Observation of Excited Superdeformed Bands in ^{132}Ce and Evidence for Identical Bands in the Mass 130 Region

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Two excited superdeformed (SD) bands have been observed in ^{132}Ce using the Eurogam gamma-ray spectrometer. Possible configurations are proposed in terms of particle-hole excitation from a theoretical analysis based on the cranking approximation with the Woods-Saxon deformed potential. From relationships between γ-ray energies of SD bands in ^{132}Ce and ^{131}Ce, the existence of identical bands and approximately quantized alignments is established in the mass 130 region.

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The first collective band associated with large prolate deformation was discovered in ^{132}Ce [1]. Later, superdeformed (SD) bands were found in $A \approx 150$ [2] and $A \approx 190$ [3] mass regions. These strongly deformed high-spin structures are usually associated with secondary minima in the potential energy surfaces at high angular momentum which, in the mass 130 region, correspond to a quadrupole deformation $\beta_2 \approx 0.40$, deduced from mean-lifetime measurements [4]. In the $A \approx 150$ and 190 nuclei, the deformations are somewhat larger with $\beta_2 \approx 0.45$–0.6. These systematic shape differences can be attributed to the pseudo-SU(3) symmetry of the nuclear field [5], which implies that, in nuclei around ^{132}Ce, the SD bands result mainly from the effects of $i_{13/2}$ neutron intruders which lower the $\beta_2 \approx 0.40$ SD minimum to the yrast position at relatively low spins [6,7].

Another special property of nuclei around ^{132}Ce is the relatively high population of the SD structures. Indeed, the intensity of the SD bands in the $A \approx 130$ mass region can reach 5%–10% of the $2^+ \rightarrow 0^+$ transition in the corresponding reaction channel while it is only about 1%–2% for the higher-mass regions. It was therefore particularly striking that, prior to the present experiments with the new generation of large γ-ray detector arrays, no excited SD band had been identified in the $A \approx 130$ nuclei while numerous such bands were found in the other regions. A further difference between SD nuclei in the $A \approx 150$ and 190 regions and those around $A \approx 130$ was the absence of identical bands in the latter. The present Letter reports on the observation of two excited SD bands in ^{132}Ce. In parallel to our investigation, a single excited SD band has recently been found in the isotone ^{134}Nd [8]. In this Letter we also report on the first evidence of "identical" SD bands in the mass 130 region.

The nucleus ^{132}Ce was produced in the ^{100}Mo(^{36}S$,4n$) reaction at the Nuclear Structure Facility at Daresbury. A 155 MeV ^{36}S beam was used to bombard a self-supporting ^{100}Mo target of 625 $\mu g/\mathrm{cm}^2$ thickness. The γ rays were detected by 42 Compton-suppressed detectors of the Eurogam (phase I) array. Only events with unsuppressed fold greater than or equal to 7, corresponding to a suppressed fold distribution peaked between 3 and 4, were registered. A total of 7×10^8 events, 84% with suppressed fold ≥ 3, were recorded. Several methods were employed for data analysis. A systematic search for SD correlations was mainly carried out on conditioned matrices. Special algorithms [9] were used for setting gates on both SD transitions and known transitions deexciting normal deformed (ND) states. An analysis has been performed to assign the new band to ^{132}Ce, whereby we require m SD transition energies ($m = 2, 3$) and n known ND transition energies ($n = 1, 2$) simultaneously in a list of transitions (i.e., m-n = 2-1, 2-2, 3-1). In this way the newly observed SD lines survived only when they were in coincidence with the n lines in ^{132}Ce. Event by event single gates were used for relative intensity determinations of the different bands to avoid distortions in the unfolding coincidences from multiplicity differences.

The yrast SD band, denoted ^{132}Ce(yr), was populated with an intensity of 5.5% relative to the yield in the ^{132}Ce channel. This band has been extended towards higher spins by two additional transitions (2.115 and

2.199 MeV). These establish the yrast SD cascade over a range of 28.2 MeV excitation energy and up to $I \approx 60\hbar$. Two excited SD bands have been identified (Fig. 1): one, denoted ^{132}Ce(2), is composed of 13 transitions ranging from 794 to 1687 keV and the other [^{132}Ce(3)] of 12 transitions from 947 to 1725 keV. Their intensities each correspond to $\approx 1\%$ of the ^{132}Ce yield (Fig. 1).

