Decay Out of the Yrast and Excited Highly Deformed Bands in the Even-Even Nucleus ^{134}Nd

C. M. Petrache,* D. Bazzacco, S. Lunardi, C. Rossi Alvarez, R. Venturelli, P. Pavan, N. H. Medina,† and M. N. Rao†
Dipartimento di Fisica and Istituto Nazionale di Fisica Nucleare, Sezione di Padova, 35131 Padova, Italy

R. Burch, G. de Angelis, A. Gadea,‡ G. Maron, D. R. Napoli, and L. Zhu§
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, 35020 Legnaro, Italy

R. Wyss
Physics Department Frescati, Royal Institute of Technology, S-10405 Stockholm, Sweden

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The decay out of the yrast and excited highly deformed (HD) bands in ^{134}Nd has been investigated via the ^{28}Si + ^{110}Pd reaction at 130 MeV using the GASP array. Several deexcitation pathways have been established for both the yrast and excited HD bands. The resulting spins remove previous ambiguities in the assignment of the excited HD band and confirm the structure assigned to the yrast HD band. The decay out is understood in terms of mixing between the normal-deformed and HD states, which is triggered by the crossing between the $\nu i_{13/2}$ and $\nu d_{5/2}$ orbitals. [S0031-9007(96)00639-4]

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The most striking signature of superdeformed (SD) nuclear shapes at high spin is their characteristic deexcitation through the emission of long sequences of rotational transitions. The regularity of the deexcitation pattern has been widely exploited in experiments performed with the last generation of Ge arrays to identify such weakly populated structures and by now SD bands have been found in nuclei with mass ~130, 150, 190 [1,2] and more recently in nuclei with mass ~80 [3]. At the point of decay towards normal-deformed (ND) states, the SD rotational sequence disappears suddenly and the transition intensity fragments into so many weak branches that a direct identification of the linking transitions has, in general, not been possible. From the theoretical point of view this feature of the decay-out mode has been explained in statistical terms, as a process triggered by small admixtures of ND states into the SD wave functions [4]. The study of the decay out is clearly of paramount importance, as it is the only safe way to determine the excitation energy and to deduce the spin and parity of the SD states.

From the experimental point of view, an ingenious attempt to identify the linking pattern by building the energy sum of two consecutive transitions has lead to a tentative location of the SD band of ^{143}Eu [5]; however, the same method was not successful in other cases. In the heavier $A = 190$ mass region the statistical nature of the process has been confirmed by Henry *et al.* [6], who isolated a quasicontinuous spectrum of the decay-out transitions in ^{192}Hg; this spectrum was qualitatively reproduced by the recent calculations of Døssing *et al.* [7]. Very recently, Khoo *et al.* [8] discovered a few discrete linking transitions in ^{194}Hg, which account for ~5% of the decay strength, with the remaining strength in unresolved (statistical) gamma rays.

The study of the decay-out process in the $A = 130$ mass region, on the other hand, has been successful in the case of odd Nd nuclei [9–12]. We call highly deformed (HD) the bands built on the second well in the nuclei of the $A = 130$ region, in order to emphasize their smaller deformation ($\beta \sim 0.3$–0.4) with respect to the SD bands in the $A =$ 80, 150, 190 regions ($\beta \sim 0.5$–0.6). The observation of discrete linking transitions has been favored here by the smaller excitation energy of the HD configuration with respect to the ND yrast line in the decay-out region (~1 MeV, in contrast with energies of ~4.5 MeV for SD bands in the Hg nuclei), as well as by the relatively higher intensity of the HD bands in the odd nuclei. The transition between the two minima requires only one or two level crossings on the path from high to low deformation and therefore induces less fragmentation of the decay-out flux than in the other regions of superdeformation [13].

In the even Nd nuclei the HD bands are only weakly populated and so far no linking transitions have been observed [14,15]. Their configurations have been essentially assigned on the basis of the behavior of the dynamical moments of inertia ($J^{(2)}$) and assume the occupation of a single $i_{13/2}$ neutron orbital. However, only the determination of spin and parity of the band levels will allow one to confirm this theoretical prediction. Moreover, the observation of linking transitions in an even-even nucleus will help, through the comparison with the odd-even ones, in understanding the interplay between the pairing correlations and mixing of ND and HD states in the decay-out process.

