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Short note

Multistep rotational energy correlations probed by high fold γ coincidence data

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Abstract. The number of discrete rotational bands in the nucleus ^{168}Yb is obtained by a fluctuation analysis of the rotational ridge structure in double and triple γ coincidence matrices. The data are compared with cranked shell model calculations including a surface delta interaction. It is found that the number of calculated bands strongly depends on the interaction strength V_0, and agreement between data and calculations supports the standard value V_0=27.5/A MeV.

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With the new generation of γ-detector arrays, high fold coincidence data sets can now be obtained with very large statistics, making it possible to study the properties of the nuclear rotational motion at finite temperature. In rare earth nuclei, of the order of 20 excited rotational bands can be resolved. They are generally well described by a rotating mean field, although interactions at crossings between them point beyond the mean field description [1, 2]. The splitting of the rotational strength occurring at crossings can be considered as precursor of the fragmentation of the rotational decay, known as the damping of the rotational motion [3]. In fact, the mixing among rotational bands, leading to the damping phenomenon, has been described as governed by a two-body residual interaction which has to include high multiple terms [4, 5].

Above the very low temperature region, containing the resolved bands, the rotational motion can be studied by analyzing unresolved γ-rays, especially the landscape [6] and the fluctuations [7] of double (two-dimensional) coincidence spectra. In this note, we present the first fluctuation analysis of rotational energy correlations extending over several decay steps. Such correlated decay sequences are especially emphasized in triple (three-dimensional) γ-ray coincidences. In the context of the band mixing model [4], this yields more precise information on the strength of the residual interaction.

For this purpose we made use of a high statistics data set on ^{168}Yb nuclei produced by the EUROGAM I array, consisting of 45 large Ge detectors, each surrounded by a BGO shield [8]. The ^{168}Yb nuclei were produced in excited states of high angular momentum by the reaction ^{124}Sn(^{48}Ca,xn)$^{172-x}$Yb, at a beam energy of 210 MeV and with a ^{124}Sn target consisting of two unbacked stacked foils each of thickness 0.5 mg/cm^2. Approximately 8×10^8 coincidence events of suppressed fold $\geq$3 were collected [9].

The data have been sorted into a two-dimensional (2D) high-resolution matrix of 4k×4k ch^2, with 0.5 keV/ch, gated on the three lowest lying transition of ^{168}Yb, selecting in the best possible way the final nucleus. In addition, a three-dimensional (3D) low resolution cube of 400×400×400 ch^3, with 4 keV/ch, has been sorted without requiring any gating condition, in order to be able to use the entire statistics of the experiment. Both 2D and 3D spectra have been background subtracted by the COR method, with a background reduction factor of 0.4 and 0.5, respectively [7].

The coincidences carrying rotational energy correlations form ridges in both 2D and 3D spectra. By cutting out slices of the 3D cube, centered at *tilted rotational planes* , the ridges are picked out and much enhanced compared to the background of uncorrelated coincidences.

