RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 49, NUMBER 5 MAY 1994

Complete decay out of the superdeformed band in ^{133}Nd

D. Bazzacco, F. Brandolini, R. Burch, S. Lunardi, E. Maglione, N. H. Medina, P. Pavan, and C. Rossi-Alvarez
Dipartimento di Fisica and INFN, Sezione di Padova, Padova, Italy

G. de Angelis, D. De Acuna, M. De Poli, and J. Rico
INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy

D. Bucurescu and C. Ur
Institute of Physics and Nuclear Engineering, Bucharest, Romania
(Received 13 January 1994)

Ten transitions linking the superdeformed band to the normal deformed states have been identified in ^{133}Nd. These transitions drain the full band intensity into the different band structures established at lower spin. The major part of the decay out of the superdeformed band is understood in terms of mixing of levels which involve orbitals differing by two major oscillator quantum numbers.

PACS number(s): 21.10.Re, 23.20.Lv, 27.60.+j

The investigation of the decay out of the superdeformed (SD) potential energy minimum is a topic of major interest in nuclear structure physics today. After the discovery of many SD bands in the $A = 130$, 150, and 190 [1,2] mass regions, many attempts have been made in order to identify discrete transitions linking the states in the SD energy minimum to the normally deformed structures. In the mass 130 region (where the SD bands are sometimes called "highly deformed") the deformation in the second minimum is somewhat smaller than in the other two mass regions; furthermore, the so-called "normal deformed states" have a sizable deformation $\beta = 0.20$–0.25. Because of these two reasons, it is believed that the decay out of the SD structure to the normal deformed one by means of discrete transitions is here more easy to observe. In fact, the first nucleus where some discrete linking transitions have been seen is ^{135}Nd [3]. Recently, in the first experiment performed with the GASP array, we could identify three transitions connecting the SD band to levels of lower deformation in the nucleus ^{133}Nd [4]. Spins and excitation energies of the SD band states in ^{133}Nd could therefore be fixed unambiguously. Only one-third of the intensity of the SD band is carried out by the three observed transitions whereas the remaining part of the decay could not be identified. In order to understand the decay mechanism of the SD bands (at least in the mass 130 region), it is important to know their complete decay and to find how they interact with the bands at normal deformation. Most likely, one of the main reasons which prevented the identification of the complete decay out of the SD band in ^{133}Nd was the very poor knowledge of the level scheme at low energy. Only few levels of the $h_{11/2}$ band were known in the literature [5] and more recently a band based on the $g_{7/2}$ Nilsson state was presented in [6]. We already obtained a substantial improvement of the level scheme of ^{133}Nd with the data of Ref. [4], mainly derived from a thin target experiment. However, we found it necessary to perform a high statistics and high resolution backed target experiment with the twofold goal of obtaining a detailed level scheme of ^{133}Nd at low excitation energy and of identifying all the transitions which depopulate the SD band. In fact, after a short thick target run with a gold backed target using the reaction ^{105}Pd(^{32}S,$2p2n$)^{133}Nd at 155 MeV, we realized, in agreement with Ref. [7], that the levels of the SD band below $I^\pi = 33/2^+$ have lifetimes larger than the stopping time of the recoiling ions in gold. This implies that the transitions deexciting the lowest levels of the SD band appear as sharp lines in a γ-ray spectrum. Since the decay out of the band occurs just below $I^\pi = 33/2^+$, the linking transitions also will not suffer from the Doppler broadening effect. When the lifetimes of the levels of interest allow it, the high energy resolution achievable in a backed target experiment is as important as high-fold coincidences for the extraction of low intensity transitions from the enormous γ-ray flux emitted in a nuclear reaction.

In this Rapid Communication we present our results on the decay out of the SD band of ^{133}Nd. The full SD band intensity has been found to divide into ten different paths which bridge the band to levels of different structure at lower spin. A complete level scheme of ^{133}Nd, comprising seven bands built on different Nilsson orbitals, has also been established.

