25 January 2001

PHYSICS LETTERS B

Physics Letters B 498 (2001) 137–143

www.elsevier.nl/locate/npe

Quantum tunneling of the excited rotational bands in the superdeformed nucleus ^{143}Eu

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Received 11 September 2000; received in revised form 9 November 2000; accepted 29 November 2000
Editor: V. Metag

Abstract

The properties of the thermally excited rotational motion up to the region of rotational damping are studied experimentally in the superdeformed nucleus ^{143}Eu. The effective lifetime of the excited discrete rotational bands forming ridge structures in γ–γ matrices is measured at the EUROBALL array using the DSAM technique, giving a quadrupole moment $Q_t \approx 10\ e\,$b, consistent with the deformation of the superdeformed yrast band. In addition, the effective number of excited superdeformed bands is extracted by a statistical analysis of the ridge structure, for transition energies down to the region where the effect of the decay-out into the normal deformed well shows up. The experimental data are compared with microscopic cranked shell model calculations including a residual interaction of surface delta type. Satisfactory agreement between data and theory is obtained when the quantum tunneling of the excited superdeformed states is included in the model. © 2001 Published by Elsevier Science B.V.

PACS: 21.10.Tg; 21.10.Re; 23.20.Lv; 27.60.+j

The study of rotational motion in largely deformed nuclei is one of the central topics extensively investigated in the last few years [1,2]. Evidence for superdeformed (SD) configurations has been found not only at the ground state level, but also in excited nuclei [3]. An interesting aspect concerning the problem of superdeformation is that of the decay-out from the SD states into the normal deformed (ND) shapes, coexisting over a rather wide spin interval [4]. It has

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PII: S0370-2693(00)01367-8

been established that the mechanism of the decay-out is controlled by the ratio of the normal deformed and superdeformed level densities and by the penetration of the potential energy barrier between the two minima [5]. This description has been developed mainly in connection with the SD yrast band [6,7], but it is expected to be valid even in the case of excited superdeformed structures. However, in the case of excited bands the additional effect of the mixing among excited levels has to be taken into account, making the overall picture more complex.

In recent years, the properties of the rotational motion in thermally excited nuclei have been microscopically investigated making use of shell model calculations including a two-body residual interaction [8]. With this model predictions have been obtained for a variety of nuclei, characterized by different masses and deformations [8–11]. In particular, in the case of SD nuclei, the coupling of the SD states to the high-density region of ND states through a potential energy barrier [4,6] and the resulting decay probability have been recently estimated and included into the band mixing model, from the yrast state up to the energy barrier [12,13].

Experimentally, the problem of the decay-out from superdeformed structures can be addressed by studying the evolution as function of spin of the superdeformed ridges present in γ–γ matrices, and populated by discrete rotational bands of low excitation energy, up to the region where the damping of rotational motion sets in [14,15]. While the ridge structures have been extensively studied in the case of normal deformed nuclei [15], few works, carried out with smaller detector arrays than presently available, have been reported on the study of the quasi-continuum in superdeformed nuclei [16–20]. Only in the case of ^{143}Eu, a quantitative analysis of the ridge structure was made using the fluctuation analysis technique [16], showing the possibility of addressing the problem of superdeformed excited rotational motion. However, no conclusions could be obtained because, due to experimental limitations, the available data had large error bars and did not cover the low-spin interval in which the effect of the decay-out is expected to show up. To obtain data in the spin region of interest for the decay-out is a difficult problem, not only because the intensity of the SD ridge structure is rather weak, but also because of the presence of transitions from other nuclear shapes of lower deformation (mainly spherical and triaxial) [21–23], at the same energies of the SD rotational ones. In addition, a measurement of the quadrupole moment associated to the ridge structures has not been available so far, information which is useful not only to confirm the superdeformed nature of the excited bands, but also to verify the basic assumption of the band mixing model [8,10], namely that the nucleus maintains its collectivity in the warm rotation. Therefore, a major step forward in the direction of a better understanding of the excited rotational motion in largely deformed nuclei needs (i) a measurement of the quadrupole moment of the excited rotational bands forming the superdeformed ridge structures, and (ii) a quantitative analysis of the ridges extending as low spin as possible, where the effects of the decay-out into the ND well start to show up. A good case for this study is the nucleus ^{143}Eu for which the previous explorative experiment has given encouraging results [16], and for which new calculations are now available [12,13].

