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Decay out of the highly deformed band in ^{133}Nd

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The mean lifetimes of the $25/2^+$, $21/2^+$, and $17/2^+$ states in the highly deformed (HD) band of ^{133}Nd, excited via the reaction ^{104}Pd(^{32}S,$2pn$)^{133}Nd, have been measured using a recoil distance Doppler-shift method. The decay out of the HD band occurs as a result of an admixture of normally deformed (ND) components into the HD states' wave function. The consistency in the mixing amplitude was assessed from the measured lifetimes, branching ratios, and quadrupole moments of the HD and the ND bands. This analysis unequivocally confirms the earlier approach to explain the decay-out mechanism.

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In the past 20 years much interest has been focused on the study of superdeformed (SD) and highly deformed (HD) bands [1]. In particular, with the identification of the γ-ray transitions linking the first SD band to the known states in ^{152}Dy [2], the decay-out mechanism continues to be an actively pursued field of research [3,4]. Although the superdeformed bands are characterized by a prolate ellipsoid with an axis ratio of 2:1 (in the $A \sim 190$ and 150 regions), the highly deformed bands in the $A \sim 130$ region have an axis ratio of 3:2 [5,6]. In the Pb region, the level-mixing hypothesis between the "cold"-SD and the degenerate "hot"-normal states has been tested via the measurement of level lifetimes at the bottom of the SD band [7]. Although level mixing seems to be a generic feature in the decay-out aspect for the observed SD and HD bands, so far a consensus among various approaches on the physics of decay out of such exotic bands has not been reached [8]. The potential energy surfaces of the nuclei in the $A \sim 130$ region exhibit energy minima at a normal, low deformation value of $\beta_2 = 0.25$, and a second minimum at a larger deformation value of $\beta_2 \sim 0.4$; rotational bands built on this latter second minimum have come to be known as HD bands. Several studies have been made in the $A \sim 130$ region with large γ-detector arrays [5,9–11], resulting in comprehensive level schemes. In particular, γ-ray transitions involved in the decay out of the HD bands of ^{133,135,137}Nd isotopes have been firmly established [9–11]. The HD bands in these nuclei are characterized by the odd-neutron occupying the high-j $i_{13/2}$, [660]1/2 Nilsson intruder orbital. Thus, the normally deformed (ND) bands and the HD bands differ by the rearrangement of only a few particles, as opposed to the SD bands in the 150- and 190-mass regions where such changes typically involve 8–10 particles. In lighter nuclei the level density is low and, if any,"accidental degeneracy" two-level mixing effects are expected to dominate the decay-out process, whereas in heavier systems ($A \sim 150$, 190) the level densities are much higher, so the level-mixing aspect is more statistical in nature. The HD bands are populated with good intensities (5–10% of the reaction channel), thereby facilitating a detailed experimental study of the electromagnetic matrix elements at the decay-out stage of a band. These matrix elements can be deduced from a measurement of the level lifetimes. In ^{133}Nd, the decay out of the HD band was completely mapped [9]; Bazzaco *et al.* attribute the decay-out process to an *accidental* mixing with the neighboring ND states. It is of significant interest to explore the physics of the decay-out process via the measurement of electromagnetic matrix elements. Such an exercise has yielded new insights, for example, into the decay-out mechanism of the SD bands in the Hg/Pb-region [7]. As the lifetimes of these states fall in the picosecond range, the recoil distance method (RDM) is an ideal technique to measure them. At higher spins a Doppler-shift-attenuation (DSA) analysis has yielded a constant quadrupole moment for the ^{133}Nd HD band [12]; however, at the decay-out spins the quadrupole moment could be different and therefore a direct method is better suited. In addition, the implementation of a coincidence RDM eliminates problems arising from the observed and unobserved sidefeeding. The technique is free from the uncertainties related to the stopping powers that

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plague the DSA method. Furthermore, when the differential-decay-curve (DDC) method is used to analyze the coincidence RDM data, the results are not influenced by the deorientation effect owing to the hyperfine field [13]; additionally, as only the relative target-to-stopper distances enter into the final analysis, a knowledge of the absolute distance is also not required [13].

