High-lying collective rotational states in Ba nuclei: Search for Jacobi Shape Transition.

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Abstract. The features of the symmetric reaction ^{64}Ni+^{64}Ni at 255 MeV are studied in detail making use of the high-fold coincidence γ-ray measurement made with the Euroball array. In the measurement the array was equipped with a 3π InnerBall of BGO used as a multiplicity filter and with 8 large volume BaF_2 detectors to measure the high energy γ-rays with Eγ > 3 MeV, emitted by the Giant Dipole Resonance built on excited states. The main focus of this contribution is the study of the E2 continuum emitted by the high-lying rotational states that feed the low-lying discrete transitions. The average transition energy of the continuous distribution was obtained as a function of spin and compared with the liquid drop predictions including the Jacobi phase transition.

1- Introduction

The existence of hyperdeformed shapes in nuclei at very high angular momenta has been predicted in several nuclei and the possibility to populate such exotic nuclear shapes has motivated a number of experiments which have been recently performed. In particular, this search has been one of the primary goals of the experimental activity at the highly efficient arrays Euroball and Gammasphere.

The first investigations concerning nuclei in the rare earth regions (^{168}Yb and $^{166\text{-}168}$Hf) clearly indicated that this search is much harder than expected and that the first important step is the understanding of the population and the decay mechanisms [1]. Only through this work one expects to be able to choose the best candidates and to develop the most suitable analysis techniques which can exploit in the best way the present experimental sensitivity.

In this connection the use of symmetric reactions is known to be a good tool because they populate compound nuclei at high spins after the evaporation of only one or two neutrons. This point is rather important because the hyperdeformed configurations are expected to exist only in a rather narrow spin window (5-6 ħ in the case of nuclei in the A=150 mass region) and therefore one has to minimize the angular momentum removed by the particle emission. The spin window has the lower limit equal to the value of the yrast crossing between normal deformed and hyperdeformed states while the upper limit is defined by the crossing between the neutron binding energy at high spin and the energy of the fission barrier.

In this contribution we focus on the study of the properties of the reaction ^{64}Ni +^{64}Ni at the bombarding energy of 255 MeV. This reaction fulfills two important requirements for the search of hyperdeformation namely the population of the nucleus at high spins but yet below the fission limit, and the yrast-crossing predicted to be at the lowest possible spin as compared to nuclei with heavier masses. According to calculations of Dudek and Pomorski [2] the residual nucleus ^{126}Ba, populated after 2 neutron emission, is expected to become hyperdeformed at around 68ħ while the fission barrier becomes zero at spin larger than 74 ħ.

In contrast to the nuclei in the rare earth region, for nuclei in the mass region 120-150 the spin interval at which hyperdeformation could be populated is in fact expected to be wider. In addition, the recent calculations based on the Lublin-Strasbourg-liquid Drop (LSD) model by Dudek and Pomorski [2] have shown the expected Jacobi transition region (from oblate to prolate) very clearly in the case of nuclei such as ^{126}Ba, ^{126}Xe and ^{144}Nd in contrast with the ^{168}Hf nucleus whose shape goes from normally deformed to fission without going through a Jacobi stability. It is believed that the Jacobi stability is very important for the population dynamics, since these potentials are valid also at much higher temperatures, where the population takes place, and the Jacobi transition might work as a gateway to lower-lying discrete structures.

In fig.1 the LSD predictions for the evolution of the liquid drop potential as a function of the spin is displayed. The Jacobi transition is clearly visible from spin 68 and becomes a stable minimum in the spin region I = 74-84 ħ. The nucleus survives up to spin 84 ħ where fission sets in.

2- The Experiment

The γ-rays emitted by the reaction ^{64}Ni +^{64}Ni were measured using the Euroball-IVarray [3] placed at the IRES laboratory in Strasbourg. For this experiment a particular configuration of the Euroball system has been used, in which 8 large BaF_2 detectors (the HECTOR array) replaced the forward 1π tapered Ge detector. The InnerBall of BGO covered a solid angle equal to 3π. In addition 4 small BaF_2 detectors were placed at the closest possible distance from the target to be used as start detector for time of flight measurement of the large volume BaF_2 detectors, allowing a good timing and therefore excellent neutron discrimination. The data set obtained with this set up allows to perform a rather complete study of the decay of the hot nucleus, as the E1 decay from the GDR, probing the shapes of the compound nucleus, was measured together with the E2 continuum, measuring the properties of the fast rotating warm residual nuclei. Finally the decay at the lower spin, giving rise to the discrete transitions, allows to investigate the intrinsic configurations of each specific state.