In the present letter we report on a EUROBALL experiment on ^{143}Eu, which has made possible, for the first time, to investigate the two previous points. The nucleus ^{143}Eu was populated by the fusion reaction $^{37}\mathrm{Cl} + {}^{110}\mathrm{Pd} \rightarrow {}^{147}\mathrm{Eu}$, at beam energies of 165 and 170 MeV. The ^{110}Pd target used (97.3% pure and 950 $\mu\mathrm{g/cm}^2$ thick) was evaporated on a Au backing of 15 $\mathrm{mg/cm}^2$. The γ-rays following the fusion reaction were detected by the EUROBALL array [24], in the special configuration in which the tapered Ge detectors were replaced by 8 large volume BaF_2 scintillators for high energy detection, as discussed in Ref. [25]. In addition, 4 small BaF_2 detectors were used as a time reference. A total of $\approx 1.4 \times 10^9$ Ge events with average fold ≈ 3 was collected after a significant fraction of delayed γ-rays and neutron induced peaks was rejected by setting a narrow energy dependent time gate on the Ge energies. It is found that more than 60% of the total statistics of the experiment leads to ^{143}Eu as final residue.

At first, the quadrupole moment Q_t of the excited rotational bands has been measured, using the DSAM technique, through a lifetime analysis of the ridge structures. Because it was not possible to have sufficient statistics in the γ–γ matrices corresponding to selected pairs of angles (due to the high angular granularity of the EUROBALL array), a different approach has been followed, which makes use of the entire statistics of the experiment. An energy dependent Doppler correction, corresponding to a given quadrupole deformation Q_t, has been applied to the backed target data, on an event by event basis. In this way, a number of γ–γ matrices, each corresponding to a different Q_t (in step of 1 unit ranging from 3 e b to 13 e b, the latter being the upper limit deduced from the analysis of the SD yrast line [26]), has been obtained. The background was then subtracted using a COR treatment [27] with a COR reduction factor of 0.95, which emphasizes the high spin region. Fig. 1 shows typical perpendicular cuts (60 keV wide) at the average transition energies $\langle E_\gamma \rangle = 1120$ and 1300 keV, on the γ–γ spectra, obtained with no Doppler correction (panels (a) and (f)) and with an energy dependent Doppler correction corresponding to the quadrupole deformation $Q_t = 3$ e b (panels (b) and (g)), 10 e b (panels (c) and (h)) and 13 e b (panels (d) and (i)). As one can see, a ridge structure with a spacing ≈ 120 keV $= 2 \times 4\hbar^2/\Im^{(2)}$, corresponding to the dynamic moment of inertia $\Im^{(2)}$ of the SD yrast band of ^{143}Eu, appears more and more clearly when a Doppler correction close to the one of the SD yrast band (with $Q_t \approx 13$ e b [26]) is applied. In the top panels of Fig. 1 the full width at half maximum (FWHM) of the ridge structures at the two different average transition energies is shown as function of the quadrupole moment Q_t, together with a quadratic fit of the data. It is found that the ridge structure acquires a minimum width which is in average a factor ≈ 2 larger than the resolution of the SD yrast line, in agreement with previous data from a thin target experiment [21]. This fact supports the choice of the Q_t values corresponding to the minimum of the FWHM curves, taking as error the values corresponding to the FWHM one standard deviation away from the minimum. Smaller and larger Q_t's have been excluded, since the corresponding Doppler corrections make the ridge structures much broader than expected [21]. The analysis of the FWHM of the ridge structure has been done at 6 different transition energies ranging from 1120 to 1420 keV (in steps of 60 keV and averaging over a 60 keV interval). This has given $Q_t = 9.7 \pm 0.9$ e b, in good agreement with the quadrupole moment of the SD yrast band $Q_t = 9.8 \pm 0.7$ e b, measured in the same γ-energy range.

