Band structure in the neutron-rich lanthanide nucleus ^{152}Nd. I. Anomalous properties of the $K^\pi = 0^+$ bands

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The β^- decay of ^{152}Pr$\rightarrow$^{152}Nd has been investigated. Levels and transitions in ^{152}Nd were studied with γ-ray spectroscopy including $\gamma\gamma(\theta)$ measurements. The level scheme of ^{152}Nd has been considerably revised and extended. Previously suggested $K^\pi = 0^-$, 2^-, and 3^- rotational bands have been confirmed, and new band members have been identified. Similarly, a positive-parity $K = 0$ band has been confirmed, and extended to the 4^+ level. The moments of inertia of the ground state band and the first excited $K^\pi = 0^+$ band were found to be strongly different, and at variance with the general systematics for both bands in the region. It is suggested that these unusual moments of inertia are due to a local, orbital dependent structure effect at proton number $Z = 60$.

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I. INTRODUCTION

The light neutron-rich lanthanides are situated in a region of rapid shape transition from spherical to deformed. The complex influence of subshell effects on the rapid process of deformation gives rise to various phenomena, including shape coexistence (between spherical and deformed shapes), which has been proposed in the neighboring samarium and gadolinium nuclei [1]. In fact, the transitional Sm and Gd nuclei have become a major testing ground for various theoretical models, including the interacting boson approximation (IBA) [2] and the pairing-plus-quadrupole (PPQ) model [3, 4].

Although various models can account quite well for the rapid transition towards deformation at neutron numbers $N \approx 90$, there are a number of structure effects which are poorly understood. These include the degree of octupole collectivity in the low-lying negative-parity states [5], and the issue of static octupole deformation near ^{146}Ba [6]. Furthermore, several even-even nuclei also show "extra" low-lying 0^+ states [7] which defy description within the IBA and some other collective models.

The lack of systematic data on band structures and transition rates, which represents an obstacle to the theoretical understanding of the excited states, is mainly due to experimental difficulties. The light ($A = 150$–160) lanthanides are in fact the heaviest nuclei, with a neutron excess of more than a few units with regard to the stability line, that can be produced today. At present, the only realistic means of nuclide production is the low-energy fission of heavy neutron-rich nuclides in the actinide region or beyond. The subsequent extraction of selected lanthanide nuclides should be an ideal task for isotope separation on-line (ISOL) systems, but has proven difficult due to the slow diffusion and desorption properties of the lanthanides. It is only due to the development of a high-temperature target and ion source system [8, 9] that strong beams of neutron-rich (short-lived) lanthanides have become available at the OSIRIS ISOL facility [10, 11], offering unique opportunities to perform detailed studies of this region.

The present study is part of our effort to systematically map the structure of the neutron-rich nuclei in the $A = 140$–160 region. In particular, it is an extension to our work on ^{150}Nd, where strongly anomalous properties of the first excited $K^\pi = 0^+$ (β) band have been reported [12]. This study, which is intended to give a detailed account of the low-lying bands of ^{152}Nd as populated in the β^- decay of ^{152}Pr, has been divided into two parts. In this part we report on the establishment of the level scheme and on a $\gamma\gamma(\theta)$ experiment made to obtain information on level spins and on the multipole mixing ratios of some transitions. We give special attention to the discussion of the anomalous properties of the ground and excited $K^\pi = 0^+$ bands.

In the second part of our study [13], results from a fast timing triple coincidence $\beta\gamma\gamma(t)$ measurement will be presented. The discussion in Ref. [13] will be focused on the transition rate systematics and other properties of the negative-parity bands in ^{152}Nd. The partial results concerning the lifetimes of the 2_1^+ states of ^{152}Nd and ^{152}Sm that were obtained in the time-delayed coincidence measurement have already been published [14].

The previous information on the levels of ^{152}Nd comes from studies of the β^- decay of ^{152}Pr [15], the prompt γ rays emitted in the spontaneous fission of ^{252}Cf [16, 17], and from the ^{150}Nd(t,p)^{152}Nd reaction [18].

II. EXPERIMENTAL DETAILS

A. Source production

The experiments were performed at the OSIRIS electromagnetic mass separator facility in Studsvik [10, 11] where thermal neutron-induced fission of ^{235}U was used to produce light neutron-rich lanthanide nuclei. The target and ion source assembly [8] was operated in the plasma ionization mode at temperatures of $\approx$2500 °C to obtain short release times and (relatively) high ionization efficiencies. The mass separated $A = 152$ beam contained strong activities of ^{152}Pr, ^{152}Nd, and ^{152}Pm, including three known Pm isomers. The levels in ^{152}Nd were populated in the β^- decay of ^{152}Pr. The contamination of the beam by molecular ion species [19], such as carbides and dicarbides, was marginal.

B. Gamma-ray singles measurement

A series of γ-ray singles measurements were performed using a multispectrum scaling (MSS) technique. The measurement cycle used was optimized for the decay of ^{152}Pr ($T_{1/2} = 3.8$ s). It comprised 6 s of beam collection followed by eight consecutive spectral measurements of 1.0 s duration each. The samples were collected on a movable Al-covered Mylar tape which was used to remove the old sample after each cycle. Both a large volume coaxial HPGe detector and a low-energy photon (LEP) spectrometer were used for these measurements.

Many γ rays in the decay of ^{152}Pr$\rightarrow$^{152}Nd were found to have energies close to, or overlapping with, transitions in other $A = 152$ isobars. Although the half-lives of those impurity lines are much longer than that of ^{152}Pr, the high density of this isobaric background created problems in the evaluation of the γ-ray data. Many of the γ-ray intensities were therefore taken from the $\gamma\gamma$ coincidence spectra (see Sec. II C) where the isobaric background seldom caused problems.