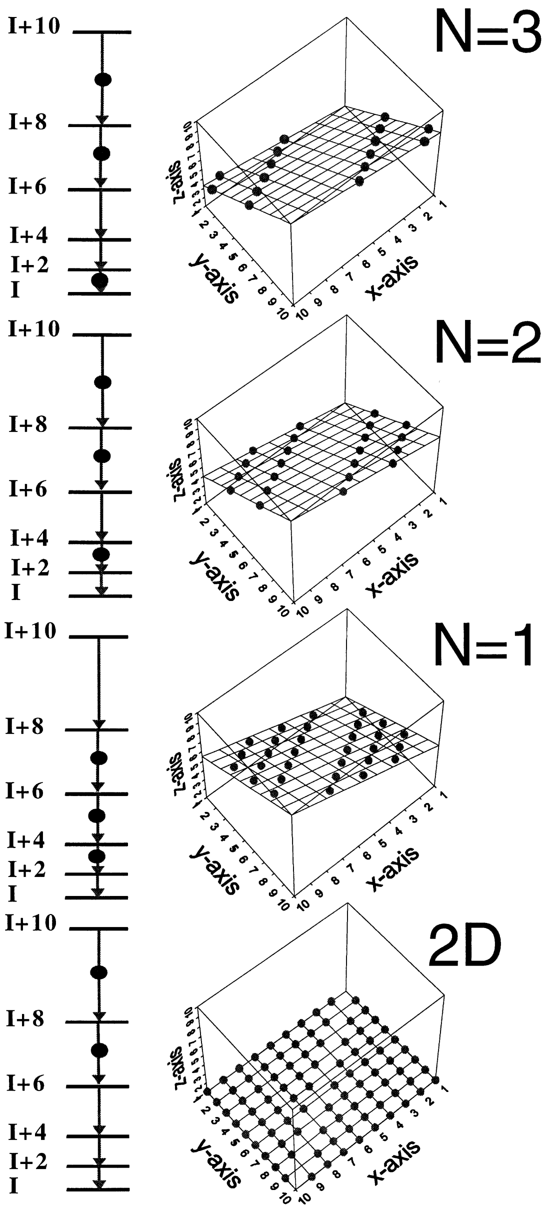

Fig. 1. Schematic illustration of the rotational correlation patterns forming ridges in both the 2D (bottom) and 3D tilted rotational planes defined by equation (1), with N=1, 2 and 3. The coincidence combinations selected by the different planes are indicated by circles in the rotational cascades shown in the left hand side of the figure

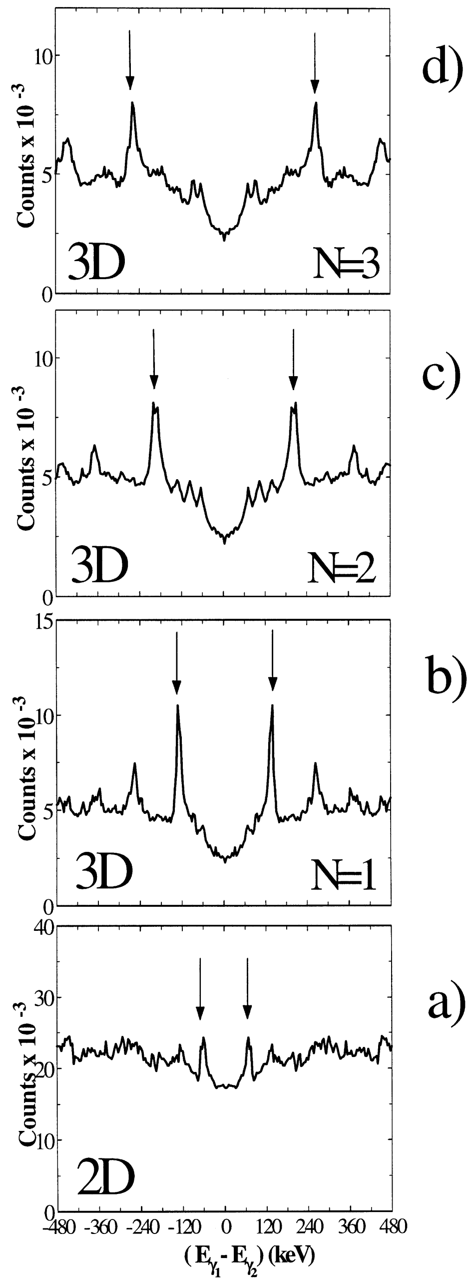

Fig. 2. Perpendicular cuts 60 keV wide at the average transition energy $<E_\gamma> = 900$ keV, on the 2D matrix (a) and on the tilted rotational planes obeying equation (1), with N=1, 2 and 3 (part b), c) and d)) in ^{168}Yb. The rotational structures analyzed by the fluctuation method are indicated by arrows

Each rotational plane, defined by the equation

$$E_{\gamma_1} - E_{\gamma_3} = N \times (E_{\gamma_3} - E_{\gamma_2}) \pm \delta/2 \qquad (1)$$

with N=1,2,3, ... [6], selects different types of coincidences along rotational bands, as schematically shown in Figure 1. The N=1 plane will contain three consecutive γ-ray transitions, or γ-ray number 1, 3 and 5 out of five consecutive, etc. The N=2 plane will contain γ-ray number 1, 3 and 4 out of four consecutive transitions, and so on. In our case the planes were produced with a thickness of slices $\delta \approx 12$ keV, allowing for some irregularities in the energy sequence.

Figure 2 shows typical perpendicular cuts with a width $\Delta E_\gamma = 4\hbar^2/\Im^{(2)} \approx 60$ keV at $< E_\gamma >= 900$ keV, on the final 2D spectrum (a) and on the symmetrized tilted rotational planes (only N=1 is in fact born symmetric), defined by equation (1) with N=1,2 and 3 (part b), c) and d)). As one can see, the ridge structures in the 3D planes are significantly stronger than in the 2D spectrum, as expected. The correlated 3D ridges clearly stand out on the background of damped, statistical and Compton scattered

