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WARM NUCLEI: NUCLEAR STRUCTURE EFFECTS ON THE ORDER-TO-CHAOS TRANSITION REGION*

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The γ-decay from the warm rotation in the transition region between order and chaos is studied in the superdeformed (SD) nuclei ^{151}Tb and ^{196}Pb, using the EUROBALL IV array. A number of observables, testing the decay dynamics in the SD well, are compared with predictions from a Monte Carlo simulation of the γ-decay based on microscopic calculations of discrete levels and decay probabilities. Agreement with the data is found only assuming an enhancement of the B(E1) strength around 1 MeV by a factor of 10–100, which is consistent with the evidence for octupole vibrations in both mass regions. The work shows the relevance of γ-spectroscopy in the order-to-chaos regime to highlight specific nuclear structure effects.

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1. Introduction

The γ-decay cooling the hot compound nucleus at high angular momentum is a tool for investigating the transition from the chaotic compound nucleus regime to the ordered system close to the yrast line [1-7]. This topic

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becomes particularly challenging in the case of superdeformed (SD) systems, where one has to focus on a fraction of the γ-decay which is at the level of few % only. This is why only few SD nuclei have been comprehensively studied experimentally, basing the data interpretation on very schematic or parameter dependent models [8-13].

In this work we present the analysis of the population and decay of the warm SD nuclei ^{151}Tb and ^{196}Pb, which are representative of the mass regions $A = 150$ and $A = 190$. In particular, from the analysis of quasi-continuum (QC) γ-spectra several independent observables are extracted, providing strong experimental constraints on the dynamics of the γ-decay flow and of the tunneling through the potential barriers between SD and normal deformed (ND) excited states, over the entire available spin range. The data are interpreted using a newly developed Monte Carlo simulation of the γ-cascades in the SD well. This is based on discrete levels calculated microscopically with the cranked shell model of Ref. [13] and penetration probabilities across the barrier separating the SD and ND states also microscopically calculated with the model of Ref. [14]. The work demonstrates the importance of a detailed study of the order-to-chaos region for testing the basic properties of cranked shell model calculations as a function of spin and temperature. It is also found that QC spectra collecting the population from the energy region at the onset of chaos are sensitive to nuclear structure effects, such as, in this case, enhanced octupole vibrations [15].

2. The experiments

The experiments were performed at the Vivitron in Strasbourg (F) with the EUROBALL IV array [16]. The reactions used were ^{130}Te(^{27}Al,6n)^{151}Tb (at 155 MeV) and ^{170}Er(^{30}Si,4n)^{196}Pb (at 148 MeV). In both cases, a stack of two self-supporting targets (with a total thickness of ≈ 1 and 1.2 mg/cm^2, respectively) were employed. In the Tb case, the full Ge ball was used, while in the Pb case the low efficiency Ge detectors in the forward hemisphere were replaced by 8 large volume BaF_2 scintillators to measure high energy γ-rays from the giant dipole resonance (GDR). In both cases an InnerBall of BGO crystals allowed to determine the γ-multiplicity of every event.

The SD nuclei ^{151}Tb and ^{196}Pb have been previously investigated in detail by discrete γ spectroscopy [17-19], giving evidence for a number of SD bands (up to 10 in ^{151}Tb and 4 in ^{196}Pb). Discrete transitions linking the SD yrast band to ND configurations were identified, therefore making it possible to assign the spin and excitation energy of the SD yrast [20, 21]. In the case of ^{151}Tb, the most recent spin assignment is found to be 2 spin units higher than previously reported in Ref. [17].

We report here the analysis of quasi-continuum γ-coincidence spectra, which provide information on the unresolved excited SD rotational bands [15].