We have populated the ^{133}Nd nucleus through the reaction ^{104}Pd+^{32}S. The measurement was performed at a beam energy of 135 MeV after testing the reaction at several points between 130 and 145 MeV. The reaction ^{104}Pd+^{32}S has been preferred to the ^{105}Pd+^{32}S of Ref. [4], since in an exploratory run it appeared to be somewhat cleaner for the channel of interest. The target consisted of 1.1 mg/cm^2 of ^{104}Pd evaporated on a 15 mg/cm^2 gold foil. The beams was provided by the Tandem XTU accelerator of Legnaro and gamma rays have been detected using the GASP array with 38 high efficiency Compton suppressed germanium detectors and with two planar germanium detectors for the lower γ-ray energies. The inner ball, composed of 80 BGO detectors, was also used. Events were collected when at least three suppressed Ge detectors and three detectors of the in-

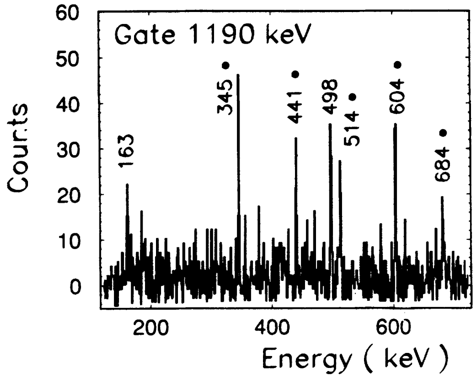

FIG. 1. Doubly gated coincidence spectrum showing that the 1190 keV transition links the $17/2^+$ state of the SD band with the $15/2^-$ state of the [514]9/2 band. The transitions of the SD band are labeled with full dots.

ner ball fired in coincidence. With such conditions the event rate was ≈7 kHz with a beam current of 4 particles nA and about 8 kHz singles rate in the germanium detectors. After unfolding the stored events, 3.2×10^9 and 1.2×10^9 of doubles and triples coincidences respectively were available for the off-line analysis.

The triples data events were sorted into a $(2k)^3$ symmetrized cube from which many matrices could be easily extracted setting gates on the different band structures of ^{133}Nd. The spectra obtained from these gated matrices are very clean allowing for a clear identification of the transitions connecting the various bands. As an example, Fig. 1 shows the spectrum obtained setting a gate on the 1190 keV transition in a matrix built with gates on the SD band members. The 1190 keV transition links the $17/2^+$ state of the SD band to the $15/2^-$ state of the [514]9/2 band.

Ten transitions, including the three already reported in Ref. [4], have been found which connect the superdeformed band to the normal deformed states. The complete level scheme resulting from the present thick target experiment and, for the high spin part, from the previous thin target data [4] is drawn in Fig. 2 where the bands are labeled in terms of the Nilsson scheme. The SD band is based on the $N = 6$ $i_{13/2}$ orbital [660]1/2 whose occupation drives the nucleus to a larger deformation [8].

Of great help in confirming the low energy part of the level scheme has been a recent β-decay study of ^{133}Pm [9] performed at the Georgia Institute of Technology. In this study a second β^+ decaying state with spin $1/2^+$ was identified 128 keV above the ground state. Furthermore, a 45 keV transition (not seen in our experiment) that connects a $3/2^+$ state to the $1/2^+$ β^+ decaying state was also observed in that study.

Spins and parities have been assigned on the basis of a differential correlation orientation (DCO) ratio analysis; for the bandhead transitions the electron conversion data of Ref. [9] have also been used. The DCO ratios extracted for six of the linking transitions give, for the SD band, as unique solution the spins and parities shown in Fig. 2. We will not discuss here in detail the rich level structure and the band properties of the ^{133}Nd nucleus which deserve a detailed interpretation in a forthcoming article; instead we will focus our attention on the decay out of the SD band and on its mechanism.