The high sensitivity of the coincidence experiment permitted the determination of γ-ray intensities down to a small fraction of 1% per decay. An example of a coincidence spectrum gated on the 164.1 keV $4^+ \rightarrow 2^+$ ground

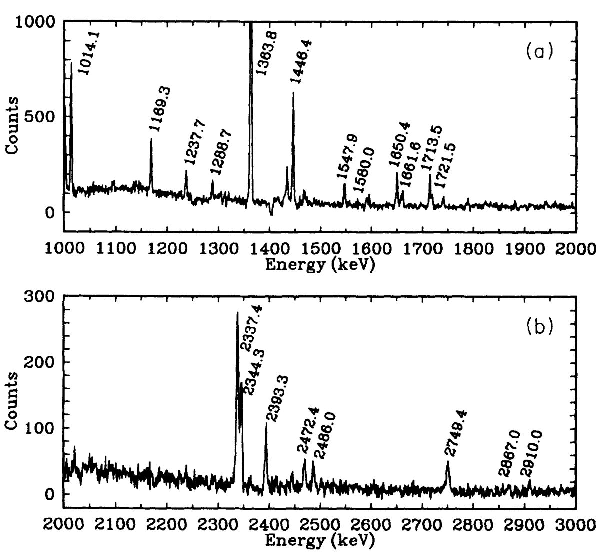

FIG. 1. Part of a background subtracted spectrum obtained by setting a gate on the 164.1 keV ground state band transition. The background was subtracted using the procedure outlined in Sec. II C. Gamma rays labeled with energies belong to the ^{152}Pr$\rightarrow$^{152}Nd decay, see Table I. (a) Coincident transitions in the energy range 1–2 MeV. Note that the scale chosen does not permit showing the full height of the peak at 1363.8 keV. (b) Transitions in the range 2–3 MeV.

state band transition is given in Fig. 1. The MSS data, on the other hand, were crucial for the identification of the short-lived γ rays from the ^{152}Pr decay, and was used for the determination of γ-ray energies and intensities for those transitions judged to be free from interfering impurity lines. The deduced γ-ray energies and intensities are listed in Table I.

C. Angular correlation and $\gamma\gamma$ measurements

The coincidence measurements employed five Ge detectors. Four of these were of the coaxial type, and the fifth was a planar low-energy photon (LEP) detector. All detectors were placed in the same plane as the beam at distances between 5 and 8 cm away from the beam deposition point. Relative to the first Ge detector, the other detectors were placed at angles of 44°, 126° (LEP), 185°, and 251°. A total of 4.2×10^7 coincidences between two or more Ge detectors were collected. The gating arrangement allowed any detector to provide the "start" pulse and any other detector to serve as "stop." Data taking was performed during beam collection, with the movable tape system set to remove old samples at intervals of 10 s.

A separate measurement of well-known angular correlations in ^{140}Ce was performed using the same detector geometry. The data from this calibration measurement enabled us to deduce the solid angle correction coefficients of the multidetector setup. This was done by adjusting a set of energy-independent correction coefficients so as to achieve the best fit to the previously obtained [20, 21] high-precision results for the a_2 and a_4 values of five different γ-ray pairs in ^{140}Ce. An independent calculation of the solid angle corrections resulted in attenuation coefficients close to the fitted ones. A more detailed discussion of the calibration procedure can be found in Ref. [22].

The $\gamma\gamma$ coincidence data were gain matched and sorted in two different fashions. In the first step the data were sorted into a symmetric two-dimensional 4096×4096 channel matrix with either of the energies of the required pair of γ rays acting as the x and y matrix coordinates. The total projection was then used for setting gates on all γ transitions present (and the corresponding background). Gated peak and background spectra were subsequently extracted as one-dimensional cuts in the matrix. The peak gates were then corrected by subtracting the corresponding background gates and analyzed to give information about the coincident transitions. In addition to the results on ^{152}Nd, this sorting also provided data on the decay of the 4.1 min isomer of ^{152}Pm$\rightarrow$^{152}Sm which has been reported in a separate publication [23].

The second sorting of the data served to provide the angular correlation information. A number of gates were set on some of the strongest γ transitions in ^{152}Nd (and the corresponding background) after which the data were sorted into spectra, one for each unique detector combination and gate energy. From these resultant spectra, information about the intensities of coincident gamma transitions as a function of the angle between the detector

TABLE I. Energies, intensities, and initial levels for gamma rays following the decay $^{152}Pr \to ^{152}Nd$, $T_{1/2} = 3.8(2)$ s [15].

E_γ (keV)	I_γ^a (rel %)	Initial level (keV)	E_γ (keV)	I_γ^a (rel %)	Initial level (keV)
72.60(20)	28.0(30)	72.6	1169.3(6)[b]	3.7(4)	1406.0[c]
141.9(8)	2.3(5)	1683.2	1178.2(9)	6.1(5)	1250.8
144.5(8)	2.3(5)	1827.5	1237.7(6)[b]	2.9(5)	1474.1[c]
164.1(1)	100	236.7	1288.7(4)[b]	2.1(3)	1772.7[c]
203.2(4)[b]	1.4(7)	1887.0[c]	1363.8(3)	34.5(20)	1600.7
214.90(20)	8.4(4)	1898.3	1446.4(6)	8.5(4)	1683.2
223.4(8)[b]	0.9(3)	1474.1[c]	1469.50(20)	70.0(40)	1542.0
226.70(20)	18.7(9)	1827.5	1506.8(6)[b]	2.1(2)	1990.8[c]
234.8(8)[b]	2.2(5)	1474.1[c]	1529.1(9)	3.3(3)	1600.7
247.31(10)	11.0(6)	484.0	1541.8(8)[d]	< 0.9(5)	1542.0
284.98(10)	72.0(5)	1827.5	1547.9(9)[b]	2.6(5)	1784.6[c]
290.96(20)	5.1(4)	1542.0	1580.0(8)[b]	1.2(2)	2064.0[c]
297.62(20)	14.1(7)	1898.3	1591.0(10)	0.6(2)	1827.5
302.8(3)	4.4(4)	1542.0	1650.4(7)[b]	3.6(3)	1887.0[c]
344.8(4)[b]	1.8(2)	1887.0[c]	1657.8(8)[b]	1.0(3)	1893.7[c]
349.8(3)	3.5(3)	2177.3	1661.6(8)	2.0(3)	1898.3
350.5(8)[b]	1.7(5)	1600.7	1713.5(5)[b]	3.6(3)	1950.2[c]
361.5(6)	2.5(2)	1600.7	1721.5(5)[b]	1.3(3)	1958.2[c]
393.30(20)	8.7(4)	1542.0	1821.5(7)[b]	5.0(10)	1893.7[c]
418.9(4)[b]	3.7(2)	1893.7[c]	2337.4(7)[b]	8.3(4)	2574.1[c]
642.5(8)[b]	4.4(10)	1893.7[c]	2344.3(8)[b]	5.7(4)	2581.3[c]
879.5(5)[b]	7.6(4)	2421.5[c]	2376.2(9)[b]	2.9(2)	2612.9[c]
922.0(4)[b]	3.3(3)	1406.0[c]	2393.3(12)[b]	2.6(2)	2629.9[c]
990.1(4)[b]	3.8(4)	1474.1[c]	2472.4(14)[b]	1.9(4)	2709.1[c]
1001.7(8)	4.8(3)	1238.5	2486.0(14)[b]	1.3(2)	2722.7[c]
1014.1(6)	7.4(4)	1250.8	2509.5(13)[b]	1.3(2)	2581.3[c]
1076.1(5)	5.2(4)	1148.4	2749.5(14)[b]	1.9(2)	2986.2[c]
1148.2(4)	3.3(5)	1148.4	2867.0(15)[b]	0.4(2)	3103.7[c]
1166.0(6)	5.2(5)	1238.5	2910.0(15)[b]	0.6(2)	3146.7[c]

