Z. Phys. A 358, 157–160 (1997)

ZEITSCHRIFT
FÜR PHYSIK A

The rotational quasi-continuum in specific configurations: high-K states and superdeformation

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Received: 26 July 1996
Communicated by B. Herskind

Abstract. The analysis of the fluctuations of the counts of unresolved γ-γ energy spectra can extend our knowledge of the rotational motion at high angular momentum and excitation energy above the yrast band. Detailed studies of the rotational quasi-continuum built on specific intrinsic nuclear configurations are here discussed. First, the validity of the K-selection rules in the quasi-continuum region is investigated in the case of the normal deformed nucleus ^{163}Er. The γ cascades feeding into low-K and high-K bands are analyzed studying variance and covariance of the spectrum fluctuations. Low-K bands are found to be fed by a much larger effective number of cascades than high-K bands, while the covariance between pairs of gated spectra shows that the cascades feeding into low-K bands are different from those feeding into high-K bands. These findings suggest a persistence of K-selection rules in the region of excitation energy and angular momentum probed by the rotational decay of ^{163}Er. As a second case, the existence of a rotational quasi-continuum in the super deformed well of ^{143}Eu is discussed. An intense bump of rotationally correlated transitions is observed to develop as function of fold in the high spin region of gated spectra. Fold distribution, angular anisotropies, moment of inertia and life time show that the bump consists of fully damped super deformed transitions. This gives experimental evidence of damped rotational motion up to several MeV excitation energy above the super deformed yrast line.

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

1 Introduction

In well deformed rare earth nuclei, up to about 20 individual bands are now identified, yielding information on the interplay between rotation, superfluidity and quantum numbers of the intrinsic configurations. Along with the study of discrete transitions, investigations of unresolved γ-spectra have extended our knowledge of nuclear structure at thermal excitation energy higher than that covered by the resolved bands. This field, named quasi-continuum γ-ray spectroscopy, allows for a more complete analysis of the γ-decay of warm rotating nuclei. The unresolved quasi-continuum forms ridge and valley structures in coincident γ-γ energy spectra [1]. The ridges are formed by transitions from states at low excitation energy obeying rotational energy correlations, while the valley is populated by γ-rays from the region of higher level density above yrast.

In the last few years, a fluctuation analysis of the counts in the γ-γ spectrum has been developed in order to extract information on the average properties of the rotational motion, even from these unresolved γ-spectra. In particular, the fluctuation analysis allows to determine the number N_{path} of paths available to the nucleus in the γ-decay through different regions of level density [1], [2], information which can in turn be related to the average properties of the rotational motion. The very existence of a finite number of paths leads, in fact, to enhanced fluctuations μ_2/μ_1, whose magnitude is fixed by the number of paths through the simple relation $\mu_2/\mu_1 = N_{eve}/N_{path} + 1$. μ_1, μ_2 and N_{eve} are the statistical moments and the number of counts in a $4^2/\Im \times 4^2/\Im$ sector, in which each rotational cascade contributes on the average one count.

In the region of rare earth nuclei, this kind of analysis has allowed to obtain a rather consistent picture of the rotational decay, even in the high level density region several MeV above yrast [1]. Large fluctuations are observed in the ridge structures, showing that only a rather low number (≈ 40) of discrete rotational bands exists up to excitation energy ≈ 800 keV above yrast. In contrast, very weak fluctuations are found along the central valley, revealing a number of coincidence combinations ($\approx 10^4 - 10^5$) larger than what found assuming that the rotational decay leads to a unique final state. These studies have experimentally unambiguously shown that the rotational transition strength gets progressively fragmented with increasing excitation energy above yrast, a manifestation of the damping of rotational motion [3].

With the new generation of γ-detector arrays, extremely intense high fold coincidence data sets can now be obtained, making it possible to go beyond the analysis of the average properties of the nuclear rotational motion and to study in great detail the quasi-continuum built on specific intrinsic nuclear configurations. In the present paper we will consider two different cases: i) the validity of the selection rules for unresolved rotational bands and for γ-ray transitions in the damped region of the normal deformed (ND) nucleus ^{163}Er, and ii) the possibility of excited rotational motion in the super deformed (SD) well of ^{143}Eu.

