



Highly deformed bands in Nd nuclei: New results and consistent interpretation within the cranked Nilsson-Strutinsky formalism

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The present work has been triggered by the new results obtained from a high-statistics JUROGAM II experiment [? ? ? ? ?], which allowed to extend the known HD bands of ^{136}Nd and ^{137}Nd at lower and higher spins, and the identification of three new HD bands in ^{136}Nd . The HD bands of ^{134}Nd , ^{136}Nd and ^{137}Nd nuclei are interpreted in the framework of the Cranked Nilsson-Strutinsky (CNS) model [? ? ?]. We included in the present work the analysis of the HD bands of ^{134}Nd because they are all linked to low-lying states and therefore have firmly established spins and parities. Their consistent interpretation can therefore give a solid starting point for the analysis of the HD bands in the neighboring ^{136}Nd , in which four bands are not linked to low-lying states. The HD bands of ^{134}Nd and ^{136}Nd which are linked to low-lying states are well reproduced by the calculations. The energies, spins and parities of the HD bands which are not linked to low-lying states are adjusted to be in agreement with the lowest excited CNS configurations in the high-spin region. The proposed interpretation suggests the involvement of two $\nu[541]1/2$ negative-parity intruder orbitals, leading to positive parity, which is different from the previously reported negative parity of the yrast HD bands of ^{134}Nd and ^{136}Nd , and represents a consistent description of the HD excitations in the second minimum of the Nd nuclei.

High-spin states in $^{136,137}\text{Nd}$ were populated using the $^{100}\text{Mo}+^{40}\text{Ar}$ reaction and a 152-MeV beam of ^{40}Ar , provided by the K130 Cyclotron at the University of Jyväskylä, Finland. The target consisted of a self-supporting enriched ^{100}Mo foil of 0.5 mg/cm² thickness. The ^{135}Nd and ^{136}Nd nuclei were the most strongly populated in the reaction, with cross sections of around 100 mb each. The ^{137}Nd nucleus was populated with a lower cross section of around 2 mb. A number of 5.1×10^{10} three-fold and higher prompt γ -ray coincidence events were accumulated using the JUROGAM II array. The events were time-stamped by the Total Data Readout (TDR) data acquisition [?], and sorted using the GRAIN code [?]. Fully symmetrized, three-dimensional (E_γ - E_γ - E_γ) and four-dimensional (E_γ - E_γ - E_γ - E_γ) matrices were analyzed using the RADWARE [? ?] analysis package.

A double-gated spectrum of band HD of ^{137}Nd is shown in Fig. 1. Double-gated spectra of the three new HD bands HD-2, HD-4 and HD-5 of ^{136}Nd are shown in Fig. 2, together with double-gated spectra of the previously known HD bands (HD1 and HD3 in the present work). The partial level schemes of ^{136}Nd and ^{137}Nd and the table with the experimental information on the new transitions are given in the supplemental material [?].

We observed five new levels (the highest one being tentative) which decay via the 1770, 1827, 1813 and 1909 keV (and a tentative 1977-keV transition) on top of the HD band of ^{137}Nd . A crossing is observed at spin around 105/2 \hbar , which is associated with a gain in alignment of a few units of spin. A new transition of 625.8 keV has

been identified at the bottom of the HD band, which now is based on the 25/2⁺ state at 4257.3 keV. Two new decay-out transitions have also been identified (see Fig. 2 of the supplemental file [?]): 1475.6 and 1629.0 keV from the 29/2⁺ and 25/2⁺ states of the HD band, to the 25/2⁺ state at 3411 keV and the 23/2⁺ state at 2631 keV, respectively [?].