In order to interpret the structure of the SD bands observed, a theoretical analysis has been made based on the cranking approximation with the Woods-Saxon deformed potential [10]. Our calculations for the ^{132}Ce yrast SD structure confirm the previous results obtained using similar techniques [6] and indicate that the deformation parameters are $\beta_2 \approx 0.40$, $\beta_4 \approx 0.015$, and $\gamma \approx 0°$. The structure of the band includes a pair of aligned $i_{13/2}$ neutrons. Because of the large gap in the single proton Routhians observed at $Z = 58$ [6], the first excited bands are expected to originate from neutron excitations. An inspection of the single neutron Routhians (labeled with $[Nn_z\Lambda]\Omega(\alpha =$ signature exponent$)$) as functions of the rotational frequency (Fig. 2) indicates that likely candidate configurations for these excited bands are rather numerous. Indeed, a promotion of a neutron from any of the following three orbitals, $\nu[411]1/2(\alpha = +1/2)$ and $\nu[523]7/2(\alpha = \pm 1/2)$, which are close lying at $\hbar\omega \approx 0.8$ MeV, to any of the three close lying orbitals $\nu[530]1/2(\alpha = \pm 1/2)$ and $\nu[651]3/2(\alpha = +1/2)$ will give comparable energy excitation and consequently, in principle, comparable population probabilities.

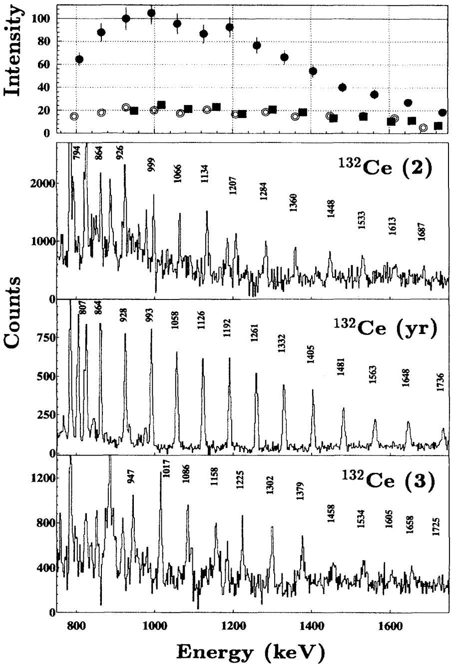

FIG. 1. Bottom: gated coincidence spectra with m-n = 2-1 (m SD transitions in the band and n known ND transitions, see text) for the two excited SD bands and m-n = 3-0 for the yrast SD band in ^{132}Ce. The γ–ray energies are labeled according to energy in keV. Top: absolute intensities of transitions in the yrast band (filled circles), ^{132}Ce(2) (open circles), and ^{132}Ce(3) (filled squares).

Among the configurations mentioned, a promotion of the $[411]1/2(\alpha = +1/2)$ neutron into the $[530]1/2(\alpha = -1/2)$ orbital seems probable from the energy point of view. Such a configuration could correspond to the ^{132}Ce(2) band as suggested by comparison of both the theoretical and experimental $\mathcal{J}^{(2)}$ dynamical moments (Fig. 3, top). Then, one expects a pair of close lying bands corresponding to the promotion of $[523]7/2(\alpha = \pm 1/2)$ neutrons into the $\alpha = +1/2$ signature member of the $[530]1/2$ orbital and, as a first hypothesis, one of them could be the ^{132}Ce(3) band. Let us examine this scenario in detail. Both excited bands exhibit experimental $\mathcal{J}^{(2)}$ moments whose global similarities are consistent with the signature partnership feature. The two configurations involving the $[523]7/2$ orbital are expected to have a low excitation energy and the agreement between their calculated and experimental $\mathcal{J}^{(2)}$ moments in this scenario is excellent if there is a small triaxiality of $\gamma = 10°$ included (Fig. 3, middle and bottom). The maxima of $\mathcal{J}^{(2)}$ visible at the highest rotational frequencies correspond to the $\Delta N = 2$ interaction between the $\nu[411]1/2(\alpha = +1/2)$ and $\nu[651]3/2(\alpha = +1/2)$ orbitals, the difference in β_2 deformation explaining the different positions of these maxima. A similar maximum corresponding to the excitation $\nu[411]1/2(\alpha = +1/2) \rightarrow [530]1/2(\alpha = -1/2)$ is caused at similar frequency range by the $\Delta N = 0$