In the present contribution we concentrate mainly on the reaction properties as a function of angular momentum and on the E2 rotational continuum that in this nucleus has not yet been studied and it is important since it is the gateway to populate discrete configurations. The relevant open question in this connection is whether or not one can

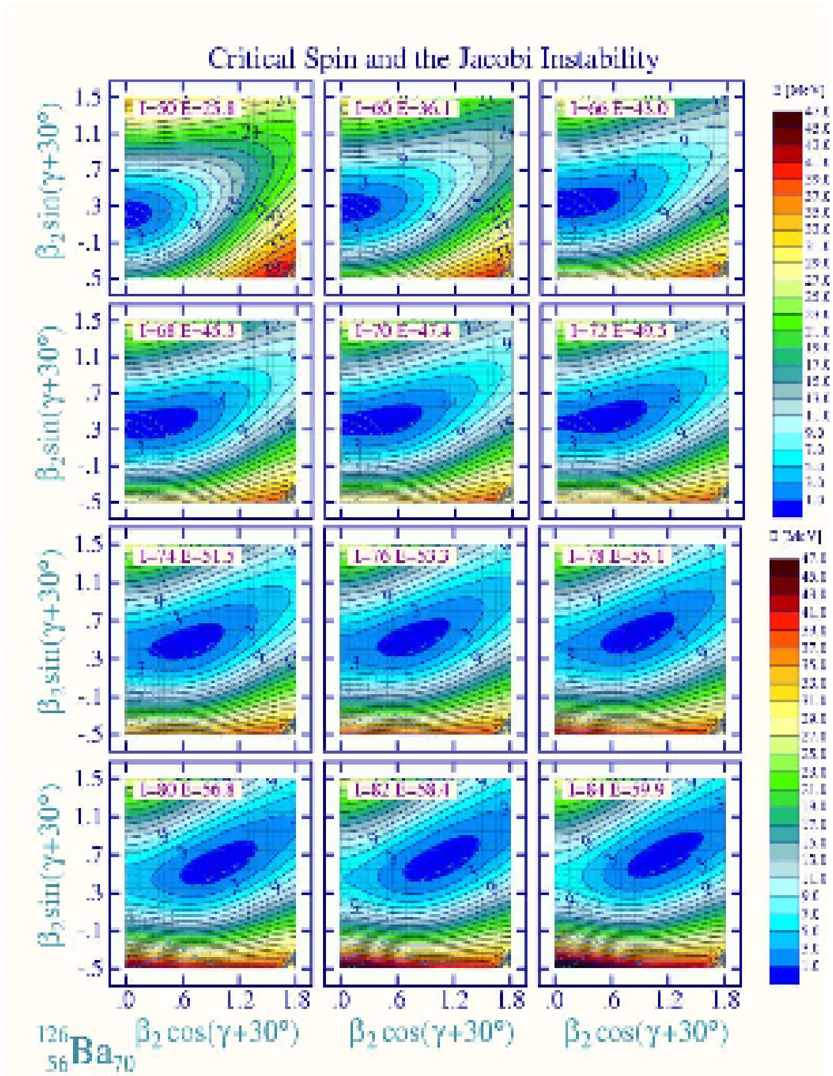

Figure 1 Liquid drop potential as a function of the deformation parameters calculated for ^{126}Ba with the Dudek and Pomoroski LSD model corresponding to different values of the nuclear angular momentum. The Jacobi transition is clearly visible above spin 68 ħ.

find evidence for the expected Jacobi shape transition.

We first studied the excitation function for the two reactions ^{64}Ni+^{64}Ni → ^{126}Ba+2n and ^{64}Ni+^{65}Cu → ^{126}Ba+p2n, to ensure that the absolutely highest spin region in ^{126}Ba was populated. In figure 2a) the fold distribution of γ-ray measured in the array is shown for the reaction ^{64}Ni+^{64}Ni →^{126}Ba+2n at 3 different bombarding energies. One can note that in the case of the bombarding energies 255 and 261 MeV the two distributions are rather similar in the region of interest, namely folds 25-35, while it is lower in the case of bombarding energy 245 MeV. This finding supports the saturation of the maximum angular momentum imparted by the reaction which according to the grazing model of Pollarolo and Winter [4] is predicted to be at 76ħ.