[a] The tabulated gamma intensities are relative to the 164.1 keV γ ray. Intensities in units of % per decay are obtained by multiplication with a factor of 0.39(4).
[b] Gamma ray not earlier observed.
[c] Level deduced in this work.
[d] Tentatively assigned gamma ray.

pairs was extracted. The intensities were then corrected for solid angle efficiencies, etc., and the results tested against theoretical angular distributions. Some details of this analysis are given in Sec. III B.

III. RESULTS

A. The level scheme of ^{152}Nd

The γ-ray spectroscopy results reported in this study confirm, to a large extent, those compiled by Peker [24] and primarily based on the work of Karlewski *et al.* [15]. However, the 83.1, 1754.5, and 1940.9 keV transitions reported by Karlewski *et al.* were not seen by us. On the other hand, more than 30 new γ rays belonging to the decay of ^{152}Pr have been identified. All γ rays were placed in the level scheme using the $\gamma\gamma$ coincidence results. Special care was taken to check those γ rays, e.g., the 285 keV transition, which can fit energetically in more than one position. As a result of this analysis, 20 new levels were established. A total β-decay energy of 5600 keV [24] was used to evaluate the log ft of the β transitions. The revised decay scheme, including the deduced I_β and log ft values, is displayed in Fig. 2.

The previous β^- decay study by Karlewski *et al.* [15] showed inconsistencies in the β-particle feeding of some levels, as deduced from the γ-ray intensity balances corrected for internal conversion. These problems were particularly severe for the levels of the ground state band which appeared to be unreasonably strongly populated by β transitions. The problems were interpreted [15] to be caused by "missing" intensities due to high-energy γ transitions of low intensity that had escaped detection. Our data confirm this explanation by showing the presence of many new γ-decaying levels at energies above 2 MeV. By including the intensities from their decay into the intensity balance, one obtains β intensities to the ground state band levels which are not significantly different from zero.

B. Angular correlations

The analysis of the $\gamma\gamma(\theta)$ data was performed by fitting theoretical angular correlation functions to the experimental distributions. The procedure has been outlined by Tegnér [26]. In a first step, all physically possible spin sequences were investigated. For each spin sequence, separate fits to the experimental data were performed for a set of regularly spaced values of the δ multipolarity mixing ratios of both transitions. For each γ-ray cascade γ_1-γ_2 the resulting goodness of fit, expressed as χ^2, was then studied (graphically) over a two-dimensional grid of $\delta(\gamma_1)$ and $\delta(\gamma_2)$. In this way, the spin sequences most in agreement with the experimental distributions were identified. The second step of the analysis comprised a similar χ^2 minimization where the mixing ratio of only one γ ray was treated as a variable. Following this procedure the δ mixing ratios were obtained successively, starting with those cascades that involve one of the ground state band transitions. These latter intraband transitions are of pure $E2$ multipolarity ($\delta = 0.0$).

For the cascades discussed below, it was possible to extract the δ mixing ratio values and/or compare the experimental angular distributions with theoretical predictions. Although the spin assignments (based on γ-ray decay patterns) of the strongest populated levels are in little doubt, the angular correlation data lend further support to these arguments. The cascades are labeled by the energies of the transitions involved, with the upper one mentioned first. The δ mixing ratios deduced in this work are summarized in Table II. The δ values obtained for some spin sequences differing from the adopted ones have been included for comparison.

164-73 and *247-164*. These cascades represent the 4^+-2^+-0^+ and 6^+-4^+-2^+ level sequences of the ground state band, respectively. The contribution from Pb x rays to the intensity of the 73 keV line in the gated spectra was estimated to be small. However, this isotropic component (from the x rays) or the long (4.5 ns) lifetime

