Observation of an Intense Quasicontinuum of Superdeformed Rotational Transitions in ^{143}Eu

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Quasicontinuum spectra in coincidence with transitions belonging to the different potential wells of ^{143}Eu are studied with increasing number of coincidence folds. An intense bump of rotationally correlated transitions is observed to develop in the high spin region. Fold distributions, angular anisotropies, moment of inertia determinations, and lower limits of lifetimes as function of the rotational frequency show that the bump originates from highly collective rotationally damped $E2$ transitions generated by superdeformed states. [S0031-9007(96)00028-2]

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Since the first superdeformed (SD) band at high angular momentum was found about nine years ago [1], up to six SD excited bands have been identified in several nuclei [2]. This has given detailed insight into nuclear structure under influence of the very strong distortions of nucleonic orbital [3]. In a few cases a SD ridge structure has been observed in γ-γ coincidence spectra, over a rather narrow spin range and with an intensity only 3 times bigger than the full intensity of the SD yrast band [4]. It was recently shown by use of the fluctuation analysis method that the SD ridge in ^{143}Eu consists on average of 20 excited rotational bands, probably extending up to $\approx$1.6 MeV excitation energy above yrast [5].

Simulation calculations of the decay flow have been made earlier, based on the coupling between states in two different potentials, representing normally deformed (ND) and SD states in the nucleus ^{152}Dy [6–8]. They have indicated that fusion reactions could also populate SD states at several MeV above the SD yrast line. Rotational $E2$ transitions have been predicted from the SD decay at high excitation energy, with a much larger intensity than experimentally observed in the narrow ridge and in the discrete SD bands. In a similar way as in normally deformed nuclei, most of the rotational SD transitions emitted from excited states are expected to be damped [9], resulting in a strong fragmentation of the decay out of each state. In addition, due to the admixture with states in the normally deformed well, the SD rotational transitions in cascade may occasionally be intercepted by ND transitions [10]. Thus, the majority of such transitions should not display pure rotational energy correlations between successive decay steps, i.e., intense ridge structure in a γ-γ spectrum, but should rather generate a smooth bump of damped rotational transitions.

The present Letter reports experimental evidence for a strong rotational component of superdeformed $E2$ transitions emitted in the γ-ray cascades of ^{143}Eu at the highest spins. This nucleus is characterized by a very complex and irregular level scheme at low spin, due to the coexistence of both spherical and triaxially deformed shapes [11–13], while a strong SD minimum is expected to dominate at high angular momenta [14]. The population of the SD excited states should be particularly strong, since the crossing between the ND and SD yrast lines occurs already around angular momentum $I \approx 40\hbar$, compared to $I \approx 54\hbar$ in ^{152}Dy. This leaves $\approx$20 units of angular momentum available for a favorable population of the SD states in the quasicontinuum, between the fission cutoff at high spin and the enhanced mixing with normal states in the $I = 40\hbar$ region. This has given the opportunity to study experimentally for the first time the quasicontinuum in a SD nucleus up to several MeV of excitation energy above the SD yrast line.

The experiment was performed using the NORDBALL detector array equipped with 20 Compton-suppressed Ge detectors, one of which was a LEP detector, and a 53 elements BaF_2 scintillator ball. The nucleus ^{143}Eu was populated by the reaction ^{110}Pd(^{37}Cl,4n) ^{143}Eu at a beam energy of 160 MeV. Two separate experiments were performed, the first using a stack of 2–3 thin targets with a total thickness of 1.2 mg/cm^2 and the second using a target of 900 μg/cm^2 backed with 11 mg/cm^2 Au for the lifetime analysis. A total of 10^9 triple (or higherfold) and of 5×10^8 double coincidence events were collected, respectively. The spectra were cleaned from delayed γ rays and a significant fraction of neutron induced peaks by setting a narrow energy dependent time gate.

