $\pi h_{11/2}^{n}\nu f_{7/2}^{2}$ configuration the proton seniority is found to increase monotonically along the yrast line, but this rule is violated for the yrast sequence of the $\pi h_{11/2}^{n}\nu f_{7/2}h_{9/2}$ configuration.

The yrast lines in $N=82$ nuclei above Gd are dominated by the gradual alignment of protons in the $h_{11/2}$ shell, and in the yrast states at $N=83$ the valence neutron couples to these proton excitations. At $N=84$, the two valence neutrons in $f_{7/2}$ provide up to 6 units of angular momentum below 2 MeV excitation, and the $6^{+}\rightarrow4^{+}\rightarrow2^{+}\rightarrow0^{+}$ transition sequence forms the lowest portion of the yrast cascade in the even-Z nuclei, while in the odd-Z species a similar triple $E2$ cascade connects the $(\pi h_{11/2}\nu f_{7/2}^{2})23/2^{-}$ state to the $11/2^{-}$ ground state. The next high-j neutron orbital is $h_{9/2}$; together with the $f_{7/2}$ neutron it forms a low-lying 8^{+} state which is also strongly populated in the yrast cascade. Above, the yrast line continues with $\pi h_{11/2}^{2}$ coupled to 10, followed again by the 2^{+} to 8^{+} couplings of the two valence neutrons, giving $I^{\pi}=12^{+}$ to 18^{+} in the even-Z and $31/2^{-}$ to $43/2^{-}$ in the odd-Z species.

In the present work, these multiparticle yrast states were investigated in the $N=84$ nuclei $^{151}_{67}$Ho, $^{152}_{68}$Er, $^{153}_{69}$Tm, and

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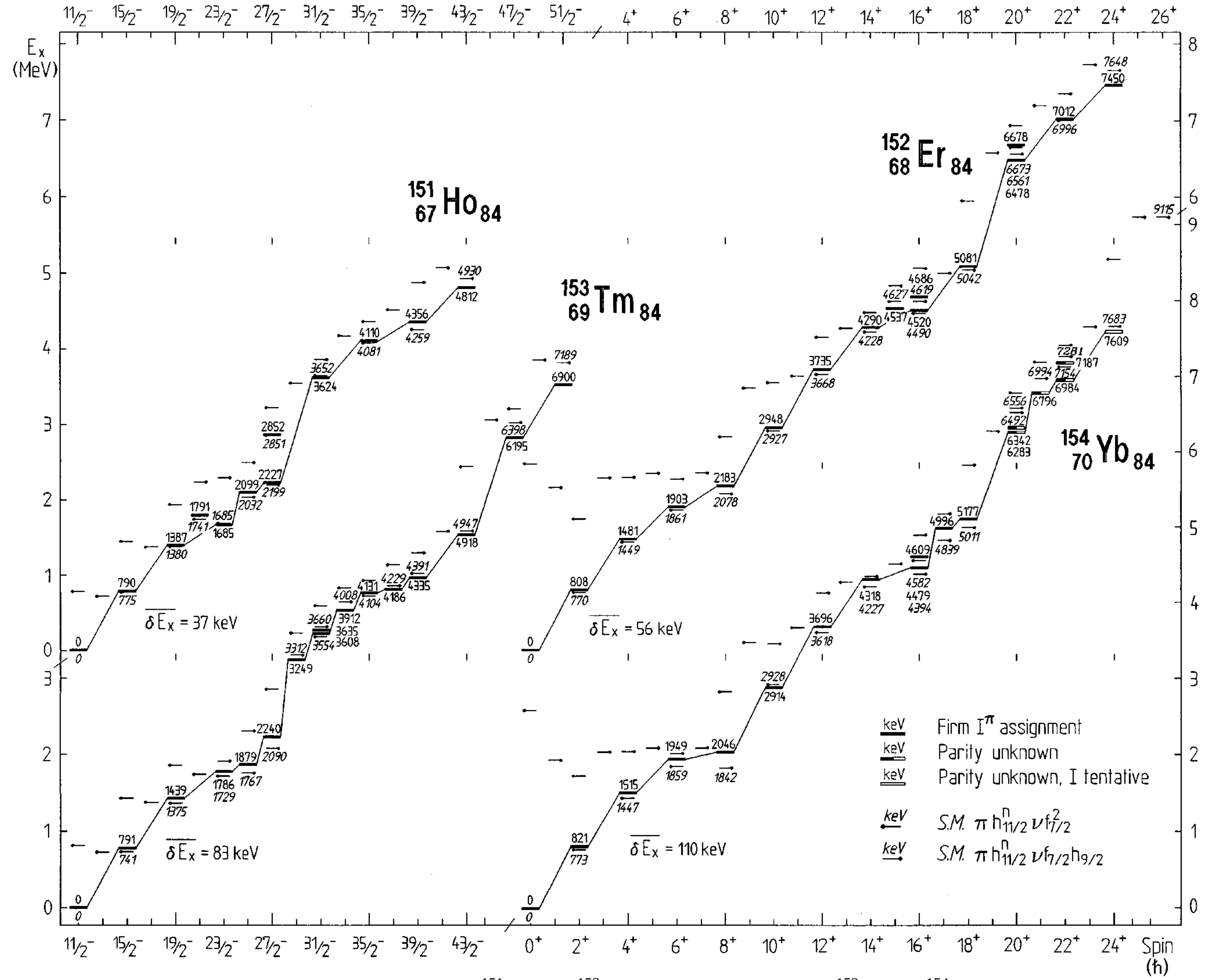