This allows to study the properties of the γ-decay flow at the onset of the transition between order and chaos in the atomic nucleus [1]. For this purpose the two data sets have been sorted into a number of γ–γ matrices in coincidence with low-lying ND transitions of the isotope of interest namely $E_\gamma = 268.4, 597.4, 604.5, 615.9$ keV in ^{151}Tb (corresponding to the transitions $31/2^+ \to 29/2^+$, $19/2^+ \to 15/2^+$, $15/2^- \to 11/2^-$ and $19/2^- \to 15/2^-$) and $E_\gamma = 468, 502, 959$ keV (corresponding to the transitions $15^- \to 14^+$, $16^- \to 15^-$ and $14^+ \to 12^+$) in ^{196}Pb. These matrices have been named Total, while the spectra sorted in coincidence with the cleanest transitions of the SD yrast band of each nucleus were named SD-gated. In addition, matrices with the triple coincidence requirement $x + y = 2z$ (x, y and z being the energies of the γ-rays) were sorted in coincidence with the nucleus of interest and named rotational planes (ROT-planes) [22]. In these spectra the sensitivity to rotational correlations among discrete bands in the γ-cascades is largely enhanced as compared to a background of fragmented/uncorrelated decays. In all cases a condition on high-fold events ($F \geq 25$ for ^{151}Tb and $F \geq 10$ for ^{196}Pb) was imposed, to better focus on high-multiplicity cascades, resulting in a population of the SD yrast of the order of 2% and 1.3% of the reaction channel ^{151}Tb and ^{196}Pb, respectively. For each matrix the major part of the background has been removed accordingly to the P/T of the gating transitions. This is of the order of 0.4 (0.2) in ^{151}Tb (^{196}Pb), in the case of the ND low-lying gating transitions. In the case of the yrast SD-gated spectra the P/T was estimated to be less than 0.02. In addition, the COR procedure has been applied, with a reduction factor of ≈ 0.8 and 0.9 for the Total matrices, ≈ 0.4 and 0.3 for the Rot-planes and ≈ 0.5 and 0.75 for the SD-gated spectra of ^{151}Tb and ^{196}Pb (accordingly to the method discussed in Ref. [2,23]). The latter treatment enhances the ridge structures and also removes some uncorrelated background which may still be present after the previous background subtraction.

Fig. 1 shows examples of cuts perpendicular to the main diagonal of the γ-coincidence spectra, for the wide spin intervals $\approx 48 - 56\hbar$ (^{151}Tb) and $\approx 20 - 34\hbar$ (^{196}Pb). Panels (a) and (b) refer to Total matrices, (c) and (d) to the ROT-Planes and (e) and (f) to the SD-gated spectra. In all cases, ridge structures are clearly visible. The spacing between the two most inner ridges in (a),(b) and (e),(f) is equal to $2\Delta E_\gamma = 8\hbar^2/\Im^{(2)} \approx 100$ and 80 keV in ^{151}Tb and ^{196}Pb, respectively, where $\Im^{(2)}$ is the moment of inertia of the SD yrast band in each nucleus. The intensities of the known ND and SD discrete peaks which have been subtracted from the Total and SD-gated matrices making use of the RADWARE package [24] (before performing any further analysis of the data) are indicated by dark areas. In the case of the ROT-planes spectra ((c) and (d)) the cuts have been instead obtained by projecting the spectra in between the SD yrast peaks. In this case, the most inner ridge

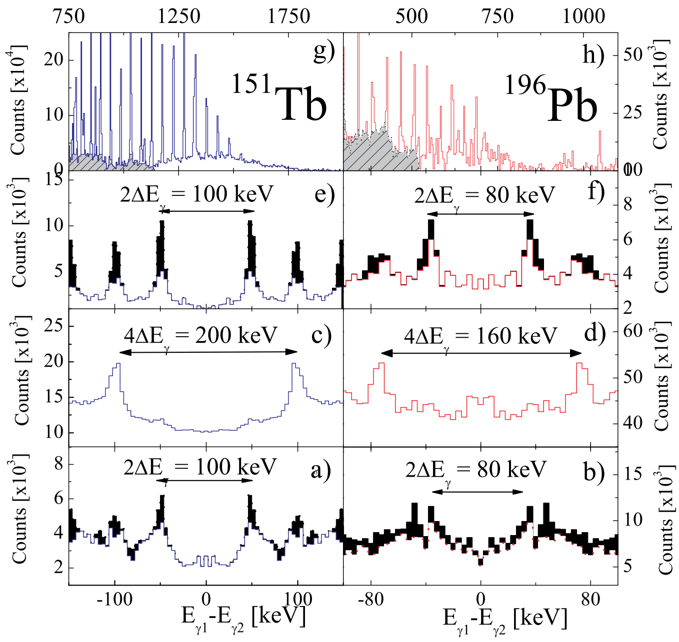

Fig. 1. Experimental spectra of ^{151}Tb (left) and ^{196}Pb (right). Panels (a) and (b) show projections perpendicular to the main diagonal of the Total γ–γ-coincidence matrices, corresponding to the spin interval 48 to 56 $\hbar$ in ^{151}Tb and 20 to 34 $\hbar$ in ^{196}Pb; panels (c), (d) on the ROT-planes and panels (e), (f) on the SD-gated spectra. The dark areas in (a)–(f) show the intensity of known ND and SD discrete peaks to be subtracted in the following analysis. The top panels (g) and (h) show one-dimensional E2 quasi-continuum spectra gated by the SD yrast of ^{151}Tb and ^{196}Pb: the shaded areas correspond to regions where contaminants from M1 transitions are expected (see text for detail).