Figure 1(a) shows spectra obtained in coincidence with clean transitions from the low spin ND yrast lines in ^{143}Eu, for increasing values of folds as measured in the BaF_2 scintillator ball. The spectra have been unfolded with respect to the Ge detector response function, after a fraction of the total projection (nongated spectrum) has been subtracted as uncorrelated background, corresponding to an average value of the peak to total of the selected gates. Above 2.6 MeV (not shown in the figure) all spectra are found to be proportional to the function $E_\gamma^3 \exp(-E_\gamma/T)$, with the common effective temperature $T = 0.53$ MeV, corresponding mainly to the tail of a statistical $E1$ spectrum. The spectra are normalized to the common tail. The absolute normalization is defined by the spectrum at fold 15, which has the largest cross section and corresponds to an average multiplicity of 22. With increasing fold the edge of the bump extends towards high γ-ray energy, a behavior generally observed in well deformed rotational nuclei [15]. This points to the existence of a quasicontinuum of rotational $E2$ transitions in ^{143}Eu. In contrast, Fig. 1(b) shows similar spectra, but now gated by transitions originating from the triaxial minimum of ^{143}Eu, identified in Ref. [12]. The striking difference between the two sets of spectra suggests that the transitions in the moving bump originate from SD states, although no gates on the SD yrast band were used. In fact a moving bump should not be expected from ND spherical states and one does not observe it in coincidence with transitions in the more collective triaxial well. We also note from the fold distribution (by comparing $\langle F \rangle = 7$ and $F > 21$) that about half of the transitions at 1500 keV appear to belong to the moving bump, which makes it possible to study this quasicontinuum structure in more detail. However, due to the presence of strong transitions below 1300 keV, firm conclusions on the lower edge of the bump will be more difficult to reach.

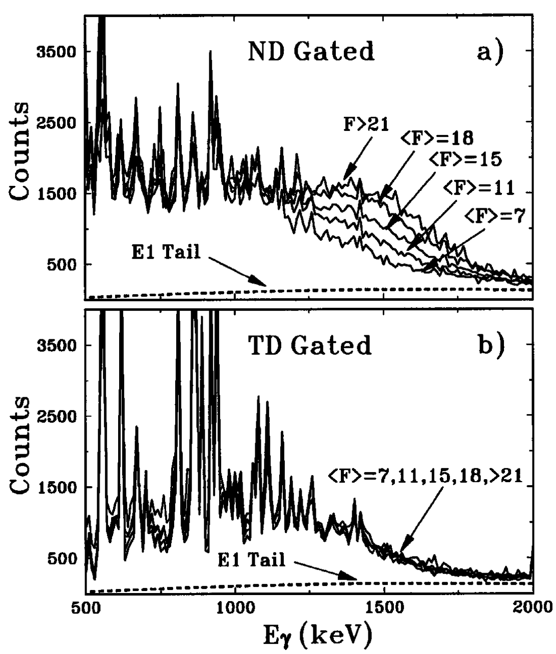

FIG. 1. (a) Unfolded Ge spectra in coincidence with the low-spin spherical (ND) yrast transitions 182, 385, 443, 533, 553, 668, 917, 1059, 1073, and 1152 keV of ^{143}Eu, for increasing values of folds measured by the BaF_2 scintillator ball. (b) Similar spectra now gated on the triaxially deformed (TD) transitions 548, 615, 853, 867, 884, and 936 keV in ^{143}Eu.

Three different analysis methods were used to investigate the nature of the continuum bump, namely, (i) angular anisotropy, (ii) effective moment of inertia determination, and (iii) lifetime analysis.

The angular anisotropy $R_\gamma = [W(37°) + W(143°)]/[W(79°) + W(101°)]$ is shown as filled circles in Fig. 2(a), for events gated on high BaF_2 fold (≥ 11) and in coincidence with transitions from the low lying ND spherical states of ^{143}Eu. The open circles show the values of R_γ obtained for the SD yrast band. Also given is the isotropic limit ($R_\gamma = 1$) expected in the region of the statistical $E1$ tail, where the spectra at different angles have been normalized ($E_\gamma > 2.6$ MeV). The data approach the value obtained for the SD transitions at ≈ 1.5 MeV, corresponding to the maximum of the bump [see Figs. 1(a) and 3]. Further, we estimate the anisotropy of the bump transitions, by extracting their intensity as a function of energy, relative to the background, which is assumed to be isotropic, consisting of statistical $E1$ transitions. The resulting anisotropy of bump transitions, marked as open squares in the figure, is ≈ 1.3 over the energy range 1.3–2.3 MeV of the bump, the same average value found for the purely stretched $E2$ transitions of the SD yrast band. This shows clearly that the continuum bump mainly consists of fully stretched rotational $E2$ transitions.

The degree of collectivity of the $E2$ bump has been estimated calculating the effective dynamic moment of inertia $I_{\rm eff}^{(2)}$, as well as the lifetime. The moment of inertia has been shown to be related to the height of the γ-ray spectrum, when normalized to the γ-ray multiplicity of the rotational decay [16]. After subtracting the statistical $E1$ component (calculated as described above) from the spectra shown in Fig. 1(a), the remaining spectra were corrected for the feeding, i.e., the fraction of the observed population which goes through a given γ-ray energy interval [17]. The moment of inertia $I_{\rm eff}^{(2)}$ calculated on the basis of the spectra corresponding to folds 15 and 18 in Fig. 1(a) is shown in Fig. 2(b) in comparison with the dynamic moment of inertia $I_{\rm SD}^{(2)}$ of the SD yrast line. It is noteworthy that $I_{\rm eff}^{(2)}$ approaches $I_{\rm SD}^{(2)}$ in the region where the $E2$ bump is dominating ($1350 \leq E_\gamma \leq 1750$ keV), while at lower transition energies a typical value of the dynamic moment of inertia corresponding to the ND spherical shape is observed. This suggests a strong collectivity of the transitions in the $E2$ bump,