FIG. 1. The observed yrast states of odd-parity in ^{151}Ho and ^{153}Tm, and of even-parity in ^{152}Er and ^{154}Yb. The data are compared with the results from shell model calculations of the $\pi h^n_{11/2}\nu f^2_{7/2}$ and $\pi h^n_{11/2}\nu f_{7/2}h_{9/2}$ configurations ($n=Z-64$). The configuration is indicated for each calculated state, and for each spin the calculated energy for the lowest unobserved level is also shown. The mean absolute deviation δE of theory from experiment in keV is shown for each nucleus.

$^{154}_{70}$Yb. Their high-spin states were excited in heavy ion induced fusion-evaporation reactions, and the level schemes were established in γ-ray measurements with the 20-detector Nordball array, giving coincidence, angular distribution, and intensity information. The pertinent high-spin states of the four nuclei are summarized in Fig. 1, with lines connecting the observed yrast levels within the joint two configurations. A few yrast states of opposite parity, containing an octupole phonon, or with a proton in $s_{1/2}$ or $d_{3/2}$ occur in ^{151}Ho and ^{153}Tm above 2.8 MeV, but are omitted from Fig. 1 since they are not included in our analysis. The $^{151}_{67}$Ho yrast states were observed up to 10 MeV excitation with spins assigned up to 49/2 at 6.2 MeV [1]. Of interest here is the odd-parity level sequence from the $11/2^-$ ground state up to $43/2^-$ at 4.812 MeV, the maximum aligned $\pi h^3_{11/2}\nu f_{7/2}h_{9/2}$ state [1,2]. The $^{152}_{68}$Er high spin states were recently investigated [3] in reactions with higher angular momentum input than in our experiment. We agree with the previous assignments up to 18^+ at 5.081 MeV, but assign $E1$ multipolarity to an intense 330 keV γ-ray deexciting the 7.450 MeV $I=24$ level, which gives even parity for that state and for the next three levels shown below it in Fig. 1. In ^{153}Tm, levels up to 9.2 MeV and spin 57/2 were established, with the odd-parity sequence up to $51/2^-$ at 6.900 MeV firmly characterized [4]. The highest state observed in $^{154}_{70}$Yb is an $I=(24)$ level at 7.610 MeV; firm spin-parities are established up to 18^+, confirming earlier [5] tentative assignments.

The pertinent yrast states for the four nuclei are compiled in Fig. 1 where they are compared with excitation energies calculated from the shell model for the $\pi h^n_{11/2}\nu f^2_{7/2}$ and $\pi h^n_{11/2}\nu f_{7/2}h_{9/2}$ configurations. We note that two levels with the same I^π are detected only in cases where theory predicts two close neighbors, and $E2$ decay occurs when $M1$ deexcitation is energetically excluded or predicted to have low energy.