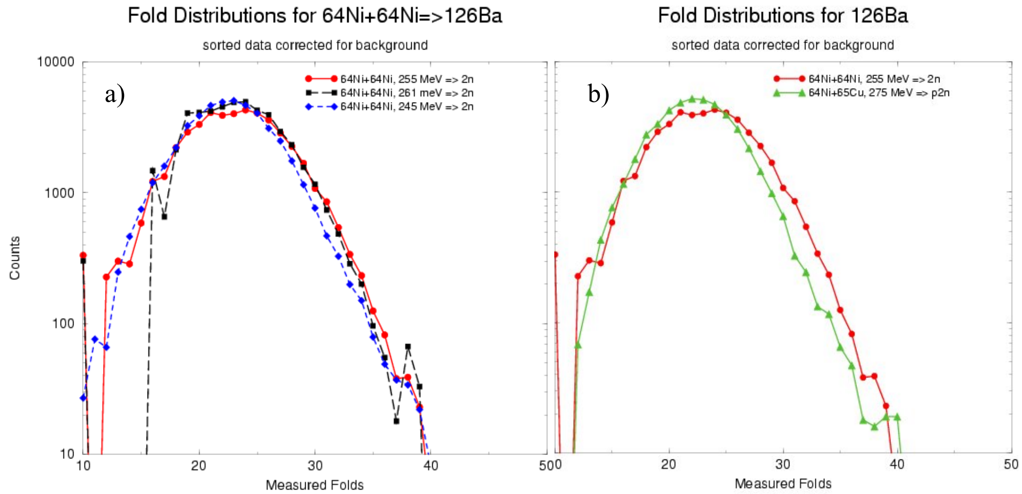

Figure 2 Panel a) shows the measured fold distribution for the reaction ^{64}Ni+^{64}Ni, gated on the 2n residue ^{126}Ba, at three different bombarding energies: 255 MeV (full line), 261 MeV (dashed line) and 245 MeV (dotted line). In the case of bombarding energy 255 and 261 MeV the two distributions are similar at high fold values, showing the saturation of the angular momentum. Panel b) shows the measured fold distribution for the two reactions ^{64}Ni+^{64}Ni at 255 MeV (circles) and ^{64}Ni+^{65}Cu at 275 MeV (triangles), gated on the ^{126}Ba nucleus, which is the 2n residue for the first and the p2n channel for the second reaction. The circles are above the triangles for high values of the fold, region of interest for the present work

Moreover the comparison of the fold distributions for the two different reactions ^{64}Ni+^{64}Ni $\rightarrow$ ^{126}Ba+2n and ^{64}Ni+^{65}Cu$\rightarrow$^{126}Ba+p2n (fig.2b)) clearly shows that fewer particle evaporation channels have to be preferred for the search of such weak structures since the residual nucleus is left in this case with a higher angular momentum.

The fold selection has been applied to high resolution spectra in order to determine the dependence of the different evaporation channels on the measured γ-rays coincidence fold.

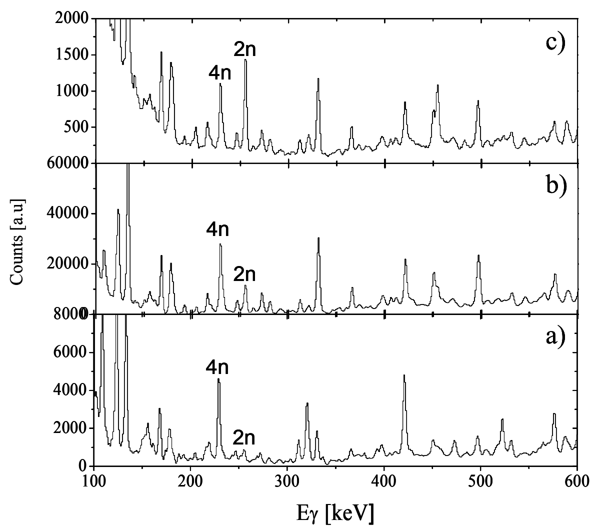

Figure 3 Experimental gamma-ray spectra gated on different fold values: panel a) corresponds to fold 9, panel b) to fold 20 and panel c) to fold 30, respectively. The transition from the first excited state to the ground state for the 2n and 4n channels are shown. The population of the 2n channel increases with increasing fold and correspondingly the 4n population decreases. All the spectra have been corrected for the efficiency of the detectors.

