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Lifetime measurements of a triaxial band in ^{133}Ce

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Lifetimes of states within a triaxial band belonging to the γ-soft nucleus ^{133}Ce have been determined through a Doppler-broadened line shape analysis. A value, $Q_t \approx 2.2$ e b, has been found for the transition quadrupole moment which is considerably smaller than that of superdeformed structures ($Q_t \approx 7.4$ e b) in this mass region. The results are discussed in terms of deformation self-consistent calculations based on the total Routhian surface formalism. [S0556-2813(98)01912-8]

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In recent years there has been great interest in the origin of stable nuclear deformations in axially symmetric nuclei at high spin due to the role of specific single-particle orbits at the Fermi surface [1]. It is also apparent that the relative position of the Fermi surface within a high-j subshell can produce significant differences in nuclear deformation properties [2]. A particularly interesting scenario occurs when the occupation of shape-driving orbitals at the Fermi surface removes axial symmetry and forces the nucleus to adopt a triaxial shape. This is particularly so for rare-earth nuclei in the $A \sim 130$ region which exhibit a softness to γ, the triaxiality coordinate in the polar description of rotating quadrupole shapes [3]. The recent observation of triaxial band structures in ^{133}Ce [4] includes a relatively strongly populated band that extends to high spin but possesses a lower dynamic moment of inertia, $\mathcal{I}^{(2)}$, than the known superdeformed (SD) bands [5] which coexist across the same frequency and spin range. The structure has been interpreted as a negative-parity configuration involving rotationally aligned neutrons from the upper $\nu h_{11/2}$ midshell and possessing a considerable triaxial deformation ($\gamma = -83°$ in the Lund convention [6]). This paper documents new information on (i) the lifetimes of in-band and side-feeding states, (ii) the transition quadrupole moment of this band, and (iii) the relative deformations of coexisting nuclear shapes at high spin.

The experiment was performed at the Lawrence Berkeley National Laboratory using the Gammasphere γ-ray spectrometer [7]. High-spin states in $A \sim 132$ cerium isotopes were populated with the ^{100}Mo(^{36}S,xn)$^{136-x}$Ce fusion-evaporation reaction. Experimental details are given in Ref. [8]. Approximately 9×10^8 fold $\geqslant 5$ prompt coincidence events were recorded over 5 days.

In order to study ^{133}Ce, the data were sorted off line into $E_{\gamma1}$-$E_{\gamma2}$ coincidence matrices gated on the 422, 488, 643, and 888 keV in-band transitions. The population intensities, estimated by comparing the intensities of low-lying normally deformed transitions in an ungated matrix, reveal that ^{132}Ce ($4n$) and ^{131}Ce ($5n$) are the strongest reaction channels while the $3n$ channel producing ^{133}Ce was relatively weaker. The measured relative population ratios were 5:4:1 for ^{132}Ce, ^{131}Ce, and ^{133}Ce, respectively. Coincidences with in-band transitions were projected into spectra defined by particular angular groups of detectors. Specifically, spectra were produced from detectors at (a) forward angles (31.7° + 37.4°), (b) 90.0°, and (c) backward angles (142.6° + 148.3°).

The Doppler shift attenuation method (DSAM) was used to determine the mean level lifetimes of the triaxial band by Doppler-broadened line shape (DBLS) analysis [9]. A γ ray that is emitted while the nucleus is slowing down will possess a broadened line shape as a consequence of the Doppler effect. The magnitude of the shift depends on the lifetimes of the band member and of the observed and unobserved transitions feeding that state. The analysis of the data was carried out using the computer program LINESHAPE [10]. The program employs Monte Carlo techniques based on the formalism of Currie [11] to simulate the velocity and directional history of recoils formed at various positions in the target and backing. It should be noted that the Monte Carlo technique can trace both the scattering directions and low recoil velocities due to nuclear stopping. Five thousand recoil histories were generated at a time step of 0.001 ps and converted into time-dependent velocity profiles for particular angular configurations of detectors. The electronic and nuclear components of the slowing-down process have been modeled using the stopping powers of Ziegler [12] and Monte Carlo methods, respectively. Spectra were obtained by summing gates on the clean lower-energy transitions of the triaxial band in ^{133}Ce (422, 488, 643, 888 keV). The side feeding intensities for the band were determined by using the relative

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TABLE I. Summary of results for transition quadrupole moments (Q_t) and mean lifetimes (τ) for high-spin states in ^{133}Ce.

