Superdeformation in the Mass A~80 Region

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A new island of superdeformed nuclei with major-to-minor axis ratio of 2:1 has recently been discovered in the A~80 medium-mass region, confirming the predictions for the existence of a large SD gap at particle number N,Z-44. The general properties of more than 20 bands observed so far will be reviewed here, and compared with those of the superdeformed bands in the heavier nuclei.

1. Introduction

Superdeformation was first discovered in the actinide fission isomers [1], and was explained as resulting from a secondary minimum at superdeformed (SD) shapes [2]. In the actinide region, the sum of the macroscopic liquid drop term, and the microscopic shell correction to the total energy gives rise to a second minimum at SD even at very low spins. However, with the weakening of the Coulomb force in lighter systems, SD minima are stabilized only at high spins and for certain nuclei close to SD magic numbers. Studies of these high-spin SD structures, and especially their mass dependence, provide an important insight into the competition between the microscopic and macroscopic effects, the role of the odd-time terms in the Hamiltonian, as well as certain aspects of the effective interactions such as the spin-orbit force.

The first high-spin SD band was observed in 152Dy in 1986 [3], and was followed in 1989 by discovery of another island of superdeformation around 192Hg [4]. These findings were in excellent agreement with the results of the earlier calculations which had predicted the existence of superdeformed magic particle numbers N,Z -44, 64, 86, and 116 [5,6]. Encouraged by these experimental successes, numerous searches were undertaken to verify the existence of the predicted superdeformed shell gaps near particle number 44. However, largely due to experimental difficulties, these efforts were not successful until recently. Among the problems specific to this mass region which hinder the observation of these weakly populated bands are the following:

(i) Due to the A-5/3 scaling, the gamma rays associated with the medium-mass nuclei (and particularly those in the SD bands) have high energies and, thus, poor detection efficiency;
(ii) Reactions used to populate the high-spin states result in large velocities and angular spread of the recoiling nuclei which cause excessive Doppler broadening and poor energy resolution;
(iii) Because of the low Coulomb barrier and high excitation energy needed to populate the high-spin states, light charged-particle emission fragments the yields of the fusion-evaporation products into a large number (typically 20 or more) of exit channels. Therefore, the γ-rays from a variety of reaction products can easily mask and interfere with those from the SD bands which are usually populated with less than 0.1% of the total cross section.

The first of these difficulties may be alleviated by the use of large Ge detectors, while the second problem may be overcome in part by segmenting the Ge crystals. Therefore, the observation of the first SD in 83Sr [7] had to await the advent of arrays of large Ge detectors such as Eurogam-I. Another breakthrough, which made the systematic studies of SD bands in the mass A~80 region possible, was to combine the charged-particle detector array...
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Microball [8] with the Gammasphere array. Full detection of the evaporated proton and \( \alpha \) particles and their energies helps in two ways. First, it serves to select and identify the exit channels of interest which are usually produced weakly at the beam energies optimal for the population of SD bands. Second, it allows the reconstruction of the recoil momenta which results in considerable improvements in the Doppler correction and, hence, gamma-ray energy resolution. This is best illustrated in Fig. 1, which compares gated \( \gamma \)-ray spectra for the yrast SD band in \( ^{83}\text{Sr} \) from two experiments. Panel (a) is the sum of several singles gates on the transitions in the band from the Eurogam-I experiment which produced the first example of superdeformation in this region [7]. Figure 1(b) was obtained by summing several double-gated spectra from a Gammasphere+Microball experiment which selected the \( ^{83}\text{Sr} \) channel by requiring that all of the four emitted protons be present in the data stream [9]. It shows a significant improvement in both the peak-to-background ratio (a factor of \(-8\)) and the energy resolution of the gamma rays. Furthermore, the clean channel selection afforded by the Microball allowed detailed characterization of the band properties, including a better assignment of the spins and the point it intersects the normally-deformed (ND) yrast band [9].

![Figure 1](image.png)

**Fig. 1.** Comparison of the gated spectra of the SD band in \( ^{83}\text{Sr} \) obtained in two experiments [7,9] (See text for explanation).
As a result of these advancements, more than 20 SD bands in ten medium-mass nuclei have been found in the past two years. They include multiple bands in $^{80,81,82}$Sr $^{[10,11,12]}$, $^{83,84}$Y $^{[13]}$, $^{83}$Zr $^{[14]}$, $^{87}$Nb $^{[15]}$, as well as the yrast SD bands in $^{83}$Sr $^{[7,9]}$, $^{82}$Y $^{[16]}$, and $^{84}$Zr $^{[17]}$. In this paper, we review the general properties of these bands and compare their characteristics with those of the SD bands in the heavier mass regions.