Since it is yrast above spin $29/2^+$, the band is the most strongly populated discrete structure at high spin (up to $I^\pi = 89/2^+$) [4]. Below $29/2^+$ the band is no more yrast and when it disappears (at spin $17/2^+$) it is the furthest from yrast of all the observed bands of this nucleus. The decay of the SD band to the other nuclear states is occuring in the spin interval ($17/2^+$-$29/2^+$) where the band is crossing levels of similar spin and parities and can mix with them. The inset of Fig. 2 shows the low energy part of the SD band together with the relevant levels of the other bands to which it decays through the ten linking transitions. In Table I we report the relative intensity of the linking transitions and of the transitions of the SD band in the decay-out region. If the intensity of the SD band is taken equal to 100 at spin $33/2^+$, the sum of the intensities of the linking transitions gives 101±6. The full intensity of the band is

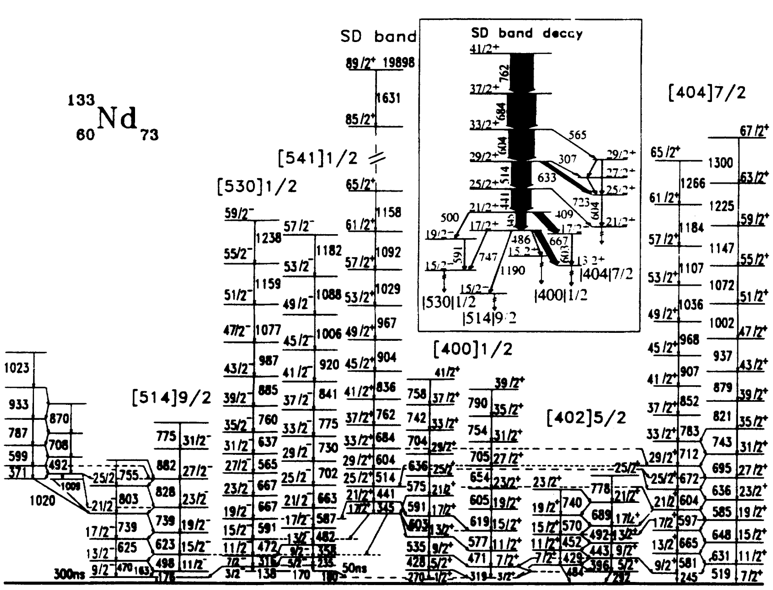

FIG. 2. Level scheme of ^{133}Nd obtained from the present work showing only partially the SD band. For the low spin part, results from Ref. [9] are also included. The inset shows the decay out of the ^{133}Nd superdeformed band.

TABLE I. Energies and relative intensities for the transitions of the lower part of the SD band in ^{133}Nd and for the transitions linking the SD band to normal deformed states.

Energy (keV)	$I_i^\pi \to I_f^\pi$	Intensity (%)
	Transitions in the SD band	
345	$21/2^+ \to 17/2^+$	33(4)
441	$25/2^+ \to 21/2^+$	61(5)
514	$29/2^+ \to 25/2^+$	65(5)
604	$33/2^+ \to 29/2^+$	93(6)
684	$37/2^+ \to 33/2^+$	100
	Linking transitions	
307	$29/2^+ \to 27/2^+_{[404]7/2}$	5(1)
409	$21/2^+ \to 17/2^+_{[400]1/2}$	25(3)
486	$17/2^+ \to 15/2^+_{[400]1/2}$	2.4(0.6)
500	$21/2^+ \to 19/2^-_{[530]1/2}$	4.5(1.0)
565	$33/2^+ \to 29/2^+_{[404]7/2}$	7(2)
633	$29/2^+ \to 25/2^+_{[404]7/2}$	24(3)
667	$17/2^+ \to 13/2^+_{[400]1/2}$	20(3)
723	$25/2^+ \to 21/2^+_{[404]7/2}$	2.9(0.7)
747	$17/2^+ \to 15/2^-_{[530]1/2}$	6(1)
1190	$17/2^+ \to 15/2^-_{[514]9/2}$	4.3(1.2)