2 The K-quantum number in the excited rotating nucleus ^{163}Er

In the compound nucleus regime, described by random combination of the available configurations, the selection rules associated with the quantum numbers of the intrinsic structures are expected to be completely lost. On the other hand, the fragmentation of the rotational decay taking place already at energies ≈1 MeV above the yrast line [1] may suggest a weakening of the selection rules in this energy region.

The validity of the selection rules for the K quantum number in the rotational quasi-continuum region has been recently investigated in the case of ^{163}Er [4]. In this nucleus two bands, K1 and K2, with high values of the projection K of the angular momentum (K=19/2) have been identified [5], [6]. The two bands lie at excitation energy 0.8 and 1.4 MeV above yrast, well into the region in which low K bands display rotational damping. This makes the nucleus ^{163}Er an attractive case to study the interaction between high-K and low-K structures, and the problem of rotational band mixing and its configuration dependence.

The experiment was performed using the GA.SP multidetector system in the standard setup. The reaction used was ^{18}O+^{150}Nd, with a beam energy E_{beam}=87 MeV, leading mainly to the population of ^{162,163}Er. A total of 10^9 triple and higher fold events were collected. The data were sorted into a number of γ-γ spectra gated by low lying transitions in bands of both low-K and high-K quantum numbers. Each spectrum was corrected for the background under the gate-selected peaks and the Compton events, before the fluctuation analysis was performed [1], [4].

The results obtained with the fluctuation analysis applied to the study of the ridge structures are summarized in Fig. 1. About 10 to 20 unresolved bands are found to feed into the gate-selected transitions, regardless of the magnitude of the K-quantum number (see Fig. 1b and c). In contrast, a total of ≈ 40 paths is obtained from the ridge analysis of the ungated matrix (scattered points in Fig. 1a), well in agreement with the systematic results previously obtained for nuclei of the same mass region [1]. On the basis of the experimental values $N^{(2)}_{path,i}$ obtained for each specific configuration i and shown in Fig. 1b and c, one can independently estimate the total number of paths $N^{(2)}_{path,Tot}$ through the additivity formula:

$$\frac{1}{N^{(2)}_{path,Tot}} = \sum_i \frac{f_i^2}{N^{(2)}_{path,i}} + \sum_{i \neq j} \frac{r(i,j) f_i f_j}{\sqrt{N^{(2)}_{path,i} N^{(2)}_{path,j}}} \qquad (1)$$

and compare it to the experimental values of Fig. 1a [6]. In Eq.(1) f_i represents the relative intensity of configuration i, as determined by discrete line spectroscopy, while $r(i,j)$ is the correlation coefficient, which measures the fraction of common paths between the two configurations i and j, i.e. the similarity between cascades feeding into the two different selected bands i and j. If $r(i,j)$ is 1, the two configurations i and j are identical. If $r(i,j)$ is 0 the two configurations are completely decoupled. If one assumes no common paths (i.e.

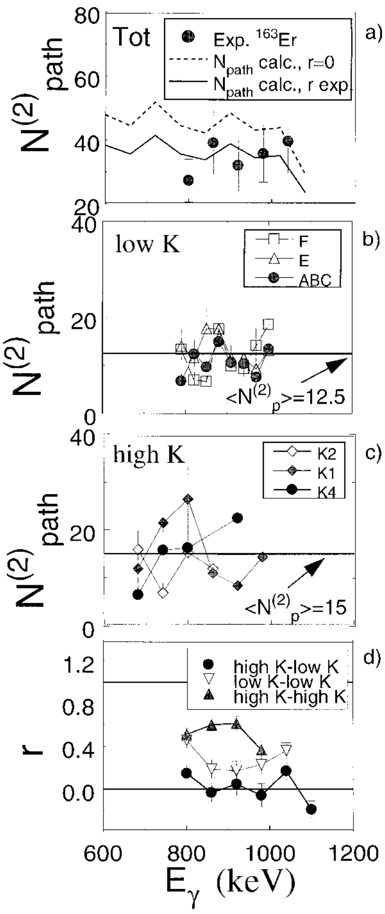

Fig. 1. a–d. Summary of the results of the Fluctuation Analysis of the ridge structures in ^{163}Er. A total number of ≈40 paths **a** is obtained from the analysis of the ungated matrix collecting the total flow of ^{163}Er, while average values of 12.5 and 15 paths are found selecting specific low-K **b** and high-K **c** configurations, respectively. The chosen configurations are labeled in the legend. The total number of paths has been also estimated through (1), assuming no common paths between different configurations (*dashed line* in **a**), or considering the experimentally determined correlation coefficients r given in panel **d** (*solid line* in **a**)

