First Observation of a Superdeformed Band in the $N, Z \approx 40$ Mass Region

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A high-spin rotational band of ten transitions between 1305 and 2641 keV with a nearly constant moment of inertia $J^{(2)} = 27\hbar^2$ MeV^{-1} has been observed and is tentatively assigned to ^{83}Sr. The properties of this band are in excellent agreement with theoretical calculations which predict the onset of superdeformation in and around ^{83}Sr at spins $I \approx 35\hbar$. These results establish a new region of superdeformation in medium-mass nuclei with particle numbers $N, Z \approx 40$.

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Superdeformation was first discovered nearly thirty years ago in the actinide fission isomers [1], and was explained a few years later as resulting from a secondary minimum at very large deformations [2]. In lighter nuclei, the combination of increasing liquid-drop energy and decreasing shell correction means that superdeformed (SD) minima are only stabilized at higher spins and for certain nuclei which are close to the SD magic numbers. The first high-spin SD band was observed in $^{152}_{66}$Dy$_{86}$ in 1986 [3], and was followed in 1989 by the discovery of another island of superdeformation centered around $^{192}_{80}$Hg$_{112}$ [4]. These findings were in excellent agreement with the results of earlier calculations, which had predicted the existence of magic particle numbers at $N, Z \approx 44$, 64, 86, and 116 for SD shapes [5]. Encouraged by these experimental successes for heavy nuclei, numerous searches were undertaken to verify the predictions for SD shell gaps near particle number 44. However, largely due to experimental difficulties, these efforts have not been successful. In this Letter we report the first observation of a discrete-line rotational SD band in a medium-mass nucleus with nearly equal proton and neutron numbers. Early accounts of this work have been reported in Refs. [6,7].

The choice of reaction was motivated by theoretical calculations which predicted the existence of large SD shell gaps at neutron number $N = 44$ and proton numbers $Z = 38$–40 [8–12]. High-spin states in the compound nucleus ^{86}Zr were populated using a 128 MeV ^{30}Si beam on a thin (315 μg/cm^2) ^{56}Fe self-supporting target. The 5 particle nA beam of ^{30}Si was produced by the Nuclear Structure Facility tandem accelerator at Daresbury Laboratory and the γ rays were detected with the 45 escape-suppressed germanium multidetector array, Eurogam [13]. Under these conditions the compound nucleus was formed with a maximum angular momentum of $52\hbar$. Thus, the residual nuclei, formed following evaporation of three and four nucleons, were populated at spins up to $I \approx 45\hbar$. A short run at a beam energy of 135 MeV did not produce an increased population of the collective high-spin states, as judged by the intensity of the collective $E2$ bump in the continuum γ-ray spectra. Presumably, the higher partial waves were lost to the residual channels that involve α-particle emission. By requiring a minimum unsuppressed-Ge coincidence fold of five, a total of 1.5×10^9 suppressed-Ge events were acquired in about two and a half days of beam time. The average suppressed-Ge coincidence fold was three γ rays per event, which corresponded to 4.5×10^9 γ-γ coincidence events.

From these data, a two-dimensional E_γ-E_γ correlation matrix was constructed which showed a clear diagonal ridge-valley structure in the energy range of 1250 to 2600 keV. The two ridges were separated by an energy of about 300 keV, which implies a dynamical moment of inertia $J^{(2)} \approx 27\hbar^2$ MeV^{-1}, corresponding to that of a rigid rotor with a quadrupole deformation of $\beta_2 \approx 0.5$. The presence of this ridge structure indicated that rotational bands with very large deformation were populated in this study. Subsequently, a discrete-line cascade of ten γ rays between 1303 and 2641 keV with a regular energy spacing of ≈150 keV was found in the data set. (In contrast, other known high-spin bands in this region have transition energy spacings of ≈180 keV at medium spins and ≈250 keV at high spins.) The transition energies of this band, with uncertainties of about ±2 keV, are given in Fig. 1. Figure 1(a) is the sum of seven spectra obtained by placing single gates on the 1613 through 2492 keV γ rays in this band. Since the 1303 and 1460 keV γ rays overlap several transitions of similar energies from other reaction products, they were left out of the above summation. The spectrum in Fig. 1(b) is the sum of double-gated spectra from all possible pair combinations except the three 1303-1460, 1303-1613, and 1460-1613 pairs, which are impure. Despite its small statistics, this

