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NUCLEAR STRUCTURE AND SELECTION RULES IN THE ROTATIONAL QUASI-CONTINUUM*

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The γ-decay of excited rotating nuclei is studied as function of heat energy through a statistical analysis of the fluctuation of counts in γ-γ coincident spectra. In particular, making use of the covariance technique between spectra gated by different intrinsic configurations, one can find if there are similarities among cascades feeding into different selected bands. This can be used to learn about the transition between order to chaos in the nuclear many-body system, in terms of the validity of selection rules associated with the quantum numbers of the intrinsic structure. Experimental results on the nucleus ^{164}Yb seem to indicate a possible weakening of the selection rules already at the moderate excitation energy ≥ 1 MeV above yrast, probed by the rotational decay-flow.

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1. Introduction

Information on the properties of the rotational motion at finite thermal excitation energy can be obtained through the study of the unresolved quasi-continuum, forming ridge and valley structures in γ-coincident energy spectra [1]. In particular, for a number of rare-earth nuclei a statistical analysis of the fluctuation of counts in double (2D) coincidence matrices has

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shown that the ridge structures are formed by a rather low number (≈ 30) of discrete rotational bands, extending up to ≈ 1 MeV excitation energy above yrast. In contrast, a number of coincidence combinations ($\approx 10^4$) much larger than expected assuming that the rotational decay leads to a unique final state has been obtained from the statistical analysis of the central valley, populated by rotational transition from the warmer excitation energy region. These experimental findings demonstrate the fragmentation of the rotational decay with increasing heat energy, a phenomenon known as the damping of the rotational motion [2].

Theoretical investigation show that the onset of rotational damping is expected to be accompanied by an onset of chaotic behaviour in terms of nearest level distributions and distribution of transition strength [3,4]. This indicates that the study of rotational damping as function of nuclear temperature can be instrumental to understand the transition from the chaotic compound nucleus region [5], described by random combinations of the available configurations, to the zero temperature region, characterized by regular ordered motion, with selection rules and complete sets of quantum numbers for every state [6].

In this paper a statistical method based on the covariance technique [7] applied to gated quasi-continuum spectra of ^{164}Yb is used to measure the similarities between decay flows originated from the same compound nucleus

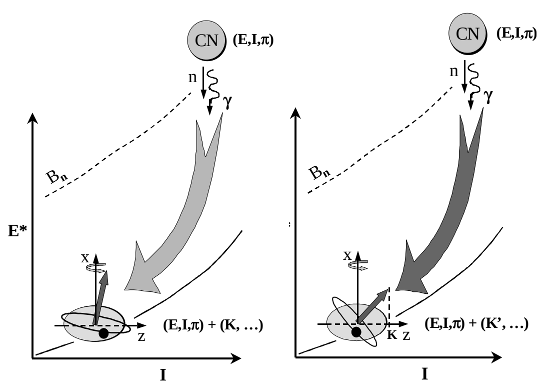

Fig. 1. Schematic illustration of γ-decay flows generated by the same compound nucleus region, and feeding into different single particle configurations close to the yrast line. While only the principal quantum numbers (E, I, π) characterize the compound nucleus system, additional quantum numbers $(K, \ldots)$ associated to the single particle configurations can be given to the nuclear system at $\approx$0 temperature. A covariance analysis of γ-γ coincidence matrices gated by different single particle configurations can be used to compare the decay flows as function of thermal energy (see text).

region, and feeding into different selected bands, in order to test to which degrees selection rules and complete sets of quantum numbers are conserved by the γ-cascades. In fact, as schematically illustrated in figure 1, while in the compound nucleus region there are no additional constants of motion besides the energy E, the total angular momentum I and the parity π, additional quantum numbers characterizing the single particle excitations of a rotating mean field, can be given to each nuclear state at $\approx$ zero temperature, making the system very close to be integrable [6].

2. The experimental analysis

A high statistics, high fold data set on ^{164}Yb has been obtained through the reaction ^{30}Si+^{138}Ba $\rightarrow$ ^{168}Yb, after 4n evaporation, using the multidetector system EUROGAM II. A stack of two targets, each evaporated on a thin Au foil of $\approx 580\mu$g/cm^2, has been used, with a total ^{138}Ba thickness of 450μg/cm^2. The initial velocity of the residual nuclei in the middle of the target was calculated to be $v/c = 1.8\%$. A total of 220 M triple and higher-fold events (with an average Ge-fold of 5) was collected.