2. Experimental observables and their systematics

Some of the general properties of SD bands that may be experimentally studied to test various theoretical models are: the $J(2)$ moments of inertia and their variations with rotational frequency, transition quadrupole moments ($Q_t$), measurements of the g-factors either directly or indirectly from the $B(M1)/B(E2)$ ratios, and identification of the excited bands and their relative spins and excitation energies with respect to the yrast SD band. To varying degrees, all these observables are sensitive to, and help identify the single-particle configurations of the SD bands. Other observables which are also relevant to this question are the relative alignments of different SD bands, either in the same nucleus or in neighboring isotopes and isotones. This quantity may be simply deduced from the γ-ray energies and determines the fractional change in the $J(2)$ of the pair of bands as discussed in Ref. [18].

The feeding pattern of the SD bands and their variations (if any) with reaction may shed some light on the fusion-evaporation reaction mechanism, and factors which limit both population and retention of the high partial waves in compound nuclei. The decay pattern is related to the quantum-mechanical tunneling through the barrier which separates the SD and ND states, and depends on such factors as the barrier height, level density, and pairing interaction.

2.1 Population and Decay: The first SD in this mass region was observed [7] using the Eurogam-I array and the $^{56}$Fe($^{30}$Si, 2pn)$^{83}$Sr reaction at a beam energy of 128 MeV. This and similar reactions, which form compound nuclei at $\sim$70 MeV excitation energy and $>50\hbar$ angular momentum, have been found to be optimal for the population of SD bands in the $4p$, $3p$, $2pn$, and in particular the $\alpha2p$ and $\alphapn$ exit channels. Our studies indicate that emission of alpha particles, which originate from the highest angular momentum states in these compound nuclei, is very effective in populating the SD and ND states, and depends on such factors as the barrier height, level density, and pairing interaction.

Similar to the SD bands in heavier nuclei, these bands are fed over a range of several transitions and generally reach a saturation intensity of $<2\%$ of the total. The exceptions are the yrast bands in $^{83}$Zr $^{[14]}$ and $^{84}$Zr $^{[17]}$, which are populated with intensities of more than 5% and 4%, respectively. Both of these values are about a factor of 2 larger than the intensities of the yrast SD bands in their Y isotones that were populated via the $3p$ channel in the same reactions. In the case of $^{84}$Zr, significant differences were observed in the feeding saturation point when the band was populated by two different reactions, namely $2pn$ and $\alpha2p$ $^{[17]}$. This is the only known example of this effect and points to an important new factor that influences the population of SD bands. Also, the common assumption that the half-intensity point (i.e., the level which receives 50% of the total intensity of the band) coincides with the point where SD bands become yrast is called into question due to the fact that this point was observed to vary with reaction.

The decay of these bands is sudden and is completed within a narrow range of one to three transitions. As is the case in the heavier nuclei, these SD bands decay statistically to
several ND bands of both parities. From the intensities of the feeding-out (of the SD) and feeding in (to the ND) transitions, one can estimate the approximate spins of the SD bands. The spins of the lowest-lying states have been estimated to be approximately $15\hbar$ in the $N=43$ nuclei $^{81}\text{Sr}$ [11] and $^{83}\text{Zr}$ [14], and close to $20\hbar$ in the more neutron-rich nuclei $^{82,83}\text{Sr}$ [12,9] and $^{84}\text{Zr}$. Many of these bands extend to a maximum spin of $\sim 40\hbar$. Assuming that the yrast SD and ND bands cross each other at a point where their sidefeeding intensities are nearly equal, it is estimated that these SD bands become yrast at $\sim 30\hbar$. Interestingly, this spin corresponds to the onset of band termination that has long been predicted [6] to occur in many of the ND bands in this region. Band termination was recently observed in several nuclei such as $^{83}\text{Sr}$ [20], $^{83}\text{Y}$[21], and $^{84}\text{Zr}$ [17], as evidenced in their rapidly decreasing $J^{(2)}$ (see Fig. 2a) and $Q_{I}$ values [22].