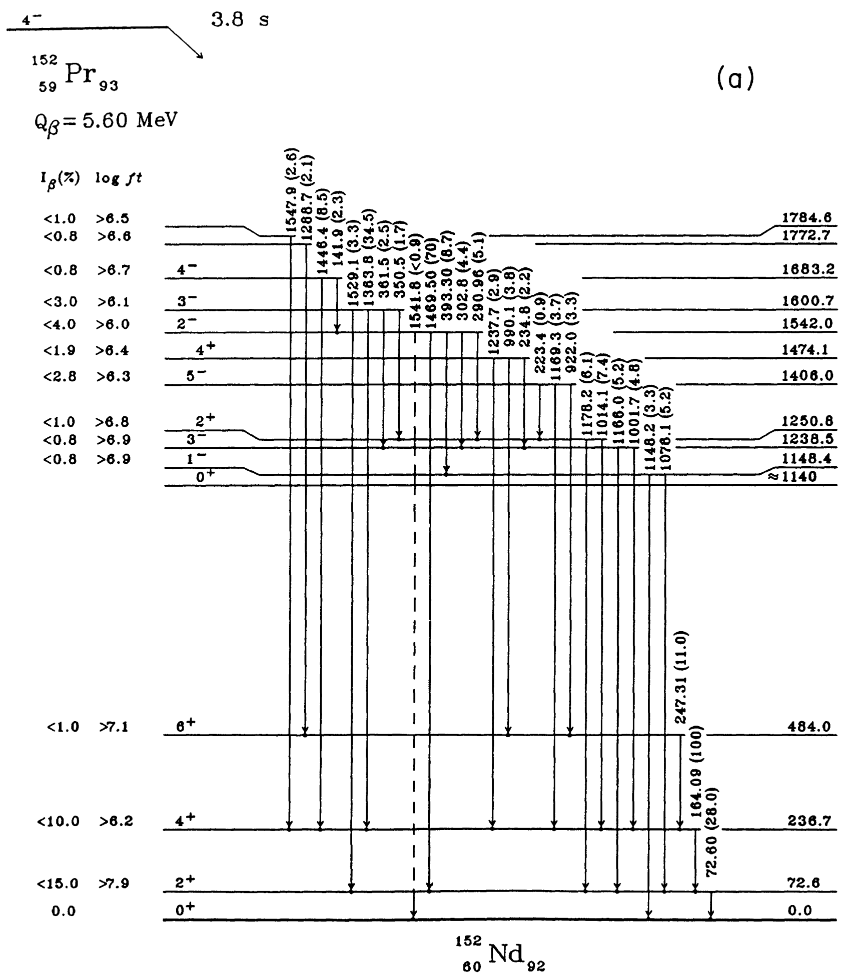

FIG. 2. (a) Levels in ^{152}Nd below the excitation energy 1.8 MeV populated in the β^- decay of ^{152}Pr. The γ transitions are marked by their energy in keV and relative γ-ray intensity (see also Table I). The energy of the 0^+ level near 1140 keV is taken from the work of Chapman *et al.* [18]. The figure is not drawn to scale. As indicated by the calculated I_β and $\log ft$ values, none of the levels shown here appear to be significantly directly populated by β transitions from ^{152}Pr. The total gamma intensities were calculated using the conversion coefficients of Ref. [25]. (b) Higher–lying states of ^{152}Nd populated in the β^- decay of ^{152}Pr. See also caption of (a).

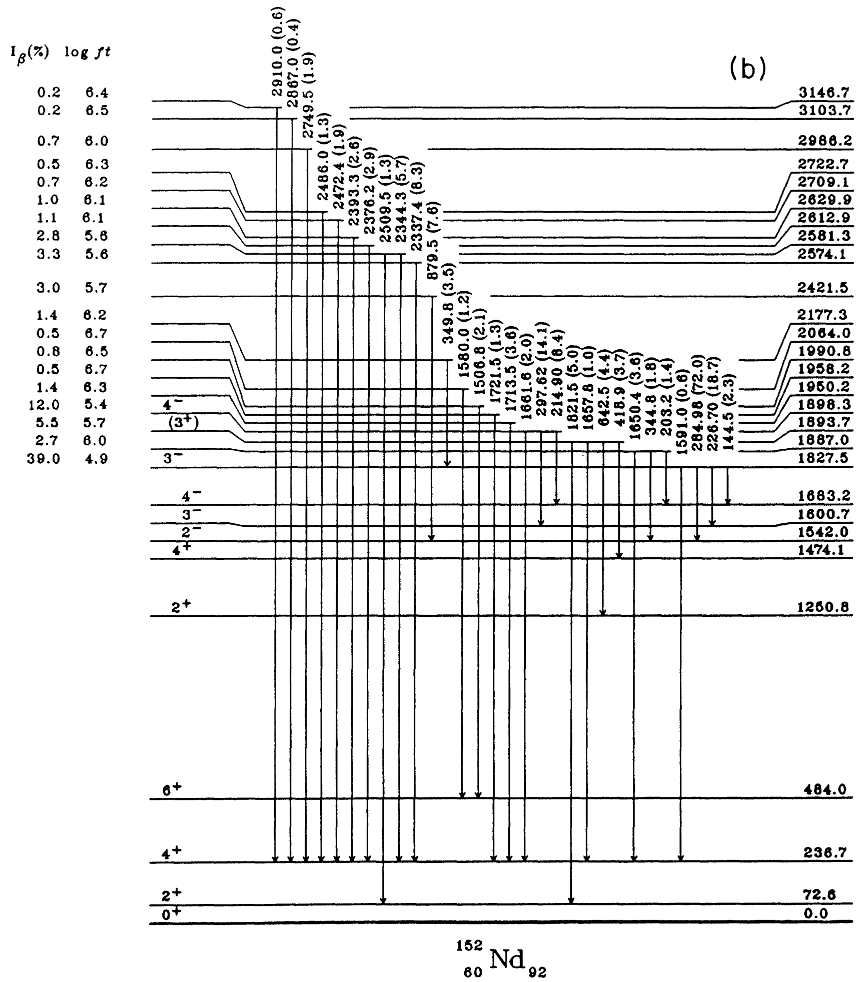

FIG. 2 *(Continued).*

of the 73 keV 2^+ state may have manifested itself as a slight flattening of the angular correlation curve. Apart from this, the experimental angular correlation data for the two cascades correspond well (within the uncertainties) to the theoretical functions calculated for $\Delta I = 2$ stretched $E2$ transitions. This suggests that the experimental data are not significantly biased by systematic errors.

1470-73. The initial level at 1542.0 keV can have $I = 2$ or 3. Setting $I(1542)$=2 results in $\delta(1470) \approx 0.0$, while for $I(1542)$=3 one obtains $\delta(1470) \geq 0.2$.

285-1470. The initial level at 1827.1 keV has been assigned as I^{π}=3^-, see Secs. IV and V. The intermediate state of the cascade is the 1542.0 keV level, again assumed to have $I = 2$ or 3. The χ^2 optimization procedure for a 3-2-2 cascade indicates $\delta(285) = 0.0$ for $\delta(1470) \approx 0.0$ or larger. The 3-3-2 case, on the other hand, suggests two possible solutions having $\delta(285) = 0.2$, $\delta(1470) = 0.0$ and $\delta(285) = 0.6$, $\delta(1470) = 0.5$. The first solution is incompatible with the $I(1542)$=3 result of the 1470–73 cascade. The second would imply a significant $E2$ admixture to the 285 keV transition, resulting in a long partial half-life which is contrary to our observations [13]. We therefore accept $I = 2$ as the only alternative for the 1542.0 keV level.

1364-164. The 1364 keV transition connects the levels at 1600.7 keV and 236.7 keV. The γ branching data suggest the initial level has spin $I = 3$. A look at the χ^2 optimization results in Fig. 3 gives that both $I(1601)$=3 and 5 produce well-defined χ^2 minima at $\delta(1364) = 0.0$ and ≈ -0.1, respectively. $I = 4$ gives a very flat minimum for $\delta(1364) \geq 1.0$. The short half-life of the 1600.7 keV level [13] is however incompatible with both $I = 4$ and 5, as well as with a large δ mixing ratio for the 1364 keV γ ray. We therefore accept $\delta(1364) \approx 0.0$ and $I = 3$ for the initial level at 1600.7 keV.