Excited states in ^{133}Nd were populated intensely with the reaction ^{104}Pd(^{32}S,2pn)^{133}Nd, at a beam energy of 135 MeV. The target and the stopper consisted of a stretched 930 μg/cm^2 thick ^{104}Pd foil and a 12 mg/cm^2 thick gold foil, respectively. The emitted γ rays from the reaction products were detected with 40 Compton-suppressed high-purity germanium detectors (CS-HPGe), which comprise the GASP array. The recoiling nuclei, with a mean velocity $v/c \sim$ 1.8%, were completely stopped in the gold foil. The beam was stopped 5 cm further downstream in an additional 50 mg/cm^2 thick bismuth foil rolled onto a copper foil, which provided the thermal cooling. The three foils were mounted in a modified version of the Köln plunger described in Ref. [14]. In total, about 1.7 billion two- and higher fold Ge events were acquired for 15 distances ranging from 23 to 3000 μm. In a previous study, a plunger experiment with the Polytessa γ-array sited at the Daresbury laboratory, the mean lifetimes of the decay-out states had large statistical uncertainties [15]. This was overcome in the present experiment by using the GASP array in a configuration without the inner bismuth germanate (BG0) ball; this configuration has a higher efficiency of 5.3% (at 1332 keV) than the one with the BGO ball (which had an efficiency of 2.5%). The level lifetimes were determined using the DDC method [13]. The CS-HPGe detectors of the GASP spectrometer can be grouped into seven rings at angles 31.7°–36°, 58.3°–60°, 72°, 90°, 108°, 120°–121.7°, and 144°–148.3°. The data taken at each distance were sorted into γ-γ matrices corresponding to all combinations of the four detector rings, farthest away from 90°, versus all other rings; for these ring combinations the Doppler shift was sufficient to separate the shifted and unshifted components of the γ-ray transitions. In the data analysis, when gates are set on the Doppler-shifted component of a γ-ray transition B, feeding directly a level of interest, which is depopulated by a γ-ray transition A, the lifetime $\tau(x)$ at each distance is given by

$$\tau(x) = \frac{I(B_s A_u)(x)}{v \frac{d}{dx} I(B_s A_s)(x)}, \tag{1}$$

where v denotes the recoil velocity; the subscripts s or u stand for the "shifted" and "unshifted" components of the γ-ray transition (A or B); the symbol $I(BA)$ denotes the measured intensities of the depopulating γ transition A, in coincidence with a directly feeding γ-ray transition B. The derivative of the intensity of the two coincident components, $\frac{d}{dx} I(B_s A_s)(x)$, is determined by fitting piecewise a continuously differentiable second-order polynomial to the data points. In an ideal case the values τ(x) as a function of the distance are constant.

Figure 1 depicts the level scheme of ^{133}Nd relevant for the present discussion. The 667-, 409-, and 633-keV γ-ray transitions account for 70% of the HD bands' decay-out flux [9]; additionally, several weak $E1$ decays were also observed in the same work. Figure 2 depicts the stopped- and

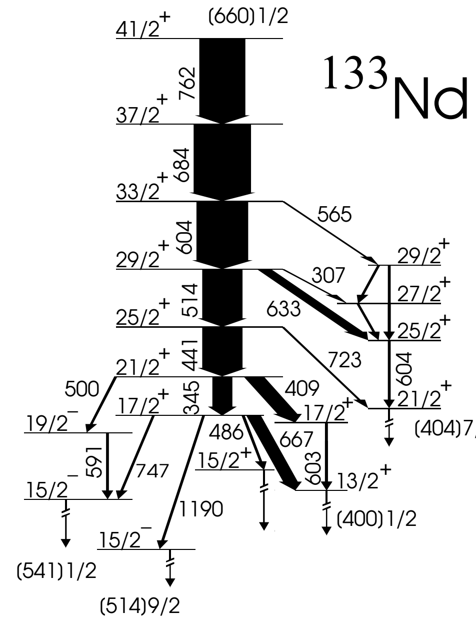

FIG. 1. The partial level scheme of ^{133}Nd relevant for the present discussion from Ref. [9]. The γ-ray transition energies are marked in keV, and the relevant Nilsson configurations of the deformed bands are indicated.

