Relative Deformations of Superdeformed Bands in ^{131,132}Ce

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The quadrupole moments Q_0 of five superdeformed bands in ^{131,132}Ce have been established using the Doppler-shift attenuation method; for the first time, we can compare relative deformations of yrast and excited bands in different nuclei to an accuracy of $\simeq(5-7)\%$. Four of the five bands have very similar deformations, while the excited band in ^{131}Ce has a somewhat larger quadrupole moment. Important new information is presented on the shape-driving force of the $\nu i_{13/2}$ orbital, the stability of the second minimum with respect to particle excitations, the relative deformations of identical bands, the nature of the sidefeeding, and the time scale of the decay process. [S0031-9007(96)00148-2]

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Since the discovery of a discrete line superdeformed (SD) band in ^{132}Ce [1], several islands of superdeformation have been established across the chart of the nuclides [2]. These structures are associated with a second minimum in the potential-energy surface at large prolate deformation. The origin of these SD nuclei involves a delicate interplay between macroscopic properties such as the surface and Coulomb energy, quantal shell effects which reflect the symmetries of the deformed mean field, and the occupation of specific valence nucleon orbitals close to the Fermi surface. The quadrupole deformations of states in some of these bands have been determined through lifetime measurements and confirm their SD nature, but very little is known about the relative deformations of yrast and excited SD bands in the same, and neighboring, nuclei. (Note, the only cases of such measurements for excited SD bands are ^{192,194}Hg [3,4].) These differences should reflect the deformation-driving effects of specific configurations and the stability of the second minimum with respect to various nucleon excitations. This information is crucial in providing a stringent test of current theoretical models.

In this Letter we report on the results from a recent experiment aimed at determining the relative deformations of the known SD bands in ^{131,132}Ce [1,5–7]. From theoretical calculations [8], ^{132}Ce may be regarded as a superdeformed "core" nucleus with favorable shell closures in the single-particle spectra at $Z = 58$ and $N = 74$ for a quadrupole deformation of $\beta_2 \sim 0.35-0.40$ (corresponding to a major-to-minor axis ratio of roughly 3:2). The detailed behavior of the SD bands in the Ce isotopes is predicted to depend strongly on the occupancy of $N = 6$ neutron intruder orbitals which are thought to have a strong polarizing effect on the nuclear shape [8]. The yrast SD configuration in ^{132}Ce is thought to involve two $N = 6$ neutrons while that in ^{131}Ce is believed to involve only one. In addition to the yrast bands, excited SD structures have been observed in these nuclei: there is one excited band in ^{131}Ce and two excited SD bands in ^{132}Ce [6,7]. The accurate determination of the relative deformations of all five of these sequences provides new information on (i) the shape-driving effect of the $N = 6$ neutron intruder orbital, (ii) the stability of the second minimum, and (iii) a measure of the relative deformations of "identical" band pairs. As will be shown, we have determined the relative deformations of the bands to an accuracy of $\simeq(5-7)\%$, which represents a considerable improvement over most previous results [which typically had errors of $\sim(10-20)\%$]. This is the first time that such an accurate measurement has been made of the relative deformations of yrast and excited bands in more than one nucleus.

Superdeformed states in ^{131,132}Ce were populated via the ^{100}Mo(^{36}S, xn) reactions at a beam energy of 155 MeV. The target comprised a $\sim$600 μg/cm^2 ^{100}Mo foil evaporated on a 12 mg/cm^2 Au backing which slows down and stops the recoiling nuclei. The beam was provided by the 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory, and γ rays were detected by the Gammasphere array [9]. For this experiment the array had 55 large-volume HPGe detectors situated at the following angles, θ, relative to the beam axis: 3 at $\theta = 17.3°$, 5 at 31.7°, 5 at 37.4°, 3 at 50.1°, 1 at 58.3°, 1 at 79.2°, 6 at 90.0°, 1 at 100.8°, 5 at 121.7°, 10 at 129.9°, 5 at 142.6°, 5 at 148.3°, and 5 at 162.7°. A total of 9×10^8 events with a fold ≥ 5 was collected. It was found that the two dominant open channels were the $4n$ (^{132}Ce) and $5n$ (^{131}Ce) channels, and they were populated with a relative ratio of 3:2. The data were sorted off-line into a number of gated spectra which contained counts registered by particular angular groups of