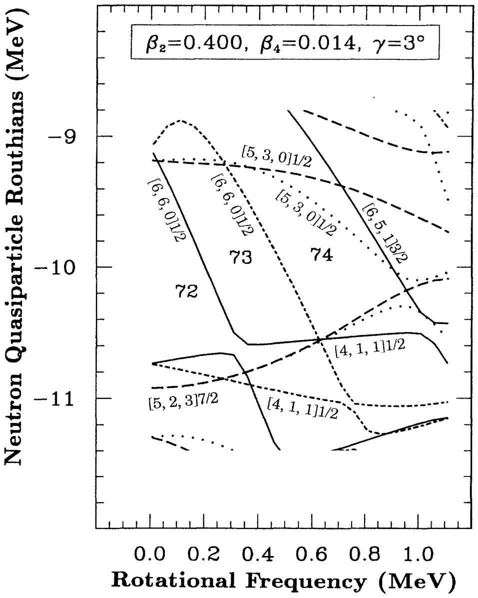

FIG. 2. Single neutron Routhians calculated at $\beta_2 = 0.41$, $\beta_4 = 0.014$, and $\gamma = 3°$. The following convention is used for the levels: ($\pi = +, \alpha = +1/2$) solid line, ($\pi = +, \alpha = -1/2$) short-dashed line, ($\pi = -, \alpha = +1/2$) long-dashed line, and ($\pi = -, \alpha = -1/2$) dotted line.

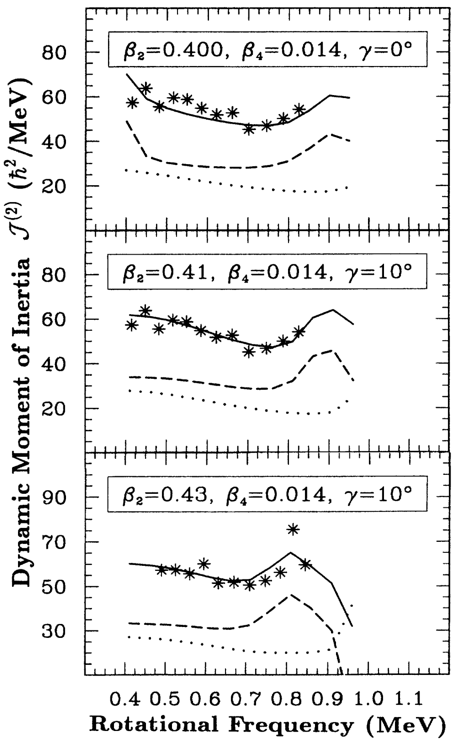

FIG. 3. Comparisons of experimental (asterisks) and calculated (full solid lines) $\mathcal{J}^{(2)}$ dynamical moments. The long-dashed (dotted) lines correspond to the neutron (proton) contribution in the calculated moments of inertia. Top: ^{132}Ce(2) compared to the excitation from [411]1/2($\alpha = +1/2$) to [530]1/2($\alpha = -1/2$) at $\gamma = 0°$. Middle: ^{132}Ce(2) compared to the excitation from [523]7/2($\alpha = +1/2$) to [530]1/2($\alpha = -1/2$) at $\gamma = 10°$. Bottom: ^{132}Ce(3) compared to the excitation from [523]7/2($\alpha = -1/2$) to [530]1/2($\alpha = -1/2$) at $\gamma = 10°$.

interaction between the ν[530]1/2($\alpha = -1/2$) and [523]7/2($\alpha = -1/2$) orbitals. However, the criterion based on $J^{(2)}$ moments of inertia does not offer an unquestionable confirmation of this partnership (see below).

