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Competing modes of excitations and the decay out of the triaxial strongly deformed well in ^{167}Lu

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An unexpected strong interaction between normal deformed and triaxial strongly deformed levels at high spin, $\sim 32\hbar$, is observed in ^{167}Lu. This constitutes the first observation of accidental degeneracy, at such high spins, causing cross talk between levels in the normal deformed and in the second potential well in any known mass region. Furthermore, evidence of quasi-particle excitations highly competing with the wobbling excitation mode in a triaxial superdeformed well has been established in ^{167}Lu.

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Triaxial strongly deformed (TSD) rotational bands in the mass region around $A \sim 165$ have received considerable attention recently. Experimentally, over 30 TSD bands are reported in this mass region in Lu and Hf isotopes [1]. Only a few of these bands are firmly connected to the normal deformed (ND) yrast states. In ^{163,165,167}Lu [2–5], and possibly ^{161}Lu [6], wobbling phonon excitations are established. The wobbling mode, uniquely related to the triaxiality of the nuclear system, was identified based on the observed properties of the decay between the bands constituting the family of wobbling phonon excitations. Most recently, a new excited TSD band, which is interpreted as likely to be a multi-quasiparticle excitation, was observed in ^{163}Lu [7]. The excitation energy of this band is higher than the one-phonon but comparable to the two-phonon wobbling excitation established in this nucleus. Thus, not only shape coexistence between ND and TSD structures but also an interplay of collective and multi-quasiparticle excitations in the TSD well exist.

Here we report on the strong interaction between the ND and TSD levels observed in ^{167}Lu at high spins, $\sim 32\ \hbar$, in addition to the interaction at lower spin that mediates the main decay out. Such an interaction is at variance with the common observation that the absence of a well-defined barrier between the two wells occurs only at the decay out points (i.e., lowest spins). In addition, we report on the discovery of a new excited TSD band in ^{167}Lu coexisting and strongly competing with the one-phonon wobbling excitation previously established in this nucleus [5]. The multi-quasiparticle interpretation of this band is based on its observed decay out properties. This interpretation is supported by Cranking calculations with the UC code [8,9].

The ^{123}Sb(^{48}Ca,4n) reaction was used to populate states in ^{167}Lu. The ^{48}Ca beam at 203 MeV was provided by the 88-inch cyclotron at Lawrence Berkeley National Laboratory. γ-ray coincidences were measured with the *Gammasphere* array, which, at the time of the experiment, consisted of 100 Compton-suppressed Ge detectors. A total of 2.2×10^9 events, requiring five or more Compton-suppressed Ge detectors in prompt coincidence, was collected and used in the off-line analysis. The coincidence events were sorted into a three-dimensional histogram (cube) using the Radware software package [10]. The extensive search through the coincidence cube, revealed a third TSD band, TSD3, in addition to the wobbling band built on the $\pi i_{13/2}$ yrast TSD band reported earlier [5]. Furthermore, two new unlinked TSD bands were found that are presented together with extensive new results on ND structures in ^{167}Lu in Ref. [11].

TSD3 is firmly linked to the ND levels in ^{167}Lu via several transitions as illustrated in Figs. 1 and 2. The population of TSD3, relative to yrast, is $\sim 4\%$ compared to $\sim 8\%$ and $\sim 2\%$ for TSD1 and TSD2, respectively. The large deformation of this band is inferred from its large dynamical moment of inertia, presented in Fig. 3. Preliminary results from recent lifetime measurements of the transition quadrupole moments associated with TSD3 confirm its large deformation [12].

To establish the spins and parity for this band, a full $\gamma\gamma$-angular correlation analysis with the spectral expansion of DCO (SpeeDCO) [13] was performed. The data were sorted into 12 two-dimensional single-gated histograms of the expansion coefficients [14]. Clean gates in TSD3 and/or in the [541]1/2$^-$ band were used in creating the correlation matrices and, subsequently, clean gates in TSD3 were used to create double-gated correlation spectra. Angular distribution analysis was also performed, and the spin alignment for several stretched electric quadrupole ($E2$) transitions in both TSD3 and ND bands over a broad region of spin was established. Based on the results obtained from this analysis, the stretched quadrupole character of the in-band transitions of TSD3 was established. The $\Delta I = 1$ mixed multipolarity character of the strongest of the decay out transitions from TSD3 at 961.0 keV was firmly established, leading to the spin assignment for TSD3 presented in Fig. 1. The multipolarity mixing ratio,