The highest transition of band HD yrast of ^{136}Nd (HD1 in the present work) of 1815 keV reported previously [?], is not observed; we observed instead one new transition of 1842 keV on top of the band. The excited HD band reported previously [?] (HD3 in the present work), has been extended to lower spins by one transition of 825 keV. The highest 1525-keV transition of band HD3 reported previously is not observed in the present data. We observe two new transitions of 1509 and 1573 keV on top of band HD3. Three new HD bands (HD2, HD4 and HD5) are identified in the present work. The intensities of the bands normalized to the relative intensity of band HD1 which is around 1%, are 0.3% for HD2, 0.2% for

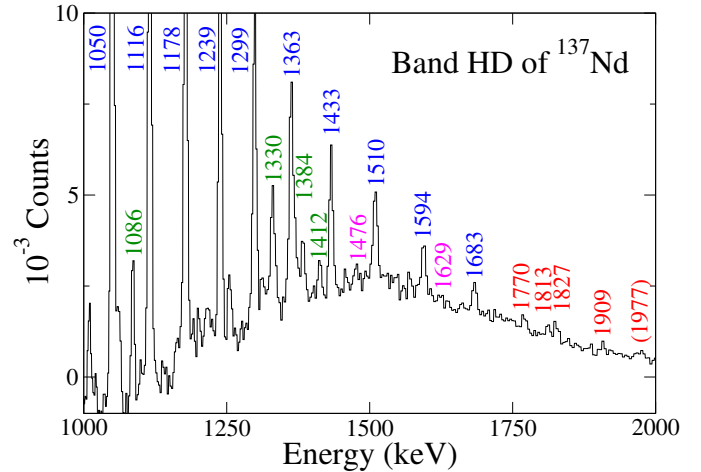


FIG. 1. (Color online) Spectrum constructed by double-gating on all observed transitions of band HD of ^{137}Nd . The new in-band (decay-out) transitions are marked with red (magenta) labels, while the previously known in-band (decay-out) transitions are marked with blue (green) labels, respectively.

In the CNS formalism, the nucleus rotates about one of its principal axes and pairing is neglected. The deformation is optimized for each configuration. The configurations are labelled by the number of particles in low- j and high- j orbitals, in the different \mathcal{N} -shells. They can be defined relative to a ^{132}Sn core as,

$$\pi(dg)^{p_1}(h_{11/2})^{p_2}\nu[(dg)(sd)]^{-n_1}(h_{11/2})^{-n_2}(hf)^{n_3}(i_{13/2})^{n_4},$$

for which the short-hand notation $[p_1p_2, n_1n_2(n_3n_4)]$ is used. The pseudo-spin partners $d_{5/2}g_{7/2}$ (dg) and $s_{1/2}d_{3/2}$ (sd) are not distinguished in the CNS formalism. Note that all particles are listed and not just those

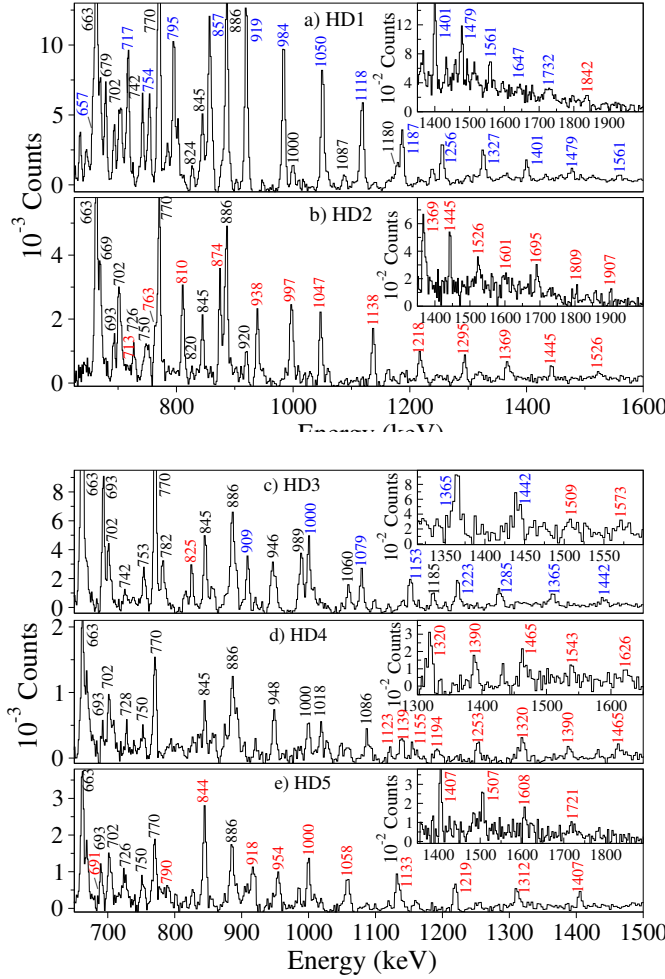


FIG. 2. (Color online) Spectra constructed by double-gating on the observed transitions of the bands HD of ^{136}Nd : a) and b) bands with assigned positive-parity; c), d), e) bands with assigned negative-parity. The previously known transitions are marked with blue labels, the new transitions marked with red labels, while the coincident ND transitions are marked with black labels.