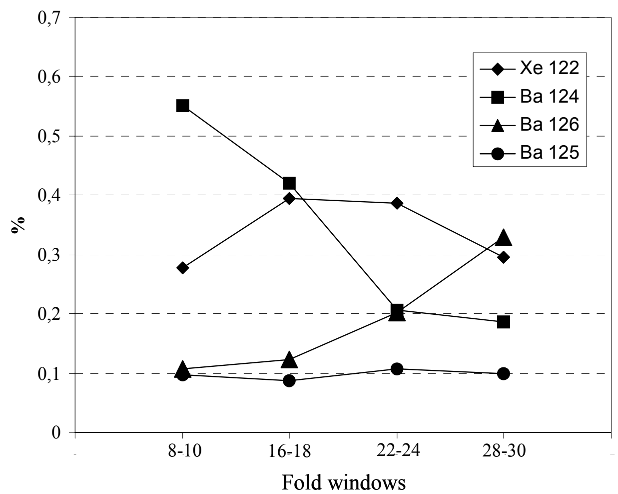

Figure 4 Population of a number of residual nuclei corresponding to different evaporation channels as a function of gamma coincidence fold. The value is the ratio of the population of the transition between the first excited and the ground state over the total yield for every fold window, expressed in percent. The population of the 4n (^{124}Ba) is shown with full squares, of the 2n (^{126}Ba) with full triangles, of the α2n (^{122}Xe) with full diamonds and of 3n (^{125}Ba) with full circles.

In fig.3 three spectra are shown corresponding to different values of the measured folds, namely 9, 20 and 30 (panels a), b) and c), respectively). The value of 30 is the largest that can be used, as the higher folds are strongly contaminated due to pile-up effects. One can observe that indeed the population of the 2n channel leading to the ^{126}Ba residual nucleus increases by a factor of 3, so that by gating on high fold one is able to select the ^{126}Ba nucleus in a rather clean way, and to reduce considerably the presence of intense transitions from the other channels.

In fig.4 the relative population of the residual nuclei $^{124-126}$Ba and ^{122}Xe are shown. They are obtained from the intensity of the decay from the first excited state in these nuclei. From the fact that the 4n channel (^{124}Ba)decreases by a factor of 3 by going at high spins it is clear that the high fold selection corresponds also to a selection of the compound nuclei with the lowest excitation energy and therefore to those emitting fewer nucleons.

3- The Rotational E2 Continuum

The spectral shape of the one dimensional spectra in the energy interval 1000-2500 keV shows a continuous distribution whose intensity is increasing as a function of the increasing fold measured in the multiplicity filter. This behavior is typical of the E2 stretch transitions from highly excited rotational states in the continuum as found in the rare earth region and at high spins in the mass region A =110 [5].

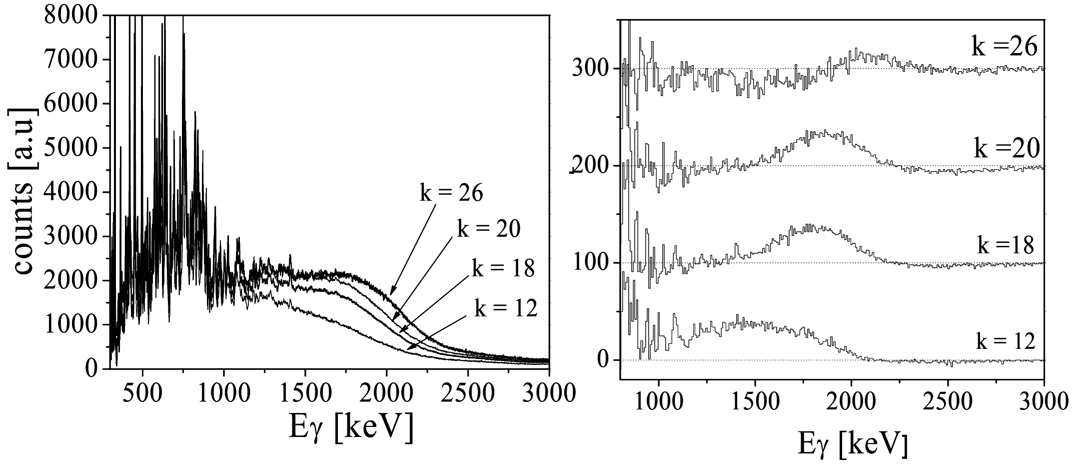

Figure 5 In the left panel the gamma-ray spectra gated on different fold values (as indicated by the arrows) are shown. The spectra are unfolded, corrected for the efficiency and the E1 tail at high energy has been subtracted. They are then normalized to each other at the 299 keV line of ^{124}Ba. In the right panel the spectra obtained as difference among spectra associated to different folds (namely $S_{fold} - S_{fold-1}$) are displayed. The centroids of these bumps are moving toward higher transition energy at increasing fold

In fig.5 the measured spectra associated to coincidence fold values 12, 18, 20 and 26 are shown. The spectra were corrected for Compton events by unfolding with the response function as measured with radioactive sources and for the efficiency. The contribution of the statistical E1 decay was also subtracted.