The data have been sorted into three γ-γ coincident spectra $G_{\alpha\pi}$ $(E_{\gamma_1}, E_{\gamma_2})$ gated by high spin transitions which exclusively select the three basic configurations of signature and parity $(\alpha,\pi) = (0,+)$, $(0,-)$ and $(1,-)$. A total statistics of $\approx$880 M, 650 M and 550 M events have been collected in the gated matrices respectively, before each spectrum was corrected for the background under the gate-selected peaks, by subtracting a properly normalized spectrum $B_{\alpha\pi}(E_{\gamma_1}, E_{\gamma_2})$ obtained from narrow gates around the peaks. The Compton and other uncorrelated events have been reduced by the standard COR treatment [8].

The fluctuations of counts in each channel of the two dimensional gated spectra have been evaluated by the program STATFIT [1] and stored into two dimensional spectra, after all discrete bands known from previous analysis of the level scheme [9] have been subtracted from each 2D matrix, making use of the Radware software package [10]. This assure a better evaluation of the fluctuations arising from weak unresolved paths [1].

Figure 2 shows typical perpendicular cuts with a width $\Delta E_\gamma = 4\hbar^2/\Im^{(2)}$ $\approx$ 60 keV at $\langle E_\gamma \rangle$= 900 keV on the first moment μ_1 spectra corresponding to the (α,π) gated matrices of ^{164}Yb. The arrows in the figure point to the ridge structures populated by weak unresolved discrete rotational bands.

The similarities between the γ-decay flows finally populating the three different (α,π) configurations of ^{164}Yb have been studied through the correlations in fluctuations between two spectra, which can be evaluated in terms

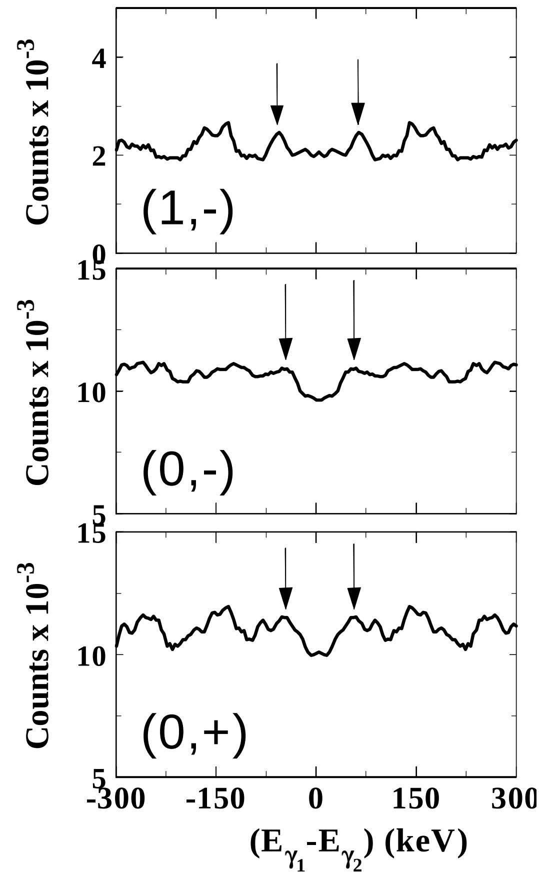

Fig. 2. Perpendicular cuts 60 keV wide at the average transition energy $\langle E_\gamma \rangle = 900$ keV, on the first moment μ_1 spectra corresponding to the $(0,+)$, $(0,-)$ and $(1,-)$ gated matrices of ^{164}Yb. The arrows point to the ridge structures populated by unresolved discrete regular rotational bands.

of covariance of counts, defined as

$$\mu_{2,\mathrm{cov}}(a,b) = \frac{1}{N_{\mathrm{ch}}} \sum_j [M_j(a) - \tilde{M}_j(a)] \times [M_j(b) - \tilde{M}_j(b)] \,, \qquad (1)$$

where $M(a)$ and $M(b)$ refer to spectra gated by transitions from two different (α,π) configurations, denoted by a and b. The sum is over a region spanning N_{ch} channels in a two-dimensional sector, and $\tilde{M}$ denotes an average spectrum, found by the routine STATFIT as a numerical smoothed third order approximation of the 2D spectrum. To determine the degree of correlation between the two spectra, the correlation coefficient $r(a,b)$ is calculated:

$$r(a,b) = \frac{\mu_{2,\mathrm{cov}}(a,b)}{\sqrt{[\mu_2(a) - \mu_1'(a)][\mu_2(b) - \mu_1'(b)]}}\,, \tag{2}$$

where the first moments μ_1' are calculated as

$$\mu_1'(\alpha\pi) = \mu_1(G_{\alpha\pi}) + g_{\alpha\pi}^2 \mu_1(B_{\alpha\pi})\,. \tag{3}$$

The label $\alpha\pi$ refers to a given signature and parity configuration, while $g_{\alpha\pi}$ is the background scaling factor, which is typically of the order of 0.5. The subtraction of the first moments μ_1' from the denominator of (2) corrects for the direct contribution to μ_2 from counting statistics, which is linear in the number of counts.