therefore taken away by the observed connecting transitions. A feature that is immediately clear from Fig. 2 and Table I is that three strong transitions (409, 633, and 667 keV) are responsible for almost 70% of the decay whereas the other seven are much weaker. We can relate this fact to a level mixing phenomenon. In fact the $29/2^+$ level of the SD band ($29/2^+_{\rm SD}$), which decays through the strong 633 keV transition to the $25/2^+_{[404]7/2}$, lies only 39 keV apart from the $29/2^+_{[404]7/2}$. Furthermore, a weak transition of 553 keV is observed to decay from the $29/2^+_{[404]7/2}$ to the $25/2^+_{\rm SD}$. These facts are a clear indication of a level mixing occurring between levels differing by two major oscillator quantum numbers ($N = 6$ and 4). Analogously, the mixing of the $17/2^+_{\rm SD}$ with the $17/2^+_{[400]1/2}$ ($\Delta E = 64$ keV) can explain the strong transitions linking the $21/2^+_{\rm SD}$ to the $17/2^+_{[400]1/2}$ (409 keV) and the one from the $17/2^+_{\rm SD}$ to the $13/2^+_{[400]1/2}$ (667 keV). Also in this case the decay of the [400]1/2 band into the SD band is observed ($21/2^+_{[400]1/2} \to 17/2^+_{\rm SD}$, 527 keV). The experimental branching ratios are reported in Table II.

In order to extract the interaction matrix elements and the mixing amplitudes of the states, a simple two-band mixing calculation [10] has been performed. We assume a constant interaction V between the two interacting bands and a vanishing interband transition strength. Solving this two-dimensional eigenvalue problem, we get the square of the ratio of the amplitudes as

$$\frac{\beta^2}{\alpha^2} = \frac{\Delta E_{\rm expt}(I) - \Delta E_0(I)}{\Delta E_{\rm expt}(I) + \Delta E_0(I)} ,$$

where α and β are the amplitudes of the superdeformed and of the normal deformed configuration in the SD state. $\Delta E_0(I)$ is the difference of the two unperturbed energies given by

$$\Delta E_0(I) = \sqrt{\Delta E_{\rm expt}(I)^2 - (2V)^2} .$$

One can then easily express the branching ratios as a function of the interaction V and of the ratio of the in-band $E2$ transition matrix elements. From the experimental branching ratios we can extract the interaction matrix elements at spin $29/2^+$ and $17/2^+$ as well as the expected branchings of the $33/2^+$ and $25/2^+$ states of the SD band into the [404]7/2 band as reported in Table II. We like to stress the remarkable agreement between the experimental and calculated branching ratios. From this analysis we can derive also the unperturbed enregies of the SD band and hence recalculate its dynamic $J^{(2)}$ moment of inertia. Figure 3 shows the moments of inertia

TABLE II. Experimental branching ratios for the levels relevant for the mixing between SD and normal deformed states in ^{133}Nd. In the last column the extracted interaction matrix elements are given, together with the calculated branching ratios of the $33/2^+_{\rm SD}$ and $25/2^+_{\rm SD}$ levels.

$I_i^\pi \to I_f^\pi$	E_γ (keV)	Expt. branching ratios (%)	V (keV)
$29/2^+_{\rm SD} \to 25/2^+_{\rm SD}$	514	69(3)	
$29/2^+_{\rm SD} \to 25/2^+_{[404]7/2}$	633	26(3)	11
$29/2^+_{[404]7/2} \to 25/2^+_{[404]7/2}$	672	92(2)	
$29/2^+_{[404]7/2} \to 25/2^+_{\rm SD}$	553	8(2)	
$21/2^+_{\rm SD} \to 17/2^+_{\rm SD}$	345	57(4)	
$21/2^+_{\rm SD} \to 17/2^+_{[400]1/2}$	409	43(4)	22
$21/2^+_{[400]1/2} \to 17/2^+_{[400]1/2}$	591	87(4)	
$21/2^+_{[400]1/2} \to 17/2^+_{\rm SD}$	527	13(4)	
			Calc. branching ratios (%)
$33/2^+_{\rm SD} \to 29/2^+_{\rm SD}$	604	93(2)	94
$33/2^+_{\rm SD} \to 29/2^+_{[404]7/2}$	565	7(2)	6
$25/2^+_{\rm SD} \to 21/2^+_{\rm SD}$	441	95(1)	93
$25/2^+_{\rm SD} \to 21/2^+_{[404]7/2}$	723	5(1)	7