2.2 Systematics of the moments of inertia and identical bands: A very distinctive feature of these bands is the high energies of their gamma rays which typically range from about 1300 to more than 2600 keV. This may be compared with a maximum gamma-ray energy of approximately 700 and 1500 keV for the SD bands in the A$\sim$190 and 150 regions, respectively [23]. The energy differences of the consecutive gamma rays in the SD bands of the A$\sim$80 nuclei are approximately 150 keV, which imply a dynamical moment of inertia $J^{(2)}-27\hbar^2/\text{MeV}$, corresponding to that of a rigid rotor with a quadrupole deformation of $\beta_2\sim 0.5$, or major-to-minor axis ratio of 2:1.

Figure 2b shows a plot of the $J^{(2)}$ versus rotational frequency ($\omega$) for the SD band in $^{83}\text{Sr}$, along with those in $^{240}\text{Pu}$, $^{192}\text{Hg}$, and $^{152}\text{Dy}$, which represent typical SD bands in their respective mass regions [23]. To better demonstrate the similarity of these bands, all moments of inertia were scaled by $A^{5/3}$ to factor out the average mass-number dependence. Apart from the A$\sim$190 region, where the values rise continuously with $\omega$, the scaled moments of inertia of the other three SD bands have comparable values and are nearly constant as a function of $\omega$. The band in $^{83}\text{Sr}$ extends to a maximum rotational frequency of about 1.3 MeV, nearly twice as high as the frequencies encountered in the A$\sim$150 region. Thus, the SD bands in the A$\sim$80 region represent the highest collective rotational frequency observed so far.

![Fig. 2. Plots of scaled $J^{(2)}$ vs. rotational frequency. (a) The SD band in $^{83}\text{Sr}$ (circles) and two ND bands in $^{83}\text{Y}$ (squares) and $^{83}\text{Sr}$ (triangles). (b) SD bands in $^{240}\text{Pu}$ (diamonds), $^{192}\text{Hg}$ (squares), $^{152}\text{Dy}$ (triangles), and $^{83}\text{Sr}$ (circles). The dashed line shows the corresponding plot for a SD rigid rotor with $\beta_2=0.5$.]

Figure 3 shows the systematics of the $J^{(2)}$ of the SD bands in ten nuclei in this region. Apart from a few cases (e.g., $^{81}\text{Sr}$ or $^{83}\text{Zr}$) where discontinuities due to band crossing are present, the majority of the $J^{(2)}$ values fall in the range of $\sim 25$-30$\hbar^2/\text{MeV}$. 
Fig. 3. Systematics of the $J^{(2)}$ moments of inertia for the SD bands in the A~80 region.

A convenient way to compare the $J^{(2)}$ values of these bands is to calculate the fractional changes $\Delta J^{(2)}/J^{(2)}$ of pairs of bands as described in Ref. [18]. A histogram of the fractional changes in moments of inertia is shown in Fig. 4, which compares all bands vs. all others (solid), and all bands vs. the yrast bands in their adjacent A+1 nuclei (dashed). In the latter category, nearly 16% of the bands are identical, as compared with ~12% and 4% for the SD bands in the A~150 and 190 regions, respectively [24]. Special among these identical bands are two pairs of twinned bands (i.e., bands with similar gamma-ray energies) in $^{82}$Sr vs. $^{83}$Y and $^{83}$Sr vs. $^{84}$Y [13], which imply the existence of a single-particle routhian with a slope of $-0.5\hbar$ at $Z=39$. As discussed in

Fig. 4. Histogram of frequency distributions of the fractional changes $\Delta J^{(2)}/J^{(2)}$ of pairs of SD bands in the A~80 region (see text).
Sec. 3, this information may be used to test theoretical models and to constrain their parameters. Other experimental observations which may be used for the same purpose are the rotational frequencies where band crossings take place and their interaction strengths. A particularly interesting case is the band crossing encountered in $^{87}\text{Nb}$ [15]. The observed interband transitions and their branching ratios indicate that the crossing between the neutron [420]1/2 and [413]7/2 orbitals is responsible for this interaction [15]. This fact may be used to infer the relative position of these orbitals. Furthermore, a second band interaction observed in only one of the two bands may be interpreted as due to the crossing with the neutron $i_{13/2}$ orbital which originates from the N=6 shell. This is the first evidence for the involvement of a "superintruder" (ΔN=3) in the configuration of a SD structure and represents a Coriolis interaction ($\hbar\omega\sim8.25$ MeV) which is about 35% larger than anything observed up to now. What makes this unique situation possible is a combination of the large deformation and extremely high rotational frequency which lowers the energy of this superintruder orbital.