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detectors. Specifically, for each band, gates were set on in-band transitions (see below) and events were incremented into separate spectra for events detected at (a) forward ($\theta < 90°$) angles, (b) backward ($\theta > 90°$) angles, and (c) each specific angle, θ. Examples of resulting spectra, after background subtraction, for the yrast band in ^{132}Ce are shown in Figs. 1(a) and 1(b). In this way, spectra were formed for all five known SD bands (two in ^{131}Ce and three in ^{132}Ce). (The energies for the bands in ^{132}Ce published in [7] are incorrect due to an error in calibration. The energies published in [6,10] correspond closely to those obtained in the present study.)

A Doppler-shift attenuation method (DSAM) centroid shift analysis was then performed [11]. The results from this standard method for relating decay time to recoil velocity have two severe limitations: (i) the electronic and particularly the nuclear stopping powers used to model the slowing down process are poorly known and result in large systematic errors [$\sim$(10–15)%] in the absolute values of Q_0; (ii) lifetimes of unobserved states feeding the in-band levels need to be accounted for in the calculation and introduce additional uncertainties in the final result.

We have overcome these limitations to a large degree. Since all the bands were populated simultaneously, and the nuclei are slowing down in the same target and backing, we can directly compare the experimental fractional Doppler shift, $F(\tau)$, curves [$F(\tau)$ is the ratio of the average recoil velocity at which a state decays to the average initial recoil velocity; τ is the lifetime of a given state] and extract information on the differences in deformation between the structures. Also, using gates above a state of interest significantly reduces the effect of the unknown sidefeeding on the lifetime of that state and the states lower in the cascade. This is only possible with the large statistics taken in this experiment.

The experimental $F(\tau)$ curves extracted for each of the bands are shown in Figs. 2(a)–2(c). Calculated $F(\tau)$ curves, assuming a rotational cascade with a constant quadrupole moment (6.4, 7.4, and 8.4 eb) and using the stopping powers of Ziegler, Biersack, and Littmark [12], are shown for comparison with the data. Table I(a) gives the quadrupole moments for each of the bands extracted through a χ^2-minimization fit of calculated curves to the data points. Note, these absolute values are subject to the large [(10–15)%] uncertainties introduced through the stopping powers.

Comparing the Q_0 values immediately allows several important points to be made. The yrast bands in ^{131}Ce and ^{132}Ce have very similar Q_0 values [see Fig. 2(a)] indicating that in this case the deformations of the two structures are very similar. [Note, the ^{131}Ce yrast band has three lower energy transitions at 591, 662, and 732 keV, and we find their respective $F(\tau)$ values to be 0.03(3), 0.18(3), and 0.37(2). The 662 and 732 keV lines are heavily contaminated in the spectra produced, and for the purpose of fitting and comparison, these data points were excluded.] This result is contrary to previous results [10,13–16] which indicate that the yrast band in ^{131}Ce has a lower deformation than the yrast band in ^{132}Ce. This can be seen in Table I(b) which presents the extracted quadrupole