In this Letter we report on the first identification of discrete transitions linking both the yrast and excited HD bands of ^{134}Nd to the ND states. The present data allow us to fix the excitation energy of the two HD bands and to infer their spins and parities, in agreement with the previously suggested configurations [14]. The decay-out mechanism is understood in terms of mixing between HD and ND states, which is triggered by the crossing between the $\nu i_{13/2}$ and $\nu d_{5/2}$ orbitals.

The ^{134}Nd nucleus has been populated via the ^{28}Si + ^{110}Pd reaction at 130 MeV. The target consisted of two self-supporting foils of ^{110}Pd with a total thickness of 1.36 mg/cm^2. The GASP array with 40 Compton-suppressed Ge detectors and the 80-element BGO ball has been used for a coincidence measurement. Events were accepted when at least three suppressed Ge detectors and three detectors of the BGO ball fired in coincidence. A total of 1.9×10^9 events have been collected. By doubly gating on all known members of each HD band [14] we obtained very clean spectra, which allowed the extension of the excited HD band at lower spins by two transitions (765.1 and 726.4 keV), as well as the determination with higher precision of the energies of the two lowest γ rays in the yrast HD band (733.3 and 667.9 keV). Examples of spectra showing the linking transitions and their coincidence relationships with other ND and HD transitions are given in Fig. 1. A partial level scheme of ^{134}Nd relevant for the decay-out process is given in Fig. 2. For the yrast HD band, four γ rays with $E_\gamma \sim 1.3$ MeV are observed. The 1336 and 1332 keV transitions are in coincidence with two other γ rays of 736 and 740 keV, respectively, whereas the 1339 and 1358 keV transitions directly deexcite the HD levels. The three linking transitions with energies $\sim$1330 keV are also in coincidence with the transitions of band 3 below the 18^+ level (see Figs. 1 and 2). The position of the HD yrast band relative to the ND levels is fixed by the 1358 keV transition which connects its lowest observed level to the ground state band. In the case of the two decay paths of 736–1336 and 740–1332 keV, the errors for the intensities of the strongly contaminated 736 and 740 keV transitions did not allow us to establish their ordering. The one adopted in Fig. 2 is preferred because it gives intermediate levels which are not yrast, in agreement with their weak population. From the γ-γ coincidence analysis we could also place unambiguously the three linking transitions of 1780, 1889, and 1928 keV of the excited HD band, as is shown in Fig. 2. The energies and relative intensities of the transitions which are relevant for the decay-out process are given in Table I. It can be seen that only $\sim$50% ($\sim$40%) of the yrast (excited) HD band intensity is carried out by the observed discrete linking transitions, to be compared with $\sim$5% for the ^{194}Hg case [8].

The spins of the HD band levels have been determined from the analysis of the differential correlation orientation (DCO) ratios using the procedure described, e.g., in Ref. [12]. Because of the very weak intensity of the high-energy linking transitions, definite values of their DCO ratio could not be obtained. However, the linking transitions of the yrast HD band show strong 90°–34° anisotropy when gating on all in-band $E2$ transitions and therefore their dipole character is established. For the 736 and 740 keV γ rays which are strongly contaminated, no