$I_i^\pi \rightarrow I_f^\pi$	E_γ (keV)	Q_t (e b)	τ (ps)	τ_{SF} (ps)
$(43/2^- \rightarrow 39/2^-)$	887.4	1.94 ± 0.10	1.11 ± 0.13	0.48 ± 0.11
$(47/2^- \rightarrow 43/2^-)$	999.3	2.65 ± 0.16	0.33 ± 0.04	0.49 ± 0.01
$(51/2^- \rightarrow 47/2^-)$	1097.6	2.66 ± 0.21	0.20 ± 0.02	0.37 ± 0.04
$(55/2^- \rightarrow 51/2^-)$	1188.1	2.15 ± 0.15	0.21 ± 0.02	0.34 ± 0.04

intensities of in-band transitions extracted from this data set. The values determined agreed with those extracted from thin target data [4]. This results in the side-feeding intensities being fixed parameters in the program. The side-feeding has been modeled as a five-state rotational band with a fixed moment of inertia of $48\hbar^2$ MeV^{-1} (estimated from an average of the experimental values for in-band transitions). The LINESHAPE program treats the transition quadrupole moment Q_t, side-feeding quadrupole moment Q_{SF}, intensities of contaminant peaks, and various background and normalization factors as variables in the fit. Spectra for forward angles, backward angles, and 90° were fitted simultaneously. The best fit was obtained through the least-squares minimization procedures SEEK, SIMPLEX, and MIGRAD outlined in [10]. Errors in the fitted quantities were found using the MINOS routine. A minimum acceptable error limit has been set at 8% of the measured values and MINOS errors lower than this limit have been adjusted upwards as prescribed in [13].

The mean lifetimes extracted from the line shapes can be used to determine the transition strengths $[T(E2)]$ and electric quadrupole moments (Q_t) through the equation

$$T(E2;I \rightarrow I-2) = 1.224 \times 10^{12} E_\gamma^5 \langle I020|I-20\rangle^2 Q_t^2, \quad (1)$$

where E_γ is the γ-ray transition energy in MeV, Q_t is in (e b), and the term in the angular brackets is a Clebsch-Gordan coefficient. The unobserved side-feeding bands that feed into the modeled rotational band have their energies estimated by using the expression

$$E_\gamma(SF) = \frac{\hbar^2(4I-2)}{2\mathcal{I}_{\mathrm{SF}}}, \quad (2)$$

where the moment of inertia $\mathcal{I}_{\mathrm{SF}}$ has been assumed to be constant at $48\hbar^2$ MeV^{-1} as stated earlier. The spins of both the side-feeding and triaxial bands are also estimated, as no linking transitions to the known low-lying bands have yet been found. Side-feeding energies calculated from Eq. (2) were used to estimate the side-feeding lifetimes from the fitted Q_{SF} values. Results of the analysis are given in Table I, and line shape fits for the 999.3 and 1097.6 keV transitions are illustrated in Fig. 1.

The results show that the triaxial band is formed by a low deformation rotor with a mean quadrupole moment of approximately 2.2 e b. Figure 2 shows the variation of Q_t as a function of estimated angular momentum. It can be seen that the transition quadrupole moment of the triaxial band, Q_t, is fairly constant with increasing spin, and a weighted average value $Q_t = 2.2 \pm 0.1$ e b is found.

