# Deformation-Driving Properties of the $\nu i_{13/2}[660]\frac{1}{2}^+$ Intruder Orbital for $A \simeq 130$ Nuclei

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Several rotational-band structures have recently been observed in mass $A \simeq 130$ nuclei, built on multi-quasiparticle states of enhanced quadrupole deformation, the so-called superdeformed states ($\beta \simeq 0.4$). In $^{137}$Sm, a decoupled band built on the $\nu i_{13/2}[660]\frac{1}{2}^+$ single-quasineutron orbital, intruding from two oscillator shells above with a predicted $\beta \simeq 0.35$, was observed to low spin and excitation energy. The role of this $\beta$-driving $\nu i_{13/2}$ orbital, which showed a 50% enhanced moment of inertia, is discussed in terms of the superdeformation in this mass region.

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The observation of strongly enhanced nuclear deformation, the so-called superdeformation, has generated considerable theoretical interest. Superdeformation, as manifested by a rotational band that originates from the second shell-gap prolate minimum in the potential-energy surface at larger deformation, was first discovered[1] in $^{152}$Dy and subsequently observed in the $^{132}$Ce nucleus[2] and several Nd isotopes.[3,4] The theoretical understanding of the superdeformation structure is not complete. High-spin orbitals, whose quasiparticle Routhians ($e'$, the energy in the rotating frame) slope strongly with increasing quadrupole deformation $\beta$ ($\beta \sim \epsilon_2$), are predicted to be influential in driving the nucleus to the larger deformation minimum. With the neutron Fermi level for the $A \simeq 130$ region being well below the $i_{13/2}$ intruder orbital, a steep slope ($-de'/d\beta$) and the related strong deformation driving force are theoretically expected for this high-$j$ orbital. Although the detailed configuration for the valence particles that stabilizes superdeformation is not known, the $i_{13/2}$ neutron is predicted to play a dominant role. Thus, a knowledge of the $\beta$-driving properties of the $i_{13/2}$ neutron orbital is necessary to identify the crucial mechanism for superdeformation in the $A \simeq 130$ mass region. Bands involving the $\nu i_{13/2}$ orbital have been observed[5,6] in the isotone $^{133}$Ce and isotope $^{135}$Sm at higher spins, but not clearly based on single-quasiparticle states.

In order to observe the $\beta$-driving properties of the $i_{13/2}$ neutron orbital, it is necessary to isolate the band associated with the $i_{13/2}$ single-quasiparticle state. Potential-energy surface calculations using the Nilsson-Strutinsky method[7] for the odd-neutron $N=75$ isotones at $\hbar\omega=0$ show the $i_{13/2}$ neutron state dropping in energy relative to the $h_{11/2}$ neutron yrast state as $Z$ increases for the sequence of nuclei $^{133}$Ce, $^{135}$Nd, $^{137}$Sm, and $^{139}$Gd. In $^{137}$Sm, the energy difference is sufficiently small to allow for near-yrast population of the $i_{13/2}$ neutron band via heavy-ion-induced reactions. The $^{139}$Gd nucleus, being very neutron deficient, would be more difficult to study. An experiment was thus designed to study the $i_{13/2}$ neutron band in $^{137}$Sm. A decoupled ($\Delta I=2$) rotational band was subsequently populated from spins $I^\pi = \frac{13}{2}^+ - \frac{49}{2}^+$, built on the single $\nu i_{13/2}$ intruder state that originates from two major harmonic-oscillator shells above the neutron Fermi surface. The low spin of the single quasiparticle allows for direct feeding into the $\nu h_{11/2}$ yrast band, unlike the superdeformed bands which suddenly terminate at relatively high spins. A remarkable 50% increase in the moment of inertia was found for this band relative to that for the upper midshell $h_{11/2}$ neutron band. This reveals the $\beta$-driving property of the $i_{13/2}$ neutron and the underlying basis for the understanding of superdeformation in the $A \simeq 130$ mass region.

States in $^{137}$Sm were populated via the reaction $^{104}$Pd($^{37}$Cl,$p3n\gamma$) at 170 MeV. The heavy-ion beams were provided by the Stony Brook Superconducting Linac injected by the tandem Van de Graaff accelerator. Both thick and thin targets were used in the experiments. Four Compton-suppressed Ge detectors were used to record $\gamma$-$\gamma$ coincidences produced by the bombardment of the thick target, while five detectors were used with the thin target. Multiplicity information was also recorded for the thin-target data with fourteen closely packed hexagonal bismuth germanate crystals. By the demand that at least one multiplicity crystal fired in coincidence with at least two of the suppressed Ge detectors, the $\gamma$-ray background caused by inelastic target excitation and activity lines was greatly reduced.

