Study of the Order-to-Chaos transition in $^{174}$W with the AGATA-Demonstrator

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Abstract. The transition between order and chaos is studied in the warm rotating nucleus $^{174}$W by $\gamma$-spectroscopy, focusing on the conservation of selection rules of the $K$ quantum number with the excitation energy, where $K$ is the projection of the total angular momentum on the symmetry axis. The $^{174}$W nucleus was populated by the fusion-evaporation reaction of $^{50}$Ti (at 217 MeV) on a $^{128}$Te backed target. The measurement was performed in July 2010 at Legnaro National Laboratories of INFN using the AGATA Demonstrator HPGe-array coupled to an array of 27 BaF$_2$ scintillators, named Helena. The data analysis concentrates on $\gamma$-$\gamma$ coincidence matrices selecting the $\gamma$-decay flow populating low-$K$ and high-$K$ structures. By a statistical fluctuation analysis the total number of low-$K$ and high-$K$ bands can be evaluated as a function of excitation energy. Comparisons with cranked shell model calculations at finite temperature are used to extract information on the onset of the chaotic regime as a function of excitation energy.

1. Introduction
The transition between order and chaos in a quantum mechanical system is a very fascinating subject that is currently investigated in different research fields, ranging from nuclear to atomic, molecular and solid-state physics.

Warm rotating nuclei produced at high spin by heavy-ion fusion-evaporation reactions give
the possibility to investigate this topic in nuclear physics. In fact, close to the yrast line (at temperature $T \sim 0$), the nucleus behaves as an ordered system with well-defined quantum numbers and associated selection rules. Moving toward higher excitation energy, energy levels start to interact giving rise to a gradual loss of selection rules. As a consequence, quantum numbers lose their meaning with temperature. The extreme regime is the chaotic region of the compound nucleus, where only energy, spin and parity are well defined for each energy level. The weakening of the selection rules with temperature can be studied focusing on the $K$-quantum number (i.e. the projection of the total angular momentum on the symmetry axis). Close to the yrast line $K$ is a well-defined quantum number, and low-$K$ and high-$K$ $\gamma$-decay flows are well-distinguished. As the internal energy increases, a statistical $K$-mixing process takes place, due to the high density of states. Therefore, by studying the $\gamma$-decay flow in coincidence with low-$K$ and high-$K$ states in the large region between the cold regime close to the yrast line and the chaotic compound nucleus levels, information on the order-to-chaos transition can be obtained [1].

The nucleus $^{163}$Er is the only investigated case [2], giving indication of a gradual transition between order and chaos at around 2.5 MeV of excitation energy. Therefore, additional experimental investigations are needed and an interesting case is represented by the $^{174}$W nucleus [3], here discussed. In particular, $^{174}$W is characterized by the existence of low-$K$ ($\sim$3-4) and high-$K$ ($\sim$8-12) rotational bands extending up to spin $39\hbar$, with two high-$K$ bands ($K=8$ and $K=12$) built on isomeric states, with lifetimes larger than 120 ns.

Preliminary results from an experiment performed in July 2010 at Legnaro National Laboratory of INFN, using the first phase of the Advanced GAmma Tracking Array (AGATA) [4], coupled to a multiplicity filter of 27 BaF$_2$ scintillators (the Helena array), will be presented in this contribution. The experimental data will be compared to Cranked Shell Model calculations at finite temperature for the specific nucleus $^{174}$W [5].

2. Experimental details

The $^{174}$W nucleus has been populated by the fusion-evaporation reaction of $^{50}$Ti (at 217 MeV) on a $^{128}$Te target (1 mg/cm$^2$ thick, backed by 50 mg/cm$^2$ of natPb). The reaction is expected to reach spins as high as $\sim$60$\hbar$ and energy of $\sim$4 MeV above the yrast line, therefore providing a good population of the warm rotational regime.

The experimental setup consisted of four triple clusters of the AGATA HPGe-array (i.e. the AGATA Demonstrator) placed at 16 cm from the target (with an absolute efficiency of $\sim$5% at 1.3 MeV), coupled with an array of 27 BaF$_2$ scintillator detectors, covering $\sim$25% of the total solid angle.

To probe the gradual weakening of selection rules of the $K$-quantum number, $\gamma$-$\gamma$ matrices selecting low-$K$ and high-$K$ structures have been constructed and analyzed by statistical fluctuation techniques [6]. This allows to estimate the number of low-$K$ and high-$K$ bands and their correlations, as a function of excitation energy. In particular, the selection of low-$K$ and high-$K$ transitions will require the use of both prompt and delayed $\gamma$ coincidences with respect to a time reference given by the Helena array. Furthermore, the scintillator array helps focusing on the high-multiplicity and high-energy part of the $\gamma$-cascades, where the full transition into the chaotic regime is expected to take place.

3. Preliminary results

The experiment was performed with an average current of 1 pnA (in order to prevent target damage), requiring as trigger conditions either four-fold events in AGATA or three-fold events in AGATA in coincidence with at least one event in Helena, since the analysis is concentrated on $\gamma$-$\gamma$ matrices.

The first part of the data analysis has been focused on the presorting of the data: all detectors
have been carefully calibrated in a very wide energy-range: an AmBe(Ni) source, which provides calibration lines up to 9 MeV, has been used for both AGATA and Helena energy-calibrations; in addition 3 other sources were used (i.e. $^{137}$Cs, $^{60}$Co and $^{88}$Y) to have low-energy calibration point for the scintillator spectra. Time-difference spectra between the 12 AGATA detectors have been constructed and carefully aligned, resulting in a time resolution of the order of 20 ns. A tracking algorithm has been applied to the calibrated Ge energies in order to reduce the Compton scattering and improve the peak-to-background ratio of the AGATA array. In figure 1 we show a comparison between a $\gamma$-ray spectrum constructed using only the core electrode signals (raw data) and the energy spectrum obtained after applying the tracking procedure [4].