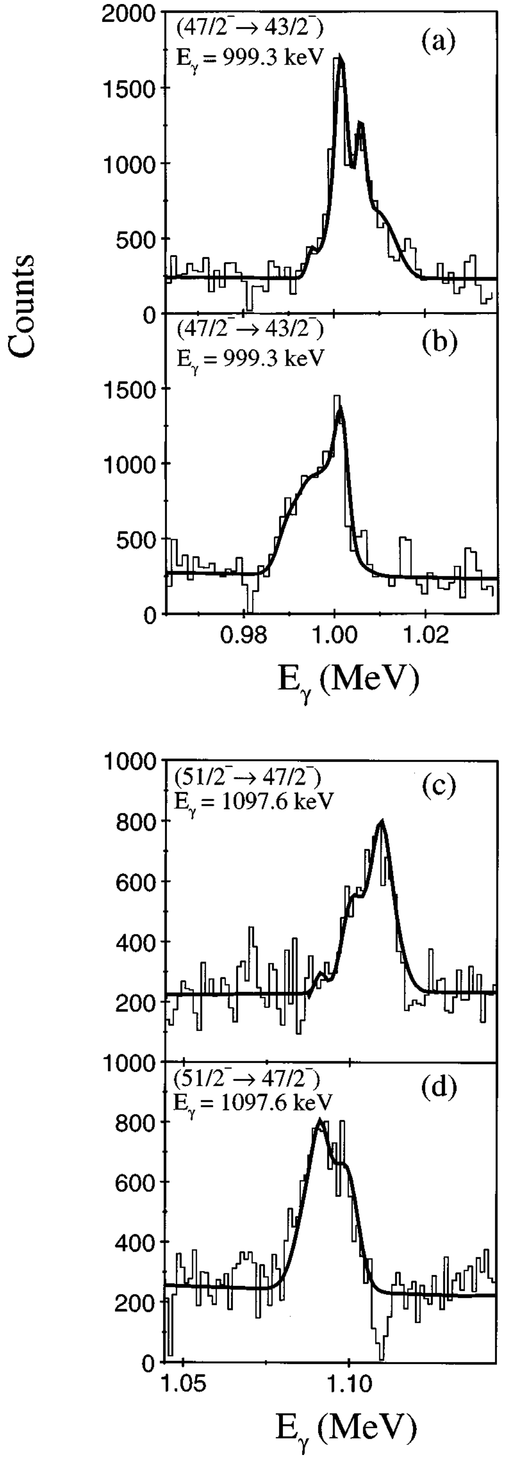

FIG. 1. Fitted line shapes for the 999.3 keV and 1097.6 keV transitions in ^{133}Ce. (a) and (c) display the forward angle spectra for the two transitions and (b) and (d) display the backward angle spectra. The solid line displays the total fitted line shape.

Deformation self-consistent Woods-Saxon cranking calculations, based on the total Routhian surface (TRS) formalism [1,14,15], have been performed for various quasiparticle configurations in ^{133}Ce. The negative-parity one-quasineutron $\nu h_{11/2}$ bands are predicted to possess triaxial shapes lying midway between the collective prolate and oblate axes with deformation parameters $\beta_2 \approx 0.19$ and $\gamma = -30°$. Calculations predict that another minimum in the potential energy surface is formed at a notably larger γ deformation ($\gamma = -73°$), displayed in the TRS contour map in

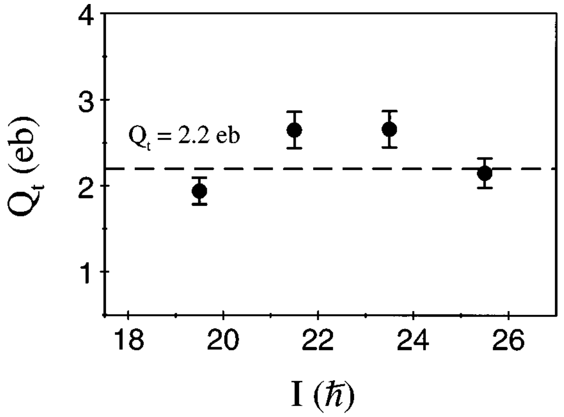

FIG. 2. Variation of transition quadrupole moments as a function of assumed spin for the triaxial band in ^{133}Ce.