297-1364. This cascade involves the 297 keV transition between the 1898.3 keV level, proposed by Karlewski *et al.* [15] to have the spin $I = 4$, and the level at 1600.7 keV discussed in the preceding paragraph. The results from the χ^2 optimization, using $I(1601)$=3 and $\delta(1364)$=0.0 as suggested by the 1364–164 cascade data, show flat χ^2 minima for $I(1898)$=4 and 5 at $\delta(297)$< 1.0. A definite spin assignment of the initial level at 1898.3 keV is thus not obtained from the $\gamma\gamma(\theta)$ data.

285-291. The final state in this cascade is the level at 1251 keV, proposed to be the 2^+ member of the $K^{\pi} = 0^+$ band. The relatively low intensity of the 291 keV γ ray precluded a direct verification of the $I = 2$ assignment of this level. The χ^2 minimization produced fits of com-

TABLE II. Values of the δ mixing ratio for some selected transitions.

E_γ (keV)	Cascade (γ_1–γ_2)	Spin sequence (I_1-I_2-I_3)	Mixing ratio[a]	Assumption[b]
285.0	285–1470	3–1–2	0.3(4)	$\delta(1470) = 0.2$
		3–2–2[c]	-0.1(5)	
		3–3–2	-0.7(3)	
291.0	285–291	3–2–2[c]	0.8(7)	$\delta(285) = 0.0$
		3–2–3	-0.1(99)	
297.6	298–1364	3–3–2	1.0(10)	$\delta(1364) = 0.0$
		4–3–2[c]	-0.2(2)	
		5–3–2	-0.6(4)	
1363.8	1364–164	3–4–2[c]	0.0(1)	$\delta(164) = 0.0$[d]
		4–4–2	1.8(19)	
		5–4–2	-0.1(1)	
1469.5	1470–73	1–2–0	-0.3(2)	$\delta(73) = 0.0$[d]
		2–2–0[c]	0.2(2)	
		3–2–0	0.2(2)	

[a] The value represents a weighted average of the results from the two (independent) sets of angular correlation data obtained by gating on γ_1 and γ_2, respectively.
[b] During the fitting the value of one of the mixing ratios was kept fixed.
[c] Adopted spin sequence, see Sec. III B.
[d] The δ mixing ratio was set to zero for all members of the ground state rotational band.

parable quality for both $I(1251)$=2 and 3. The mixing parameter of the 291 keV transition did not differ significantly from zero in either case, see Table II.

In summary, we find that the angular correlation results support $I = 2$ and 3 for the levels at 1542.0 keV and 1600.7 keV, respectively. The strong transitions with energies of 284.96, 1363.8, and 1469.5 keV were found to have insignificant admixtures of multipolarities higher than one.

IV. ROTATIONAL BANDS IN ^{152}Nd

A. The $K^\pi = 0^-$ band

We confirm the proposition of Karlewski *et al.* [15] that the levels at 1148.4 and 1238.5 keV are the $I^\pi = 1^-$ and 3^- members of a $K^\pi = 0^-$ band. A level seen by us at 1406.0 keV is most likely the 5^- band member. All three levels decay to the ground state band with relative γ-ray intensities in good agreement with the Alaga predictions for $K = 0$. Other values of K are not compatible with the experimental intensities. These three levels are probably not significantly populated by direct β transitions. The possible β population of the 1406.0 keV level, see Fig. 2, is probably an artifact due to undetected γ-ray feeding. Some of the low-energy γ transitions expected to feed this state were obscured by strong random peaks from daughter activities in the $\gamma\gamma$ coincidence spectra.

The level energies of this band yield a rotational energy parameter A of about 9 keV, similar to those of the $K^\pi = 2^-$ and 3^- bands discussed next.

B. The $K^\pi = 2^-$ and 3^- bands

The dominant β transition in the decay of ^{152}Pr populates the 1827.5 keV level in ^{152}Nd. This level subsequently decays by strong γ rays to three states at 1542.0, 1600.7, and 1683.2 keV, which have been proposed [15] to be members of a $K^\pi = 2^-$ band. The negative parity of this $K = 2$ band follows with near certainty from the fact that the γ-ray decay patterns of these levels are inconsistent with observations of the decays of positive-parity bands in other deformed nuclei. The strong 285 keV transition between the 1827.5 and 1542.0 keV levels has a sufficiently high conversion coefficient to allow the detection of K x rays in the coincidence gates involving this transition. From the coincident intensities of γ and x rays, a K conversion coefficient $\alpha_K = 0.040(15)$ was calculated, thus indicating a multipolarity of $M1$ (or $E2$) for the 285 keV transition. This result supports the assignment of negative parity to the 1827.5 keV level.

There are strong reasons to adopt $I^\pi = 3^-$ for the level at 1827.5 keV. The most important one is the fact that the $I^\pi = 2^-$ or 4^- alternatives would require some of the deexciting transitions to have $M2$ or $E2$ multipolarity. This is extremely unlikely in view of the level half-life which we found to be [13] much below 1 ns. Secondly, our γ-ray branchings for the transitions feeding the levels at 1542.0, 1600.7, and 1683.2 keV are in good agreement with those expected from a $KI^\pi = 33^-$ level to members of a $K^\pi = 2^-$ band. Accepting the 1827.5 keV level as the bandhead of a $K^\pi = 3^-$ band, one may adopt the 1898.3 keV level as the 4^- band member. The β intensities feeding these two levels are in good agreement with expectations for transitions from a 3^- or 4^- state to a $K^\pi = 3^-$ band, which may give additional support for the $I^\pi = 3^-$ assignment of the 1827.5 keV level. (The β^--decaying ground state of ^{152}Pr is likely to have $I^\pi = 3^-$ or 4^-, see Ref. [13] for a discussion.)

There is little doubt that the five levels discussed above are the members of two different bands with rather high values of K. The lifetime measurements [13] show that all these levels have half-lives in the range of approximately 10 to 150 ps. These relatively long half-lives also serve as an independent confirmation of the assignment of negative parity to the bands.