corresponds to the second ridge in the Total and SD-gated matrices, and its spacing is therefore twice as large. The top panels (g) and (h) of Fig. 1 show one-dimensional (1D) quasi-continuum spectra double gated by the SD-yrast band of ^{151}Tb and ^{196}Pb, respectively. The spectra have been subtracted from the background and unfolded using the procedure provided by the RADWARE package. In addition, the E1 component in coincidence with the SD yrast has been removed, as previously done in the analysis of the SD nucleus ^{143}Eu [8]. The remaining spectra should therefore contain pure E2 contributions, except for possible M1's contaminants (dashed areas in panels (g) and (h)), which have been observed to be significant at low spins (*i.e.* below $\approx$ 1100 keV and $\approx$ 550 keV in ^{151}Tb and ^{196}Pb, respectively) in neighboring nuclei [10, 25, 26].

3. Experimental results

The experimental data have been analyzed in terms of intensities and fluctuations of the event distributions. In first place, the intensities of the ridge structures have been evaluated and compared to the SD yrast (shown by circles in Fig. 2(a)–(b)). In both ^{151}Tb (left) and ^{196}Pb (right) nuclei the total intensity of the 1-st (panels (a), (b)) and 2-nd ridge [15] is found to be up to 3 times larger than the population of the SD yrast at the plateau: this indicates the existence of several discrete unresolved SD bands which do not feed the SD yrast band, but decay into the low deformation minimum.

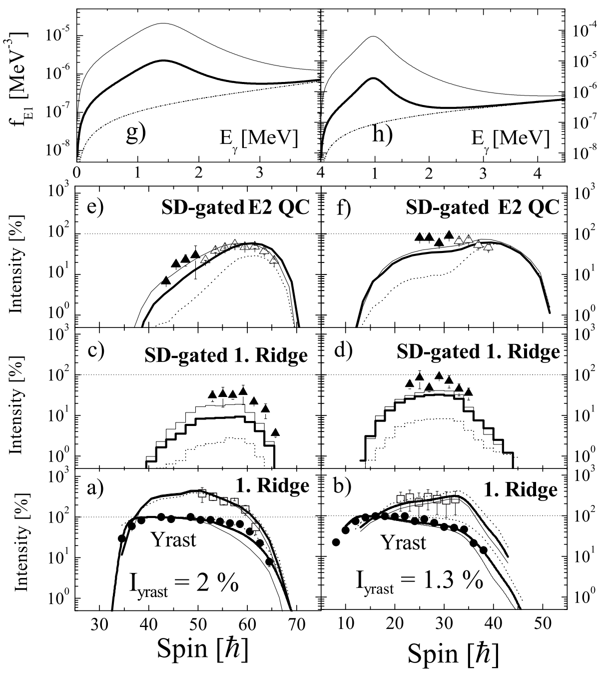

Fig. 2. The intensities of the various component of the rotational decay in the SD well of ^{151}Tb (left) and ^{196}Pb (right): the intensities of the yrast and 1-st ridge are given in panels (a),(b); panels (c),(d) refer to the SD-gated 1-st ridges, while panels (e),(f) show the SD-gated E2 QC. Data are shown by symbols, dashed (thick/thin solid) lines give predictions from simulations of the γ-decay assuming a standard (enhanced by a factor of 10/100) E1 strength (as shown in panels (g) and (h)).

