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STRONG DEFORMATION EFFECTS IN HOT ROTATING ^{46}Ti*

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Exotic-deformation effects in ^{46}Ti nucleus were investigated by analysing the high-energy γ-ray and the α-particle energy spectra. One of the experiments was performed using the charged-particle multi-detector array ICARE together with a large volume (4 in×4 in) BGO detector. The study focused on simultaneous measurement of light charged particles and γ-rays in coincidence with the evaporation residues. The experimental data show a signature of very large deformations of the compound nucleus in the Jacobi transition region at the highest spins. These results are compared to data from previous experiments performed with the HECTOR array coupled to the EUROBALL array, where it was found that the GDR strength function is highly fragmented, strongly indicating a presence of nuclei with very large deformation.

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1. Introduction

Theoretical calculations using the recent Lublin–Strasbourg Drop (LSD) model [1, 2], predict the Jacobi shape transitions in ^{46}Ti in the spin region of $I \sim 30$–$40\,\hbar$ implying an existence of the dramatic shape instability and a rapid increase in elongation corresponding to relatively small spin changes. More precisely, the nucleus changes its shape from an oblate — with the spin parallel to the symmetry axis — to an elongated prolate or triaxial shape at high spins. The results of the LSD model calculations are shown in Fig. 1, where the potential energy distributions of ^{46}Ti are plotted in the (β,γ)-plane for six selected values of spin. The minimum (shown with a circle) corresponds to the equilibrium shape of the nucleus at each given spin. The figure illustrates the energy-minimum evolution with increasing spin — the evolution path is shown in the figure with solid line. The nucleus is nearly spherical at low angular momenta; it increases its oblate deformation up to $I \approx 26\ \hbar$ where it becomes triaxial. For the highest spins, the nucleus becomes strongly elongated, it becomes nearly axial at $I \approx 38\ \hbar$ where the fission barrier amounts to ~ 6 MeV only.

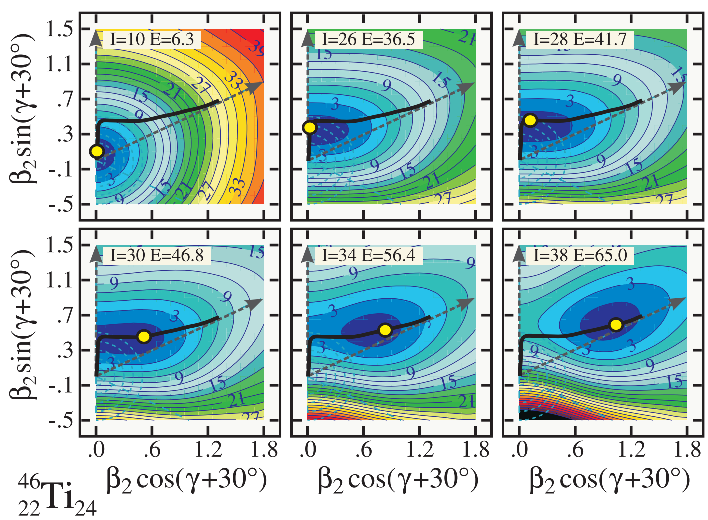

Fig. 1. Potential energies for ^{46}Ti nucleus as a functions of quadrupole β_2 and γ deformations. At each (β_2,γ)-point the energy was minimised over β_{40}, β_{60} and β_{80}. The corresponding spin values I are given in every panel together with the calculated minimum energies E.

The large deformation effects in the light-mass nuclei have been studied over the last years, using both gamma and charged-particle spectroscopy. In particular the very elongated prolate or triaxial shapes were observed from the spectra of the Giant Dipole Resonance (GDR) decay for ^{46}Ti* [3] and

^{45}Sc* [4]. Large deformations were also observed in ^{44}Ti* [5] by the measurement of light charged particle (LCP) spectra originating from the statistical decay of this compound system. Additionally, in this mass region, a number of superdeformed bands of discrete γ-ray transitions were discovered (*cf. e.g.* [6–8]).

2. The GDR from the highest spin region of the ^{46}Ti nucleus

The shape of the ^{46}Ti nucleus at high spins was first studied in the experiment [3] performed using HECTOR BaF_2 detectors [9] coupled to the EUROBALL IV HPGe detector array. The excitation energy of the ^{46}Ti nuclei, populated in the ^{18}O+^{28}Si reaction at 105 MeV bombarding energy was $E^* = 85\,\mathrm{MeV}$ and the maximum angular momentum, $L_{\max} \approx 35\hbar$. High energy γ-rays coming from the GDR decay (detected in HECTOR) were measured in coincidence with the gamma multiplicity measured in the Innerball, and with the discrete transitions in the ^{42}Ca final nucleus identified with the help of EUROBALL.