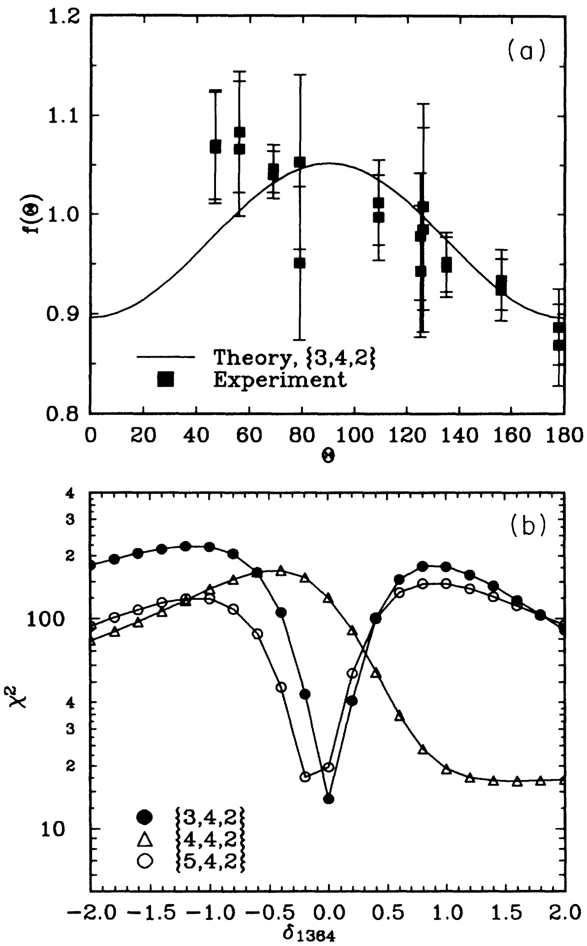

FIG. 3. (a) The angular correlation function of a 3-4-2 cascade fitted to the data of the 1364–164 keV γ rays. (b) The resultant goodness of fit (χ^2) as a function of the multipolarity mixing parameter δ of the 1364 keV transition. This panel also includes fits for the initial level at 1600.7 keV having an angular momentum $I = 4$ or 5. These spins are physically excluded on grounds of the level half-life [13], but have been included to illustrate that reasonable fits can be obtained also with other parameters than those of a 3-4-2 cascade. The δ parameter of the 164.1 keV ground band transition was kept fixed at 0.0 during all fits.

When comparing level energies in bands of different parities, one usually finds the parameter A of the rotational energy formula to be 20–30 % smaller for bands of negative parity. Indeed we obtain values of A of about 9, 10, and 9 keV for the $K^\pi = 0^-, 2^-$, and 3^- bands, respectively, to be compared with the ground band value of about 12 keV.

C. The first excited $K^\pi = 0^+$ band

The 0^+ and 2^+ levels of a $K^\pi = 0^+$ band were seen at $\approx$ 1139 and 1251 keV in the (t,p) study of Chapman *et al.* [18]. Following the proposition by Karlewski *et al.* [15], we identify the level at 1250.8 keV as this 2^+ state. The level seen by us at 1474.1 keV can only be assigned as 4^+ from its γ-decay pattern. The 223.4 keV intraband transition identifies this level as the 4^+ band member. Both of these levels are probably populated only by γ rays from higher-lying levels. As in the case of the 1406.0 keV level discussed above, it is possible that some weak γ transitions feeding the 4^+ level were obscured in the coincidence spectra. A relatively high-lying level at 1893.7 keV (possibly with $I^\pi = 3^+$) decays by γ rays to both the 2^+ and 4^+ levels.

The 0^+ bandhead is expected to decay to the 2^+ level of the ground band. As we did not observe this transition, we conclude that the total population of this 0^+ state is too low to render it observable in our experiments. As in the case of ^{150}Nd, we find the γ-ray branchings to the ground state band to deviate strongly from the Alaga predictions. Furthermore, the deduced rotational energy parameter A is about 50% larger than for the ground band. These anomalies will be further discussed in Sec. V below.

V. DISCUSSION OF THE $K^\pi = 0^+$ BANDS OF ^{152}Nd

The first excited 0^+ band of ^{152}Nd has an unusually small moment of inertia compared to that of the ground state band. The ground band, on the other hand, has one of the highest moments of inertia presently known in the rare earth region [27]. A similar difference, but not so extreme, has been pointed out in the case of ^{150}Nd [12]. The two Nd nuclei are unusual in this respect. Such differences in the moments of inertia are in strong disagreement with the collective model of Bohr and Mottelson [28] and cannot be reproduced by the standard interacting boson models [2] for deformed nuclei. All these models require the moments of inertia for all low-lying bands of the same parity to be similar, a requirement which is generally confirmed by experimental observations.

To better illustrate the locality of this effect, we show in Fig. 4 the ratio of the level spacings of the ground and excited 0^+ bands of the $N = 90$ and $N = 92$ isotones, up to the 4^+ levels. The ratio is close to unity except for the neutron-rich Nd ($Z = 60$) nuclei. We will in the following show that both the ground and first excited 0^+ bands of ^{150,152}Nd have exceptional moments of inertia, and that

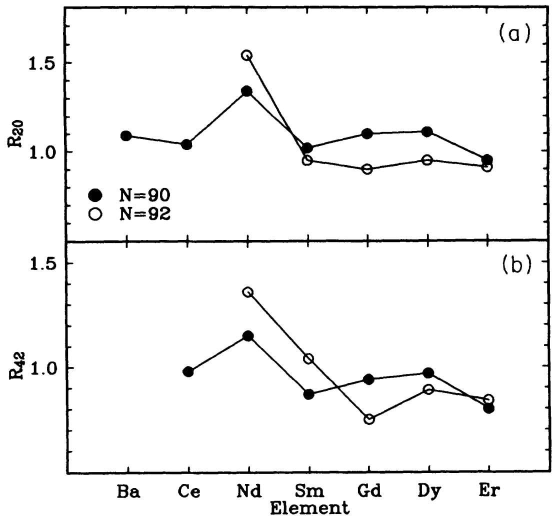

FIG. 4. (a) The ratio $R_{20} = \Delta E(2_\beta - 0_\beta)/\Delta E(2_g - 0_g)$ of the 2^+-0^+ level spacings of the first excited $K^\pi = 0^+$ and the ground state bands of the $N = 90$ and 92 isotones Ba-Er. (b) The corresponding ratio $R_{42} = \Delta E(4_\beta - 2_\beta)/\Delta E(4_g - 2_g)$. The low R_{42} ratio obtained for ^{156}Gd ($N = 92$) may be due to a subshell effect at $Z = 64$. The high ratios obtained for ^{150,152}Nd are exceptional, as discussed in Sec. V.

this phenomenon can be traced to the properties of the single-particle levels in this region.