inflight-peak components of the 409-keV γ-ray transition and illustrates the data quality; Fig. 3 depicts the τ curve deduced from Eq. (1). The final lifetime values, shown in Table I, were obtained by averaging results from different angular groups. The mean lifetimes derived from the present work are 2.8(1) ps ($25/2^+$), 8.0(3) ps ($21/2^+$), and 1.6(4) ps ($17/2^+$); good statistics enabled us to improve considerably the precision compared to the previous work [15] and also to deduce a new lifetime value for the $17/2^+$ level. Because of problems related to fast γ-ray transitions and contaminations, the lifetimes of higher members of the band could not be measured. From the same experiment lifetimes of other ND states have been previously reported [16].

The decay out of the HD band was attributed by Bazzacco *et al.* [9] to an accidental mixing with the $17/2^+$ and $29/2^+$ states, belonging to two different ND bands based on the [400]1/2 and [404]7/2 Nilsson orbitals, respectively. Following the identification of the decay-out γ-ray transitions and assuming that the $17/2^+$ states of the ND and HD bands mix, there are independent ways to assess the mixing amplitude. The two $17/2^+$ states, lying 64 keV apart, have components of both the normal and highly deformed bands, which explains the observation of the $21/2^+{}_{\rm HD} \rightarrow 17/2^+_{\rm ND}$, 409-keV γ-ray transition. One can thus assess the mixing amplitude from a two-state mixing analysis, given by the following equations:

$$|17/2_1\rangle = \alpha|17/2_{\rm HD}\rangle + \beta|17/2_{\rm ND}\rangle,$$
$$|17/2_2\rangle = \beta|17/2_{\rm HD}\rangle - \alpha|17/2_{\rm ND}\rangle,$$

where the indices 1 and 2 correspond to the mixed states belonging to the HD and ND bands. The lifetimes, and thus the $B(E2)$ values, of the states can be used to extract the information on the mixing amplitudes. A $B(E2)$ value of