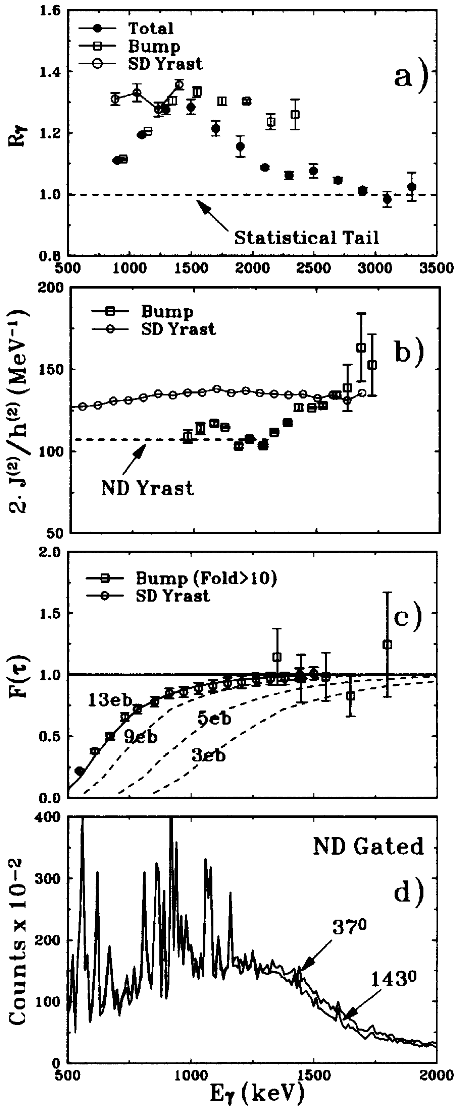

FIG. 2. The top part shows the anisotropy of the angular correlations for the total intensity spectrum (closed circles), the transitions in the moving bump (open squares), and the SD yrast band (open circles). The effective moment of inertia $I^{(2)}_{\rm eff}$ of the bump and the dynamical moment of inertia $I^{(2)}_{\rm SD}$ of the SD yrast band are shown in part (b). (d) The spectra obtained in forward and backward angles (as marked) in the experiment with Au backed target, gating on high BaF_2 fold (≥10) and ND yrast transitions of ^{143}Eu [same as in Fig. 1(a)]. The fractional shift $F(\tau)$ from the lifetime analysis of the transitions in the bump is given by open squares in part (c), in comparison with the DSAM results obtained for the SD yrast transitions [19]. The behavior of $F(\tau)$ for different values of the intrinsic quadrupole moment Q_0 is given by the dashed curves.

as if it would originate from a collective rotation of a superdeformed nucleus. However, such a high value of the effective moment of inertia may also be achieved by other effects, as, for example, when a change in alignment takes place [16].

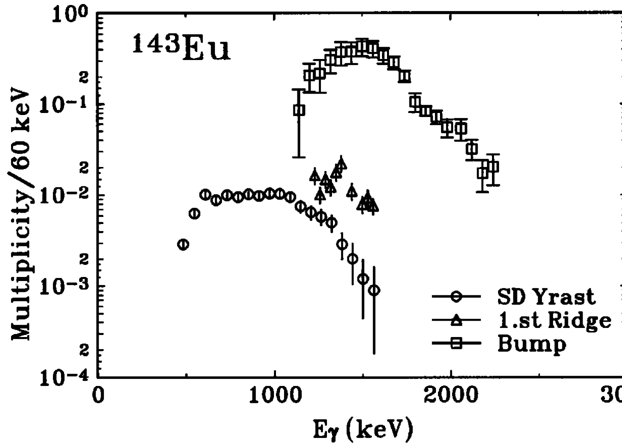

FIG. 3. The multiplicity per 60 keV interval of the SD yrast transitions, the SD ridge, and the quasicontinuum bump in ^{143}Eu as a function of transition energy.