considered as active (unpaired). Note also that the labels do not refer to the pure j -shells, but rather to the dominating amplitudes in the Nilsson orbitals. For an odd number of particles in a group, the signature is specified as a subscript $+$ ($\alpha = +1/2$) or $-$ ($\alpha = -1/2$). We will use the so-called Lund convention for the triaxiality parameter γ in relation to the main rotation axis, where for the positive γ shape, $0 < \gamma < 60^\circ$, the rotation (x) axis is the shortest principal axis, while for the negative γ shape, $-60^\circ < \gamma < 0$, it is the intermediate principal axis. In the present calculations the $A = 130$ parameters are used. They are identical with the $A=110$ parameters [?] in the valence space, $N=4,5$, but with μ increased from 0.34 to 0.40 for neutrons in the $N=6$ shell [?] in order to get the $i_{13/2}$ neutron sub-shell at a lower energy and furthermore with μ increased from 0.52 to 0.60 for

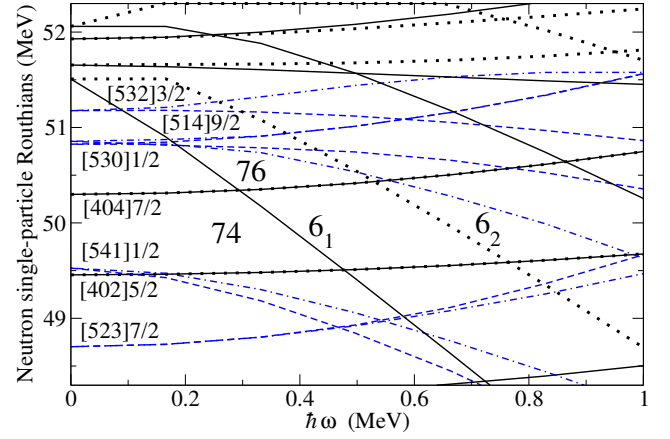


FIG. 3. (Color online) Single-particle neutron Routhians for ^{136}Nd calculated at $\epsilon_2 = 0.30$, $\epsilon_4 = 0.016$ and $\gamma = 0^\circ$. Signature and parity of the states are as follows: black solid = $(+, +1/2)$, black dashed = $(+, -1/2)$, blue dashed = $(-, +1/2)$, blue dashed-dotted = $(-, -1/2)$. The relevant orbitals for the present discussion are indicated as follows: the neutron orbitals are labelled with the asymptotic Nilsson quantum numbers, while the signature partners of the $i_{13/2}$ intruder orbital with 6_1 and 6_2 .

the higher proton shells, $N \geq 6$.

In the present work we will also use the short notation $5^x 6^y$ which includes only the intruder orbitals $[(\nu h_{9/2}/f_{7/2})^x (\nu i_{13/2})^y]$. In order to facilitate the understanding of the configuration assignments, we include a neutron single-particle Routhian diagram calculated for ^{136}Nd at a typical deformation of $\epsilon_2 = 0.30$, $\epsilon_4 = 0.016$ and $\gamma = 0^\circ$ in Fig. 3. One can compare it with the similar neutron single-particle Routhian diagram shown in Fig. 3c of [?], which was calculated for ^{134}Nd at the same deformation using a Woods-Saxon potential, and observe their resemblance. This gives us additional confidence in the configuration assignments based on the present CNS calculations.

The present study is mainly devoted to the newly observed HD bands of ^{136}Nd . However, in order to qualify the proposed theoretical interpretation based on CNS calculations, we first calculated the neighboring ^{134}Nd nucleus, in which all HD bands have been linked to low-lying states and therefore have firm energies and spins. We then calculated the HD configurations of ^{136}Nd , and tried to obtain a coherent interpretation of the HD bands in both ^{134}Nd and ^{136}Nd . Finally we calculated the HD band of ^{137}Nd , investigating the origin of the observed crossing at high spins. In the following we discuss the obtained results and the configuration assignments, which lead us to achieve a new view on the excitations in the second minimum of Nd nuclei.