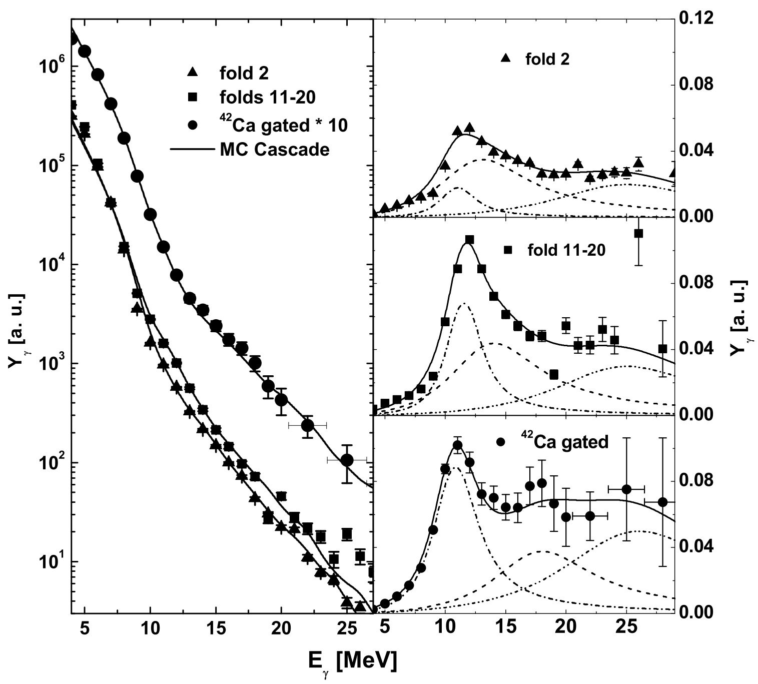

Fig. 2. Left panel: The high energy spectra measured for two regions of fold corresponding to high and low spins shown together with a spectrum gated with discrete transitions in ^{42}Ca. Right panel: The GDR strength function obtained from Monte Carlo Cascade fit to the experimental data.

We have analyzed the GDR spectra for different gamma folds (defined by the number of Innerball detectors that fired) corresponding to various spin regions. The spectra for fold = 2 and folds = 11–20 are presented in the left-hand side panel of Fig. 2 together with the high energy gamma spectrum measured in the decay channel leading to ^{42}Ca, selected by requiring coincidences with discrete transitions in this final nucleus.

To compare the GDR line-shapes (GDR strength functions) all experimental spectra were linearized, using the method described in [4], by fitting the experimental spectra with the spectra calculated by the Monte Carlo version of the statistical model code CASCADE [10]. The GDR strength functions, obtained from the fit to the experimental data measured for different folds (the top and middle right-hand panel of Fig. 2), show a fragmented structure with a low energy component growing with spin together with two broad components at significantly higher energies. Similar line-shape of the GDR (the bottom right-hand panel of Fig. 2), but with an even larger splitting, was obtained for the high energy spectra gated by the discrete transitions in ^{42}Ca [3]. It was demonstrated (see [3]) that choosing this decay channel we select the Ti compound nuclei of the highest spins such that the splitting of the GDR strength is the largest possible, as shown in Fig. 2.

In Fig. 3 the experimental ^{42}Ca gated strength function is shown again and compared to the LSD model calculations for two different spin regions: $I \leq 24\,\hbar$ — governed mostly by oblate shapes and $I = 28$–$34\,\hbar$ pointing to strongly elongated prolate shapes ($\beta \approx 0.8$) in the upper Jacobi transition region just below the fission limit [11]. One should note that the limiting angular momentum for fusion is predicted by the Finite-Range Liquid Drop Model (FRLDM), consistent with LSD [1,2]), to be around 35 $\hbar$ in agreement with experimental data [11]. A significant Coriolis splitting at high spin was included in these calculations similarly as in Refs. [2,3].

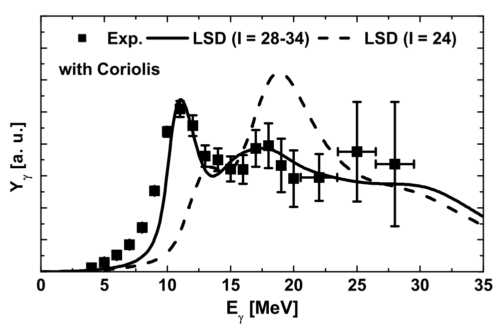

Fig. 3. The experimental GDR strength function obtained in Ref. [3] from data gated by discrete transitions in ^{42}Ca (points) compared to LSD model calculations obtained for two spin regions shown by dashed line ($I = 24\hbar$) and solid line ($I = 28$–$34\,\hbar$).

The GDR line-shape calculated for the Jacobi shape transition region is in good agreement with the experimental data proving the existence and importance of the Jacobi shape transition and the strong Coriolis effect. Our estimates give the splitting of the two GDR components by $\Delta E \approx 5\,\mathrm{MeV}$. Such strong Coriolis effect on a GDR spectrum was observed for the first time in the experiment presented in Ref. [3].