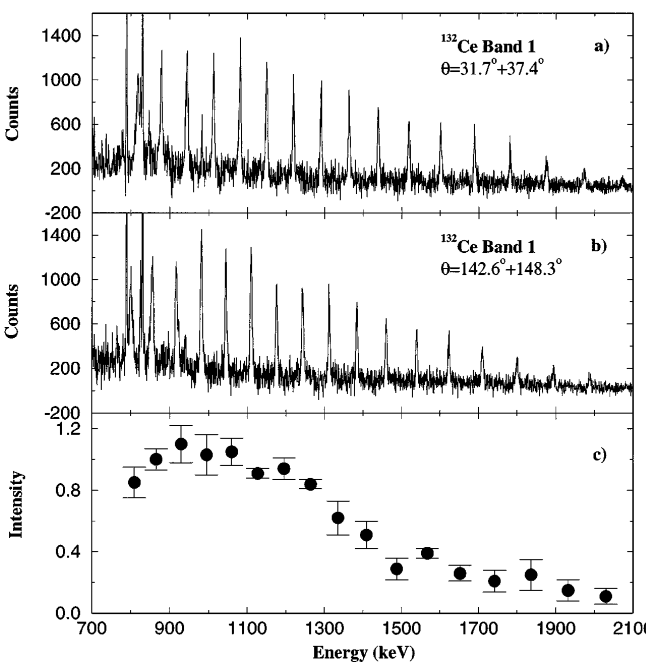

FIG. 1. Spectra obtained for (a) $\theta = 31.7° + 37.4°$ and (b) $\theta = 142.6° + 148.3°$, formed from combinations of all double gates on transitions above and including the 1197 keV γ ray for the yrast SD band in ^{132}Ce. The spectra were formed assuming that the recoils were fully stopped and the Doppler shift of superdeformed lines is clearly visible; (c) relative intensity profile of the band.

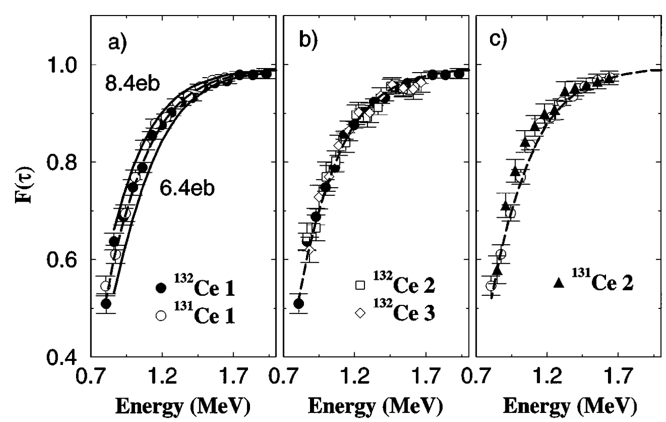

FIG. 2. Extracted $F(\tau)$ values for the five known SD bands in ^{131,132}Ce. The comparisons are (a) ^{131}Ce 1 (open circles) and ^{132}Ce 1 (closed circles); (b) ^{132}Ce 1 (closed circles), ^{132}Ce 2 (open squares), and ^{132}Ce 3 (open diamonds); (c) ^{131}Ce 1 (open circles) and ^{131}Ce 2 (closed triangles). The long-dashed line is a calculation for the ^{132}Ce yrast SD band assuming a Q_0 of 7.4 eb; it is shown in each part of the figure as a guide. The solid lines shown in (a) are calculated curves assuming a Q_0 of either 6.4 or 8.4 eb.

TABLE I. (a) The quadrupole moments Q_0 extracted in the present study for the five bands in ^{131,132}Ce; (b) the quadrupole moments extracted for the yrast bands in ^{131,132}Ce from previous studies. Note, all the absolute values quoted in this table are subject to a (10–15)% systematic error from uncertainties in the stopping powers—see text.

(a) Structure	Q_0 (e b)	(b) Structure	Q_0 (e b)	Reference
^{132}Ce 1	7.4(3)	^{132}Ce 1	8.8(8)	[10]
^{132}Ce 2	7.3(4)	^{132}Ce 1	7.5(6)[a]	[15]
^{132}Ce 3	7.6(4)	^{132}Ce 1	≃7.1	[16]
^{131}Ce 1	7.4(3)	^{131}Ce 1	≃6.0	[13]
^{131}Ce 2	8.5(4)	^{131}Ce 1	5.5(5)	[14]
		^{131}Ce 1	≃6.4	[16]

[a]This result came from a reanalysis of the data described in [10] and did not come from an independent experiment.

moments Q_0 from each of the prior experiments. It has been suggested that the additional $N = 6$ neutron in the yrast SD configuration of ^{132}Ce compared with ^{131}Ce (see above) has a strong polarizing effect on the nuclear shape and pulls the nucleus to a higher deformation. Moreover, cranked Woods-Saxon total Routhian surface calculations [8] predict a difference in deformation, and consequently in Q_0, of ~10% between the two yrast structures. Two possible scenarios can explain our new results: (i) the polarizing effect of the $N = 6$ neutron on the core is much smaller than previously thought or (ii) the configurations of the yrast bands, in fact, contain the same number of $N = 6$ neutrons. We favor the first explanation since it becomes difficult to reconcile the second scenario with other features of the bands such as the differences in the shapes and magnitudes of their $\Im^{(2)}$ values.