The calculated results for all three nuclei ^{134}Nd , ^{136}Nd and ^{137}Nd are shown in Fig. 4, in which the experimental bands are shown in panels a), d) and g), the calculated

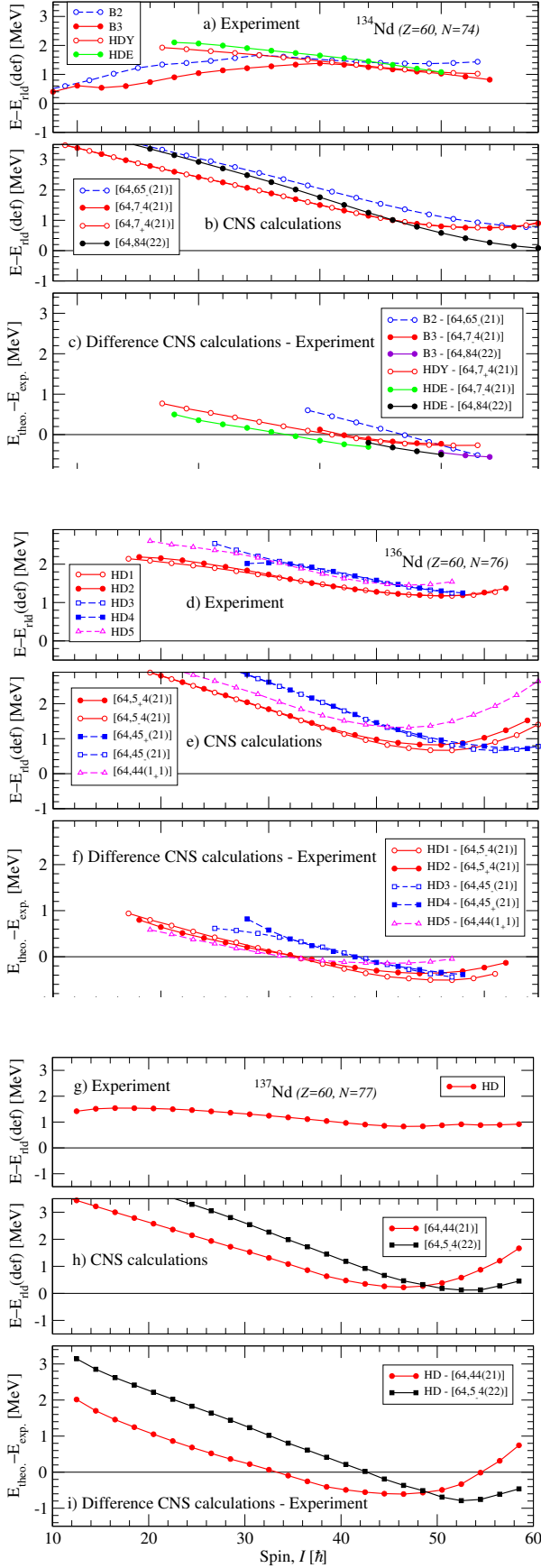


FIG. 4. (Color online) Comparison between the experimental and calculated CNS configurations of the HD bands of ^{134}Nd , ^{136}Nd and ^{137}Nd .

bands are shown in panels b), e) and h), and the difference between CNS calculations and the experimental bands are shown in panels c), f) and i).

The observed bands of ^{134}Nd and their evolution at high spin represent an unique set of HD bands which are all linked to low-lying states, and therefore have experimentally determined excitation energies and spins. A comprehensive discussion of all bands using the cranked Strutinsky approach based on the Woods-Saxon potential including pairing interaction has been reported in Refs. [? ?]. The present CNS calculations show that in the spin range $I = 25\hbar - 40\hbar$ in which the HD bands involve only one $\nu i_{13/2}$ intruder orbital, the calculated deformations are nearly prolate, rather stable, with values decreasing slightly with increasing spins, from $(\varepsilon_2, \gamma) \approx (0.32, 4^\circ)$ and $(\varepsilon_2, \gamma) \approx (0.28, 8^\circ)$. The deformation of the bands involving two $\nu i_{13/2}$ intruder orbitals, is, as expected, larger at spin $I \approx 40\hbar$, *i. e.* $(\varepsilon_2, \gamma) \approx (0.34, 4^\circ)$.