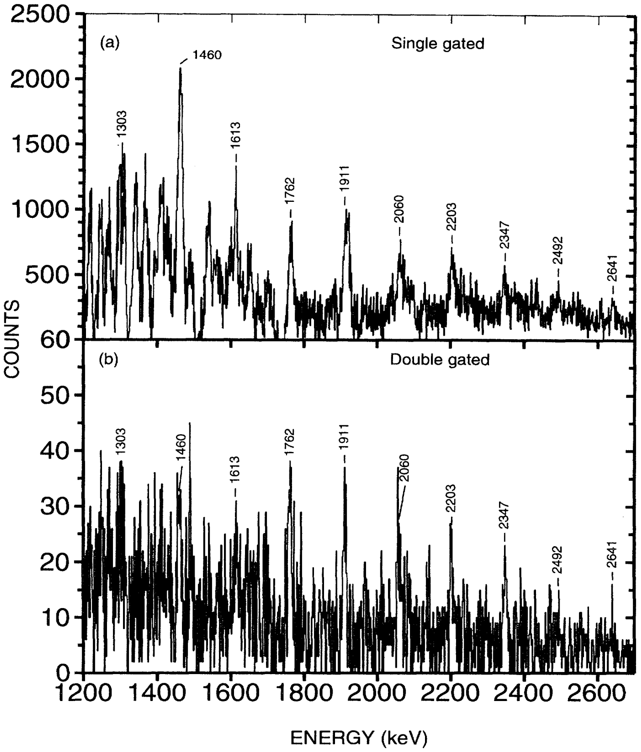

FIG. 1. γ-ray spectra generated by summation of several gated spectra in the proposed SD band: (a) single-gated spectra in coincidence with the 1613 through 2492 keV γ rays; (b) double-gated spectra from all possible pairs except the 1303-1460, 1303-1613, and 1460-1613 pairs which are impure.

double-gated spectrum closely resembles the single-gated sum spectrum shown in Fig. 1(a).

Our efforts to further characterize this band were hampered due to both its weak intensity and contaminant γ rays from various reaction products. Nevertheless, the following conclusions may be drawn from these data. The assumption of $E2$ character for the band is consistent with the quadrupole character deduced for the 300 keV wide ridges mentioned above. Moreover, the alternative of a high-K band of $M1$ transitions may be safely ruled out as it would result in a rotational band with $E2$ transition energies in excess of 5 MeV; a situation never encountered anywhere before. Because of the contaminant γ rays, assignment of this band to a unique nucleus was not possible using single-gated spectra. However, the contaminant γ rays were significantly reduced in the AND spectra generated from the singles spectra gated by various members of the band. (The AND of two spectra is defined as the spectrum which contains the minimum counts per channel of the two.) One such spectrum, obtained from the singles spectra gated by the 2203 and 2347 keV transitions in the band, is shown in Fig. 2. In addition to the lower-lying members of the proposed SD band (diamonds), Fig. 2 shows a large number of γ rays that belong to several of the normally deformed (ND) bands in ^{83}Sr [14]. More significantly, these are the only transitions that appear *consistently* in various AND combinations. On this basis, we tentatively assigned this band to ^{83}Sr. Its assignment to other nuclei such as ^{83}Y (up arrow) or ^{80}Rb (down arrow) is less likely, but cannot be completely ruled out.

In the present reaction, which maximized the production of the four-particle evaporation residues, ^{83}Sr was produced at very high spin via ($2pn$) evaporation. Relative to the total production yield for ^{83}Sr, the intensity of the new band is estimated to be (1.4 ± 0.5)%. A particularly noteworthy feature of the decay of this band is that it depopulates into *both* positive- and negative-parity bands in ^{83}Sr with comparable intensity (compare, e.g., the 875 and 404 keV γ rays in the bottom panel). This pattern of statistical decay is similar to those of the SD bands in heavier nuclei. The approximate spin of the band may