Fig. 2 shows the fractional Doppler shift $F(\tau)$ experimentally obtained from the analysis of the discrete yrast transitions of the SD band (circles) [26], of the superdeformed ridges (squares, this work) and of the triaxial transitions of ^{143}Eu [22], in comparison with the calculations from Ref. [26], corresponding to different values of the quadrupole moment Q_t. In the case of the ridges, the experimental values of $F(\tau)$ correspond to the Q_t values obtained from the analysis of the FWHM of the ridge structures, previously discussed. In this case, due to the non linear dependence of $F(\tau)$ on Q_t, as one can see from the $F(\tau)$ curves at given energies, the originally symmetric errors on Q_t correspond to asymmetric error bars in $F(\tau)$. As already pointed out, the experimental results for both SD yrast and ridge structures are in agreement with a quadrupole moment of the order of ≈ 10 e b for $E_\gamma > 1000$ keV, proving the superdeformed nature of the excited rotational bands. This shows that the superdeformed nucleus ^{143}Eu maintains its collectivity with increasing excitation energy, at least until damping sets in, as also observed in normal deformed nuclei [28,29]. One should also notice that this Q_t value is slightly lower than obtained from the analysis of the SD yrast in the most sensitive region below 1000 keV, as a possible consequence of a delayed sidefeeding, originating from the mixing with normal states at the excitation energies from where the feeding of the SD yrast and ridge structures takes place [30].

As a second point in the analysis, the effective number $N^{(2)}_{\text{path}}$ of excited rotational bands populating the superdeformed ridge of ^{143}Eu has been obtained. This has been done by a *statistical analysis* of the fluctuations in the number of counts [15,31] of the γ–γ spectrum sorted applying the Doppler correction corresponding to the quadrupole moment of the ridge structures, $Q_t \approx 10$ e b. The number $N^{(2)}_{\text{path}}$ of paths available to the nucleus in the γ-decay through different regions of level density, namely the number of excited bands, as well as the effective number of damped transitions, can in fact be extracted from the simple relation $\mu_2/\mu_1 = N_{\text{eve}}/N^{(2)}_{\text{path}} + 1$ [15]. Here, μ_1, μ_2 and N_{eve} are the first and second statistical moments and the number of counts in a $4/\Im^{(2)} \times 4/\Im^{(2)}$ sector, in which each rotational cascade contributes on the average one count, $\Im^{(2)}$ being the dynamic moment of inertia of the nucleus.