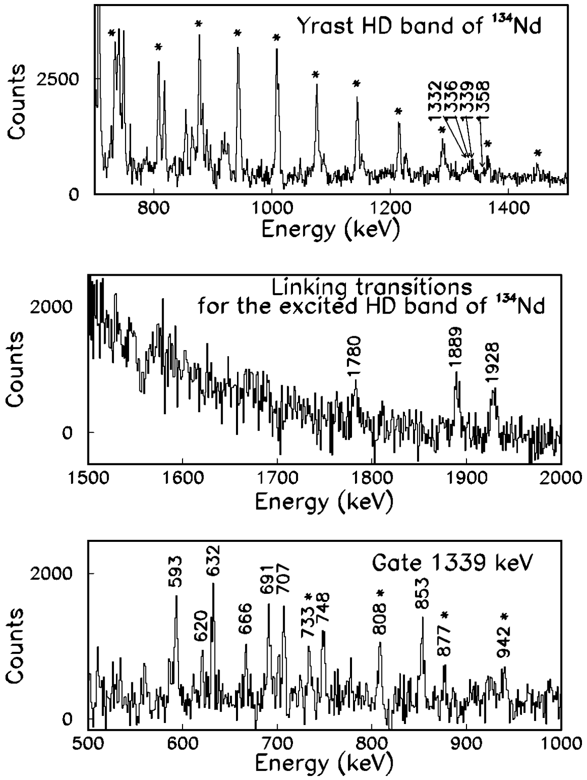

FIG. 1. Doubly-gated spectrum of the yrast HD band in which the γ rays of the HD band are indicated by asterisks (upper panel), high-energy part of the single-gated spectrum of the excited HD band (middle panel), and double-gated spectrum with gates on the transitions of the yrast HD band and on the 1339 keV linking transition (bottom panel).

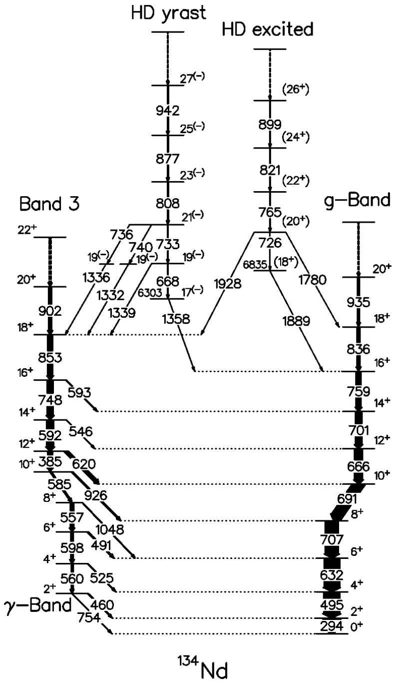

FIG. 2. Partial level scheme of ^{134}Nd showing the part relevant for the decay-out process. The arrow thickness is proportional to the transition intensity.

TABLE I. Gamma-ray energies, relative intensities, spins, and DCO ratios for the transitions in the lower part of the yrast and excited HD bands of ^{134}Nd and for the transitions relevant for the decay out.

E_γ (keV)	I_γ (%)	$I_i^\pi \rightarrow I_f^\pi$	DCO ratio
	Yrast HD band		
876.6	100(5)	$25^{(-)} \rightarrow 23^{(-)}$	1.00(2)
808.1	100(5)	$23^{(-)} \rightarrow 21^{(-)}$	1.00(2)
733.3	37(5)	$21^{(-)} \rightarrow 19^{(-)}$	0.88(10)
667.9	10(5)	$19^{(-)} \rightarrow 17^{(-)}$	1.00(3)
1331.9	13(3)	$19^{(-)} \rightarrow 18^{+}$	...
1336.3	7(3)	$19^{(-)} \rightarrow 18^{+}$	...
1338.6	27(3)	$19^{(-)} \rightarrow 18^{+}$	...
1357.5	4(3)	$17^{(-)} \rightarrow 16^{+}$	...
	Excited HD band		
E_γ (keV)	I_γ (%)	$I_i^\pi \rightarrow I_f^\pi$	DCO ratio
898.6	100(2)	$(26^{+}) \rightarrow (24^{+})$	1.10(10)
821.4	78(3)	$(24^{+}) \rightarrow (22^{+})$	1.07(10)
765.1	60(5)	$(22^{+}) \rightarrow (20^{+})$	...
726.4	32(5)	$(20^{+}) \rightarrow (18^{+})$	...
1780	12(4)	$(20^{+}) \rightarrow 18^{+}$	...
1889	17(5)	$(18^{+}) \rightarrow 16^{+}$	...
1928	10(3)	$(20^{+}) \rightarrow 18^{+}$	...