The high-spin part of the negative-parity band B2 of ^{134}Nd (band 2 in Ref. [?]) above spin 27^- has a $5^2 6^1$ configuration ($[64, 65_-(21)]$ in CNS notation), involving therefore three neutron intruder orbitals. The positive-parity and B3 (band 3 in Ref. [?]), which involves a pair $\pi h_{11/2}$ protons above 10^+ , exhibits a smooth alignment of the $h_{11/2}$ and $h_{9/2}$ neutrons in the spin range $I = 10\hbar - 30\hbar$, increasing progressively the deformation towards a HD shape, at which the successive occupation of the 6^1 and 6^2 orbitals through crossings with the $\nu[402]5/2^+$ orbitals was experimentally observed. In CNS notation, the two successive HD configurations $5^2 6^1$ and $5^2 6^2$ of band B3, are $[64, 7_-(21)]$ and $[64, 84(22)]$, respectively.

At difference from the bands B2 and B3 which evolve from low-spin ND to high-spin HD configurations, the band HDY ("HD yrast" in Ref. [?]) is observed only at high spins, where the 6^1 intruder orbital is occupied. A configuration involving the two opposite-parity $\nu h_{9/2}/f_{7/2}$ and $\nu i_{13/2}$ ($[64, 64(11)]$ in CNS notation), has been assigned in Ref. [?], suggesting therefore a negative parity for band HDY. However, in the CNS calculation this configuration is very non-yrast and therefore can be safely discarded. The most natural configuration is $[64, 7_+(21)]$, the signature partner of the $[64, 7_-(21)]$ configuration assigned to band B3 in the corresponding spin region, which nicely reproduces the near degeneracy of bands B3 and HDY, induced by the occupation of the two degenerate signatures of the $\nu d_{5/2}[402]$ orbital (see Fig. 3 and Fig. 3c of Ref. [?]).

Band HDE ("HD excited" in Ref. [?]) decays via high-energy transitions to positive-parity bands with even spins. Most probably it has even spins, as assigned in Ref. [?], since a spin lower by $1\hbar$ would make it unrealistically non-yrast. At low spins it is parallel and slightly more excited than band HDY, suggesting the occupation of only one $\nu i_{13/2}$ intruder, and therefore a $5^2 6^1$ configuration ($[64, 7_-(21)]$ in CNS notation), which is

identical to that assigned to band B3. At this point we should remember that in the CNS formalism the pseudo-spin partners $d_{5/2}$ and $g_{7/2}$ are not distinguished. We can therefore propose the occupation of the $\nu g_{7/2}[404]$ orbital in the configuration of band HDE. The energy of the $\nu g_{7/2}[404]$ orbital is 0.5 - 1 MeV higher than that of $\nu d_{5/2}[402]$ (see e. g. Fig. 3 and Fig. 3c of Ref. [?]), which well accounts for the higher excitation of band HDE relative to the nearly degenerate bands B3 and HDY involving the $\nu d_{5/2}[402]$ orbital.

We can therefore conclude that the CNS and the Total Routhian surface (TRS) calculations for ^{134}Nd are in agreement, except for the band HDY which is now interpreted as signature partner of band B3.

The configurations assigned to the HD bands of ^{136}Nd involve only one $\nu i_{13/2}$ intruder over the entire observed spin range, since no crossings are observed at high spins, as in the case of ^{134}Nd . The missing crossings are nicely explained by the calculated deformations, which, at difference from those of ^{134}Nd , decrease with increasing spins from $\varepsilon_2 \approx 0.30$ to $\varepsilon_2 \approx 0.25$, associated with a significant increase of triaxiality from $\gamma \approx 5^\circ$ to $\gamma \approx 25^\circ$ in the spin range $I = 15\hbar - 50\hbar$. This calculated softness of ^{136}Nd in the γ -direction, which is also present in the HD band of the odd-even neighbour ^{137}Nd (see e. g. Ref. [?] and Fig. [5] of Ref. [?]), is the reason for which no sharp crossings are observed up to very high spins, since the decreasing quadrupole deformation pushes the crossings of the $\nu i_{13/2}$ intruder orbitals with the $\nu d_{5/2}[402]$ and $\nu g_{7/2}[404]$ ones at higher rotational frequencies (see Fig. 3).