The decay scheme of $^{137}$Sm deduced from this work is presented in Fig. 1 with the decoupled ($\Omega = \frac{1}{2}$) $\nu i_{13/2}$

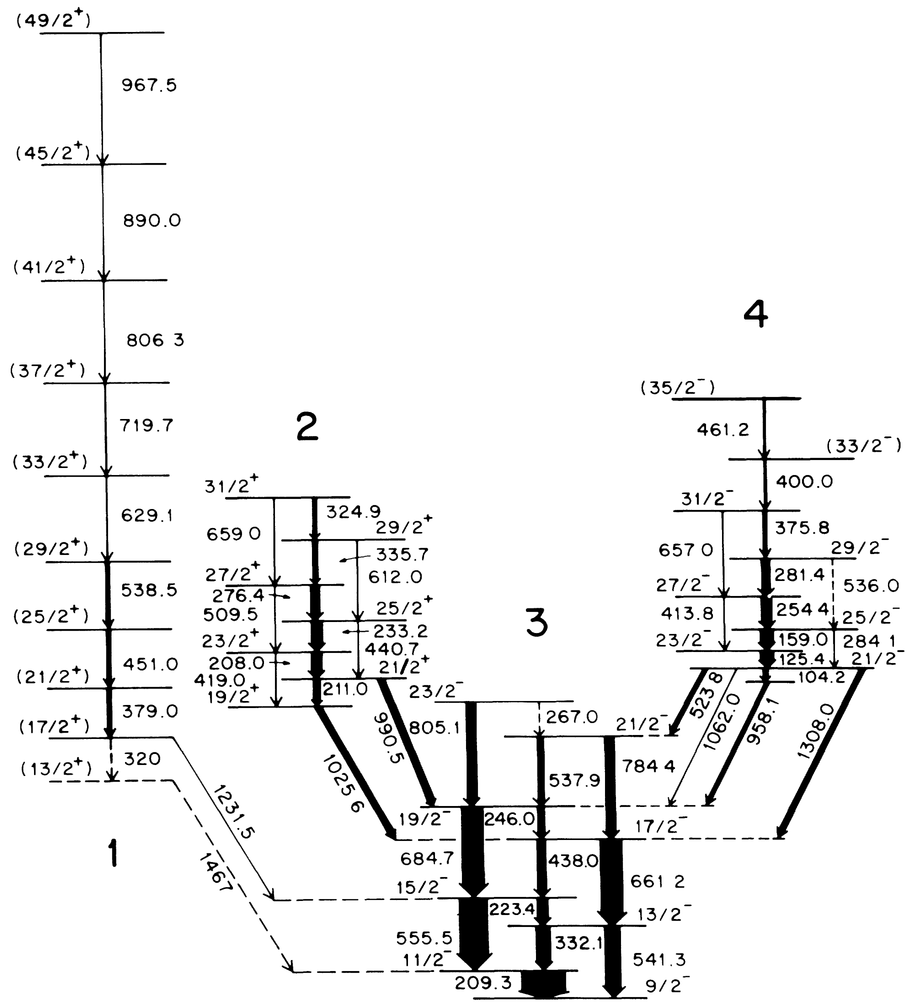


FIG. 1. Level scheme of $^{137}Sm$ deduced from this work. The energies of the transitions are given in kiloelectronvolts and the widths of the arrows represent the relative transition intensities.

band, labeled 1, shown to the left. At low spins, the yrast band (3) of $^{137}Sm$ is based on a coupled neutron orbital from the upper $h_{11/2}$ midshell. Two further coupled band structures (2 and 4), consisting of relatively strong dipole transitions, were observed at higher spins; these structures have been identified with the $\nu h_{11/2} \otimes \pi h_{11/2} \otimes \pi g_{7/2}$ and $\nu h_{11/2} \otimes [\pi h_{11/2}]^2$ configurations, respectively, by the observed spins, alignment, signature splitting, and $B(M1)/B(E2)$ ratios as in the lighter $N=75$ isotones[5,8] $^{133}Ce$ and $^{135}Nd$.