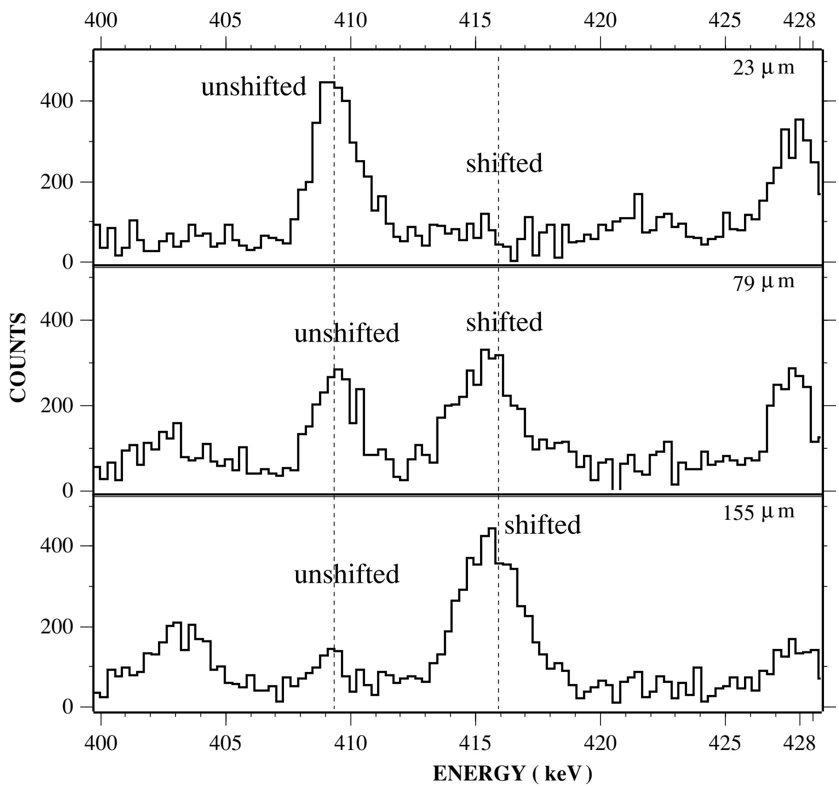

FIG. 2. The 409-keV decay-out γ-ray transition from the HD band for three different distances at 34.5°. Spectra are gated on the shifted component of the feeding γ-ray transition.

290(20) W.u. was deduced for the $21/2^+ \rightarrow 17/2^+$ in-band 345-keV γ-ray transition, whereas the $B(E2)$ value for the decay-out 409-keV γ-ray transition was inferred to be 95(10) W.u. This clearly shows that as a result of mixing the decay-out γ-ray transition also has substantial collectivity. Assuming that the transition probability between pure HD and ND states is negligible, it is possible to recast the two-state mixing amplitudes in terms of the ratio of the $B(E2)$'s as

$$\frac{\beta^2}{\alpha^2} = \frac{B(E2)_{409}}{B(E2)_{345}}. \tag{2}$$

Since $\alpha^2 + \beta^2 = 1$, the amplitude of the ND state in the $17/2_1^+$ state is

$$\beta^2 = 0.24 \pm 0.02. \tag{3}$$

The quadrupole moment of a rotational band, with the same intrinsic structure, is a constant. Thus, a deviation from the high-spin, nearly constant value of quadrupole moments of the HD and the ND values independently gives a measure of the mixing amplitude. This could be assessed from the lifetimes of the in-band 345-keV and the decay-out 409- and 667-keV γ-ray transitions. From the measured lifetime of the $25/2^+$ state in the present experiment, a Q_0 value of 6.92(14) e b is deduced for the HD band (a value close to 6.5(2) e b [12], inferred from a differential DSA analysis). The Q_0(ND) value was assumed to be 5.4(4) e b, similar to the quadrupole moment of the ground-state band of ^{132}Nd (5.4 e b) [17]. Following the earlier procedure we arrive at the relation

$$\alpha^2 = \frac{Q_t(345)^2}{Q_0(\mathrm{HD})^2}.$$

Similarly,

$$\beta^2 = \frac{Q_t(409)^2}{Q_0(\mathrm{HD})^2}$$

and

$$\beta^2 = \frac{Q_t(667)^2}{Q_0(\mathrm{ND})^2}.$$

The interaction strength between the two $17/2^+$ states can be expressed as a product of the mixing amplitudes and the energy separation between them [18]. Thus,

$$V_{\mathrm{int}} = \alpha\beta(E_{\mathrm{HD}} - E_{\mathrm{ND}}).$$

The deduced interaction strength and squared mixing amplitude of the ND component in the HD levels is shown in Table II. The extracted amplitudes are consistent and thus confirm that the decay out of the HD band is, to a large extent, due to the admixture of the $17/2^+$ ND state. Total Routhian surface calculations suggest a reduced barrier between the ND and HD minima at the different decay-out frequencies in Nd isotopes; such an argument has been suggested to account for the different spins at which the HD bands decay out in ^{133}Nd (at $17/2^+$), ^{135}Nd (at $25/2^+$) [10], and ^{137}Nd (at $29/2^+$) [11]. The case of ^{133}Nd is rather special in that there is an accidental mixing of the $17/2^+$ HD state with the $17/2^+$ state of the $N = 4$ [400]$1/2^+$ band, which drives a major flux of the decay to that particular band; other decay branches from the HD band in ^{133}Nd have much lower intensities. Therefore, it appears that the specific orbitals present close to the Fermi surface play a crucial role in the decay out of the HD band in ^{133}Nd. Indeed, because of this aspect a different behavior has been reported in ^{131}Nd [19], where an ND band, based on the [411]$1/2^+$