derived, as usual, from the expression $J^{(2)} = 4/\Delta E_\gamma$ using both the experimental energy differences between two consecutive transitions and the ΔE_γ which result when the level shifts due to the mixing with normal states are removed. The irregular behavior of $J^{(2)}$, typical of the SD bands in the mass 130 region at the decay, disappears when the new energy values are used. This result clearly shows that the mixing with normal deformed states is the most likely interpretation of the strange $J^{(2)}$ behavior at lower frequency.

The SD band ends at spin $17/2^+$; in fact, we could not see in our spectra any indication of the $17/2^+_{SD} \rightarrow 13/2^+_{SD}$ transition which should have an energy of 250–300 keV. A transition in that energy range should have an intensity $\approx$5% of that of the 667 keV transition if one takes into account the composition of the $17/2^+$ state of the SD band and the energy factor in calculating the branching ratios. This gives for the $17/2^+_{SD} \rightarrow 13/2^+_{SD}$ transition an intensity of $\approx$1% of that of the SD band at $I^\pi = 33/2^+$. This value is two times smaller than that of the weakest linking transition and explains why the SD band has been observed only from the $17/2^+$ upwards.

In summary, we have experimentally identified the complete decay out of the ^{133}Nd SD band to levels of normal deformation. The decay can be understood in a quantitative way in terms of the mixing of the SD states with the normal deformed levels. The mixing occurs when the SD band is above yrast and crosses a region where the density of levels is high. The comprehension of the ^{133}Nd case may be of help in elucidating the decay mechanism of SD bands in other mass regions where a possible explanation in terms of level mixing has been proposed [11].

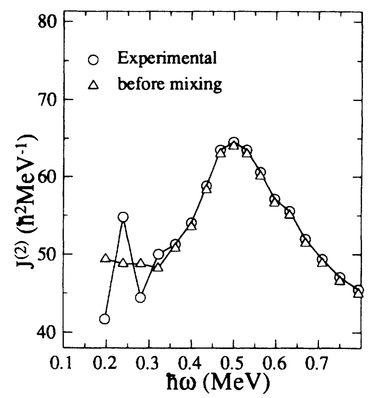

FIG. 3. Experimental (○) $J^{(2)}$ moment of inertia for the SD band of ^{133}Nd compared with the one obtained (△) when the mixing with normal deformed states is taken into account. Only the mixing with states below 4 MeV has been considered in the calculations.

One of us (N.H.M.) would like to acknowledge financial support from CNPq-Conselho Nacional de Desenvolvimento Científico e Tecnológico (Brazil).

[1] P. J. Nolan and P. J. Twin, Annu. Rev. Nucl. Part. Sci. **38**, 533 (1988).

[2] R. V. F. Janssens and T. L. Khoo, Annu. Rev. Nucl. Part. Sci. **41**, 321 (1991).

[3] E. M. Beck *et al.*, Phys. Rev. Lett. **58**, 2182 (1987).

[4] D. Bazzacco *et al.*, Phys. Lett. B **309**, 235 (1993).

[5] Y. Choquer, J. Gizon, and A. Gizon, J. Phys. (Paris) **38**, L157 (1977).

[6] S. M. Mullins, Ph.D. thesis, University of York, 1989.

[7] S. M. Mullins *et al.*, Phys. Rev. C **45**, 2683 (1992).

[8] R. Wyss, J. Nyberg, A. Johnson, R. Bengtsson, and W. Nazarewicz, Phys. Lett. B **215**, 211 (1988).

[9] J. B. Breitenbach, Ph.D. thesis, Georgia Institute of Technology, 1993.

[10] R. Bengtsson and S. Frauendorf, Nucl. Phys. **A314**, 27 (1979).

[11] E. Vigezzi, R. A. Broglia, and T. Døssing, Phys. Lett. B **249**, 163 (1990).