Band HD1 of ^{136}Nd has been previously linked to low-lying states [?], and therefore has firmly established excitation energies and spins. The negative parity was assigned based on TRS calculations which suggest the $5^1 6^1$ configuration. The present experimental data and CNS calculations suggest instead a $5^2 6^1$ ($[64, 5_{-4}(21)]$ in CNS notation) positive-parity configuration, which has a minimum at $I \approx 47\hbar$ in the $(E - E_{rld})$ versus I plot, clearly higher than those of the $5^1 6^1$ configurations at $I \approx 40\hbar$ (see Fig. 4 e). As the $[64, 5_{-4}(21)]$ configuration is nearly degenerate with its signature partner $[64, 5_{+4}(21)]$, we adjusted the energies and spins of the newly observed band HD2, second most intense populated in the reaction, to get it nearly degenerate with band HD1. In these conditions, band HD2 has a pattern strikingly similar to that of band HD1, inducing us to assign the $5^2 6^1$ ($[64, 5_{-+4}(21)]$ in CNS notation) configurations to bands HD1, HD2.

The previously observed excited HD band (HD3 in the present work) is confirmed, and a new band, HD4, is observed. HD4 can become nearly degenerate with HD3 if one adjusts adequately their energies and spins. The resulting nearly degenerate pair (HD3, HD4) has a $E - E_{rld}$ minimum at spins definitely larger than those of the (HD1, HD2) pair, suggesting thus configurations

with a larger number of occupied high- j orbitals. Scanning among the possible candidates, it became clear than the configurations with one additional neutron-hole in $\nu h_{11/2}$ lead to minima in the $E - E_{rld}$ plot at higher spin, inducing us to assign the $5^2 6^1$ ($[64, 45_{-+}(21)]$ in CNS notation) configuration to bands HD3, HD4.

Band HD5 has a different pattern than the other HD bands of ^{136}Nd , presenting a $E - E_{rld}$ minimum at lower spin of around $41\hbar$. This suggests a configuration with a lower number of intruder orbitals, and the lowest suitable configuration appeared to be $5^1 6^1$ ($[64, 44(1_{+1})]$ in CNS notation).

The HD band of ^{137}Nd has been extended to higher spins by five transitions, revealing the presence of a crossing at spin around $105/2\hbar$. This is important, because it gives the opportunity to evaluate the adequacy of the adopted $A = 130$ parameters for the Nilsson potential. As one can see in Fig. 4h, a crossing at spins around $96/2\hbar$ between the $5^2 6^1$ and $5^2 6^2$ configurations is calculated, which can be associated with the observed crossing at around $105/2\hbar$. The difference of $\approx 4\hbar$ between the observed and calculated crossing spins is to be attributed to the adopted model parameters. In any case, one can consider that a difference of the order of 10% between the calculated and observed crossing spins is a good agreement.

Summarizing, we experimentally observed three new HD bands in ^{136}Nd and extended the HD bands of ^{136}Nd and ^{137}Nd to lower and higher spins by several transitions. The new results are interpreted by extended CNS calculations performed not only for the HD band of ^{136}Nd , but also for those of ^{134}Nd and ^{137}Nd , which are linked to low-lying states and give a solid base to the interpretation of the HD bands of ^{136}Nd . A consistent description of the HD bands is achieved, which gives a new view on the single-particle excitations in the second minimum of the Nd nuclei. The adequacy of the CNS model to investigate the high-spin excitations in nuclei is demonstrated, this time contributing to solve ambiguities of the previous interpretations. The present results point to the necessity to further pursue the investigation of HD bands both experimentally, to firmly establish their energies, spins, parities and quadrupole moments, and theoretically, to confirm, through different self-consistent approaches, the newly proposed interpretation.

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