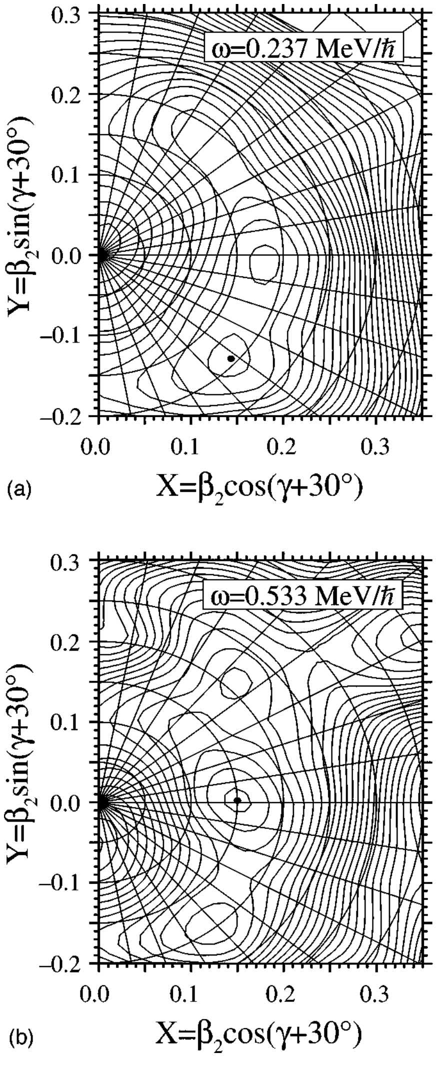

FIG. 3. Total Routhian surfaces for parity and signature $(\pi,\alpha)=(-,-1/2)$. (a) displays the triaxial minimum at low rotational frequencies ($\gamma=-73°$) associated with the $(\nu h_{11/2})^3$ configuration (solid circle) while another minimum occurs at $\gamma\approx-30°$ associated with the single $\nu h_{11/2}$ configuration. In (b) a number of coexisting minima are evident including the triaxial $\gamma=-83°$ minimum and a prolate superdeformed minimum at $\beta_2\approx0.4$.

TABLE II. Comparison of experimental Q_t values for rotational bands in ^{132,133}Ce. In extracting the β_2 values, theoretical γ values have been used.

Band	Q_t (e b)	β_2	γ	Reference
^{133}Ce triaxial band	2.2 ± 0.1	0.186 ± 0.007	$-83°$	Present work
^{132}Ce SD band 1	7.4 ± 0.3	0.411 ± 0.021	0°	Present work
^{133}Ce triaxial band	≈2.3	≈0.180	$-80°$	[19]
^{132}Ce SD band 1	7.4 ± 0.9	0.411 ± 0.045	0°	[18]
^{133}Ce SD band 1	7.4 ± 0.7	0.409 ± 0.040	0°	[18]
^{133}Ce SD band 2	7.5 ± 0.8	0.414 ± 0.040	0°	[18]

Fig. 3(a), and is based on a $(\nu h_{11/2})^3$ three-quasineutron configuration.

For nonaxial shapes, Q_t is related to the intrinsic quadrupole moment Q_{20} by the equation [16]

$$Q_t=Q_{20}\frac{\cos(\gamma+30°)}{\cos 30°}. \tag{3}$$

Assuming $\gamma=-83°$ and using $Q_t=2.2\pm0.1$ e b, the above equation yields $Q_{20}=3.2\pm0.1$ e b and corresponds to a

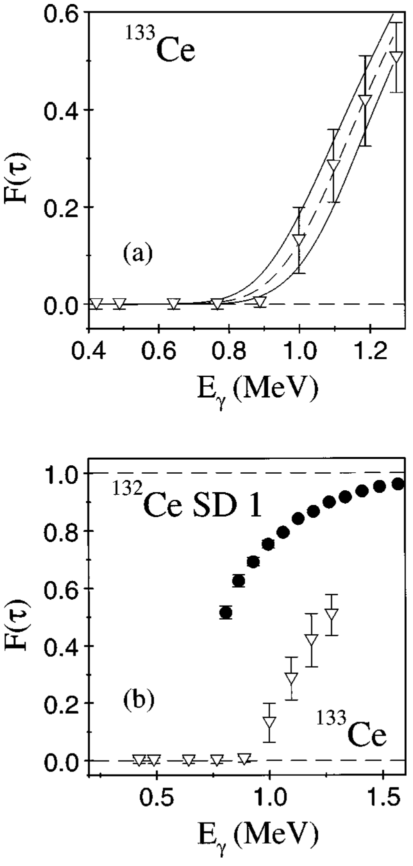

FIG. 4. (a) $F(\tau)$ curve for the ^{133}Ce triaxial band. The dashed line is the calculated curve for $Q_t=2.0$ e b and the solid lines for comparison above or below are calculated for $Q_t=2.2$ and 1.8 e b, respectively. Note that the top state has a slightly lower $F(\tau)$ value than the calculated curve. This possibly reflects an effective lifetime value that includes side-feeding contributions enhanced by gating on the lower in-band transitions. (b) Comparison of centroid-shift measurements between the ^{133}Ce triaxial band (open triangles) and superdeformed band 1 in ^{132}Ce (solid circles).