Two possible low-$\Omega$ neutron orbitals near the Fermi surface that could give rise to the observed decoupled band in $^{137}Sm$ are the $f_{7/2}[541]\frac{1}{2}^-$ and $i_{13/2}[660]\frac{1}{2}^+$ Nilsson orbitals. The energy of the $i_{13/2}$ state relative to that of the $f_{7/2}$ state is lowered by both an increase in rotational frequency and an increase in quadrupole deformation. The extracted dynamic moment of inertia ($dI_x/d\omega$, where $I_x$ is the component of the spin along the rotation axis) of the decoupled band is plotted as a function of rotational frequency in Fig. 2, where it is compared to that extracted for the $\nu h_{11/2}$ yrast band. It can be seen that the value extracted for this band is approximately 50% larger than the values extracted for both signature components of the $\nu h_{11/2}$ one-quasineutron band and is close to the spherical rigid-body estimate. The moment of inertia is an experimental quantity that is sensitive to changes in the quadrupole deformation. Since both bands are built on single-quasineutron states and the $i_{13/2}$ orbital is located even further away from the Fermi surface than the $h_{11/2}$ orbital, the enhanced moment of inertia cannot be explained by the blocking of orbitals near the Fermi surface, which would induce a decrease in the neutron pairing correlations. Lifetime measurements for the $E2$ intraband transitions would provide a more rigorous proof of the connection between the enhanced moment of inertia and the increased deformation.

The observed enhancement in the moment of inertia is

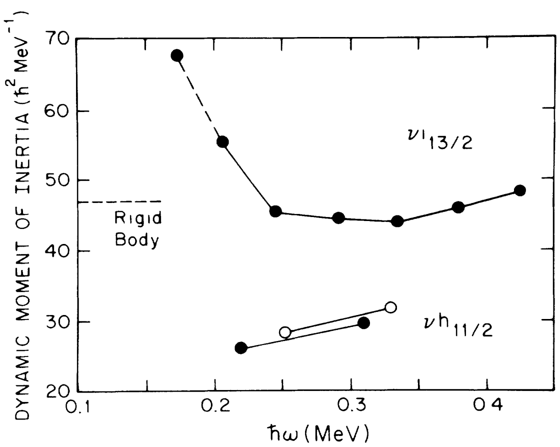


FIG. 2. The dynamic moment of inertia ($dI_x/d\omega \sim 4\hbar^2/\Delta E_\gamma$, where $\Delta E_\gamma$ is the energy difference between two consecutive $E2$ transitions) of the $i_{13/2}$ neutron band compared to the $h_{11/2}$ neutron band. The rigid-body estimate for a spherical shape is also shown.

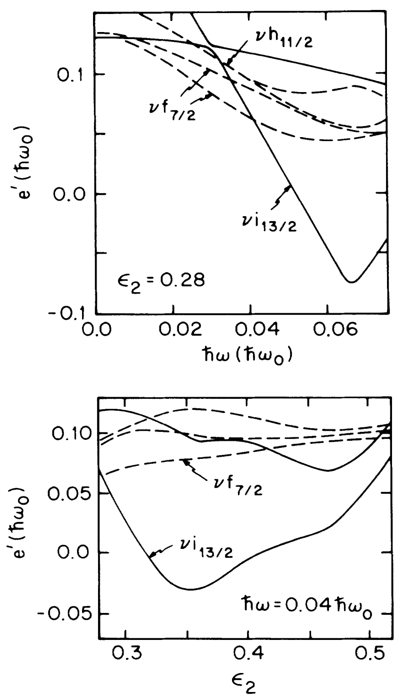


FIG. 3. Calculated single-quasineutron energies as functions of rotational frequency (top) and quadrupole deformation $\epsilon_2$ (bottom) for states of positive parity (full lines) and negative parity (dashed lines). The oscillator $\hbar\omega_0$ value is equal to 7.95 MeV.

consistent with an increased quadrupole deformation as predicted for the single $i_{13/2}$ quasineutron state by potential-energy surface calculations with the Nilsson-Strutinsky method.[7] Indeed the predicted deformation for this configuration in $^{137}$Sm at $\hbar\omega = 0$ is $\epsilon_2 \simeq 0.28$ as compared to $\epsilon_2 \simeq 0.20$ for the single $h_{11/2}$ quasineutron state. The results of these calculations, showing the predicted shapes $(\epsilon_2, \epsilon_4)$ for the $\nu i_{13/2}$ and $\nu h_{11/2}$ states, are presented in Table I for a series of $N = 75$ isotones. The relative excitation energy of the $\nu i_{13/2}$ configuration with respect to the $\nu h_{11/2}$ yrast configuration is also shown for each nucleus.