2.3 Transition quadrupole moments and deformations: Because of both the large B(E2) values and high energies of the intraband transitions, the SD states have very short lifetimes. For example, the sum of the feeding and decay times for the top few states is typically a few fs, while the whole band decays in about 50 fs which is comparable to the transit times of the recoils through a thin (~400 µg/cm²) target foil. Therefore, the traditional DSAM technique with backed targets is too slow to be useful for the measurements of the lifetimes of these states. On the other hand, since the recoils do experience detectable reductions in their velocities as they traverse through the thin target foil, their velocity profiles provide a useful clock to measure the decay times. Thus, by measuring the centroids of the Doppler-shifted gamma rays in the forward and backward Ge detectors, one can obtain average fractional shifts $F(\tau)=\langle v(\tau)/v_0 \rangle$ which can be compared with the calculated values to obtain the $Q_\tau$ of the band [25]. ($v(\tau)$ is the instantaneous recoil velocity of the nucleus as deduced from the observed centroid shifts and $v_0$ is the maximum recoil velocity in the experiment.) This method was successfully used to measure an average $Q_\tau$ of $5.2\pm0.8$ eb for the SD band in $^{84}\text{Zr}$ [17], which corresponds to a B(E2) strength of 440 W.u. or a quadrupole deformation of $\beta_2=0.53$ for an axially symmetric prolate shape. This and other $Q_\tau$ measurements clearly establish the SD character of these bands.

An important question to be addressed by future $Q_\tau$ measurements is what are the particle numbers that give rise to the largest SD gaps. The present data (which are admittedly of poor statistical quality) indicate a gradual increase of $Q_\tau$ for the Sr isotopes from N=42 toward N=44 [10,11,22], and a larger $Q_\tau$ for $^{84}\text{Zr}$ than either $^{82}\text{Sr}$ or $^{83}\text{Y}$ for the N=44 isotones [22,13,17]. The latter trend is shown in Fig. 5, which is a plot of

![Graph showing plots of $F(\tau)$ curves vs. γ-ray energies for the SD and some ND states in $^{82}\text{Sr}$ and $^{84}\text{Zr}$.

Fig. 5. Plots of $F(\tau)$ curves vs. γ-ray energies for the SD and some ND states in $^{82}\text{Sr}$ and $^{84}\text{Zr}$.](image)
the $F(\tau)$ vs. $\gamma$-ray energy for the transitions from the ND states in $^{82}\text{Sr}$, and from the SD levels in $^{82}\text{Sr}$ and $^{84}\text{Zr}$. It is worth noting that the data points for the longer-lived ND states cluster around the dashed line at $v/v_0=0.94$, which corresponds to the velocity of the recoils after they have left the target. Nearly all the data points for $^{84}\text{Zr}$ band lie above those for $^{82}\text{Sr}$, indicating shorter lifetimes for the former band.

Although $Q_t$ values are sensitive to other variables (e.g., the number of the high-$j$ intruder orbitals involved in their configurations [26]), these preliminary results suggest that $N=44$ and $Z=40$ are optimal particle numbers for the formation of SD structures. As noted in Sec. 2.1, the SD bands in $^{83,84}\text{Zr}$ are populated twice as strongly as other SD bands studied so far which also supports the idea that $Z=40$ is an optimal proton number. Nevertheless, these early conclusions await confirmation by future precision measurements which would populate these bands under identical conditions. For example, the bands in the $^{82}\text{Sr}$, $^{83}\text{Y}$, and $^{84}\text{Zr}$ ($N=44$) isotones may be studied via $(\alpha p)$ reactions induced by the $^{30}\text{Si}$, $^{31}\text{P}$, and $^{32}\text{S}$ beams on the same $^{58}\text{Ni}$ target and at beam energies that produce the same entry-state distributions in the corresponding compound nuclei. Similarly, the $N=44$ to 46 $\text{Sr}$ isotopes may be produced by the reactions of $^{28,29,30}\text{Si}$ beams on the same $^{60}\text{Ni}$ target. A comparison of the feeding patterns, total intensities, and the $Q_t$ values of these bands populated under similar conditions would provide valuable insight into the relative contributions of the $N=45$ and $Z=39$ orbitals to their structures.