Since we observed only two excited bands, the question arises about the population differences among the three bands in question at $\hbar\omega \approx 0.8$–0.9 MeV, i.e., at frequencies where the two observed bands are populated. The arguments formulated below and following from the analysis of the identical band mechanism imply that the ^{132}Ce(2) and ^{132}Ce(3) bands most likely are not strongly coupled signature partners. One sees in Fig. 2 that the lowest excitation energy at $\hbar\omega \approx 0.8$–0.9 MeV corresponds to the ν[523]7/2($\alpha = +1/2$) $\rightarrow$ [530]($\alpha = +1/2$) configuration and that the signature partner band with [523]7/2($\alpha = -1/2$) undergoes a crossing. This crossing implies that the corresponding excitation energy increases and the population probability decreases, thus offering a plausible scenario for populating the former band and not populating the latter, its signature partner.

The possibility that the [660]1/2($\alpha = -1/2$) neutron excitation (for example, towards the ν[530]1/2 orbitals) is present in the discovered band structures has also been investigated. The corresponding comparison of the calculated $J^{(2)}$ moments with the experimental data reveal pronounced disagreement and thus this configuration is considered as much less likely for the excited bands.

The first identical SD bands, characterized by γ rays having, on the average, energies identical within an accuracy of $\approx$(1 to 2):1000, have been reported for the $A \approx 150$ region [11]. In this Letter we present the first experimental evidence of the existence of such SD bands in the $A \approx 130$ region. Comparisons of the $J^{(2)}$ dynamical moments of SD bands in ^{131}Ce and ^{132}Ce, namely, the yrast bands ^{131}Ce(yr) [12], ^{132}Ce(yr), the two excited bands ^{132}Ce(2), ^{132}Ce(3), and the newly identified excited band ^{131}Ce(2) [13], indicate strong similarities between pairs of bands [14]. In the discussion we will refer to the twinning relationship $E_\gamma(I') = (1 - x)E_\gamma^{\text{ref}}(I) + xE_\gamma^{\text{ref}}(I + 2)$, with $x = 0, 1/2, 1/4$, and 3/4 which parametrizes, in the strong coupling asymptotic limit, the γ-ray energies in a given band relative to a reference band [15]. Because of peaks showing up in the experimental $J^{(2)}(\hbar\omega)$ curves (Fig. 3), comparisons related to the twinning relationship and involving the two excited SD bands in ^{132}Ce have to be limited to the $0.43 < \hbar\omega < 0.72$ MeV rotational frequency range. The bands ^{132}Ce(2) and ^{131}Ce(yr) (reference) satisfy the twinning relationship with $x = 3/4$ (Fig. 4), the mean value of the differences ΔE_γ between the γ-ray energies in ^{132}Ce(2) and those calculated from the reference ^{131}Ce(yr) being $\approx 2.5 \pm 2.0$ keV in the 0.46–0.68 MeV rotational frequency range. This identity between the two bands should be attributed to the nucleon whose excitation only slightly modifies the energy of the reference nucleus. Such an argument

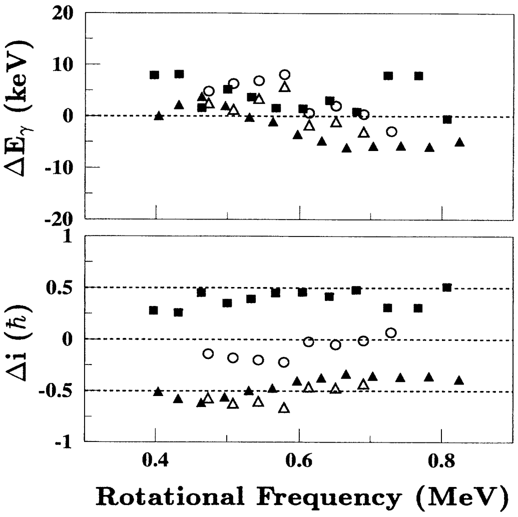

FIG. 4. ΔE_γ energy differences calculated for SD bands in ^{131}Ce and ^{132}Ce (upper part) and associated Δi incremental alignments (lower part). Filled squares are for ^{132}Ce(2) relative to ^{131}Ce(yr) ($x = 3/4$), filled triangles for ^{132}Ce(yr) relative to ^{131}Ce(2) ($x = 1/4$), open triangles for ^{132}Ce(3) relative to ^{132}Ce(2) ($x = 1/4$), and open circles for ^{132}Ce(3) relative to ^{131}Ce(yr) ($x = 0$).