The more selective analysis of 1D- and 2D-spectra in direct coincidence with the SD yrast band is shown in Fig. 2 (c)–(f). The intensity of the 1-st ridge in coincidence with the SD yrast (panels (c) and (d)) shows that only a fraction of the total population of the discrete excited bands is finally collected into the SD well, corresponding at most to 40% and 80% of the SD yrast intensity in ^{151}Tb and ^{196}Pb, respectively. This is only a part of the entire E2 population feeding into the SD yrast, which for both nuclei includes also the contribution from fragmented/damped bands at higher excitation energies, where rotational damping largely dominates [1]. This is shown by the analysis of the E2 quasi-continuum displayed in panels (e) and (f), where full symbols refer to data partially contaminated by M1's transitions. The present results differ from the peculiar case of ^{194}Hg, were exceptionally narrow ($\approx$ 10 keV) ridges have been observed, exhausting nearly all E2 decay strength, as expected in the case of ergodic nuclear systems [12]. In the present work the ridge structures are instead found to be of the order of 20(16) keV wide in the Total and SD-gated matrices, similarly to previously reported cases of ND and SD nuclei [1, 9].

More quantitative information on the properties of the γ-decay in the SD well and on the decay-out mechanisms into the ND states have been obtained by the experimental analysis of the fluctuations of counts in the γ-coincidence matrices [1, 2]. This method provides the number of discrete bands populating the ridge structures and it has been successfully applied in different region of mass and deformation [1]. The fluctuation analysis of the ridge structure of ^{151}Tb and ^{196}Pb, shown in Fig. 3, gives a rather large number of SD discrete bands (more than 30) populating the Total ridges ((a) and (b)). In addition, the study of the SD-gated ridges, shown in panels (c) and (d), indicates that only half of the discrete excited bands are feeding into the SD yrast, supporting the analysis of the ridge intensities, previously discussed.

4. Interpretation of the data

The interpretation of the experimental data is based on a Monte Carlo simulation of the γ-decay flow of ^{151}Tb and ^{196}Pb [15]. The code is an extended version of MONTESTELLA, originally developed to study the γ-decay of a warm rotating nucleus from the residual entry distribution down to the yrast band, within a well defined potential well [27]. The code can now treat the γ-decay within two potentials (*i.e.* the ND and SD wells), based on the competition between E2 collective and E1 statistical transitions in both minima and on a tunneling probability across the barrier separating the two wells calculated accordingly to the equations of Ref. [28]. In the SD well energy levels, E2 transition probabilities and potential barriers are microscopically calculated by the models of Ref. [13, 14], up to the excitation energies covered by the microscopic states. Above this region, quantities extrapolated from the region of microscopic levels are used. The γ-decay in the ND well is described schematically, as done in Ref. [8, 10], with a density of states taken from Ref. [29]. The simulation starts from an entry distribution of the nucleus of interest, which is calculated making use of the heavy ions-collision model of Ref. [30] (providing the compound nucleus fusion cross section), followed by a neutron evaporation Monte Carlo calculation, done by the code CASCADE [31]. The final entry distributions for the γ-decay of ^{151}Tb and ^{196}Pb, corrected for the experimental response of the EUROBALL IV array, are found to be centered at spin $I \approx 60$ and 40 $\hbar$ and excitation energy $U \approx 8.3$ and 7.7 MeV above yrast, respectively.

Fig. 2 shows by lines the predictions obtained by the Monte Carlo simulations for the intensities of the various SD components of the γ-coincidence spectra of ^{151}Tb and ^{196}Pb. It is found that the model reproduces well the population of the SD yrast and the more inclusive quantities, such as the intensity of the 1-st and 2-nd ridge (dotted lines in Figs. 2(a), (b) and Ref. [15]). On the contrary, the model largely underestimates the more selective data, namely the intensities of the 1-st ridge and E2 QC in direct coincidence with the SD yrast band, as shown by dotted lines in panels 2(c)–(f). These quantities are, in fact, very sensitive to the balance between E2 and E1 transitions at low excitation energy ($U < 2$ MeV in ^{196}Pb and $U < 3$ MeV ^{151}Tb), where nuclear structure still plays a role, although they refer to the onset region between order and chaos. In particular, we find that by enhancing the E1 strength by 1 to 2 order of magnitude in a limited transition energy region (between 1 and 2 MeV), as compared to the standard Lorentzian parametrization for SD nuclei [28, 33] (see solid and dashed lines in the Fig. 2(g) and (h)), much better agreement is obtained for all quantities. These results are in agreement with the experimental evidence for octupole vibrations in both $A = 150$ and 190 mass regions, resulting in strongly enhanced E1 transitions linking the excited SD bands to yrast, as in the case of SD ^{152}Dy [32], ^{196}Pb [34] and ^{190}Hg [35] nuclei, in agreement with theory [36, 37].