To calculate the couplings of the valence particles distributed in the three orbitals of the configurations one needs in total 36 diagonal two-body interactions and one single particle energy separation, viz. $\nu h_{9/2}$ to $\nu f_{7/2}$, taken as 1397 keV, as observed in the one-neutron nucleus $^{147}_{64}$Gd$_{83}$. The

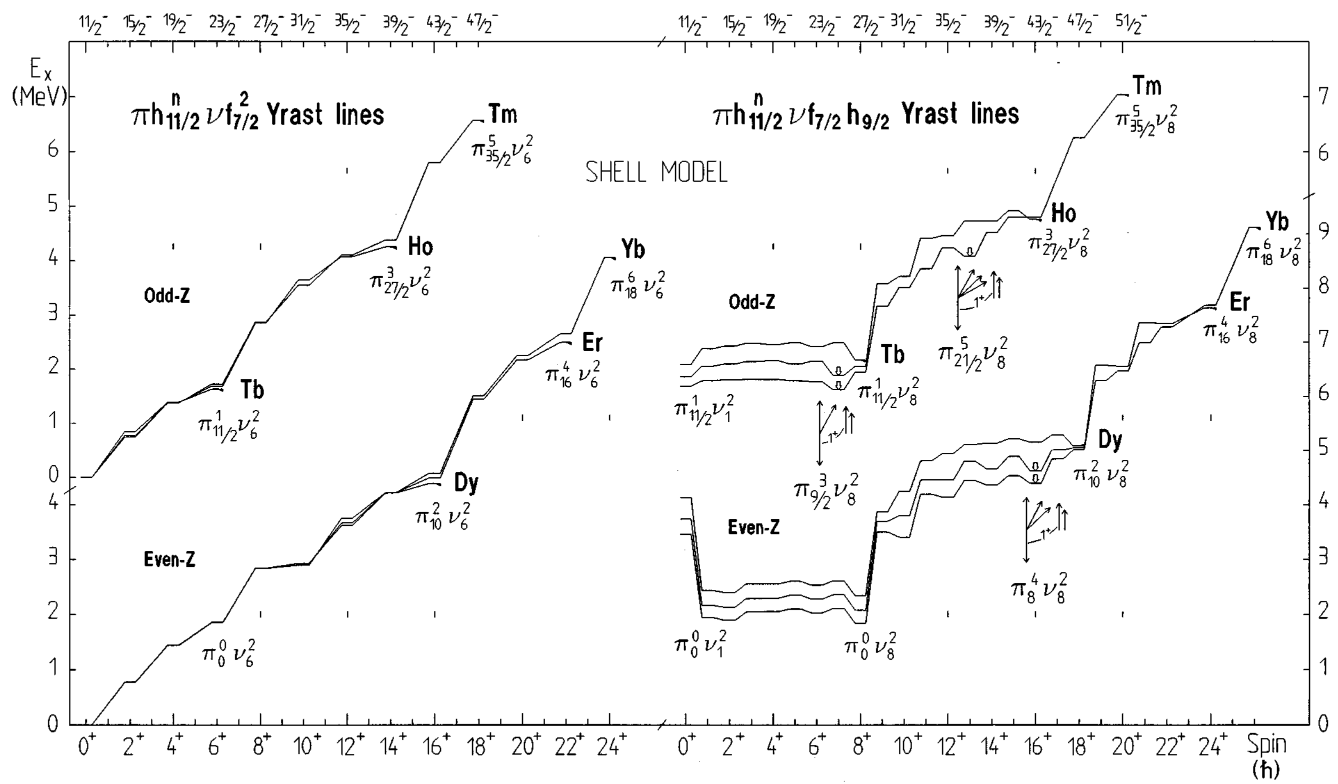

FIG. 2. Comparison of the configuration yrast lines calculated for the six $N=84$ isotones from ^{149}Tb to ^{154}Yb for $\pi h^n_{11/2}\nu f^2_{7/2}$ (shown to the left) and for $\pi h^n_{11/2}\nu f_{7/2}h_{9/2}$ (to the right). For the respective yrast line termination the isotope and the aligned valence particle spin is indicated, where the exponent to the proton specifies the dominant proton $h_{11/2}$ seniority v_p (rather than n). The states marked with an open arrow are strongly lowered in energy through the $(\pi h_{11/2}\nu h_{9/2})1^+$ attraction selectively activated in these states. This is indicated by the angular momentum coupling diagrams, where the two arrows to the right represent the $h_{9/2}$ and $f_{7/2}$ neutrons coupled to 8^+, and the arrows to the left symbolize the n protons coupled to the spin given in the configuration shown below.

$h^2_{11/2}$ $\pi\pi$ interaction is fully specified by the six lowest even-parity yrast states of $^{148}_{66}\mathrm{Dy}_{82}$, and similarly the $f^2_{7/2}$ $\nu\nu$ interaction is taken from the 0^+ to 6^+ sequence of $^{148}_{64}\mathrm{Gd}_{84}$. In Li-induced in-beam experiments [6] the complete $\pi h_{11/2}\nu f_{7/2}$ multiplet in $^{148}_{65}\mathrm{Tb}_{83}$ and also the three highest-spin $\pi h_{11/2}\nu h_{9/2}$ states were identified, and estimated energies are given for the intermediate 2^+ to 7^+ levels where the residual interaction is expected to be small. The important highly attractive $(\pi h_{11/2}\nu h_{9/2})1^+$ state is firmly established in ^{148}Dy Gamow-Teller decay. Likewise, the $\nu f_{7/2}\nu h_{9/2}$ 8^+, 7^+, and 6^+ levels are observed in $^{148}_{64}\mathrm{Gd}_{84}$, and the members with $I\leqslant 5$ were estimated from data in $^{210}_{84}\mathrm{Po}_{126}$ [7], where the complete $\pi f_{7/2}\pi h_{9/2}$ multiplet is known. A compilation of these input data is given in Ref. [8]. The level energies for the $N=84$ nuclei were calculated separately for each configuration, by fractional parentage decomposition into the two-body substructures, and matrix diagonalization.