The collectivity would most convincingly be shown by a lifetime measurement. An attempt has therefore also been made to estimate the lifetime of the $E2$ bump, by studying the Doppler shift of the distribution of the continuum transitions in a similar way as earlier made for a distribution of normally deformed states [18]. The same fusion reaction was applied, using the Au backed palladium target. The average recoil velocity in the target was calculated to be $v_0/c = 2.2\%$. Figure 2(d) shows spectra taken in the forward (37°) and backward (143°) angles of NORDBALL, gating on high BaF_2 fold (≥10) and on low lying transitions of the ND yrast states of ^{143}Eu. The spectra have been background subtracted, unfolded, and normalized to the 917 keV $(15/2^- \rightarrow 11/2^-)$ fully stopped ground state transition of ^{143}Eu, as shown in Fig. 2(d). Corrections due to the relativistic solid angle effect have also been taken into account. A clear Doppler shift of the $E2$ bump is observed. Figure 2(c) shows the fractional velocity $F(\tau) = v/v_0$ (open squares) obtained for the transitions in the moving bump in the region clear from contamination from strong discrete peaks. The results are shown to be consistent with the lifetime analysis of the SD yrast band (open circles) [19], which determined the intrinsic quadrupole moment to be $Q_0 = 13 \pm 1.5\ e$ b. If the transitions in the continuum bump are fully shifted, the lifetime of the corresponding rotational states is very short, less than 10^{-14} sec. However, due to the rather large error bars and due to the fact that no data points could be extracted in the region below 1250 keV, we cannot rule out that the intrinsic quadrupole moment may be as small as 5 e b, as shown by the dashed curves in Fig. 2(c). If Q_0 were so small, the lifetime of the quasicontinuum states would be about 7 times longer than for the SD yrast band. This possibility is still an open question and it has been earlier predicted by simulation calculations of the γ-decay flow [7]. Because of the mixing between normal and superdeformed states the transitions of SD type could be slowed down by the influence of a much smaller decay rate of the ND states, depending on the height of the barrier between ND and SD states, and in particular on the ratio ρ_{SD}/ρ_{ND} of the level densities in the two minima.

In a previous work, a fluctuation analysis was also performed along the central valley of the total γ-γ matrix obtained in the thin target experiment, after requiring a high fold gate (≥ 12) in the BaF_2 detectors. The results obtained for the number of paths ($\approx 10^5$) at rotational frequency ≈ 750 keV are consistent with predictions for damped rotational motion in the SD well [20].

The relative intensities of the SD yrast, the SD ridge, and the $E2$ bump are shown in Fig. 3 as a function of transition energy. The intensities are normalized to the multiplicity of the cascades per 60 keV interval, since $4/\mathcal{I}_{SD}^{(2)} \approx 60$ keV. The main intensity of the bump consists of transitions emitted from states in the warm region of rotational damping. In particular, the intensity of the bump appears to be roughly 20 times stronger than the SD ridge, with a maximum value of about 50% reached at $E_\gamma \approx 1500$ keV.

The experimental results of Fig. 3 support qualitatively the following picture of the decay cascades containing superdeformed transitions, described in Ref. [6]. In the region of the decay flow around $I \approx 50\hbar$, the ratio between level densities ρ_{SD}/ρ_{ND} has such a value, that about 50% of all transitions are generated by the SD part of the mixed SD-ND states. Going down in angular momentum, ρ_{SD}/ρ_{ND} decreases, due to the lifting of the energy of the SD well relative to the ND well. Eventually the ND part of the states will dominate and take over the decay. This explains the decrease of the bump intensity below 1500 keV. Such ND transitions are probably distributed over a rather wide transition energy interval, not significantly affecting the moving bump. The decrease of the bump with increasing E_γ above 1500 keV is due to the cutoff of the reaction cross section and fission at high angular momentum. In contrast to the intense bump, only a small percentage of the cascades cool down to the lowest lying SD bands forming the ridge structure, and fewer still survive in the second well following the SD yrast band down to rotational frequency around 300 keV.

In conclusion, in the present Letter we have shown the appearance of a collective quasicontinuum of transitions originating from SD states in the nucleus ^{143}Eu. They form a pronounced bump in the energy region 1250–1750 keV. The analysis of angular anisotropies, effective moments of inertia, and lifetimes of the transitions demonstrates that the bump is made out of stretched $E2$ transitions, with the same character of collectivity known for the SD yrast band. Since it has been earlier demonstrated that the regular rotational SD structures in the ridge carry about 3% only of the intensity and seem to disappear at an excitation energy of ≈ 1.6 MeV above yrast, we can finally conclude that the first experimental evidence has been given for a fully damped rotational continuum in the SD well of ^{143}Eu. It is interesting that the cascades of γ rays which form the bump feed into the ND spherical states of low deformation, bypassing the triaxial states. This agrees with the fact that the observed linking transitions from the SD band do not feed into the triaxially deformed states of ^{143}Eu, but connect directly the superdeformed and the spherical potential wells [14].

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