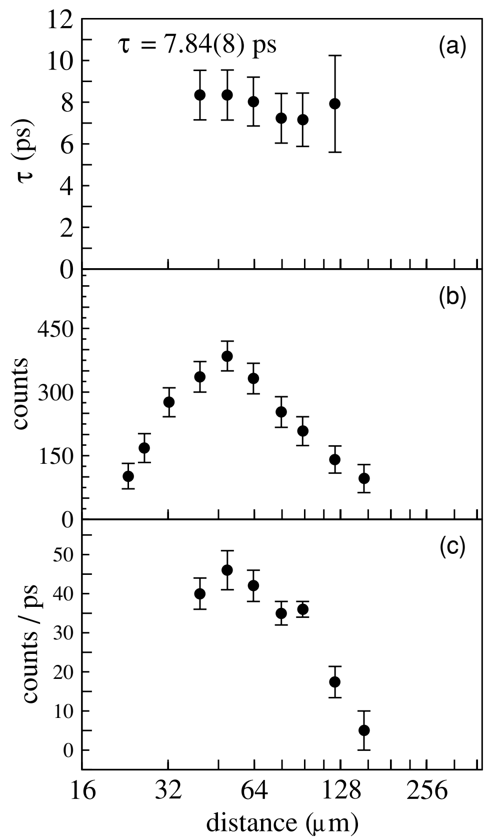

FIG. 3. The τ curve for the 409-keV γ-ray transition at 34.5°. Panels (a), (b), and (c) depict Eq. (1), its numerator, and its denominator, respectively.

Nilsson state, makes a smooth transition to the HD $\nu i_{13/2}$ band. However, it could be generalized that in the HD bands of Nd isotopes, the decay out is due to a interaction between the "cold" ND and "cold" HD states (i.e., both the states are yrast or near yrast). Interestingly, the dominant mechanism to depopulate the SD bands in the Dy and Hg/Pb regions was found to be statistical in nature [4], and from the observed discrete linking-γ-ray transitions, it could be deduced that a weak mixing between the "cold" SD states and the "hot" ND states provides a mechanism for decay out of the band [3,7]; although, once again the specific position of the ND and SD levels seems to influence the decay pattern.

Knowledge of the deduced lifetimes, the known γ intensities, and branching ratios [9] facilitates extraction of the $B(E1)$ transition rates, which were calculated using the following

TABLE II. Interaction strengths and squared amplitudes of the ND component.

I^π	Method	$V_{\rm int}^{\rm pres}$(keV)	$V_{\rm int}^{\rm Ref.[9]}$(keV)	β^2
$21/2^+$	branching ratios	27.3(2)	22	0.24(2)
$21/2^+$	$Q^{\rm HD}, \tau$	22.5(2)	—	0.27(7)
$21/2^+$	$\tau, Q^{\rm ND}$	27.3(2)	—	0.24(3)
$17/2^+$	$\tau, Q^{\rm ND}$	27.3(1)	—	0.24(7)

formula:

$$\frac{B(E1; I \rightarrow I-1)}{B(E2; I \rightarrow I-2)} = \frac{1}{1.3 \times 10^6} \frac{E_\gamma^5(E2)}{\lambda E_\gamma^3(E1)} \text{ fm}^{-2},$$