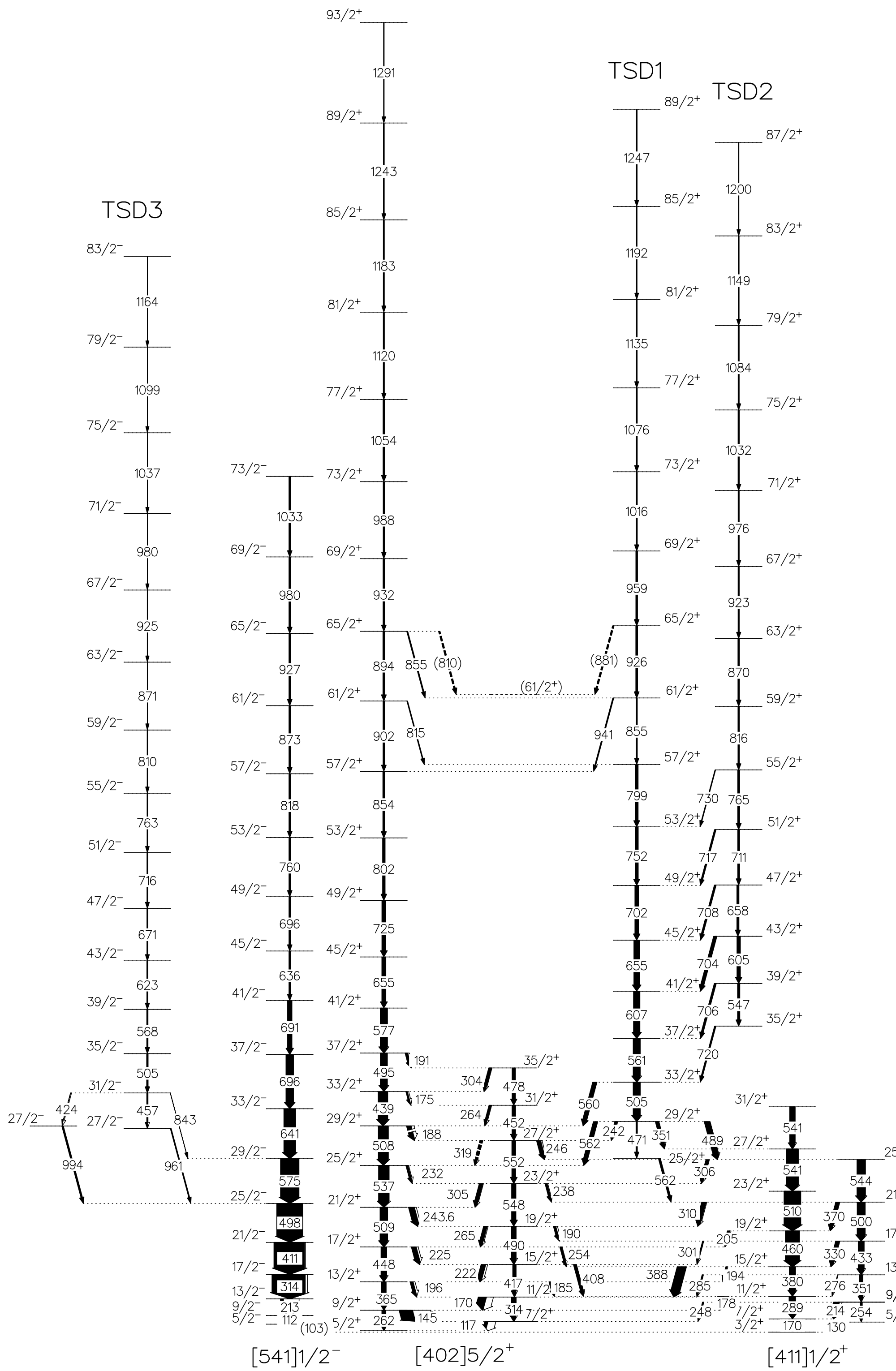

FIG. 1. The partial level scheme of ^{167}Lu showing the two wobbling bands and the new TSD3 band along with two of the normal deformed structures in this nucleus. The ND bands are labeled with Nilsson quantum numbers.