2.4 Forking and unusual decays: One of the SD bands in each of the $^{83}\text{Zr}$ [14] and $^{87}\text{Nb}$ [15] nuclei fork into two branches near the bottom of the cascade. Their $J^{(2)}$ moments of inertia indicate that the close-lying levels in the two branches interact with each other. Evidence has also been presented that two levels in one of the bands in $^{81}\text{Sr}$ [11] interact with two other states which lie only $\sim 10$ keV away. More interestingly, in the case of the $N=83$ $\text{Sr}$ and $\text{Zr}$ isotones, the routhians of the bands curve down and reapproach those of the ND states, allowing for their mutual interaction. (This unusual situation cannot be avoided for any reasonable values of the bandhead energies which are consistent with the sidefeeding intensities.) A similar situations has not been encountered in the heavier SD regions. The proximity of these SD bands to the ND bands may provide a favorable condition for the observation of the direct linking transitions.

3. Comparisons with theoretical calculations

Many of the observed properties of the SD bands in the $A\sim 80$ region are in good agreement with the predictions made using the cranked Strutinsky method (see, e.g., Refs. [7,9,11,12,17] for comparisons of $J^{(2)}$, $\beta_2$, and the calculated low-lying SD bands). These calculations incorporate the Woods-Saxon potential for the microscopic part and the Yukawa-plus-exponential mass formula for the macroscopic part of the total energy. For a given configuration, the equilibrium deformations at fixed values of $\omega$ were determined by minimizing the total energy at each ($\beta_2,\gamma$) grid point with respect to the hexadecapole deformation. Pairing correlations were neglected, as they are expected to play a minor role at high-spins in the $A\sim 80$ mass region. Details of the calculational procedure and technique are given in Refs. [6,27]. These calculations predict a number of low-lying SD structures that have deformations ranging from $\beta_2=0.45$ to 0.55, depending on how many $h_{11/2}$ intruder orbitals are involved in their configurations (see, e.g., Refs. [7,11,12]). At high spins, they generally have one proton in the $h_{11/2}$ orbital, symbolized as $\pi s^1$. The neutron configurations of the yrast SD bands contain one to three $h_{11/2}$ orbitals for $N=43-45$, respectively. Therefore, a gradual increase in deformation is expected in going from $N=42$ in $^{80}\text{Sr}$ to $N=45$ in $^{83}\text{Sr}$, in good agreement with the preliminary $Q_t$ measurements. On the other hand, some disagreements with data have also been encountered. For example,
theoretical proton single-particle routhians do not show a significant energy gap at $Z\sim40$
which could account for the large population intensity and quadrupole moments observed
in the Zr isotopes. Similarly, the twinned bands observed in the $^{82}\text{Sr}$-$^{83}\text{Y}$ and $^{83}\text{Sr}$-$^{84}\text{Y}$
isotones can be explained only for a large deformation of $\beta_2$=0.58, which is in
disagreement with the measured transition moments. It seems that some modifications
of the single-particle energy spectra are called for to accommodate these experimental
observations.

In general, results of other models [e.g., Refs. 28,29] share many similarities with
these calculations, but they also differ in some details. For example, while cranked
relativistic mean field calculations [29] for the SD band in $^{83}\text{Sr}$ predict the same $v5^3\pi5^1$
configuration, they calculate a larger equilibrium deformation ($\beta_2$=0.65 vs. 0.57). Future
time measurements using the completed Gammasphere array will be able to distinguish
between these models.

4. Summary and Outlook

Thanks to the development of a new generation of powerful γ-ray detector systems, a new
region of SD in the mass A=80 was recently discovered. The identification and
characterization of the properties of these bands have been greatly facilitated by the use of
the Microball charged-particle detector system. So far, more than 20 SD bands have been
observed in 10 nuclei which span $N\sim42-46$ and $Z\sim38-41$, thus confirming the earlier
predictions for the existence of a large SD gap at $N\sim44$. In general, the properties of these
bands are in good agreement with the predictions of the cranking models. However, the
presence of several disagreements point to possible shortcomings in the single-particle
energy spectra at large deformations and rotational frequencies. The high rotational
frequencies sustained by these bands correspond to the largest Coriolis force encountered
so far, and allow for the observation of the $i_{13/2}$ superintruder orbital in these medium-
mass nuclei. Another consequence of the high rotational frequency and large SD energy
gaps is that the $T=1$ pairing correlations become negligibly small. This paves the way to
observe the influence of the $T=0$ p-n interaction in the SD bands of the $N=Z=30$ nuclei
which are yet to be discovered. Finally, because of the dominance of charged-particle
emission in this region, it is now possible to probe possible nuclear structure effects on the
energies and angular distributions of the emitted protons and alpha particles. This will
open up new and exciting opportunities to study nuclear structure and reaction at their
interface.

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