Rotation lowers the energy of the decoupled $(\Omega = \frac{1}{2})$ $i_{13/2}$ neutron orbital with respect to both the decoupled $(\Omega = \frac{1}{2})$ $f_{7/2}$ and the coupled $(\Omega = \frac{9}{2})$ $h_{11/2}$ neutron orbitals, as can be seen in Fig. 3 (top) where single-quasineutron Routhians $(e')$ are plotted as a function of rotational frequency with $\epsilon_2 = 0.28$. These cranked-shell-model calculations were performed with the modified Nilsson parameters $\kappa$ and $\mu$ of Bengtsson and Ragnarsson.[9]

The enhancement of the quadrupole deformation for the $\nu i_{13/2}$ state is caused by the strong $\beta$-driving effect of this orbital on the quadrupole deformation. Calculated single-quasiparticle Routhians $(e')$ for $^{137}$Sm are shown in Fig. 3 (bottom) as a function of the quadrupole deformation $\epsilon_2$. These calculations were performed for axially symmetric shapes $(\gamma = 0°)$ and a rotational frequency $\hbar\omega = 0.04\hbar\omega_0 = 0.32$ Mev. The steep slope $(-de'/d\epsilon_2)$ of the $\nu i_{13/2}$ orbital seen below $\epsilon_2 = 0.35$ represents the strong driving force of this orbital to larger quadrupole deformation. Although this orbital drives towards $\epsilon_2 \simeq 0.35$ at $\hbar\omega = 0.32$ MeV the potential energy has a minimum at $\epsilon_2 \simeq 0.28$ for $\hbar\omega = 0$ as shown in Table I. More recent calculations using the total-Routhian-surface formalism[10] indicate a deformation $\epsilon \simeq 0.35$ for the $\nu i_{13/2}$ configuration above a rotational frequency $\hbar\omega = 0.2$ MeV. Such a quadrupole deformation is close

TABLE I. Predicted shapes $(\epsilon_2, \epsilon_4)$ for the configurations built on single $h_{11/2}$ and $i_{13/2}$ quasineutron states in several $N = 75$ isotones. The excitation energy of the $i_{13/2}$ configuration is given relative to the yrast $h_{11/2}$ state. The calculations were performed at $\hbar\omega = 0$.

| Nucleus | $h_{11/2}$ $\epsilon_2$ | $h_{11/2}$ $\epsilon_4$ | $i_{13/2}$ $\epsilon_2$ | $i_{13/2}$ $\epsilon_4$ | Relative excitation energy (MeV) |
|---|---|---|---|---|---|
| $^{133}$Ce | 0.165 | 0.019 | 0.215 | 0.003 | 3.1 |
| $^{135}$Nd | 0.185 | 0.024 | 0.270 | −0.002 | 2.6 |
| $^{137}$Sm | 0.195 | 0.026 | 0.280 | 0.003 | 2.1 |
| $^{139}$Gd | 0.205 | 0.031 | 0.285 | 0.014 | 2.0 |

to the value expected for a prolate rotor with a 3:2 axis ratio.

Theoretical calculations[10] for this mass region have shown superdeformed shapes stabilized by multiquasiparticle configurations, including one or more $\beta$-driving $i_{13/2}$ orbitals. The $\beta$-driving effects of the single $\nu i_{13/2}$ state, which has been isolated in $^{137}$Sm, appear to be the vital mechanism for the increase in the nuclear deformation towards the second shell-gap minimum. This empirical information for an isolated $\beta$-driving orbital is essential for the theoretical description of superdeformation. It is interesting to note that the $i_{13/2}$-related bands observed[5,6] at higher spin of possibly more complicated configurations in $^{133}$Ce and $^{135}$Sm do not show this larger relative enhancement in the moment of inertia. On the other hand, the neighboring isotones[3,4] $^{135}$Nd and $^{133}$Nd have revealed the so-called superdeformed bands. It is obviously important to determine all of the conditions required for stabilization of superdeformation.

In summary, it has been demonstrated that the $\beta$-driving properties of the $\nu i_{13/2}[660]\frac{1}{2}^+$ single-quasineutron configurations are sufficient to increase significantly the quadrupole deformation of $^{137}$Sm. This single-quasineutron state is an important mechanism in the evolution towards the so-called superdeformed shapes observed in the $A \simeq 130$ mass region.

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