$\delta(E2/M1)$, for the 961.0 keV transition, which is assumed to be identical for the 843 keV decay, is presented in Table I. For both transitions, the alternative possibility of $\delta(M2/E1)$ mixing is highly unlikely due to the unrealistically large $B(E1)$ and $B(M2)$ values extracted from the measured δ. Therefore, parity and signature $(\pi, \alpha) = (-, -1/2)$ were assigned for TSD3 (see Fig. 1). Because a polarization measurement for the decay out of TSD3 was not possible from the current

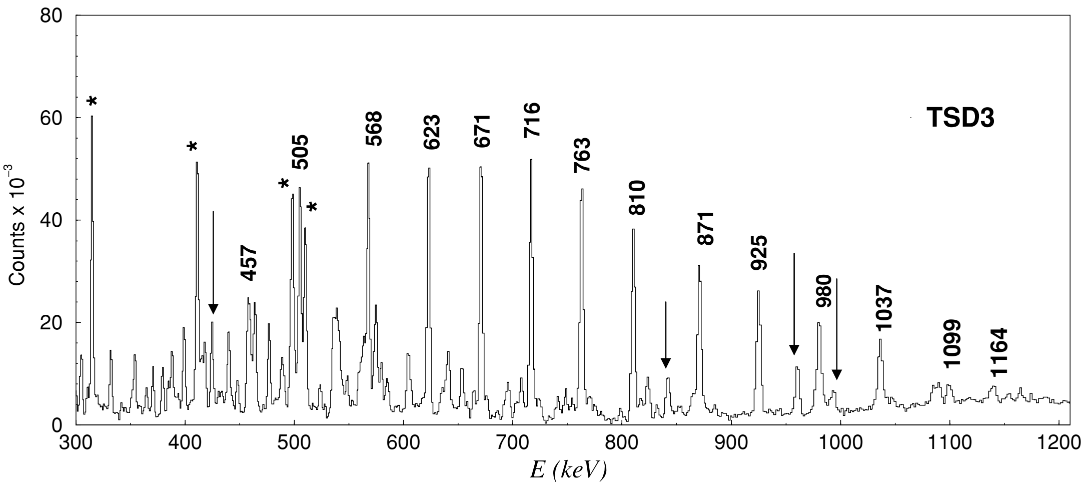

FIG. 2. Efficiency corrected coincidence spectrum showing the sum of double gates on all combinations of transitions in TSD3. Coincidences between TSD3 and the known ND transitions in ^{167}Lu, marked by an asterisk, can be seen in this spectrum. The arrows mark the decay out of TSD3.

data, the decay out of TSD3 is either mainly $M1$, ∼80%, or $E2$, ∼77%, as extracted from the numerically small and large solutions of $\delta(E2/M1)$, respectively. The parallel decay route from the $31/2^-$ state via the 424/994 keV transitions has about half the intensity of the 457/961 keV decay. The decay out via these mixed $E2/M1$ transitions to the [541]$1/2^-$ band is most likely mediated by mixing at $I = 27/2^-$ to an ND state, close to ∼33 keV, which decays to the [541]$1/2^-$ band. The estimated reduced $B(E2)$ and $B(M1)$ values for these decay branches listed in Table I do not, therefore, represent matrix elements between TSD and ND structures.

From the excitation of TSD3 relative to TSD1 and TSD2, as illustrated in Fig. 4, and the lack of connecting transitions to TSD1 it is clear that TSD3 cannot have any collective relation to TSD1 but is most likely a multi-quasiparticle excitation. The UC calculations predict a low-lying band with $(\pi, \alpha) = (-, -1/2)$ fairly close in excitation energies to the $(\pi, \alpha) = (+, +1/2)$, $\pi i_{13/2}$ configuration (TSD1). The predicted intrinsic configuration for this band is $\pi i_{13/2} \otimes \nu(j_{15/2}, g_{7/2})$. The observed energies of TSD3, agree fairly well with the UC predictions. However, the observed alignment of TSD3 is less than or ∼$2\hbar$ larger than that of TSD1 rather than ∼$6\hbar$, which is expected for such a configuration (see the upper panel of Fig. 3). It might be possible that the location of the $j_{15/2}$ intruder orbital is not accurate in the UC calculations and the second neutron is occupying a different orbital with

