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Low-spin termination of the superdeformed band in ^{135}Nd

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The decay of the superdeformed (SD) band in ^{135}Nd was studied with the early implementation of gammasphere. The results suggest that the SD band "terminates" at spin 25/2. This termination is explained by a change of the SD minimum toward a triaxial lower deformation. Ultimate cranker calculations with the $i_{13/2}$ orbital occupied relate this change to a shift of a proton and neutron pair out of deformation-driving Nilsson orbitals. This is a completely new and unexpected mechanism for the decay of SD bands.

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In almost all cases, the decay path of superdeformed (SD) bands into lower-deformation states is not yet established experimentally. Recent data [1] in the mass 150 region show a configuration dependence of this decay that is hard to understand microscopically on the basis of a barrier-penetration scenario [2]. Nuclei like ^{133,135,137}Nd [3–5] in the mass 130 region also exhibit two energy minima, one at low [6] deformation ($\varepsilon \approx 0.2$) and one at larger [7] deformation ($\varepsilon \approx 0.32$) characteristic of superdeformed bands in that region.[1] These nuclei are interesting since the intensities of the SD bands are large and the change between smaller and larger deformation involves the rearrangement of only a few particles, giving us a chance to study the role of these changes in detail. The two nuclei most studied are ^{133}Nd and ^{135}Nd, but their decay patterns are quite different, giving us new insights into this process. In ^{133}Nd, the SD band decays through mixing with accidentally close-lying normally deformed states [4,5]. This is a scenario that has been suggested to be general for the decay of these bands, but in this case, one can see it in detail because of the low level density. In ^{135}Nd, there are no accidentally close-lying levels and no such mixing. At the 25/2 level in ^{135}Nd, the SD band apparently ends and the strength is fragmented into many weak transitions. This letter proposes a novel mechanism that explains the decay observed in ^{135}Nd. This decay is related to a shift of a proton and a neutron pair out of deformation-driving Nilsson orbitals.

Two experiments were carried out with the early implementation of gammasphere at the 88-in. cyclotron of the Lawrence Berkeley Laboratory. A target consisting of two 0.5 mg/cm^2 ^{100}Mo foils was bombarded by an ^{40}Ar beam at energies of 182 and 176 MeV in two separate experiments, using 24 and 36 Compton-suppressed Ge detectors, respectively. Approximately 1.0×10^9 and 1.8×10^9 three and higher fold suppressed events were recorded, respectively. The lower energy data were used mostly for angular correlations as there were no 90° detectors in the higher energy experiment. We recorded angular correlations between the SD lines at $\approx 28°$ symmetrically around the beam direction and the other lines taken either at $\approx 28°$ or 90°. This amounts in effect to determining the angular distribution of these lines (see Table I). We found four more transitions in the SD band than previously published [3] in a triple-coincidence spectrum, double-gated on all SD transitions from 546 to 1215 keV (except the 602 keV transition). These are lines at

TABLE I. Angular distributions, intensities relative to the SD band, and reduced transition probabilities for some transitions in ^{135}Nd.

$E\gamma$ (keV)	[a]28°/90°	[b]I/I_{SD}	$B(E\lambda)_{spu}$
601.9	1.49(11)	1	436
545.4	1.51(15)	0.77	225
548.9	1.86(52)	0.14	31
621	1.97(86)	0.13	16
529[c]	1.19(34)	0.2	
766.5	0.62(13)	0.10	
949	0.90(24)	0.12	3×10^{-5}
523.5		0.06	
618	0.93(41)	0.10	
964.6	0.75(20)	0.07	
1183.7	0.85(23)	0.15	

[a]The average value for known dipole transitions is 0.71 and for known stretched quadrupole transitions is 1.46.

[b]The angular distributions are taken into account. The errors, of order 10-20% are essentially entirely systematic.

[c]This γ ray is double, with the two transitions of about equal intensity (0.1 each).