DCO ratios could be obtained. They are assumed to have $\Delta I = 2$, $E2$ character. The negative parity indicated in parentheses for the yrast HD band accounts for the theoretically assigned configuration (see discussion below). The linking transitions of the excited HD band do not show significant anisotropy between 90° and 34°; this is consistent with a $\Delta I = 2$, $E2$ character and leads to even spins and positive parity. The present measured energies and spins of both HD band-head levels determine their excitation energy relative to the yrast ND line at ~1100 keV in the decay-out region.

Two different types of decay-out pathways are observed experimentally: that of the excited HD band, which most likely consists of stretched $E2$ transitions, and that of the yrast HD band, where the decay out proceeds via $E2$ and $E1$ transitions. For the 1780 and 1928 keV linking transitions of the excited HD band we estimated the $B(E2)$ strengths from the ratio between the decay-out and the in-band (726 keV) transition intensities by a simple energy scaling of the transition operators. Assuming an in-band $B(E2)$ strength of 400 W.u., similar to that measured for the HD band in the neighboring ^{133}Nd nucleus [16], $B(E2)$ strengths of the order of 1 W.u. are obtained for the linking transitions. Such sizable out-of-band strengths clearly indicate a spread of the ND states into the HD minimum, which leads to a significant mixing between the HD and ND states. The final 1889 keV decay-out transition deexciting the lowest observed HD state has somewhat stronger intensity than the other linking transitions (see Table I). Since the energy of the in-band transitions is decreasing in contrast to that of the out-of-band ones, the enhanced decay-out strength is indeed expected.

Examining the decay out of the yrast HD band one observes that the 21^- state decays into three 19^- levels that are within 6 keV of excitation energy. It is difficult to give an exact assignment for the additional two states. However, knowing the limited number of HD configurations and the high level density at that excitation energy, we can rather firmly conclude that their origin involves states with ND shapes. The presence of even a very small interaction will lead to a sizable mixing of the corresponding wave functions, a fact which is indicated by the similar deexcitation pattern of the three $19^{(-)}$ states. The analysis of the out-of-band strengths of both HD bands in ^{134}Nd, together with the ~50% intensity of the observed discrete transitions, suggests that the decay-out mechanism in ^{134}Nd is only partially due to the stochastic mixing between the ND and HD states as proposed by Vigezzi, Broglia, and Døssing for the $A = 150$, 190 regions [4]. In other words, it indicates that the quantum structure of the mixed ND bands is still of importance.

The identification in this measurement of one more HD state below the 19^- level allows us to extract a value of 0.11×10^{-6} fm^{-2} for the $B(E1)/B(E2)$ ratio between the 668 keV ($E2$) and 1339 ($E1$) transitions. Assuming again a $B(E2)$ value of 400 W.u., we get a $B(E1)$ strength of $\sim 10^{-3}$ W.u., comparable to those observed in the heavy Ba-Sm region, for which stable octupole deformations have been predicted. Since the neutron Fermi surface at high deformation is almost between the $f_{7/2}$ and $i_{13/2}$ orbitals and the HD yrast band of ^{134}Nd is assumed to involve the $\nu i_{13/2}$-$h_{9/2}/f_{7/2}$ configuration [14], one can indeed expect octupole couplings to be present. Apparently, the enhanced deformation has a similar effect as an increase of the neutron number.