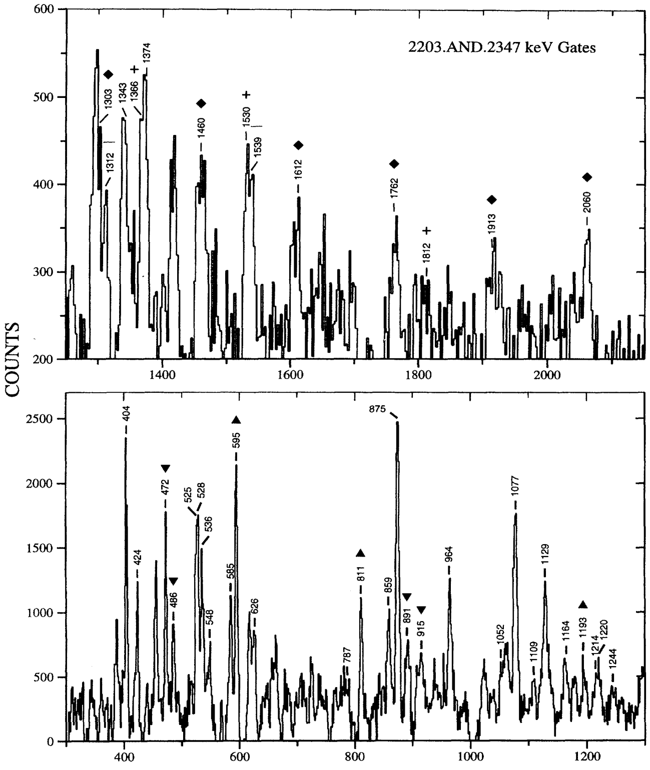

FIG. 2. The AND spectrum generated from the two spectra gated by the 2203 and 2347 keV γ rays. Identified in the top panel are γ rays attributed to (i) members of the proposed SD band (diamonds), (ii) the three highest-spin members of the positive-parity ND band in ^{83}Sr (+), and (iii) the two highest-spin members of the negative-parity ND band in ^{83}Sr (−). Identified in the bottom panel are γ rays attributed to (i) the yrast positive-parity band in ^{83}Y (up arrow), and (ii) a few of the known transitions in ^{80}Rb below spin ≈10$\hbar$ (down arrow). All other γ rays in both panels that are marked by their energies belong to the ND bands in ^{83}Sr.

be estimated by the observation that it depopulates into the highest-spin states known in ^{83}Sr. These are states with spin-parity of $I^{\pi} = 45/2^{+}$ and $39/2^{-}$ which decay by 1812 and 1539 keV γ rays, respectively (top panel in Fig. 2). Thus, we estimate that this band extends from a spin of $I = 20\hbar$ to $I = 40\hbar$. Naturally, future experiments that would populate ^{83}Sr more strongly and selectively are needed to confirm and refine these estimates.

To better appreciate the noteworthy features of this band, we have compared its $J^{(2)}$ moment of inertia in Fig. 3(a) with those of two ND bands in ^{83}Y [15] and ^{82}Sr [7,16], which have been established to a similarly high rotational frequency ω. Although the $J^{(2)}$ values of these normally deformed bands are large at low to medium spins (due to the occurrence of several band crossings), at high rotational frequencies they fall precipitously to about 50% of the rigid-rotor value. This behavior is typical for all of the ND bands in ^{82}Sr and its neighbors, which are predicted to terminate in noncollective structures as their spin approaches $30\hbar$ [8]. In contrast, the $J^{(2)}$ of the new band remains nearly constant for all frequencies.

Figure 3(b) shows a plot of the $J^{(2)}$ versus rotational frequency for the new band, along with those for the yrast SD bands in ^{240}Pu, ^{192}Hg, and ^{152}Dy which represent typical SD bands in their respective mass regions [17]. 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 [18]. The band in ^{83}Sr represents the highest rotational frequency encountered for a SD band. Apart from the $A \approx 190$ region, where the $J^{(2)}$ values rise continuously with ω, the scaled moments of inertia of the other three SD bands have comparable values and are nearly constant as a function of ω. Therefore all observed properties of the new band, namely its regular and large $J^{(2)}$ moment of inertia, its statistical decay into several normally deformed bands, and its high spin, are consistent with its characterization as a SD band. Of course, future lifetime experiments are needed to firmly establish the large collectivity of this band.

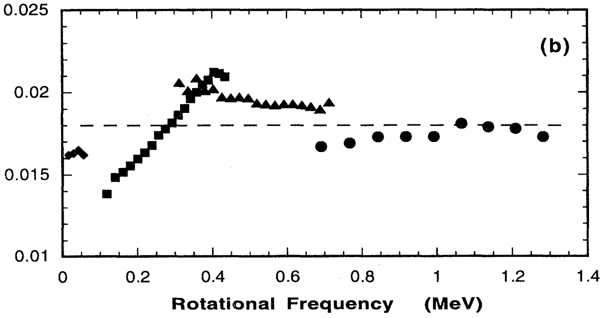

FIG. 3. Plots of dynamical moments of inertia $J^{(2)}$ versus rotational frequency. (a) The SD band in ^{83}Sr (circles) and two normally deformed bands in ^{83}Y (squares) and ^{82}Sr (triangles). Note the rapid decrease of $J^{(2)}$ for the normally deformed bands at high frequencies. (b) SD bands in ^{240}Pu (diamonds), ^{192}Hg (squares), ^{152}Dy (triangles), and the new band in ^{83}Sr (circles). For comparison, the corresponding plot for a SD rigid rotor with a deformation of $\beta_2 = 0.5$ is also displayed (dashed line).