$r(i,j)$ = 0, dashed line in Fig. 1a) the values of $N^{(2)}_{path,Tot}$ overestimate the experimental numbers. This clearly indicates that some paths must be shared between different configurations, which implies a correlation coefficient r different from 0. Fig. 1d shows the experimental estimate of the correlation coefficient r, obtained on basis of the newly developed analysis of the covariance of the fluctuations between different pairs of gated spectra [4]. The extracted values of r are positive for similar configurations (low-K with low-K, and high-K with high-K), and approximately zero for the combination low-K with high-K, showing that there are basically no cross transitions between the ≈12 bands feeding low-K bands and the ≈15 bands feeding high-K bands. This result has been interpreted as an effect of the persistence of a strong K selection rule governing the rotational bands forming the ridges. These bands are characterized by energy up to the onset of damping [1], [2] and by γ-transition energies corresponding to the angular momentum region 30-40 . Furthermore, inserting the experimental values of r into (1), a much better estimate of

$N^{(2)}_{path,Tot}$ is also obtained (solid line in Fig. 1a), supporting the consistency of the results.

In contrast to the results of the ridge analysis, the number of paths obtained by analyzing the valley region has been found to depend significantly on the nuclear configuration [4]. As in previous studies for the same region of mass and deformation [1], a number of the order of $\approx 10^4$ paths is found from the analysis of the valley of the total spectrum. This number is very similar to the values found for spectra gated by low-K bands. On the contrary, the number of paths in the valley spectra gated by high-K bands is different than that of low-K bands and about 5 times smaller. This has suggested that high- and low-K states do not mix together even in the region of unresolved damped transitions, at excitation energy higher than ≈800 keV above yrast. A more stringent test of such hypothesis could be obtained by the covariance analysis of the valley spectra, which unfortunately could not be performed due to lack of statistics. In addition, since the number of paths in the valley is expected to be larger in the presence of rotational damping [2], the smaller values found in the valley of the high-K bands suggest a reduced mixing among high-K bands, as compared to that of low-K bands.

In conclusion, both ridge and valley analysis seem to indicate a persistence of the K-quantum number in the spin region 30-40 and excitation energy probed by the γ rotational decay of ^{163}Er ($\leq$ 2.5 MeV). These results can not be explained by simply considering the Coriolis interaction effects that reproduce rather well the low energy spectra. Similar conclusions on K conservation at high excitation energies were obtained from the analysis of neutron resonances [7, 8]. The conservation of K at high spins and internal energies is not yet understood, and this new covariance analysis may provide a general tool to address experimentally this question when many decay paths are available.

3 The super-deformed quasi-continuum in ^{143}Eu

While a rather consistent picture of the rotational decay in normally deformed nuclei starts to emerge, little is known about the quasi-continuum in SD nuclei. Since the first SD band was found, several SD excited bands have been identified in different mass regions [9]. In a few cases a SD ridge structure has been observed in γ-γ spectra, over a narrow spin range and with an intensity only 3 times bigger than the full SD yrast, but little is known on the existence of a fully damped SD continuum.

Simulation calculations of the decay flow, based on the coupling between states in the ND and SD potential [10], have indicated the possibility of populating SD states at several MeV above the SD yrast line. However, the intensity of the SD quasi-continuum is expected to be strongly influenced by the position of the crossing between the ND and SD yrast lines, which determines the spin region for a favourable population of the SD well, before the fission cutoff at high spin. In this respect the nucleus ^{143}Eu represents a special case, since the crossing between the ND and the SD yrast lines occurs already around ≈40 , compared to the more typical case of ≈54 in ^{152}Dy. A comparison between simulation calculations in ^{152}Dy and ^{143}Eu nuclei (Fig. 2a and b) clearly indicates ^{143}Eu as a much better case to study experimentally the quasi-continuum in a SD nucleus [11, 12].