Possible configurations of the HD bands of ^{134}Nd were already discussed in Ref. [14] in terms of occupation of the available Nilsson orbitals at high deformation. In order to interpret the present more detailed informations, we have performed new calculations for ^{134}Nd within the cranked Strutinsky approach based on a Woods-Saxon potential including pairing interaction [17,18]. Each configuration is treated diabatically, thus avoiding unphysical level crossings between different structures. As established previously [14], a proton gap is present at $Z = 60$ for deformations ranging from $\beta_2 \approx 0.20$ to 0.37, which cover the quadrupole deformations of the ND and HD states. The occupied proton orbitals do not encounter therefore any level crossing in the collective path from high to low deformation. The situation is different for neutrons, in that a pair of particles is moved from the up-sloping $[404]7/2^+$ Nilsson orbit into the down-sloping $[541]1/2^-$ one when the deformation is changing from ND to HD (see also Fig. 3 in Ref. [14]). In addition, at least one neutron is moved from the $[402]5/2^+$ Nilsson state into the $[660]1/2^+$ ($i_{13/2}$) one. In our assignment, the excited HD band involves the $\nu i_{13/2}$-[402]$5/2^+$ configuration that is crossed at higher frequencies by the $\nu(i_{13/2})^2$ one, whereas the yrast HD band involves the $\nu i_{13/2}$-$\nu h_{9/2}/f_{7/2}$ configuration. The spins and parities indicated for the HD bands in Fig. 2 are in accord with these assignments. A more detailed discussion about the configurations of the different bands involving the neutron $i_{13/2}$ orbital will be published in a forthcoming paper.

In the decay-out region, the dynamical moment of inertia of both HD bands shows an irregularity which is also observed for all HD bands of the other Nd nuclei [9,11,12] and appears at rotational frequencies which decrease with decreasing neutron number.

From the present calculations, but also from an inspection of the single-particle diagram reported in Fig. 3 of Ref. [14], one can easily see that the $\nu i_{13/2}$ intruder crosses the ν[402]$5/2^+$ ($d_{5/2}$) Nilsson orbital in the frequency region where the increase in $J^{(2)}$ is observed in the HD bands of Nd nuclei. As the variation of $J^{(2)}$ is always associated with a change in structure of the corresponding rotational band, we associate the observed irregularity to the crossing between the $\nu i_{13/2}$ and $\nu d_{5/2}$ orbitals. The rise in $J^{(2)}$ thus corresponds to a partial deoccupation of the strongly deformation driving $\nu i_{13/2}$ intruder orbital. When no pairing is present, the transition between the states at different deformations (which form orthogonal sets) are severely hindered, since the related operators act only on a single particle. The presence of pairing correlations, on the other hand, helps the nucleus to tunnel between the minima.

A further insight into the role played by the pairing correlations in the decay-out process can be obtained from a comparison of the decay-out pattern in the even-even nucleus ^{134}Nd with the known decay out in the odd isotope ^{133}Nd. There, the crossing between the $N = 4$ and $N = 6$ ($i_{13/2}$) neutron orbitals is actually observed, but the HD band is traced to lower spin values. The reason for this difference can be related to the lower excitation energy of the $\nu i_{13/2}$ band in ^{133}Nd; in fact, the crossing here occurs when the HD band is rather cold and this explains why it continues at lower spins. In the case of ^{134}Nd the HD structures involve two-quasiparticle (qp) excitations that lie higher in energy with respect to the ground state, because of the pair gap. Moreover, the pairing correlations are smaller in the two-qp HD bands of ^{134}Nd than in the one-qp HD band of ^{133}Nd. As the decay out occurs at similar excitation energies above yrast in both HD nuclei, we can conclude that the mixing with the ND states plays a more important role than the sliding via the pairing interaction. In all cases, however, static pair gaps are calculated to exist and pairing is believed to be essential for the decay towards the ND states.

In conclusion, the present results suggest that the decay out of the HD bands in ^{134}Nd is triggered by the crossing with the $N = 4$ [402]$5/2^+$ Nilsson orbital that has a smaller deformation than the corresponding $N = 6$ intruder configuration. The crossing favors the mixing with the ND rotational bands strongly enhancing the decay-out process and weakening the in-band transition strength. The HD band becomes fragmented and loses part of its character. The intensity of the decay-out transitions increases when the spin of the deexcited HD state decreases, indicating enhanced ND amplitude in the wave function when going down the band. Lifetime measurements of the HD bands are crucial to further elucidate the decay-out process.

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*On leave from Institute of Physics and Nuclear Engineering, Bucharest, Romania.

†On leave from Instituto di Física, Universidade de São Paulo, São Paulo, Brazil.

‡On leave from Istituto de Fisica Corpuscolar, Valencia, Spain.

§On leave from Institute of Atomic Physics, Beijing, China.

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