A. The high moment of inertia of the ground state band

^{152}Nd exhibits the ground state band properties of a well-deformed rotational nucleus. The energy of the 2_1^+ level (72.6 keV) is among the lowest in the rare earth region. The correspondingly large moment of inertia is, however, not simply a consequence of a large deformation. The deformation parameter β_2 can be derived from the value of $B(E2; 0_1^+ \to 2_1^+)$, which, for ^{152}Nd, was recently measured [14]. Table III gives a comparison of the magnitude of the deformation parameter β_2 of a few nuclei having 2_1^+ level energies similar to those of ^{150,152}Nd. The data of Table III show that the two Nd nuclei have β_2 values which actually are significantly smaller than those of the neighbors, even in cases where the moments of inertia of the Nd nuclei are higher. This is remarkable, since one expects, from the liquid drop model [28], the moment of inertia to be approximately proportional to the square of the deformation. Deviations from this proportionality must be attributed to local variations in the nuclear structure. At these low energies and angular momenta there are very few structural effects that need to be considered. The perhaps most important is a local variation of the strength of the pairing interaction.

TABLE III. Energies of the 2_1^+ states and deformation parameters β_2 of selected light lanthanides.

Nuclide	$E(2_1^+)$ (keV)	β_2 [a]	$\beta_2/\beta_{2(\text{s.p.})}$ [a]
^{150}Nd	130.1	0.285	10.75
^{152}Sm	121.8	0.306	11.91
^{154}Gd	123.1	0.310	12.49
^{156}Dy	137.9	0.293	12.16
^{152}Nd	72.6	0.333	12.5
^{160}Gd	75.3	0.353	14.22
^{164}Dy	73.4	0.348	14.45

[a] See Ref. [29] for a definition. The data in this column are from Ref. [29] except for ^{152}Nd where the β_2 deformation parameter was deduced from the $B(E2)$ of Ref. [14].

It is well established [28, 30, 31] that the pair correlations have a major influence on the nuclear moments of inertia. The $N \approx 90$ region is sufficiently well understood that one may search for local variations in the pairing interaction energies using empirical data on nuclear masses. Strictly speaking, one cannot make a direct determination of the pairing energy gap for a particular nucleus. An indirect determination of the gap applicable for the ground state can, however, be obtained using the differences in the neutron or proton separation energies between odd and even nuclei. We have used the prescription by Nilsson and Prior [31], in which the average of the separation energies in the odd nuclei on either side of the even-even one is used to indirectly determine the gap energy. The averaging procedure reduces the scatter

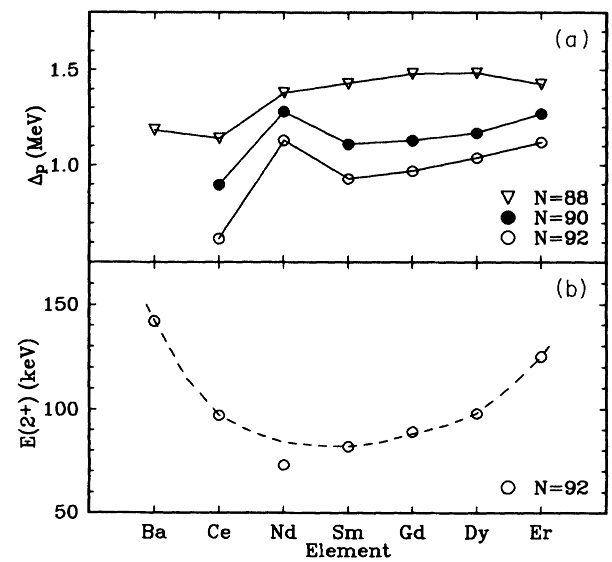

FIG. 5. (a) Proton pairing energies for a series of isotones as deduced from empirical nuclear mass data [32] using the method of Ref. [31]. The deformed shell gap at Nd ($Z = 60$) is seen to be negligible for neutron number $N = 88$, but is significant for higher neutron numbers. The data point for ^{150}Ce ($N = 92$) has a high uncertainty, which, however, is of no importance for the discussion in Sec. V. (b) Energies of the first excited 2^+ states for selected $N = 92$ isotones. The smooth trend of the 2_1^+ energies is interrupted at ^{152}Nd due to the increase in the moment of inertia of the ground state band caused by the increase in the proton pairing gap. The dashed line serves only to guide the eye.

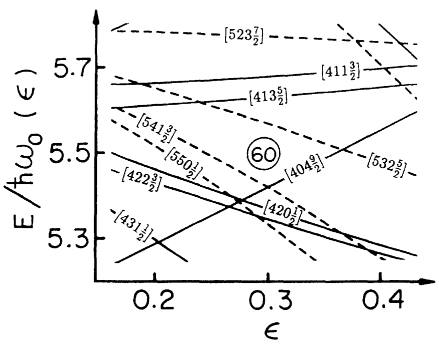

FIG. 6. The calculated energies of some proton single-particle orbitals as a function of the deformation parameter ϵ with regard to the neutron-rich isotopes of Nd ($Z = 60$). For deformations $\epsilon \approx 0.3$, the Fermi level is situated near the $[541\frac{3}{2}]$ orbital. (At $\epsilon \approx 0.3$, the deformation parameters ϵ and β_2 are approximately equal.) The figure has been adapted from Ref. [33].

in the deduced pairing gap data. By using the nuclear mass compilation of Wapstra *et al.* [32], we obtain the proton pairing gap energies shown in Fig. 5(a). For neutron numbers $N \geq 90$ the smooth trends in the data are interrupted at Nd (Z=60). The proton pairing gaps of ^{150,152}Nd are clearly of the order of 25% larger than expected from the systematics of the heavier isotones. The neutron pairing gaps (not shown in Fig. 5) do not exhibit a local variation of this type. Following Bohr and Mottelson [28], one may qualitatively estimate that a 25% increase in the pairing energy gives a 20% reduction in the $0^+ - 2^+$ spacing due to the change in the moment of inertia. In the present case, we expect the effect to be smaller by a factor of 2, since only the protons are involved. An inspection of Fig. 5(b), showing the 2^+ level energies of several $N = 92$ isotones, suggests that a reduction of about 10% agrees well with the empirical data.