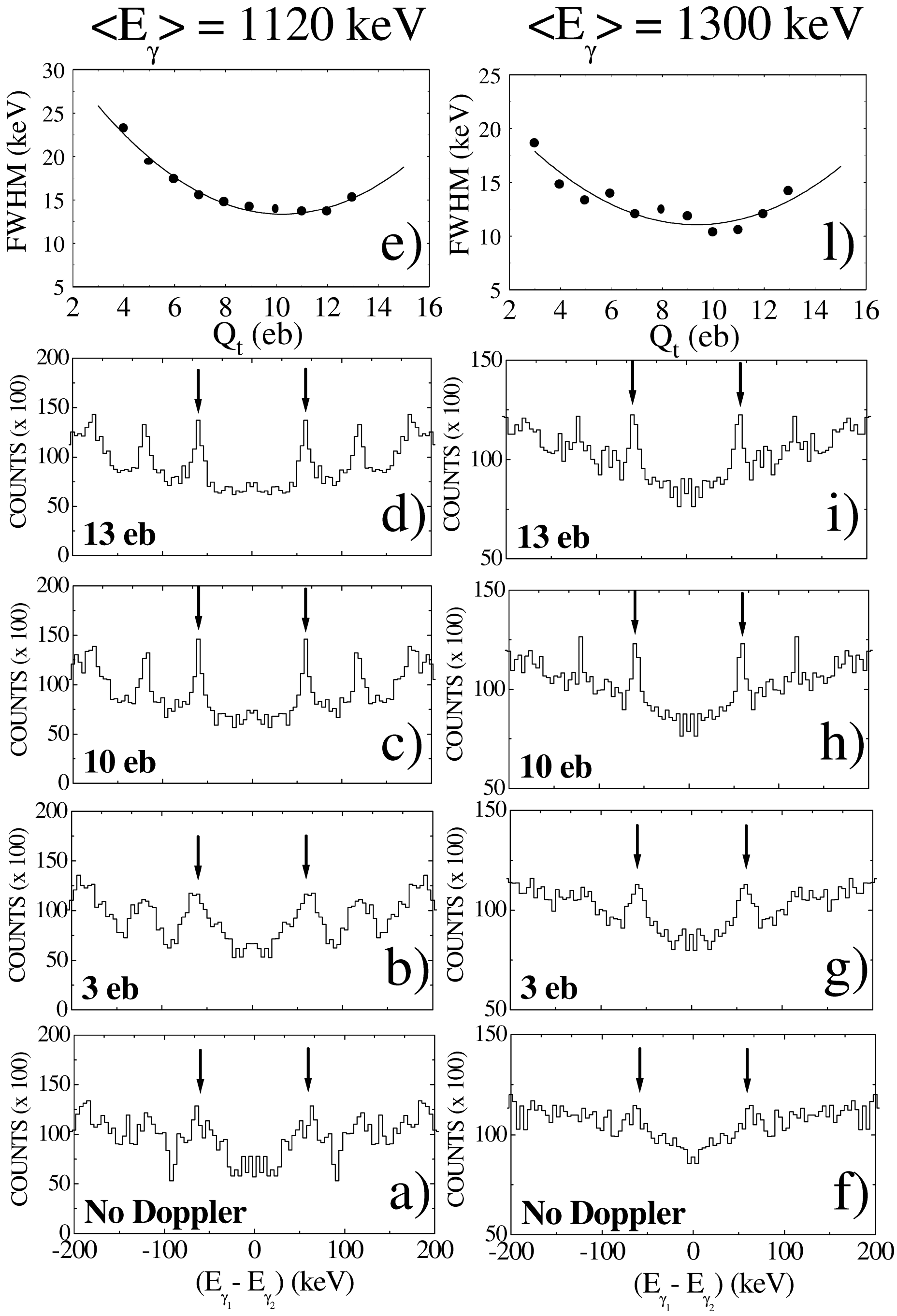

Fig. 1. Perpendicular cuts (60 keV wide) at the average transition energies $\langle E_\gamma \rangle = 1120$ (left column) and 1300 keV (right column), on the γ–γ spectra of ^{143}Eu, obtained with no Doppler correction (panels (a) and (f)), with an energy dependent Doppler correction corresponding to a quadrupole moment $Q_t = 3\ e\,$b (panels (b) and (g)), 10 $e\,$b (panels (c) and (h)) and 13 $e\,$b (panels (d) and (i)). The top panels (e) and (l) show the dependence of the full width at half maximum (FWHM) of the ridge structure (marked by arrows in the previous panels) on the quadrupole moment Q_t, at the two average transition energies.