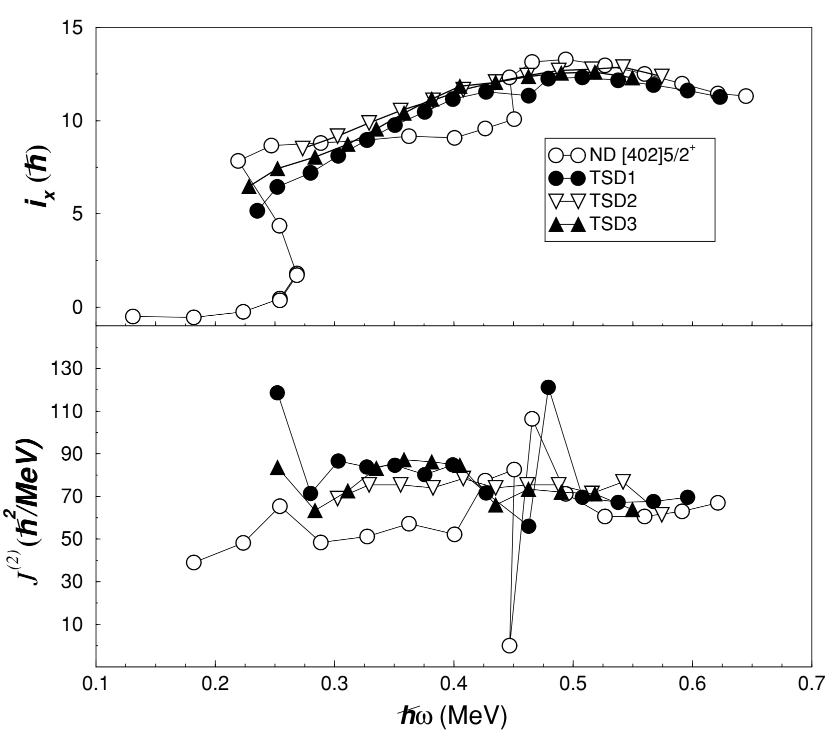

FIG. 3. Alignment $i_x = I - I_{ref}$, where $I_{ref} = 30\hbar^2$ MeV$^{-1}\omega + 30\hbar^4$ MeV$^{-3}\omega^3$, and the dynamic moment of inertia as a function of rotational frequency for TSD1, TSD2, TSD3, and the ND [402]$5/2^+$ bands in ^{167}Lu. The large fluctuation in the moments of inertia for TSD1 and [402]$5/2^+$ bands observed at ∼0.4–0.5 MeV is a result of the strong interaction between these bands.

TABLE I. Experimental values of branching ratio λ, mixing ratio δ, $B(E2)_{\text{out}}/B(E2)_{\text{in}}$, and $B(M1)_{\text{out}}/B(E2)_{\text{in}}$ for the decay out transitions in TSD3.

E_γ(keV)	λ	δ	$\frac{B(E2)_{\text{out}}}{B(E2)_{\text{in}}}$	$\frac{B(M1)_{\text{out}}}{B(E2)_{\text{in}}}$
843.1	0.27 ± 0.05	-1.9[a]	0.010	0.0014
		-0.5[a]	0.003	0.005
961.0	$\sim 0.6 \pm 0.05$[b]	$-1.9^{+1.14}_{-20.0}$	0.006	0.001
		$-0.5^{+0.50}_{-0.82}$	0.001	0.005

[a]Same δ as measured for the 961-keV transition is assumed.
[b]Assuming that the total measured intensity feeding that level goes into the decay out and the unobserved in-band decay (expected at ~400 keV).

less alignment. Other possible configurations of this band are discussed in Ref. [11].

To firmly establish the decay from the TSD1, all ND bands to which TSD1 decays are extended to much higher spins are shown in Fig. 1. The unfavored signature partner of the $[411]1/2^+$ orbital was observed for the first time. The $[402]5/2^+$ and $[411]1/2^+$ bands appear strongly mixed at low spins as many $\Delta I = 1$ and a few $\Delta I = 2$ transitions between them are established.