The difference spectra ($S_{Fold} - S_{Fold-1}$) are displayed in fig.5 right panel. The centroid of these distributions is moving toward higher values as the coincidence fold distribution increases, pointing to a very clear rotational behavior.

In order to compare the present results with the theory of Dudek and Pomorski, we have to convert the fold value into angular momentum. We have then measured the response function of the array using a ^{60}Co source from which a matrix has been derived that converts the measured coincidence folds in multiplicity. In this response also the Ge detectors were included with their relative weight determined by their solid angles and efficiency. The conversion from multiplicity to angular momentum was done using the expression L=2*(M-4), where L is the angular momentum and M the multiplicity. The systematic error for this conversion maybe as high as 4 ħ.

In fig.6 the present results are shown in comparison with the predictions [6] for ^{126}Ba. One can note a rather good agreement between data and predictions which include the Jacobi shape transition that occurs at around spin 70 ħ. From this finding one cannot exclude the effect of the Jacobi transition in the shape of the nucleus at high spin in the warm region probed by the continuum E2 transitions. This kind of behavior has been found also in this mass region by the Berkeley group [7,8].

Data extending even at higher spin would be desirable to draw more firmly the conclusion of Jacobi shapes in these nuclei.

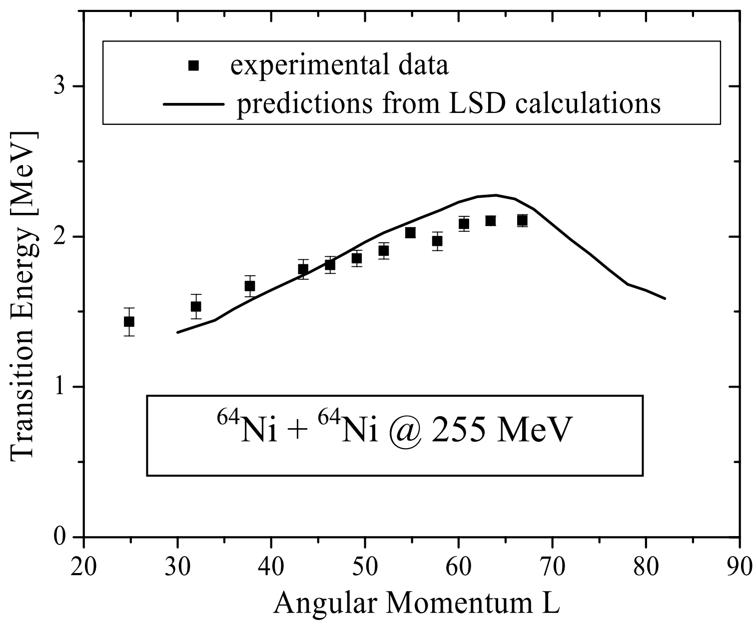

Figure 6 The value of the average gamma transition energy for the transitions in the E2 continuum obtained as described in the text. The full drawn line is the calculation [5] based on the liquid drop model of reference [2]. The fall down in the energy with spin corresponds to the Jacobi transition.

4- Conclusion

The decay of the reaction $^{64}Ni + ^{64}Ni$ has been measured with the Euroball array. The main features of the reaction mechanisms were studied as a function of spin. The 2n decay channel leading to the residual nucleus ^{126}Ba, of particular interest for the search of hyperdeformed nuclear shapes, has been found to be populated at very high spin (>60ħ) and with a population intensity which increases by a factor of 3 by going from low to the very high spins.

A rather intense E2 bump formed by unresolved transitions emitted by the warm fast rotating nuclei has been found. The E2 bump increases in intensity and in its average energy as expected from the rotational behavior of the continuum.

The deduced average energy of the E2 transitions in the continuum as a function of angular momentum is well reproduced by liquid drop calculations including the Jacobi shape transition. A clear and firm evidence of the Jacobi shape transition needs more data particularly at high spins. In addition, if this Jacobi shapes are formed at high nuclear temperatures they are expected to be seen in the high energy spectra of the decay of the Giant Dipole Resonance. This seems to be the case for the nucleus ^{46}Ti at very high spins [9]. The analysis of the GDR will be undertaken in the near future and is expected to shed more light on this interesting problem.

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