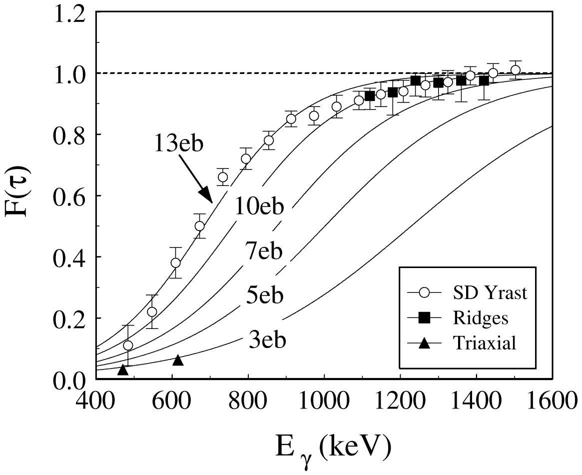

Fig. 2. The measured fractional Doppler shifts for the superdeformed yrast (circles) [26], the triaxial transitions (triangles) [23] and the superdeformed ridges (squares, this work) of ^{143}Eu. The lines represent the expected theoretical values for $Q_t = 3$, 5, 7, 10 and 13 *e* b.

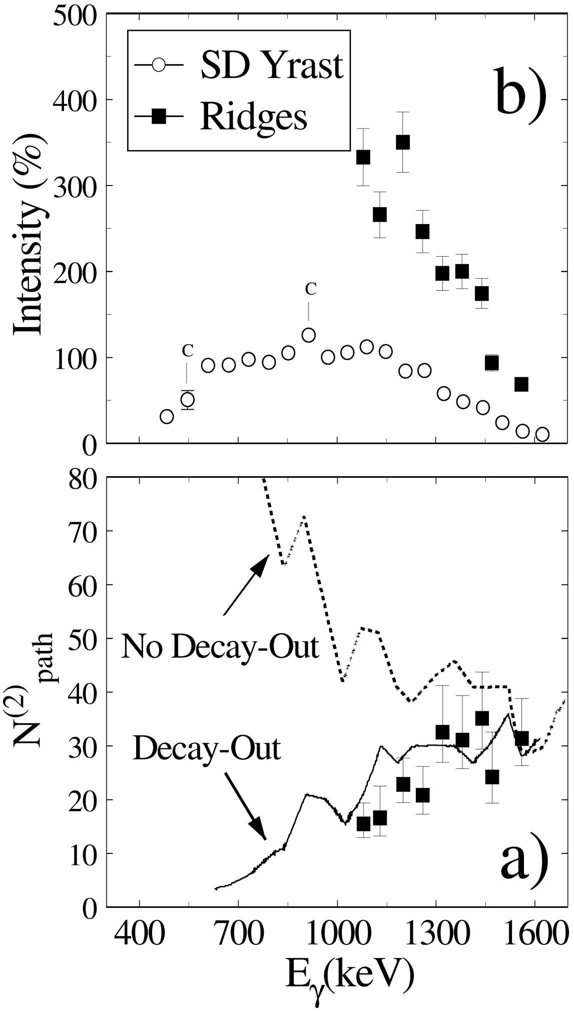

Fig. 3. (a) The number of excited rotational bands obtained by the fluctuation analysis of the superdeformed ridge structures of ^{143}Eu, compared with cranked shell model calculations plus a SDI two-body residual interaction including (solid line) or not (dashed line) the decay-out process into the normal deformed well [12]. (b) Relative intensity of the SD yrast (circles) and of the ridge structure (squares) of ^{143}Eu, normalized to an average of the highest points of the SD yrast pattern. The intensities of the yrast transitions marked by *c* could not be properly measured due to the presence of close lying contaminant peaks.

The results obtained from the fluctuation analysis of the SD ridge of ^{143}Eu are shown in Fig. 3(a) by squares. Before the statistical method was applied, all known discrete lines of the SD yrast band have been removed from the γ–γ spectrum by the Radware software programs [32], in order to obtain a better estimate of the unresolved paths [15]. As one can see, the number of bands is found to depend very strongly on the transition energy, reaching a constant value of ≈ 30 at $1300\ \text{keV} < E_\gamma < 1600\ \text{keV}$. This corresponds to the transition energy region where the SD ridge is populated, following an intensity pattern similar to the SD yrast, as one can see in Fig. 3(b). At lower transition energies a continuous decrease is observed in the number of bands, while the intensity of the ridge structure seems to increase and the intensity of the yrast band saturates.