Figure 2(b) shows the experimental $F(\tau)$ curves for the yrast and two excited bands in ^{132}Ce. Once again we find that there is no significant difference, implying that the deformations are very similar. This result indicates that the second minimum in ^{132}Ce is stable in the presence of the various excitations responsible for the excited SD bands. Note, no firm configuration assignments to these excited structures have been made, but possible excitations include a promotion of a neutron from either the $[411]1/2(\alpha = +1/2)$ or $[523]7/2(\alpha = \pm 1/2)$ levels to either the $[530]1/2(\alpha = \pm 1/2)$ or $[651]3/2(\alpha = +1/2)$ states [7].

The one band that remains to be discussed is the excited band in ^{131}Ce. The most plausible excitation responsible for this band is considered [6] to involve the promotion of a neutron from the $[411]1/2(\alpha = +1/2)$ orbital to the $[660]1/2(\alpha = -1/2)$ orbital. It is clear from Fig. 2(c) that the $F(\tau)$ values extracted for this band lie considerably higher than those for any of the other four sequences. In fact, we extract a quadrupole moment that is roughly 15% higher than that for the yrast band in ^{131}Ce: 8.5(4) compared with 7.4(3) e b, respectively. It should be noted that this band also has a different feeding profile from any of the other structures. It is fed very rapidly over the topmost two or three states and retains 100% of its flux over a much longer spin range than any of the other bands. As yet we have no explanation for this behavior. A similar situation is encountered for two of the excited bands in ^{133}Pr [17], and it will be instructive to see if these bands have higher deformations than the yrast band.

Several pairs of "identicality" relationships have been suggested between the bands we observe [7]. Here identical means that a band has transition energies that lie at the half, quarter, three-quarter points, or are exactly the same as those of some other reference band. It is interesting to note that the bands in the suggested relationships all have similar deformations with the one exception: band 2 in ^{131}Ce lies close to the 3/4 points of band 1 in ^{132}Ce. It is difficult to understand how an identical pair of bands can have different deformations without invoking an extremely subtle, compensating interplay between the change in deformation and differences in, for instance, pairing strength.

Identical bands necessarily have very similar dynamic moments of inertia, since $\Im^{(2)}$ is inversely proportional to the γ-ray energy spacing. $\Im^{(2)}$ is dependent on several factors, namely, the nuclear deformation, the strength of pairing correlations, and particle alignments. It is clear from the discussion above that SD bands in the $A \sim 130$ region with similar $\Im^{(2)}$ values need not necessarily have similar deformations. However, we also find that bands with $\Im^{(2)}$ of differing magnitude can have extremely similar deformations. For example, the $\Im^{(2)}$ of the ^{131}Ce yrast band is lower in magnitude by ≈10% over the entire observed range when compared with that of the ^{132}Ce yrast band and yet, as we have shown, the two bands have similar Q_0 values. The very important point that needs to be made is that the relative behavior of the $\Im^{(2)}$ is not a good indication of variations in deformation.

An aim in the present study was to substantially reduce the effects of unknown sidefeeding in extracting the $F(\tau)$ ratios by gating above the transitions which are sensitive to changes in the quadrupole moment. It is also possible to extract $F(\tau)$ values when the sidefeeding is allowed to take full effect. Comparing the two sets of results allows one to deduce information on the magnitude and nature of the sidefeeding. To do this, spectra for the two yrast bands were formed using gates placed on in-band transitions above (gated high) or below (gated low) ~1150 keV. Note, these two bands have similar intensity profiles indicating that they are fed over similar ranges of rotational frequency. Most of the sidefeeding into the yrast bands occurs in the region of the bands with transition energies above 1150 keV [see Fig. 1(c)]. For spectra formed with gates set above 1150 keV (gated high) the effect of sidefeeding is much reduced for states lower in the cascade. For spectra formed using gates below 1150 keV (gated low) the sidefeeding is allowed to take full effect. Figure 3 shows the resultant $F(\tau)$ values extracted with full sidefeeding and reduced sidefeeding. The effect of the