The increased proton pairing energies of the neutron-rich Nd nuclei follow from the single-particle level energies in this region, see Fig. 6. The small deformed shell gap at $Z = 60$ is negligible at deformations of about $\epsilon = 0.2$, corresponding to ^{148}Nd, but adds significantly to the energy required to break a pair when ϵ is near 0.3. The ϵ deformation parameters of ^{150,152}Nd are close to the latter value, see Table III.

B. Anomalously small moment of inertia of the first excited 0^+ band

The very large level spacings of the first excited 0^+ bands of ^{150,152}Nd can be understood as a consequence of a change in the deformation due to the excitation of proton or neutron pairs. The lowest excited 0^+ states of deformed nuclei are, in a microscopic picture [34], predominantly composed of diagonal two-quasiparticle excitations, where coupled pairs of nucleons have been promoted to a higher-lying orbital. The situation as regards the protons can be seen in Fig. 6. The ground state of ^{152}Nd has a proton pair in the low-Ω deformation driving $3/2^-[541]$ orbital. Excitation of this pair across the Z=60 gap leads to the occupation of the $3/2^+[411]$, $5/2^+[413]$, or $5/2^-[532]$ orbitals which are either neutral or weakly deformation driving. Importantly, we now have a hole pair in the original orbital, which tends to drive the nuclear shape towards smaller deformations. The same situation exists for the neutrons, where the odd neutron of ^{151,153}Nd occupies [35, 36] the deformation driving $3/2^+[651]$ orbital. Assuming that the same orbital is occupied by the valence neutron pair of ^{152}Nd, one finds that any reasonable excitation of that pair leads to orbitals having higher Ω, thereby not tending as strongly towards deformation as the ground state configuration. An occupation of the low-lying $11/2^-[505]$ orbital would actually tend to reduce the deformation rather strongly. The pairing gaps of protons and neutrons are practically equal in the neutron-rich Nd isotopes, implying that pairs of both nucleon types will contribute approximately equally to the low-lying 0^+ excitation.

The most important effect in both cases is probably that the excitation of an entire particle pair leaves a hole pair in a low-Ω orbital which decreases the deformation and thereby the moment of inertia. A rough approximation of the magnitude of this effect can be obtained simply by examining the isotones of ^{150,152}Nd lacking a proton pair. The 0^+-2^+ spacings of the first excited 0^+ bands of the Nd nuclei, 174 and 111 keV, respectively, should thus be compared with the ground band spacings of 158 and 97 keV of ^{148,150}Ce, respectively. A similar comparison of the influence of the neutron hole pairs is made more difficult through the influence of the pairing effect discussed in the preceding section, and the proximity of the $N = 82$ shell closure. However, the strongly different moments of inertia of the ground and excited 0^+ bands of ^{150,152}Nd can be qualitatively well understood on grounds of the single-particle level structure.

The arguments above favor a shape coexistence picture of the first excited 0^+ bands, although the differences in quadrupole deformation between these bands and the ground state bands are moderate. [This assertion is based on the low values of the relative excitation energies of the 2^+ states of each band, and on the level energy ratio $E(4^+)/E(2^+)$, which is 3.3 for the g.s. band and 3.0 for the excited band.] Direct experimental evidence on the magnitude of the deformation parameter β_2 of the excited bands, e.g., through the intraband $B(E2)$ values, is currently not available.

C. Anomalous γ-ray branching to the ground band levels

The relative $E2$ transition probabilities from the first excited $K^\pi = 0^+$ bands of the $N = 90$ isotones have been shown [37] to deviate considerably from the Alaga predictions [38], even when taking band mixing into account. The $E2$ branching of the $KI^\pi = 02^+$ level of ^{150}Nd was found [12] to be an extreme case with an exceptional low intensity of the $I \rightarrow I - 2$ transition. In the present study of ^{152}Nd, we were unable to detect the $I \rightarrow I - 2$ transitions from both the 2^+ and 4^+ levels of the first excited 0^+ band. The experimental upper limits of about 0.25% per decay of γ-ray intensity correspond to relative $B(E2)$ values which are more than 8–12 times lower than the Alaga values, when compared to the $I \rightarrow I+2$ transitions. These upper limits are near the relative $B(E2)$ values actually observed for the $KI^\pi = 02^+$ levels of the $N = 90$ isotones ^{152}Sm and ^{154}Gd.

It was shown by Kumar [4] that the microscopic treatment used in the PPQ model was able to well reproduce the the experimental $B(E2)$ ratios in the decay of the β band 2^+ level of the $N = 90$ isotone ^{152}Sm. Unfortunately, similar calculations have not been performed for the neutron-rich nuclei ^{150,152}Nd. The latter are, as discussed above, characterized by strongly different moments of inertia of the two lowest 0^+ bands. This fact, which causes problems for many models of collective excitations, is likely to be automatically incorporated in the PPQ model by a proper choice of the active single particle states. The explicit microscopic wave functions provided by the model for each excited state should indeed permit direct calculations of the β_2 deformation parameters and the moments of inertia. A PPQ model study of the heavy Nd isotopes would thus be highly desirable.

VI. SUMMARY AND CONCLUSIONS

We have investigated the levels of ^{152}Nd as populated in the β^- decay of ^{152}Pr. Our γ-spectroscopic study has revealed more than 30 new γ rays and 20 new levels compared to what was previously known. We were able to confirm, and extend, the $K^\pi = 0^-, 2^-$, and 3^- rotational bands suggested by Karlewski *et al.* [15]. The existence of an excited $K^\pi = 0^+$ (β) band was also confirmed, and this band has been extended to the 4^+ level.

The moment of inertia of the β band was found to be unusually small compared to the g.s. band. The latter, however, has one of the highest moments of inertia in the rare-earth region. A similar difference, but not as extreme, has also been observed in ^{150}Nd [12]. The locality of this effect can be explained to be due to a subshell gap at $Z = 60$ in the deformed proton single-particle orbitals at a deformation of $\epsilon \approx 0.3$.

The issue is, however, of a broader interest. To describe cases where two states, e.g., the ground state and one of the excited 0^+ levels, have very different deformations, the concept of shape coexistence has been introduced. This concept is generally based on the presence of an "intruder" configuration [39] having a relatively complex structure. The nuclei ^{150,152}Nd represent an intermediate case where the shapes are significantly different, yet not to the point where shape coexistence, as defined in Ref. [39], would firmly apply. The new experimental evidence on these neodymium nuclei clearly requires new theoretical efforts to account for the properties of the ground and excited 0^+ bands in a microscopical way, without the constraint of a common moment of inertia.

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