quadrupole deformation $\beta_2 = 0.186 \pm 0.007$; the β_2 value was obtained from the expansion of Q_{20} in terms of β_2 given in [17] assuming no hexadecapole deformation. This is in agreement with the TRS calculations of Fig. 3(b). The extracted mean value of $Q_t = 2.2$ is considerably lower than the measured quadrupole moments of the superdeformed bands in this nucleus ($Q_t \approx 7.5$ *e* b). Figure 3(b) displays the potential energy surface for negative-parity structures at higher spin. Several coexisting minima can be observed in Fig. 3(b) including the $\gamma = -83°$ triaxial minimum and a superdeformed prolate minimum ($\beta_2 \sim 0.4$) that is lowered in energy at higher spin. The three known superdeformed bands in ^{133}Ce [5] are much less intense than the triaxial band in these data and are not observed in this experiment due to the weaker nature of this particular reaction channel. However, previous lifetime measurements of SD bands in ^{132,133}Ce, based upon target-thickness-induced Doppler broadening [18], have indicated that the excited SD bands in ^{133}Ce possess similar quadrupole moments to the yrast SD band in ^{132}Ce. Table II compares our deformation measurements for rotational bands in ^{132,133}Ce with prior experiments. The yrast band in ^{132}Ce is intensely populated in this data set and the similar nature of the quadrupole moments of these bands allows a direct comparison to be made between highly deformed prolate bands and the much less deformed triaxial structure. Since both structures are populated concurrently and recoil with the same stopping conditions, we can directly contrast the deformation measurements and obtain a good relative deformation comparison. Note that the absolute Q_t values have large uncertainties at the $\approx 10-15\%$ level that arise due to poor knowledge of the recoil stopping in the target foils. Experimental $F(\tau)$ curves which have been obtained from centroid-shift measurements are shown in Fig. 4. The results of Fig. 4(b) clearly display the difference in Q_t values for the triaxial band and the superdeformed band in ^{132}Ce. The present centroid-shift measurements for the ^{133}Ce triaxial band are consistent within experimental errors with a previous centroid-shift measurement performed by Nyberg *et al.* who obtained $Q_t \approx 2.3$ *e* b [19].

The mean lifetimes τ of the in-band transitions also show marked differences between the triaxial and superdeformed bands. Transition strengths $[T(E2)]$, obtained using the experimental lifetimes and Weisskopf estimates, were found to be $T(E2) \approx 35$ Weisskopf units (W.u.) which are lower than those derived for the yrast SD band in ^{132}Ce where the values are typically ≈ 490 W.u. A further comparison can be made with the normally deformed ground-state band in ^{132}Ce that is known to have transition strengths of the order of $T(E2) \approx 100$ W.u. [20]. This implies that the degree of collectivity is even lower in the triaxial structure than in normally deformed prolate shapes. This is entirely consistent with TRS calculations which suggest that the minimum in which the band is formed lies between the noncollective prolate ($\gamma = -120°$) and collective oblate ($\gamma = -60°$) axes. Note that a recent recoil-distance Doppler shift experiment has measured the lifetimes for the low-spin $\nu h_{11/2}$ band in ^{133}Ce and deduced transition strengths at the $T(E2) \approx 50$ W.u. level [21]. This band is associated with the minimum at $\beta_2 \approx 0.19$, $\gamma \approx -30°$ in Fig. 3(a).

In summary, the mean lifetimes of a triaxial band in ^{133}Ce have been measured and transition quadrupole moments deduced. The band is formed by a rotating triaxial shape at large γ deformation and possesses a transition quadrupole moment Q_t of average value 2.2 *e* b.

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