The overall agreement of theory and experiment is excellent, with average deviations of less than 0.12 MeV, as indicated for each nucleus in Fig. 1. In light of these results, and keeping in mind that no other levels of the same parity are expected in these ranges of the yrast lines, the configuration assignments based on comparison with theory can be considered firm. It is worth mentioning that Gamow-Teller decay of the respective $N=83$ 9^+ and $27/2^-$ parents [9–12] independently establishes $\pi h^n_{11/2}\nu f_{7/2}h_{9/2}$ character for the 8^+ yrast states in ^{152}Er and ^{154}Yb, and for the $25/2^-$ state in ^{151}Ho.

Figure 1 shows a trend for the maximum-aligned states to be calculated too high in energy, e.g., in ^{153}Tm by as much as 0.3 MeV. A similar trend is known in the $N=82$ nuclei ^{150}Er and ^{151}Tm, where the maximum-aligned 16^+ and $35/2^-$ $\pi h^n_{11/2}$ states are also calculated [13] to lie a few hundred keV above their experimental energies [14]. Accordingly, this particular mismatch at $N=84$ is an expected one which in no way weakens the proposed assignments.

We have normalized the calculated and experimental level energies in Fig. 1 at the ground states. The ground state binding energies of the four $N=84$ nuclei calculated with the shell model using as input data the known masses of the $^{146}_{64}\mathrm{Gd}_{82}$ core and its five one- and two-valence particle neighbors [15] are in good agreement (within $<$ 200 keV) with experiment, although for the seven- and eight-valence particle ground state configurations the errors propagated in their decomposition are unavoidably large.

For a more detailed discussion we present in Fig. 2 the calculated yrast lines for each of the two configurations in the six $N=84$ isotones from $^{149}_{65}$Tb to $^{154}_{70}$Yb. The full recoupling calculation for the $\pi h^n\nu f^2$ configuration gives essentially identical yrast lines for the three even-Z as well as for the three odd-Z species, in good agreement with experimental findings. This clear similarity, especially for the levels up to 10^+ and $27/2^-$, indicates that here the proton interaction remains diagonal in the seniority scheme, i.e., that the proton seniority will increase monotonically along the yrast line [16].