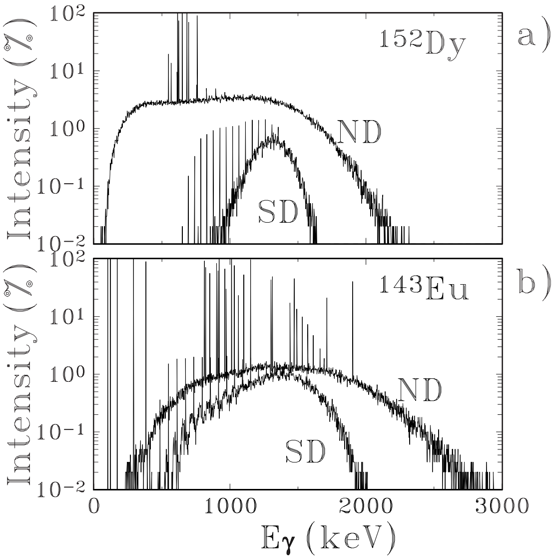

Fig. 2. Spectra of the collective E2 transitions within SD and ND states obtained by simple simulation calculations [10], in the case of ^{152}Dy **a** and ^{143}Eu **b** nuclei. A stronger population of the SD quasi-continuum is observed in the case of ^{143}Eu, mainly due to the lower crossing (≈40) between the SD and ND yrast lines

The experiment was performed using the NORDBALL setup. The nucleus ^{143}Eu was populated by the reaction ^{110}Pd(^{37}Cl,4n)^{143}Eu, at a beam energy of 160 MeV. After requiring a high fold ($\geq$12) and high sum-energy cut in the BaF_2 innerball, 500×10^6 triple and higher fold coincidence events have been stored into a high resolution matrix. A clear ridge-valley structure with a spacing corresponding to the second moment of inertia of the SD band has been observed in the γ-γ matrix. The relative intensities of the SD yrast and of the first and second ridge are given in Fig. 3, together with the results of the analysis of the fluctuations along the ridges [11]. An average value $N^{(2)}_{path}$ ≈20, about 2 times smaller than observed for ND nuclei, has been obtained from the analysis of the first ridge, with a maximum of 40 bands around 1350 keV, carrying ≈2% of the total decay flow. This implies that each excited band is on average populated by an intensity of 0.05 %. Such extremely small value may explain the difficulty in finding even a single excited band in ^{143}Eu. The experimental estimate of the number of paths can be compared to theoretical cranked shell model calculation (solid curve in Fig. 3a) [13, 14]. The calculation well reproduces the data at the maximum of the distribution, while deviates strongly at lower and higher transition energies, possibly due to the effect of barrier penetration to the first well and fission competition respectively, not included in the calculations. The onset of damping predicted by the microscopic calculation is at 1.3-1.6 MeV above yrast, which is much higher than observed in ND nuclei, as a consequence of the considerably smaller level density expected in the SD well [15].

In the case of the valley analysis the results obtained for the number of paths ($\approx 10^5$) at rotational frequency ≈750 keV are well reproduced assuming parameters for the level density and onset of damping relevant for SD nuclei [1]. This represents the