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[1]There is not a generally accepted definition of superdeformation. In this paper we refer to SD states as those built on a second minimum at higher deformation in the potential-energy curve as a function of deformation.

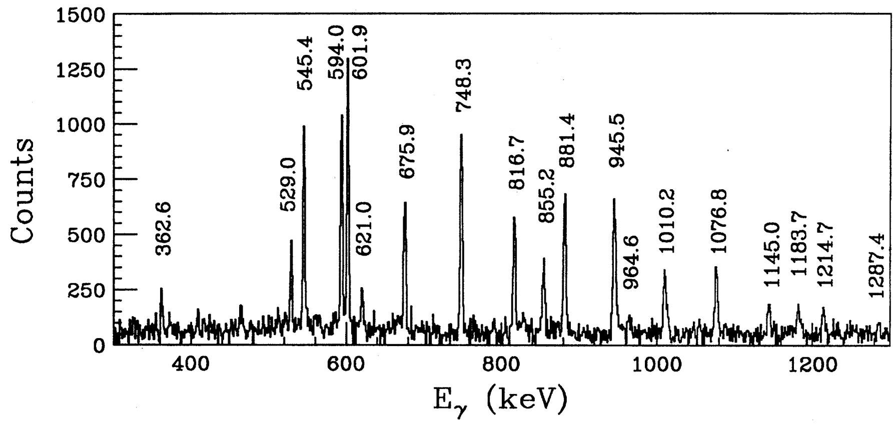

FIG. 1. Triple-coincidence spectrum at 182 MeV (see text) with one gate on any of the SD band members and one on the 727 keV line.

1437.2(4), 1519.5(5), 1605.0(7), and 1692.0(10) keV. The dynamic moment of inertia calculated from the new transitions continues the decreasing trend that was observed previously. The structure of this band can be inferred from a Nilsson diagram. Compared with the low-deformation configurations, the neutron $i_{13/2}$ orbital is occupied. It strongly drives the nucleus toward large deformations. The pairing correlations are expected to be present at low frequencies ($\hbar\omega \leq 0.3$ MeV). At large deformations ($\varepsilon \sim 0.35$), a pair of neutrons is predicted to occupy the $h_{9/2}$ orbital [541]1/2 and a pair of protons to occupy the $h_{11/2}$ [541]3/2 orbital.

To find the linking transitions between the SD band and the normally deformed states, we constructed an $E\gamma$-$E\gamma$ matrix, gated by any one of the four clean (and background subtracted) lines in the SD band with energies 676, 817, 1010, and 1145 keV. With the second gate set on the 727 keV line, for example (Fig. 1), one clearly sees the strongest 621–1184 keV and the 529–965 keV branches, as well as the 949 keV line (appearing as a broadening of the 946 keV SD line). A total of 75% of the decay of the SD band (and 84% of the decay of the 3.324 MeV state) has been placed in the level scheme of Fig. 2.

The decay scheme, together with the angular distribution data (see Table I), determines the spins of the SD states. In particular, the quadrupole character of the 621 keV transition and the dipole character of the 1184 keV transition, as well as the dipole character of the 767 keV transition give an unambiguous spin assignment of 25/2 for the 3.324 MeV state. The parity cannot be unambiguously determined but the value adopted is consistent with lifetimes expected for the various types of transitions. The proposed positive signature for the SD band is consistent with that of the configuration previously assigned, i.e., the lowest-energy neutron $i_{13/2}$. The relatively low excitation energy at the decay point may explain why rather strong (up to 15% of the SD band intensity) discrete linking transitions are observed.