The one-phonon wobbling band exclusively decays to the yrast, TSD1, structure [5]. The decay out of TSD1 is observed at both low and high spins. At low spins, mixing between levels in TSD1, and ND structures causes this band to decay out over a range of $4\hbar$ starting at $\sim\frac{33}{2}\hbar$. Although the decay of the $\frac{33}{2}\hbar$ level proceeds by a single stretched $E2$ transition, the decay from the $\frac{29}{2}\hbar$ state is fragmented via several transitions to ND states with different—although mutually somewhat mixed—intrinsic structures. At high spins, a band mixing is observed at $\sim 32\hbar$, causing several cross-band transitions between TSD1 and the $[402]5/2^+$, $\alpha = +1/2$ band. In fact, it was not possible from coincidence considerations to firmly distinguish the top of TSD1 from that of the $[402]5/2^+$ band above the $61/2\hbar$ level as discussed in Ref. [5]. The $[402]5/2^+$ band is subject to an alignment most likely from a pair of quasiprotons at the same spin, which complicates the issue. The assignment of the sequence of transitions as the top part of TSD1, as presented in the partial level scheme, is mainly based on the fact that the dynamic moments of inertia, $\mathcal{J}^{(2)}$, are larger for these transitions and therefore makes a more smooth connection of TSD1 across the interaction point. The opposite assignment above $I = 61/2\hbar$ is possible and would actually produce the level repulsion at $I = 61/2\hbar$ expected for a pure two-level mixing case. Yet a two-level mixing has severe constraints on the matrix elements of the cross-band transitions which are incompatible with the absence of the $65/2(\text{TSD1}) \rightarrow 61/2\hbar$ (ND) transition and therefore ruled out. A third $I = 61/2\hbar$ level must be interacting as well, and a candidate state with transitions observed from both $I = 65/2\hbar$ levels was indeed found (see Fig. 1). This state could quite naturally belong to the low spin continuation of the $[402]5/2^+$ band below the proton crossing. Results from our recent lifetime measurement of the transition quadrupole moments of these bands should settle this issue [12].

A close inspection of Fig. 4 and the partial level scheme presented in Fig. 1 reveals that the levels with spin and parity $\frac{61}{2}\hbar$ in TSD1 and $[402]5/2^+$ band have a small energy separation of 39 keV, and the third $\frac{61}{2}\hbar$ level is ~46 keV above that of TSD1. Although these interactions are complex, the observed energy separations at the interaction points may, together with the estimated shifts in level energies, necessary to produce a smooth dependence of $J^{(2)}$ on rotational frequency, provide an estimate of the maximum interaction strength between those levels. We find at both low spin, $\frac{29}{2}\hbar$, and high spin, $\frac{61}{2}\hbar$, an energy perturbation of ~10 keV, which with observed level distances of around 50 keV at both spins imply similar interaction strengths of ~18 keV at these interaction points. The rather large branching ratios, ~30–45%, measured for the interband transitions at high spins in TSD1 are consistent with this estimated value for the interaction strength. Such strong interactions indicate the absence of an "efficient" barrier even at high spin.

This picture is quite surprising because it is inconsistent with the observed decays out of the SD well in all mass

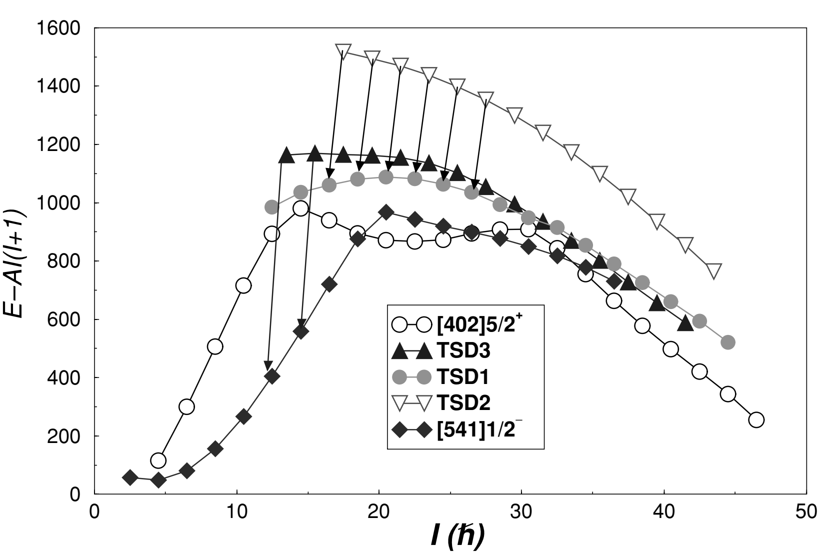

FIG. 4. Excitation energy minus a rigid rotor reference for TSD1, TSD2, and TSD3 and the $[402]5/2^+$, $[541]1/2^-$ ND bands in ^{167}Lu. The arrows indicate the decay out of TSD bands.