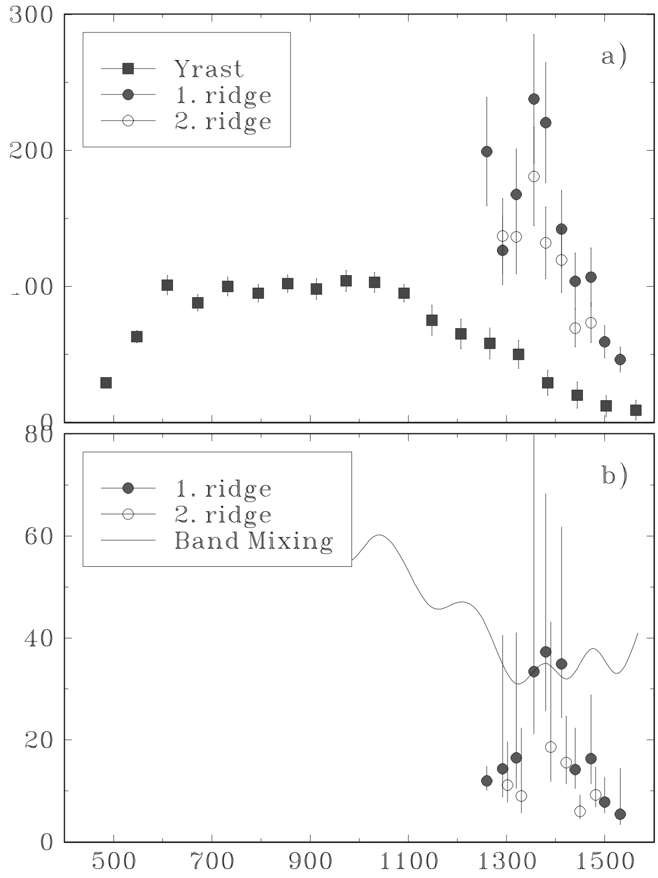

Fig. 3. The *upper part* of the figure shows the relative intensities of the SD yrast (*squares*) and of the first and second ridge (*closed* and *open circles*, respectively). The values of $N^{(2)}_{path}$ deduced for the first and second superdeformed ridge are shown in the *bottom part*, for intervals of 60 keV width along the ridges, in step of 30 keV. The solid curve in **b** represents the prediction for the first ridge from cranked shell model calculations with residual interaction [13]

first experimental evidence of damping of rotational motion in the SD well.

Further experimental evidence of damped rotational motion in the SD well of ^{143}Eu has been found by studying the intensity of the E2 bump as function of spin [12]. Spectra in coincidence with clean transitions from the low spin ND yrast line, for increasing values of folds as measured in the BaF_2 scintillator ball, have shown a pronounced E2 bump, which extends towards high γ-ray energy with increasing fold (see Fig. 4). This behaviour has been generally observed in well deformed nuclei [16], and has suggested that the transitions in the moving bump originate from SD states, since such a 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 of ^{143}Eu [17]. Angular anisotropies, moment of inertia determination and lifetimes analysis have confirmed that the bump originates from highly collective rotationally damped E2 transitions generated by SD states [12].

The intensity of the bump appears to be roughly 20 times stronger than the SD ridge, with a maximum value of about 50% of the total flow reached at $E_\gamma \approx$1500 keV (corresponding to spin $\approx$50), as one can see in Fig. 4 by comparing fold

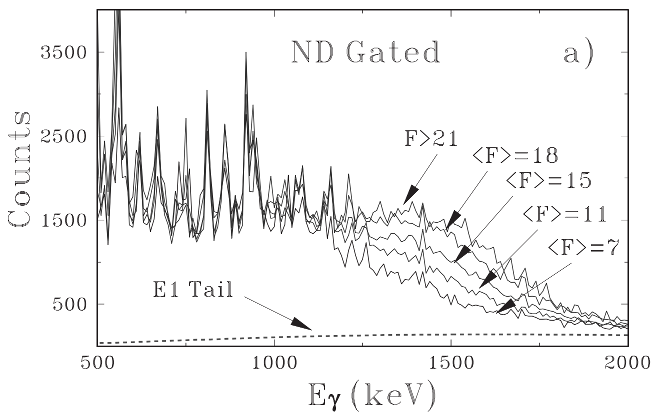

Fig. 4. Unfolded Ge energy spectra in coincidence with low-spin spherical (ND) yrast transitions of ^{143}Eu, for increasing values of fold F, as measured by the BaF_2 scintillator ball

<F>=7 and F$\geq$21. This means that the main intensity of the bump consists of transitions emitted from states in the warm region of rotational damping, in good agreement with the predictions of the simulation calculations shown in Fig. 2.

In conclusion, a complete analysis of the SD quasi-continuum has been performed in the case of the nucleus ^{143}Eu. Up to $\approx$40 excited bands extending up to 1.6 MeV above yrast have been estimated by the fluctuation analysis of the SD ridges. A strong fully damped rotational continuum has been also observed, extending even higher up in excitation energy, and collecting 50% of the total flow at E_γ $\approx$1500 keV. Such a favourable population of the SD well is strongly determined by the low crossing between the SD and ND yrast lines.

Further studies aiming at finding the value of the damping width Γ_{rot} in the SD well should be made, in order to obtain a more complete picture of the rotational decay in highly deformed nuclei.

The support of I.N.F.N. and of the Danish Natural Science Research Council is acknowledged.

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