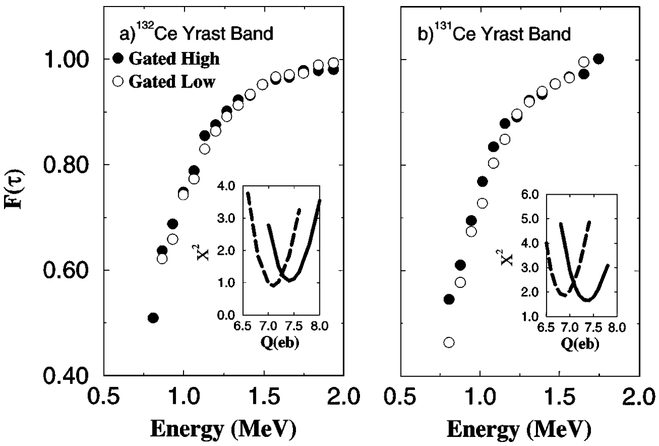

FIG. 3. $F(\tau)$ values extracted from spectra formed by gating on transitions above 1150 keV ("gated high," closed circles) and below 1150 keV ("gated low," open circles) for (a) ^{132}Ce yrast band; (b) ^{131}Ce yrast band. The insets show the χ^2 fit of the calculated quadrupole moments for the $F(\tau)$ points determined from spectra either gated high (solid curves) or gated low (dashed curves) if no account is taken of differences in sidefeeding.

sidefeeding seems to be greater for the ^{131}Ce yrast band, and the result is to lower the extracted $F(\tau)$ over the region where we are sensitive to such differences. Consequently, we can conclude that if the sidefeeding is not taken account of correctly, the extracted Q_0 will be lower than the true value. We found the difference in the curves to correspond to a change in Q_0 of roughly 10% [6.7(3) compared with 7.4(3) eb]. We estimate that this change in Q_0 implies that the sidefeeding is ~1.5 times slower than the in-band feeding. The effect seems to be much less for the ^{132}Ce SD yrast band [Q_0 lowered from 7.4(3) to 7.1(3) eb which is consistent with no change—see Fig. 3(a)]. The transition rate into the bands is dependent upon the collectivity and the relative excitation energy of the unseen sidefeeding states. From the present information we are unable to precisely determine the cause of the apparent slower sidefeeding into the ^{131}Ce yrast SD band.

Finally, an important point can be made concerning the mechanism of decay for the ^{132}Ce yrast SD band. Since this is the strongest band in the data, we have looked carefully for information on the decay process. To date, no linking transitions have been identified. However, we can clearly see all transitions in the normal deformed yrast band up to and including the 822 keV ($18^+ \rightarrow 16^+$) γ ray, and no evidence for the 936 keV ($20^+ \rightarrow 18^+$) yrast line can be found. No spectrum could be found in which the 822 keV line showed some Doppler shift; i.e., the 822 keV line was at its fully stopped position in all spectra produced under a wide variety of gating conditions. However, the lowest transition in the SD band decays with approximately half the initial recoil velocity [$F(\tau) = 0.51(2)$]. We estimate that it would take about 1 ps, from this point, for the nucleus to fully stop. This implies that the decay from the second well to the first well for ^{132}Ce takes $\geq$1 ps; if it were much shorter we should expect to see some Doppler shift of the 822 keV line.

In summary, we have extracted the relative deformations of five SD bands in ^{131,132}Ce to an accuracy of $\simeq(5-7)\%$. We find that the yrast bands in these two nuclei have very similar deformations implying that the shape-driving force of the $N = 6$ neutron orbital is less than previously thought. The yrast and excited bands in ^{132}Ce have very similar deformations indicating that the second minimum is stable to the excitations responsible for these excited bands. The excited band in ^{131}Ce has a significantly larger deduced Q_0 than any of the other bands. Information on the effect and nature of sidefeeding has also been extracted. We find that there is a significant slow sidefeeding component for the yrast band in ^{131}Ce.

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