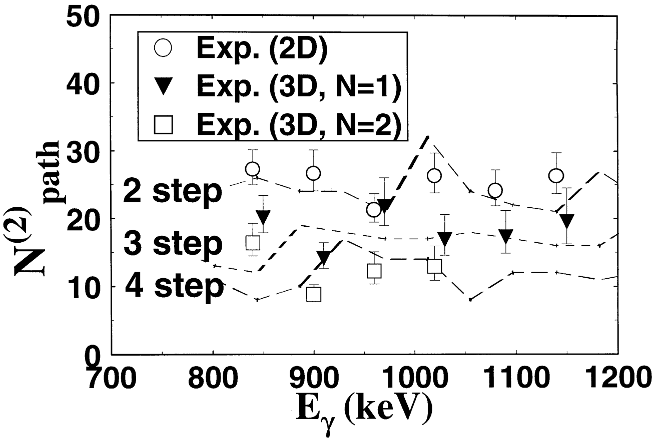

Fig. 3. Number of discrete rotational bands 2, 3 and 4 steps long (points) as function of transition energy, as obtained from the fluctuation analysis of the experimental ridge structures of ^{168}Yb. The lines correspond to predictions from cranked shell model calculation plus a two-body residual interaction, with interaction strength V_0=27.5/A MeV [4]

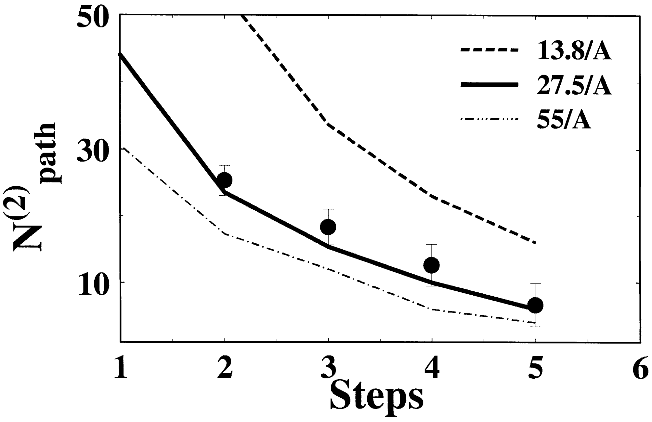

Fig. 4. The average number of bands obtained from the experimental analysis of the measured ridge structures of ^{168}Yb as function of the number of decay steps (points), in comparison with the prediction from cranked shell model calculations plus a two-body residual interaction with interaction strength V_0=13.8/A, 27.5/A and 55/A MeV (lines)

transitions. Each 3D ridge contains typically about 20000 counts within the energy interval ΔE_γ=60 keV.

A statistical analysis of the fluctuation of counts in two-dimensional spectra has been used to study the ridge structures of both the 2D spectrum and the tilted rotational planes with N=1,2 and 3 [7]. The fluctuation analysis of the ridges allows to determine the number N_{path} of regular rotational paths 2 or more steps long.

Before the statistical method is applied, all discrete peaks known from previous analysis of the level scheme [9] have been removed from both the 2D and the 3D spectra, making use of the Radware software programs [10], in order to obtain a better estimate of the unresolved paths [7]. Figure 3 shows the total number of paths (adding back also the known discrete bands), as obtained from the analysis of the first ridge of the 2D matrix (2 step paths) and from the N=1 and 2 tilted rotational planes (3 and 4 step paths), as function of transition energy. In the case of the tilted plane analysis, N_{path} has been multiplied by the factor 0.35, calculated in accordance with the fluctuation analysis as $\Sigma_i f_i^2$, being f_i the relative intensity population of the main reaction channels. In this way one takes care of the contributions from the other nuclei (mainly ^{167,169}Yb) present in the 3D matrix. As one can see from the figure, a fewer number of regular rotational bands is found when the length of the cascade is increased. This is caused by the fragmentation of the E2 strength at band crossing, which destroys the rotational energy correlations (expressed by equation (1)).

The experimental data shown in Fig. 3 are compared to the number of discrete bands 2, 3 and 4 steps long, as obtained from microscopic cranked shell model calculations including an effective two-body residual interaction of surface delta type (SDI), with standard strength V_0=27.5/A MeV (lines in the figure) [4]. As one can see, the agreement found between data and calculations seems very convincing.

In order to test the sensitivity to the strength of the SDI residual interaction used in the model, the calculation have been repeated, using interaction strengths equal to 13.8/A and 55/A MeV, respectively. Figure 4 displays the number of paths averaged over transition energy, as function of the cascade length, for the data as well for the calculations with different interaction strength. Again, a good agreement between data and calculations is found using the standard interaction strength V_0=27.5/A MeV.

In conclusion, the study of the *tilted rotational planes* from triple γ coincidence matrices has shown an enhanced experimental sensitivity to the ridge structures formed by unresolved regular rotational cascades. This has allowed, for the first time, to determine the number of discrete bands, as function of the length of the cascades . Such quantity has been used to determine the strength of the two-body residual interaction which is known to strongly affect the properties of the nuclear many body system at finite temperature.

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