The decay pattern and the lifetime measurements suggest that the band "terminates" at the 3.324 MeV level. The first indication comes from the highly fragmented decay of that level without the energy available for high-energy statistical transitions. In this work, no observed transition directly deexciting the 25/2 level has an intensity greater than 14% of the band, nor an energy greater than 1 MeV. Another indication comes from the crucial information [6] that the lifetime of that state is (2.4 ± 0.8) ps, which is about the value expected if the SD band continued with the same collective strength and 100% intensity at the appropriate transition energy (about 500 keV). The fact that we see only transitions of intensity around 10% deexciting that state means that any $E2$ transition of about 500 keV would have a reduced transition probability that is a factor ~ 10 lower than that of a SD band transition (see Table I). Thus the observed $E2$ transitions in this energy region, the 621 and the 549 keV transitions, do not belong to the SD band as it is known above the 3.324

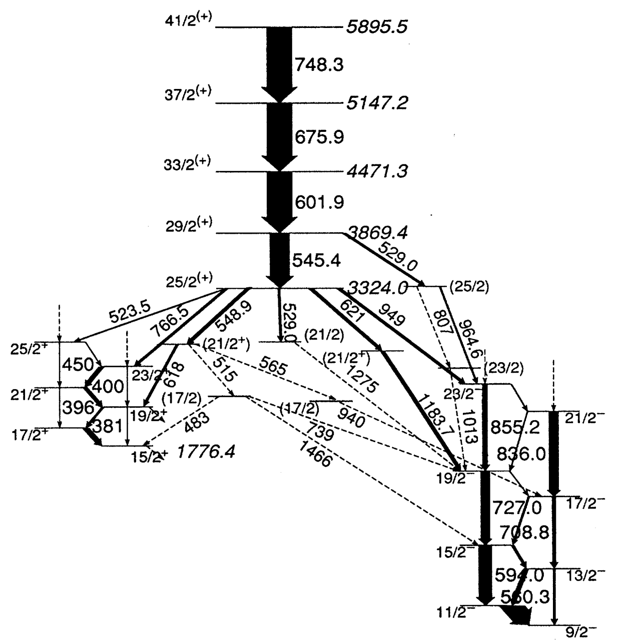

FIG. 2. Lower part of the level scheme of ^{135}Nd, showing the lower states of the SD band, the lower part of the previously known normally deformed states, and the newly established decay pattern of the SD band into them. The widths of the lines represent the measured γ-ray intensities. The transitions represented by a dashed line are tentative. The uncertainties in the transition energies in the SD band are typically 0.25 keV except for the new transitions (see text). For the linking transitions, they are 0.4 keV for the most intense lines and 1 keV for the multiple and tentative lines.

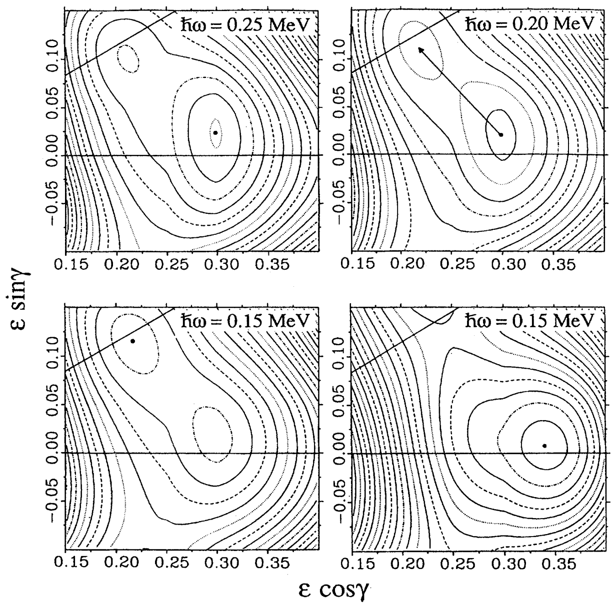

FIG. 3. Total Routhian surfaces as a function of deformation ε and triaxiality γ for the neutron $i_{13/2}$ configuration at three different frequencies $\hbar\omega=0.25$, 0.20, and 0.15 MeV in ^{135}Nd and at $\hbar\omega=0.15$ MeV in ^{133}Nd (bottom right). The lines corresponding to $\gamma=0°$ and $\gamma=30°$ are indicated. The contours are separated by 0.2 MeV and the energies of the minima are -1.421, -0.67, -0.097, and -0.319 MeV, respectively.