regions, where the effective barrier begins to disappear only at the lowest spins, causing the decaying to occur. In the neighboring ^{163}Lu, the interaction at the decay was estimated, based on similar considerations but here also from measured cross-band branchings, to be ∼22 keV at $\frac{21}{2}\hbar$, whereas a lower limit of ∼5 keV was given at $\frac{45}{2}\hbar$, from the absence of cross-band transitions at the closest distance to ND states. In ^{165}Lu, the interactions occur over a spin range of $\frac{29-27}{2}\hbar$, and the strength at $\frac{37}{2}\hbar$, based on the same considerations, is estimated to be ∼3–4 keV. It should be pointed out that the interaction that causes the decay out of the yrast TSD structures in ^{165}Lu occurs at $\frac{29}{2}\hbar$, whereas in ^{163}Lu it takes place at $\frac{21}{2}\hbar$. Therefore, the $\pi i_{13/2}$ band could be established to the band head at $\frac{13}{2}\hbar$ in ^{163}Lu, which is not the case in ^{165,167}Lu.

There is no clear explanation yet as to how the height of the barrier in ^{167}Lu could have very little dependence, if any, on spin. But perhaps we might gain some perspective by investigating how the quadrupole deformation of the TSD and ND structures evolves with both spin and neutron number in neighboring TSD nuclei. A trend toward smaller deformation with increasing neutron number is observed in the TSD structures in ^{163,164,165}Lu [15,16]. In contrast, an increase in the deformation of the ND structures with increasing N is expected. Such trends suggest a smaller deformation gap between TSD-ND structures with increasing N. Moreover, quadrupole moments of TSD bands in ^{163}Lu show a decreasing trend toward higher spin [15], which may indicate a decreasing gap with increasing spin for a given N. These observations suggest that the barrier between ND and TSD wells vanishes at higher spins with increasing N. This may explain why the decay out, caused by TSD-ND mixing, of yrast TSD structures in ^{165,167}Lu occurs $4\hbar$ earlier than TSD1 in ^{163}Lu because such mixing indicates similar deformation of the mixed levels and the vanishing of a well-defined barrier at the decay point. Clearly, the interaction strengths observed in ^{163,167}Lu are consistent with this scenario. Conversely, the interaction strengths estimated in ^{165}Lu are inconsistent with such a scenario.

In conclusion, a new excited TSD band built on a multi-quasiparticle excitation has been observed to coexist and compete rather well with the wobbling mode in the TSD well of ^{167}Lu. Spin, parity, excitation energies, and configuration were assigned for this band. Surprisingly, the observed interactions between TSD and ND levels indicate that the barrier between the two wells is rather small and exhibits almost no dependence on spin in this nucleus.

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[1] G. B. Hagemann *et al.*, Eur. Phys. J. A **20**, 183 (2004).
[2] S. Ødegård *et al.*, Phys. Rev. Lett. **86**, 5866 (2001).
[3] D. R. Jensen *et al.*, Phys. Rev. Lett. **89**, 142503 (2002).
[4] G. Schönwaßer *et al.*, Phys. Lett. **B552**, 9 (2003).
[5] H. Amro *et al.*, Phys. Lett. **B553**, 197 (2003).
[6] P. Bringel *et al.* (to be published).
[7] D. R. Jensen *et al.*, Eur. Phys. J. A **19**, 173 (2004).
[8] T. Bengtsson, Nucl. Phys. **A496**, 56 (1989); Nucl. Phys. **A512**, 124 (1990).
[9] R. Bengtsson, www.matfys.lth.se/~ragnar/ultimate.html
[10] D. C. Radford, Nucl. Instrum. Methods A **361**, 297 (1995).
[11] D. Roux *et al.* (to be published).
[12] H. Amro *et al.* (to be published).
[13] I. Wiedenhöver *et al.*, Phys. Rev. C **58**, 721 (1998).
[14] K. S. Krane, R. M. Steffen, and R. M. Wheeler, Nucl. Data Tables **11**, 351 (1973).
[15] A. Görgen *et al.*, Phys. Rev. C **69**, 031301 (2004).
[16] G. Schönwaßer *et al.*, Eur. Phys. J. A **15**, 435 (2002).