where

$$\lambda = \frac{T_\gamma(I \rightarrow I-2)}{T_\gamma(I \rightarrow I-1)}$$

is a ratio of the transition probabilities and the γ-ray energies are in MeV. For the $21/2^+ \rightarrow 19/2^-$ 500-keV γ-ray transition, the $B(E1)$ value is estimated to be $0.5(1) \times 10^{-4}\, e^2\,\text{fm}^2$ or $0.29(8) \times 10^{-4}$ W.u.; similarly, based on the deduced lifetime of the $17/2^+$ state, the $B(E1)$ transition rate from the HD band to the $15/2^-$ level, based on a [514]9/2 Nilsson configuration (Fig. 1), is $0.35(15) \times 10^{-4}\, e^2\,\text{fm}^2$ or $0.087(37) \times 10^{-4}$ W.u.; the $B(E1)$ transition rate to the second $15/2^-$ level, based on a [541]1/2 Nilsson configuration, is $1.4(5) \times 10^{-4}\, e^2\,\text{fm}^2$ or $0.83(30) \times 10^{-4}$ W.u. The 500- and 747-keV $E1$ γ-ray transitions to band [541]1/2 (Fig. 1), or band 3 (Fig. 3 (a) [9]), are "K-allowed" and, compared to the normal $B(E1)$ estimates, a slight enhancement would suggest octupole correlations. This feature is expected from a coupling between the $i_{13/2}$ and $h_{9/2} \otimes f_{7/2}$ orbitals, which are relevant for the observed $E1$ decays between the two bands. Such arguments have indeed been put forward for the decay out of the HD band in the even-even nucleus ^{134}Nd [20]. This is a surprising feature as pairing is expected to be different in the two nuclei and the $B(E1)$ matrix elements strongly depend on the position of the Fermi surface, deformation, and pairing [21]. Therefore, an investigation of the lifetimes of the decay-out γ-ray transitions in ^{134}Nd would be very useful to clarify this interesting issue.

Finally, it would be interesting to experimentally observe the bandhead corresponding to the [660]1/2 $\nu i_{13/2}$ band, which should be a level of spin parity $13/2^+$. This is important in light of the suggestion that the HD band in ^{135}Nd ceases to exist below the $25/2^+$ state [10]. From the present analysis it is possible to deduce a branching ratio to this state. From

TABLE I. Experimental results of lifetimes and the reduced transition probabilities from the present and earlier [15] experiments.

I^π	E_γ (keV)	$b_{ij}^{\rm Ref.[9]}$	$\tau_{\rm present}$ (ps)	$B(E2)_{\rm present}$ (W.u.)	$\tau_{\rm Forbes}$ (ps)	$B(E2)_{\rm Forbes}$ (W.u.)
$25/2^+$	441.3	0.95(1)	2.8(1)	406(16)	3(1)	380(130)
$21/2^+$	345.2	0.57(4)	8.0(3)	290(20)	7.1(2.2)	330(100)
$21/2^+$	409.1	0.43(4)	8.0(3)	95(10)	7.1(2.2)	100(30)
$17/2^+$	667.1	0.6(1)	1.6(4)	58(19)	—	—

an extrapolation of a fit to the (unperturbed) energies in this band, the $17/2^+ \rightarrow 13/2^+$ γ-ray transition is estimated to be $\sim$296 keV. This would place the bandhead more than 300 keV above that of the known $13/2^+$ state of the ND band; as a consequence we can assume an almost pure HD $13/2^+$ bandhead state. With this assumption and the determined amplitude of the $17/2^+$ state, by using Eq. (3), the in-band $B(E2)$ value of the $17/2^+ \rightarrow 13/2^+$ transition is estimated to be 300(60) W.u., which suggests a substantial collectivity. The branching ratio to this level is estimated to be about 5.7(2)%, leading to a γ-ray transition intensity just below the detection threshold in the earlier experiment [9]. Although this picture is simplistic, it is difficult to rule out additional unobserved decay paths that would further reduce the branching ratio and hence the detection probability. Nevertheless, it would be interesting to observe and characterize the decay-out spectroscopy with the present generation of large γ-detector arrays.

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