There are two principal effects which give rise to the different properties of the $\pi h^n \nu f h$ yrast lines shown to the right. First, while the two-neutron $\nu\nu f^2$ interaction increases monotonically with spin, essentially only a single state is yrast in the $\nu\nu f h$ family, viz. $I_{\max}=8^+$; the remaining 1^+ to 7^+ couplings lie above it. This is apparent in the even isotones where the 8^+ yrast state is always $\nu f_{7/2} h_{9/2}$. The second effect originates from the significantly larger spin-averaged proton neutron interaction for the $h_{9/2}$ neutron of -0.41 MeV compared to -0.28 MeV for the $\pi h_{11/2} \nu f_{7/2}$ average interaction. This difference becomes more obvious in the even-Z $N=83$ nuclei with a $\nu f_{7/2}$ ground state, where the excitation energy of the $\nu h_{9/2}$ state decreases regularly with the addition of $h_{11/2}$ proton pairs from 1.397 MeV in ^{147}Gd to 0.567 MeV in ^{153}Yb, a trend which within 10 keV is reproduced [5] in respective $\pi h^n \nu f$ and $\pi h^n \nu h$ multiparticle calculations using the present two-body interactions. This same trend is reflected at $N=84$ in the regular energy decrease with Z of the $\nu f_{7/2} h_{9/2}$ 8^+ yrast state and likewise of the (not observed) lower spin levels of the configuration. Above 8^+, where at least one proton pair is broken, the Z dependence of the level energies naturally becomes irregular since now the individual $\pi h \nu h$ couplings no longer contribute with their statistical weights.

A particularly transparent and interesting result is the nature of the levels marked in Fig. 2 with an arrow, which all are significantly lowered in energy compared to their neighbors. In these states the strongly attractive $(\pi h_{11/2} \nu h_{9/2})1^+$ two-body interaction is selectively activated giving rise to this pronounced energy depression. All these states involve proton couplings where both the $m=+11/2$ and $-11/2$ substates are occupied. In the pure πh^n configurations at $N=82$, these states should [12] lie 920 to 350 keV above the maximum aligned proton state of next lower seniority. As shown in the vector coupling diagrams of Fig. 2, the antiparallel coupling of the $h_{9/2}$ neutron to one of the $h_{11/2}$ protons fully exploits the $(\pi h \nu h)1^+$ attraction. As a consequence these states are lowered in energy and occur at $N=84$ 130 to 730 keV below their respective lower-seniority maximum spin states (cf. Fig. 1), where the 1^+ coupling is inhibited. It is apparent that these states destroy the monotonic increase of the proton $h_{11/2}$ seniority along the yrast line.

An important aspect of the present investigation is the overall very good agreement of theory and experiment for nuclei with up to eight valence particles covering a wide range of excitation energy and spin, including the ground state. Theoretical shell model results of similar accuracy have so far not been reported for yrast states in heavy nuclei; the closest example may be the early analysis for Dy isotopes with up to 4 valence neutrons [17], which very successfully predicted their yrast lines over a spin interval of $7\hbar$ at high excitation (using Schiffer-True interactions adjusted to reproduce low lying levels in these nuclei). The present success can be attributed to the exclusive use in our analysis of experimental two-body matrix elements, since current nuclear theory can predict these quantities only within an accuracy near a factor 2. Although the experimental input data may not represent the pure configurations, the admixtures often remain essentially unaffected in high-spin states, and the present treatment in general compensates these energy shifts to second order. We note however that complete identification of the required two-body excitations often needs dedicated and unconventional experiments [6], and at present similar analyses in other regions may be hindered by a lack of input data.

It should not escape attention that our calculated results are parameter free since the theory exploits exclusively the symmetries of angular momentum coupled multiparticle configurations while all dynamic input quantities are extracted from experiment. The excellent agreement obtained demonstrates the high predictive power of such shell model analysis for heavy nuclei.

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