The experimental results have been compared with recently available microscopic cranked shell model calculation plus a two-body surface delta residual interaction (SDI) for the specific superdeformed nucleus ^{143}Eu [9,10]. The effective number of discrete bands can, in fact, be directly obtained from the model by counting the number of two consecutive transitions having a branching number n_{branch} less or equal to 2 [8]. The value of n_{branch} gives a measure of the fragmentation of the E2 strength, and it is defined as $n_{\text{branch}} = (\sum_j b_{ij}^2)^{-1}$, where $b_{i,j}$ is the normalized strength from level i at spin I to level j at spin $(I-2)$. Using n_{branch} it is also possible to deduce the onset energy U_0 for rotational damping, energy corresponding to $n_{\text{branch}} = 2$, which in the case of ^{143}Eu is found to be ≈ 1.3–1.6 MeV above yrast. As shown in Fig. 3(a), the calculation (dashed line) is close to the data at the maximum of the distribution, while it deviates strongly at lower transition energies. As suggested in the previous work [16], this might be related to the barrier penetration into the first well, which is expected to remove intensity from the excited bands. This depopulation mechanism would eventually leave only the yrast band and few low lying bands to survive further down in angular momentum with full strength, explaining the increasing intensity of the ridge structures in spite of the decreasing number of paths measured experimentally.

The gradual reduction observed in the number of bands at low transition energy (low spin) is well explained by the theoretical model, once the decay-out mechanism of the excited states is taken into account (solid line) [12,13]. In fact, if there is a finite probability P_{out}, for decaying from level i out of the SD well, the strength b_{ij} must be multiplied by $1 - P_{\mathrm{out}}$, so that the effective number of bands becomes correspondingly smaller. The probability P_{out} has recently been calculated in detail in the microscopical model [12,13], as a function of the excitation energy of the SD states above yrast, extending a statistical model which has been previously applied to the decay-out of the SD yrast band [6,7] (cf. also [33]). The resulting P_{out} increases strongly with increasing excitation energy and with decreasing angular momentum, giving a calculated number of excited bands at $E_\gamma \approx 1200$ keV, surviving the decay to the ND well, which is about one half compared to $E_\gamma \approx 1400$ keV, in good agreement with the data.

It is remarkable how essential was in this work the use of a backed target, which has made possible not only to study the ridge structures over a transition energy interval approximately two times larger than in the previous thin target experiment [16], but it has also given data which are found in good agreement with the model in the entire investigated interval. This is in contrast with the thin target analysis which showed a decreasing number of bands in the high transition energy region ($\geqslant$ 1450 keV), behaviour which was not understood. This is now explained as due to small contaminations from low spin spherical and triaxial states, that are now better eliminated with the use of the backed target. In the present spectra these peaks are in fact smeared out, since the Doppler correction appropriate for the SD structures is definitely not correct for the low deformation transitions, emitted when the nucleus is basically stopped in the backing.

In conclusion, the collective character of the excited superdeformed bands forming the ridge structure and the decay-out effects from these excited bands have been shown for the first time. The superdeformed ^{143}Eu nucleus was found to maintain its collectivity at increasing excitation energy until, at least, rotational damping takes place. In addition, the number of SD excited rotational bands, before damping sets in, was estimated by a statistical analysis technique down to the transition energy region where the effect of the decay-out shows up. The results are well reproduced by new prediction based on band mixing calculations including for the first time a modeling of the decay-out into the normal states. This gives the first evidence that the decay-out mechanism is controlled, not only for the SD yrast but also for the excited SD bands, by the quantum tunneling through the barrier between the normal deformed and the superdeformed minima.

Acknowledgements

The authors wish to thank M. Matsuo, K. Yoshida and Y.R. Shimizu for providing the theoretical comparison with the data, and T. Døssing for the several illuminating discussions. Financial supports from the Polish State Committee for Scientific Research (KBN Grant No. 2 P03B 001 16), from the Danish Natural Science Research Council and from INFN, Italy, are gratefully acknowledged.

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