A theoretical analysis of SD band structures in ^{83}Sr was carried out using the cranked Strutinsky method. 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 deformation, at a fixed value of angular momentum, was determined by minimizing the total energy at each (β_2, γ) grid point with respect to the hexadecapole deformation. Pairing correlations were neglected, as they are expected to play a minor role in high-spin SD bands in the $A \approx 80$ mass region [8,12]. Details of the calculational procedure and technique are given in Refs. [8,12,19], where additional references may be found.

The calculated high-spin band structures of ^{83}Sr, displayed in Fig. 4, are very similar to those of ^{84}Zr discussed in detail in Ref. [12]. The predicted yrast and near-yrast structures at medium spins in ^{83}Sr correspond to weakly deformed bands (unconnected symbols in Fig. 4) which terminate at noncollective configurations

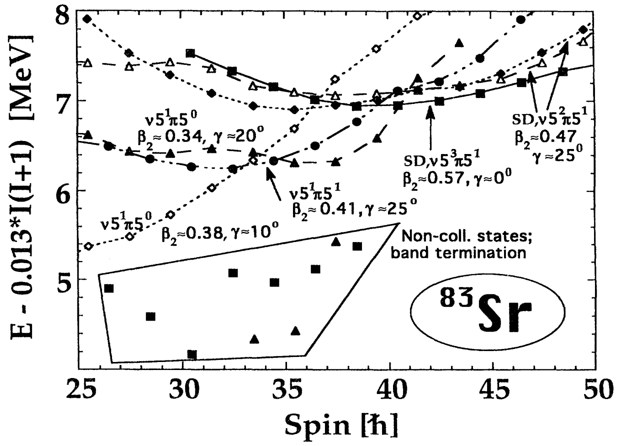

FIG. 4. Calculated lowest-energy SD structures of both signatures and parities for $25\hbar \leq I \leq 50\hbar$ in ^{83}Sr. The energies E_I are displayed relative to an average reference of $0.013I(I + 1)$ MeV. The yrast structures appearing at normal deformations are also indicated. For clarity, many other calculated excited bands are omitted. The collective bands are indicated by lines while the predicted noncollective states ($\gamma = 60^{\circ}$) are indicated by unconnected symbols. Deformations and configurations of several of the deformed bands are also given.

[8]. At higher spins, well-deformed and SD bands are predicted to appear close to the yrast line at $I \approx 30\hbar$, and they become yrast at $I \approx 35\hbar$. Indicated in Fig. 4 are the quadrupole deformation (β_2), triaxiality (γ), and the configurations (number of protons and neutrons in the $N = 5$ $h_{11/2}$ orbitals) for a number of such well-deformed structures. In our calculations, the low-lying SD bands in ^{83}Sr are predicted to contain one aligned $N = 5$ proton and two or three aligned $N = 5$ neutrons. As is the case for the SD bands in the $A = 150$ mass region [20], the $J^{(2)}$ moments of inertia of SD bands in ^{83}Sr are very sensitive to the number of particles in the high-N orbitals. For example, while the $\nu 5^3 \pi 5^1$ configuration ($\beta_2 \approx 0.57$, $\gamma \approx 0^\circ$) is predicted to have a nearly constant $J^{(2)}$ of $26\hbar^2$ MeV^{-1}, the moments of inertia of the $\nu 5^2 \pi 5^1$ configurations ($\beta_2 \approx 0.47$, $\gamma \approx 25^\circ$) show a rapid decline with increasing rotational frequency. The experimental $J^{(2)}$ values are in excellent agreement with the behavior of the $\nu 5^3 \pi 5^1$ band ($\beta_2 \approx 0.57$, $\gamma \approx 0^\circ$) which has positive parity and a signature quantum number of $+1/2$.

In summary, we have observed a cascade of ten γ rays that have a nearly constant energy difference of $\approx$150 keV and decay into several bands in ^{83}Sr at spin values of about $20\hbar$. The moment of inertia of this band, $J^{(2)} = 27\hbar$ MeV^{-1}, corresponds to that of a rigid rotor with a quadrupole deformation of $\beta_2 = 0.5$ and follows the trends of the $J^{(2)}$ values for the SD bands in other mass regions. The properties of this band are in excellent agreement with cranked Strutinsky calculations that had predicted the onset of superdeformation in ^{83}Sr and its neighbors at spins $I \approx 35\hbar$. These results provide the first evidence for the existence of a new region of high-spin superdeformation in medium-mass nuclei with particle numbers $N, Z \approx 40$. A systematic study of SD bands in this region would establish the details of the shell structure in medium-mass nuclei and would form an important test of theoretical models.

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