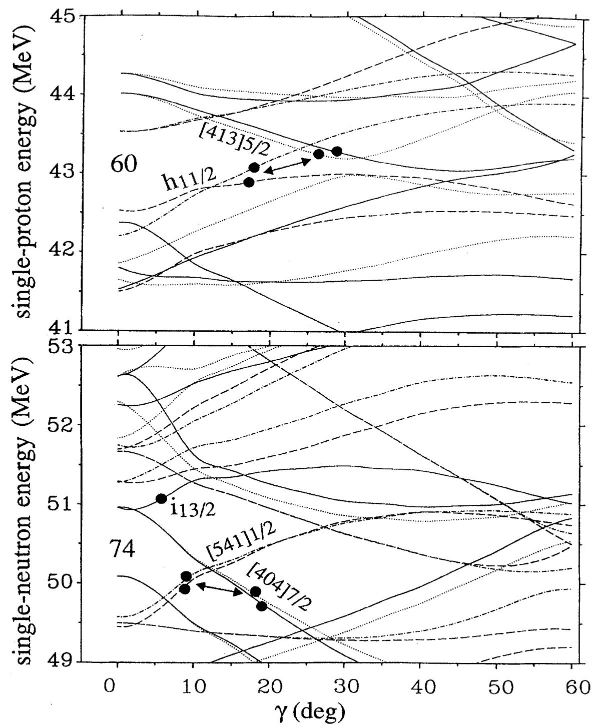

FIG. 4. Single-particle energies as a function of γ at $\hbar\omega=0.2$ MeV for a variable (ε,γ) path as indicated in Fig. 3, for (top) protons and (bottom) neutrons. The intruder orbitals are labeled by the l_j quantum numbers. Orbital changes are schematically indicated.

MeV state. The observations above are not consistent with the assumption that the SD band continues but is not observed. Therefore we propose that the band ceases to exist.

In order to understand such a termination we have calculated the structure and shape evolution of the SD band at low spin. The energy as a function of deformation and frequency is calculated for the positive parity, positive signature configuration, keeping the odd neutron always in the $i_{13/2}(6_1)$ level. The calculations were made using the ultimate Cranker [8] program. The pairing gap parameters are fixed to $\Delta_p=0.85$ MeV and $\Delta_n=0.75$ MeV which are typical parameters in this region. The chemical potentials are fixed to give the correct particle number expectation values at $\omega=0$. The wave functions are projected onto exact particle number for all ω values, thus correcting for the shifts in the Fermi level for $\omega>0$. Figure 3 shows the result of these calculations for cranking frequencies $\hbar\omega=0.25$, 0.2, and 0.15 MeV.