favors the [411]1/2($\alpha = +1/2$) neutron orbital which is relatively flat as a function of the rotational frequency but does not exclude the [523]7/2 neutron orbitals which also have a small curvature and, in consequence, a nearly constant alignment at high rotational frequency. A correlation exists also between ^{132}Ce(3) and ^{131}Ce(yr) with $x = 0$ and a mean variation $\Delta E_\gamma \approx 3.3 \pm 2.0$ keV over seven transitions. The relationships between ^{132}Ce(2) and ^{131}Ce(yr), on the one hand, and ^{132}Ce(3) and ^{131}Ce(yr), on the other hand, imply that the bands ^{132}Ce(3) and ^{132}Ce(2) (reference) are related to $x = 1/4$ and suggest that they are not strongly coupled signature partners. Indeed, by considering a simple rotor energy expression $E(I) = aI(I + 1)$, we conclude after elementary calculation that, within the strong coupling limit, if a band A in a even-even nucleus is directly degenerate with a band B in the neighboring odd one, the signature partner of A must not produce either the (1/4,3/4) or the (3/4,1/4) degeneracy relation with band B.

An identity is also found between the bands ^{132}Ce(yr) and ^{131}Ce(2) which have the same $\mathcal{J}^{(2)}$ dynamical moments. Their γ-ray energies are correlated ($x = 1/4$) with a mean difference of $\approx -2.3 \pm 2.0$ keV for 13 transitions ranging from $\hbar\omega = 0.40$ to 0.82 MeV. Again this identity agrees with a possible configuration involving the [411]1/2($\alpha = +1/2$) orbital. Then, the excited band in ^{131}Ce could very likely originate from the [411]1/2($\alpha = +1/2$) to [523]7/2($\alpha = +1/2$) particle-hole excitation.

It has been shown that the incremental alignment for pairs of identical SD bands can be approximately quantized, i.e., expressed as a multiple of $0.5\hbar$ [16]. Such an observation applies also for the four pairs of SD bands discussed which are characterized by incremental alignments close to $+0.5, 0, -0.5$, and $+ 0.5\hbar$, respectively (Fig. 4).

The first observed identical SD bands [11] have been discussed in terms of the strong-coupling approach and pseudo-SU(3) symmetry [17]. Nucleonic configurations which satisfy the observed identities were attributed the values of the decoupling parameter $a = 0, +1$ corresponding to $x = 1/4$ and 3/4, and 0, respectively. For the Ce isotopes we consider, there is apparently no $[\tilde{N}\tilde{n}_z\tilde{\Lambda}]$ orbital in the pseudospin concept having decoupling parameters that could provide an analogy to the interpretation given in Ref. [17]. Indeed, as suggested in Ref. [18], because of the presence of two close lying $\Omega = 1/2$ orbitals there are cases poorly described by the asymptotic values of the decoupling parameters. This is the case for the [530]1/2 and [541]1/2 Nilsson neutron orbitals—whose pseudospin counterparts are $[\tilde{4}\tilde{4}\tilde{0}]1/2$ and $[\tilde{4}\tilde{3}\tilde{1}]1/2$, respectively—which are precisely involved in ^{131,132}Ce. The correlations shown in the Letter test these specific orbitals for the first time. It should be noted that a systematic search for identical bands at normal deformation in the $A \approx 130$ mass region [19] has shown the rareness of such correlations compared with the $A \approx 150, 190$ regions. This fact points yet to another difference between the $A \approx 130$ mass region and the higher mass regions where identical bands have been found.

In summary, two excited superdeformed bands have been identified in ^{132}Ce. Among the possible configurations of the neutron particle-hole excitation type, the most probable seem to be that from the [411]1/2($\alpha = +1/2$) and [523]7/2($\alpha = +1/2$) to the [530]1/2($\alpha = -1/2$) neutron orbitals. Furthermore, identical SD bands have been observed for the first time in the $A \approx 130$ mass region. However, puzzles still remain. To date a microscopic understanding of the identical band mechanism has been neither addressed nor achieved, however, the discovery of the presence of such bands in a new mass region is important to the investigation of the underlying mechanism of this striking feature of the nucleus.

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