Correlation coefficients (2), measuring directly the similarities between the $M(a)$ and $M(b)$ spectra, have been extracted from the analysis of both ridge and valley regions for combinations of the selected configurations, and the results are shown in figure 3. The shaded areas in the figures indicate the transition energy region covered by the gate selected transitions, while the lines at $r = 0$ and 1 correspond to the expected values of the correlation coefficient in case of completely different or identical $M(a)$ and $M(b)$ distributions, respectively. In particular, while the limit $r \to 0$ is expected to be reached when comparing the decay flows at ≈ 0 temperature, where the nuclear system is governed by strong selection rules, the opposite value $r \to 1$ is expected in a compound nucleus limit. In fact, since in this case there are no strong selection rules besides those associated to parity and signature, one expects that a given state can feed democratically the other configurations, so that the cascades populating different low-lying configurations may have many transitions in common.

As one can see from figure 3a), the average value of the correlation coefficient r, as obtained from the analysis of the ridge structure for all possible pairs of γ-γ spectra gated by the different (α,π) configurations, is found to be positive and of the order of 0.3, over the all transition energy region. This result seem to indicate that only $\approx$30% of the decay paths followed by the nucleus at moderate excitation energy above yrast, before damping sets in, is in common among all cascades, as a consequence of the existence of cross talk transitions between rotational bands based on different (α,π) configurations. In the remaining 70% of the cases, the γ-cascades seem to be governed by strong selection rules, which will keep the decay-flow within a given (α,π) configuration.

As shown in figure 3b) and c), the covariance analysis of the valley gives instead a correlation coefficient r close to 0 in the transition energy region covered by the gate selected γ-rays, while at higher transition energies r seems to approach 1, suggesting a stronger sharing of decay paths among

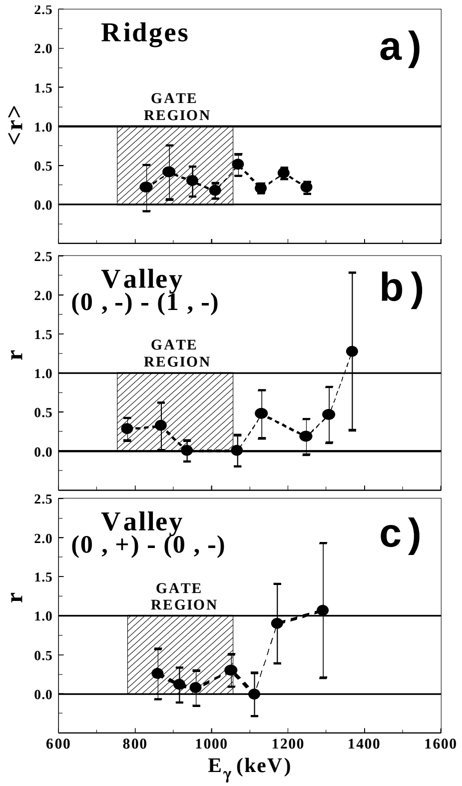

Fig. 3. The correlation coefficient r extracted from the experimental analysis of ^{164}Yb. Part a) shows the average value of r, as obtained from the analysis of the ridge structure for all possible pairs of (α,π) gated spectra, while b) and c) refer to the covariance analysis of the valley for the combinations $(0,-)-(1,-)$ and $(0,+)-(0,-)$, respectively. The shaded area indicate the energy region covered by the transitions selected as gates.

cascades which finally feed into different intrinsic configurations. This can be taken as an indication of a compound behavior of the part of the decay which lies at heat energy $\geq$1 MeV, with rotational frequency between 500 and 650 keV. This can be explained assuming a statistical nature of the $E1$, $M1$ and possibly unstretched $E2$'s feeding transitions connecting the different (α,π) configurations. However, the large error bars on r at the highest transition energies, related to the poor counting statistics in the valley region of the gated γ-γ matrices, suggest that further investigations are necessary to obtain more firm conclusions.

3. Conclusions

Statistical analysis of the fluctuation of counts in γ-γ spectra can be used to obtain general information on the rotational decay of excited nuclei even in the region a few MeV above the yrast line. In the present paper the covariance technique between pairs of 2D spectra, gated by different intrinsic configurations close to the yrast line, has been presented and discussed in connection with the experimental analysis of the quasi-continuum of ^{164}Yb. The method can give information on the transition between order to chaos in the nuclear system, in terms of loss of quantum numbers and validity of selection rules. The obtained results seem to indicate a possible weakening of the selection rules already at the moderate excitation energy ≥ 1 MeV above yrast, probed by the rotational decay-flow. The analysis encourages further experimental and theoretical studies for the understanding of the complex mechanism of mixing between single particle configurations, as function of thermal energies.

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