As seen in Fig. 3, there are two competing energy minima in the ε-γ plane. The one with large nearly axially symmetric deformation ($\varepsilon=0.3$, $\gamma=8°$) is the lowest for $\hbar\omega>0.2$ MeV. It represents the SD band. For $\hbar\omega=0.15$ MeV the less deformed triaxial minimum ($\varepsilon=0.22$, $\gamma=30°$) is lower. Between $\hbar\omega=0.2$ MeV and 0.15 MeV both minima have the same energy with almost no barrier between them. We suggest that with decreasing angular frequency the nucleus slides over from the high-deformation to the low-deformation minimum, resulting in the observed band termination. The shape and deformation changes connected with this slide of γ are indicated in Fig. 3 for $\hbar\omega=0.20$ MeV. Figure 4 shows the single-particle levels along this path. The two minima appear as a consequence of the $N=74$ gaps between the $g_{7/2}$ ([404]7/2) and $h_{9/2}$ ([541]1/2) neutron levels near $\gamma=0°$ and 30°. The structures of the two minima differ by the rearrangement of one pair of neutrons ($h_{9/2}\leftrightarrow g_{7/2}$) and one pair of protons ($h_{11/2}(5_2)\leftrightarrow g_{7/2}([413]5/2)$). At low frequency there are additional minima which have a lower energy than the triaxial minimum. Since they do not contain the $i_{13/2}$ neutron they are not shown in Fig. 3. They represent the known low deformation bands in ^{135}Nd. Their exact structure and deformations are not studied in this paper. For the discussion of the decay out of the SD band, it is sufficient to realize that the triaxial minimum differs from these low-deformation bands by particle-hole excitations that lift one neutron into the $i_{13/2}$ level. Such a configuration will show the observed decay pattern. Relatively fast $E1$ transitions will connect it with the negative-parity bands. Since the low-deformation $i_{13/2}$ structure lies about 500 keV above the yrast states, couplings to other positive-parity states are expected, which will also favor out-of-band $E2$ transitions. In-band transitions are slower in the $i_{13/2}$ triaxial minimum and the 621 keV transition may be such an in-band transition.

The rapid slide-over from the high-deformation to the triaxial minimum is a consequence of the pair correlations, expected to be substantial at these low frequencies. The pair field will scatter pairs between the neutron levels ($h_{9/2}\leftrightarrow g_{7/2}$) and proton levels ($h_{11/2}\leftrightarrow g_{7/2}$) distinguishing the two minima. Bertsch [9] estimates the scattering matrix element to be about 1 MeV; however it is quite sensitive to the strength of the pairing. In any case this allows a fast transition from the SD minimum.

This interpretation is also in accordance with the lifetime measurements. The decrease of the transition quadrupole moment in Fig. 4 of Ref. [6] between the 602, 546, and 621 keV transitions is then consistent with a detailed scenario in which the $29/2^+$ state is superdeformed, the $25/2^+$ state at 3.324 MeV is a mixture of low deformation and high deformation with about equal amplitudes, and the $21/2^+$ states at 2.704, 2.774 (and probably 2.795 MeV) have a low deformation. The exact structure of these states cannot be determined since we do not see bands to which they belong, but the general scenario is consistent.

A similar calculation for ^{133}Nd (see Fig. 3, lower right) shows that there is not a competing triaxial low-deformation structure containing the $i_{13/2}$ neutron. The reason is apparent from Fig. 4, which shows that for $N=73$ the $g_{7/2}$ level, which favors the triaxial shape, is empty. This result is consistent with the experiment of Ref. [4] where it is found that the population stays in the high-deformation minimum down to $I=17/2$, decaying prior to this point only via band mixings generated by accidental degeneracies. However, we should note that the decay at lower spin in ^{133}Nd is also due to the fact that the crossing of the SD band and the yrast line occurs at lower spin in this nucleus than in ^{135}Nd [4,5].

The example of ^{135}Nd clearly demonstrates the importance of the underlying structural changes in the decay of highly deformed configurations. Pairings is important, allowing the nucleus to "slide" easily from the high-deformation to the low-deformation triaxial minimum, which results in the sudden termination of the band. In the neighboring nucleus ^{133}Nd, this is not possible because the appropriate neutron level generating the low-deformation triaxial minimum is above the Fermi level. A similar microscopic mechanism may play a role in the decay of SD bands in the $A=150$ and $A=190$ regions. There, the number of pair rearrangements is larger (typically 8 or 10 instead of 2) and it may become difficult to follow the intermediate steps in a calculation. Nevertheless, as in the case discussed here, the configuration reached by the first rearrangement of a neutron and/or a proton pair, when going into the barrier from the SD side, may play the role of "doorway states." Their energy will determine whether some SD configurations can decay easier than others. This conclusion is in agreement with a recent report of some configuration dependence of the decay of SD bands in the mass 150 region [1].

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