The number of paths $N_{\rm path}$ used by the warm SD nucleus in the cooling process can also be estimated by the model and compared to the experimental results of the fluctuation analysis, as shown in Fig. 3 by thick solid lines for the total and SD-gated 1-st ridge. $N_{\rm path}$ gives the number of discrete bands which are more strongly populated, being given by $1/\sum w_i^2$, where w_i indicates the relative population w_i of each path. $N_{\rm path}$ is determined by the level density, by the onset of damping and by the E1 versus E2 competition along the decay. As shown in panels (e) and (f) of Fig. 3, low-lying bands up to 1–1.5 MeV are strongly favored by the γ-decay flow, especially at low spins, since they both tunnel less easily through the potential barrier and also receive stronger E1 feeding. This results in a reduced number of paths, as compared to the total number of discrete bands $N_{\rm band}$ predicted by the cranked shell model ignoring the flow (dotted lines in Fig. 3(a)–(b)), even after taking into account the depopulation of the bands due to the tunneling to ND states (thin solid lines in (a)–(d)) [14].

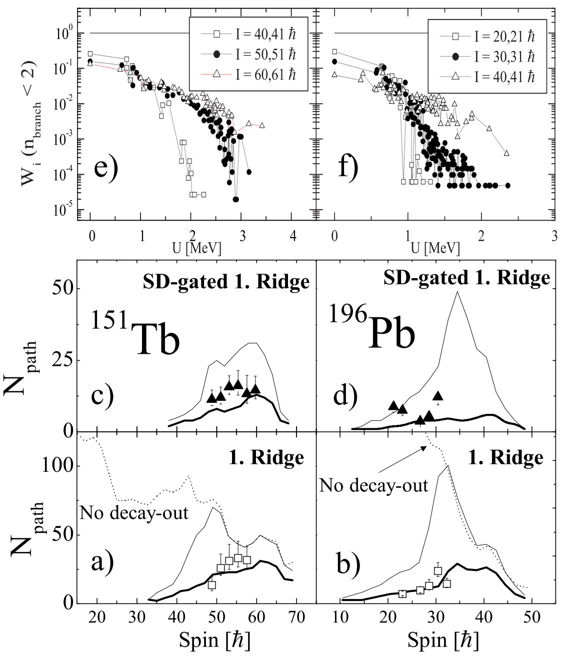

Fig. 3. Results of the analysis of the count fluctuations of the total and SD yrast-gated 1-st ridge of ^{151}Tb and ^{196}Pb are given by symbols in panels (a), (c) and (b), (d), respectively. The thick solid lines show predictions from the Monte Carlo simulation of the γ-cascades, which gives for the discrete bands of ^{151}Tb and ^{196}Pb the relative population shown in panels (e) and (f), for spins $I = 40, 50, 60\hbar$ and $I = 20, 30, 40\hbar$, respectively. The thin and dotted lines in panels (a)–(d) correspond to the number of bands calculated by the cranked shell model of Ref. [13] including or not a tunneling probability towards the ND well.

5. Conclusions

The present work deals with the study of the warm rotation in the SD nuclei ^{151}Tb and ^{196}Pb. A number of independent experimental quantities, such as the population of both discrete and fragmented SD bands and the number of excited SD rotational bands are obtained. This allows to test our understanding of the γ-decay in the SD well over the whole spin range, *i.e.* from the feeding region, down to the decay-out into the ND minimum. A key point in the data interpretation is a newly developed Monte Carlo code which simulates the γ-decay within two potential wells, namely ND and SD, on the basis of microscopic quantities for the SD configuration, clearly showing how the experimental observable are strongly affected by the cascades flow. It is found that the model can reproduce well all observables, except for the E2 strength gated on the SD yrast, which is very sensitive to the balance between the E2 and E1 decay along the γ-cascades. Agreement can be obtained only increasing the E1 strength at low excitation by one to two orders of magnitude, as compared to the standard Lorentzian parametrization for SD nuclei. This agrees with the observation, in both mass regions, of strong E1 transitions between discrete bands, which have been interpreted as octupole vibrations. The work shows how the study of the warm rotation in the transition region between order and chaos can provide valuable information on nuclear structure properties beyond mean field over a wide range of spins and excitation energies.

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