![Figure 1](image1.png)

**Figure 1.** Comparison between $\gamma$-ray spectra before and after the $\gamma$-ray tracking procedure. The strong peaks correspond to the $\gamma$-transitions of the yrast line of $^{174}$W. The inset shows the Ge fold distribution.

One can notice the large reduction of low-energy background events, resulting in a significant improvement of the peak-to-background ratio. The inset of figure 1 shows the Ge fold distribution, which is found to be peaked around 3, an essential requirement for the data analysis based on $\gamma$-$\gamma$ matrices.

The Helena array has been mainly used as a multiplicity filter. To enhance the selectivity to the $^{174}$W nucleus and to focus on the high-multiplicity and high-energy part of the $\gamma$-cascades (where the transition into the chaotic regime is expected to take place) the fold and sum-energy measured in Helena have been used.

![Figure 2](image2.png)

**Figure 2.** Comparison between the sum-energy spectra obtained for $^{174}$W (black line) and $^{173}$W (grey filled) nuclei. The inset shows the Helena fold distribution for the two nuclei.

Figure 2 shows the sum-energy and fold distributions of the Helena array, in coincidence with

![Figure 3](image3.png)

**Figure 3.** BaF$_2$ scintillators time spectrum. The red lines denote the limits for the prompt and delayed time-gate, used in the subsequent data-analysis.
low spin transitions of $^{174}$W and $^{173}$W. These are the two main evaporation channels open in the reaction, with relative intensity of the order of 40% and 50%, respectively. As expected, the sum-energy and fold distributions associated to $^{174}$W are peaked at higher values, indicating the possibility to favor the selection of this type of events by requiring an high-fold and high-sum energy gating condition. Based on these considerations and since the sum-energy information is not so selective, we have chosen as a discrimination condition for the further analysis, fold$_{Helena} \geq 4$. The time information of the Helena array has also been used, the time-spectra of each BaF$_2$ detector (constructed with respect to the trigger signal) have been aligned to each other. Figure 3 shows the Helena time spectrum, evidencing the regions of prompt and delayed $\gamma$-events, the latter ones being mainly associated to high-$K$ transitions built on isomeric states.

Since the intensity of $\gamma$-rays belonging to high-$K$ states is very weak, they can not be used as a gate in energy to build $\gamma\gamma$ matrices, because the selectivity would be too poor. An alternative way to proceed is selecting these high-$K$ bands through the long lived isomeric gammas, associated to their decay. This possibility has been confirmed by the following: i) by gating on the delayed part of the time spectrum, the isomeric $\gamma$ transitions associated to the decay of the high-$K$ bands show an increased intensity, while contributions from prompt $\gamma$-rays are largely suppressed (see figure 4); ii) when gating on the energy of isomeric $\gamma$-transitions the corresponding time spectrum shows an enhanced bump in the delayed region (as shown in the inset of figure 4) as compared to the time-spectrum gated on energy of prompt $\gamma$-rays.

These results clearly indicate that we can use time-gate instead of energy-gate to select the contribution of high-$K$ bands from the total decay flux. Therefore two different $\gamma\gamma$ matrices have been built: the first with gate on prompt transitions in the Helena array, the second requiring delayed gammas in the scintillators. The obtained matrices show in both cases a ridge-valley structure typical of rotational nuclei: the ridges are populated by discrete bands close to the yrast line (ordered region), the valley by $\gamma$ transitions from the warmer regime, where band mixing sets in (onset of chaos). Before performing any further analysis the uncorrelated background (e.g. Compton scattered $\gamma$-rays) and the discrete resolved lines have been subtracted [6]. Figure 5 shows projections at the average transition energy of 820 keV of the matrices built with gate on prompt (on the left) and delayed transitions (on the right). The corresponding ridge structure are populated by the total discrete bands and the high-$K$ bands only, respectively. A quantitative study of the ridge structure of both matrices can be performed by a statistical fluctuation analysis [6], providing the total number of bands of $^{174}$W and the number of bands of high-$K$ nature.
Figure 5. Projections of $\gamma$-$\gamma$ matrices built with gate on prompt (on the left) and delayed (on the right) transitions at the average transition energy of 820 keV. The observed ridge structures have in both cases a separation of $2 \times 4h^2/\Im^{(2)} \approx 120$ keV, where $\Im^{(2)}$ is the dynamical moment of inertia of the discrete rotational bands.

Figure 6. The number of discrete paths (regular bands) obtained by the statistical fluctuation analysis of the ridge structures of $^{174}$W. Blue squares indicate the total number of bands (after correction for contaminants of $^{173}$W and $^{175}$W in the region $E_\gamma \approx 650-800$ keV), red circles refer to discrete bands of high-$K$ nature. The dashed line is the prediction of the Cranked Shell Model for the total number of discrete bands, averaged over the 20-50$h$ spin region.

Figure 6 shows very preliminary results about the experimental number of bands for the $^{174}$W nucleus, as a function of the transition energy $E_\gamma$. We find that there are $\sim$35-40 bands in total (that is the sum of low-$K$ and high-$K$ contribution) (blue squares) out of which roughly half are of high-$K$ nature (red circles). This is similar to what was previously obtained for the $^{163}$Er nucleus [2]. In addition, the results for the total number of bands in $^{174}$W are in quite good agreement with preliminary Cranked Shell Model calculation [5] (dashed line in figure 6).

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