3. Deformation studied by the charged-particle spectra

The very large deformations presented in the previous section for ^{46}Ti at high angular momentum, are also suggested in the following by the present study of the α-particle spectra measured in the experiment performed at the Strasbourg Vivitron tandem facility using the multi-detector array ICARE [5, 12] together with a large volume ($4\,\mathrm{in}\times 4\,\mathrm{in}$) BGO detector. The compound nucleus ^{46}Ti was populated at the excitation energy of $E^* = 85\,\mathrm{MeV}$ and at angular momenta approaching $L_{\max} \approx 35\,\hbar$. The latter angular momentum limit was similar to the one reached in the experiment discussed above; it is close to the fission limit predicted by the FRLDM [11], except for the inverse kinematics reaction corresponding to 144 MeV ^{27}Al beam on ^{19}F target. The heavy fragments were detected in 10 telescopes, each consisting of an ionisation chamber (IC) followed by a 500μm Si detector, located at $\Theta_{\mathrm{Lab}} = \pm 10^\circ$ in three reaction planes. The light charged particles were measured using 10 triple telescopes (40μm Si, 300 μm Si, 2 cm CsI(Tl)) and 18 two-element telescopes (40μm Si, 2 cm CsI(Tl)) [13, 14].

The energy spectra of the α-particles emitted in the laboratory frame at the angle $\Theta_{\mathrm{Lab}} = 45^\circ$ in coincidence with the residual nuclei of $Z = 18$, 19 and 20 are shown in the top panel of Fig. 4 by solid points. The bottom panel presents the angular correlations of the α-particles with the evaporation residues (ER) of $Z = 18$, 19 and 20 detected in the IC placed at $\Theta_{\mathrm{Lab}} = -10^\circ$. The lines are the results of the analysis performed using the code CACARIZO [15], the LCP Monte Carlo version of the statistical model code CASCADE [10], for several hypotheses concerning the yrast line.

The high energy part of the α-particle spectra depends on the final state level density. The level density is calculated in the code using the Rotating Liquid Drop Model (RLDM) [10] and can be changed using different sets of deformation parameters describing the yrast line in question. In the code, the yrast line is parameterized by the numerical values of r_0, δ_1 and δ_2 and described by the formula: $E_L = \hbar^2 L(L+1)/2\,\mathcal{J}_{\mathrm{eff}}$ where $\Im_{\mathrm{eff}}$ denotes the effective moment of inertia defined as $\Im_{\mathrm{eff}} = \Im_{\mathrm{sphere}}(1 + \delta_1 L^2 + \delta_2 L^4)$ and $\Im_{\mathrm{sphere}} = (2/5) A^{5/3} r_0^2$ is the rigid body moment of inertia of the spherical nucleus; r_0 is the radius parameter (see Ref. [15] for more details).

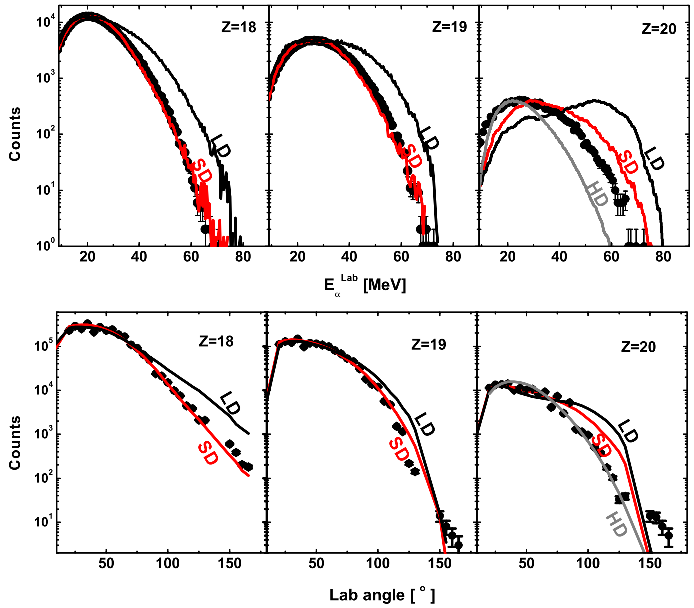

Fig. 4. Top panel: The α-particle experimental spectra measured at $\Theta_{\mathrm{Lab}} = 45°$ in laboratory frame (from Ref. [14]). Bottom panel: The α-particle angular correlations measured in laboratory frame in coincidence with residues detected at $\Theta_{\mathrm{Lab}} = -10°$. The lines presented in both panels are statistical model calculations performed for different deformation parameters as explained in the text.

In Fig. 5, the yrast lines used in the CACARIZO calculations are displayed as solid lines. The standard RLDM yrast line (shown as "liquid drop") can be approximated by the rigid body yrast line with small deformation ($\beta = 0.2$). The calculated α-particle spectra and angular correlations obtained for this parameterization, denoted as "LD", do not reproduce the experimental spectra.

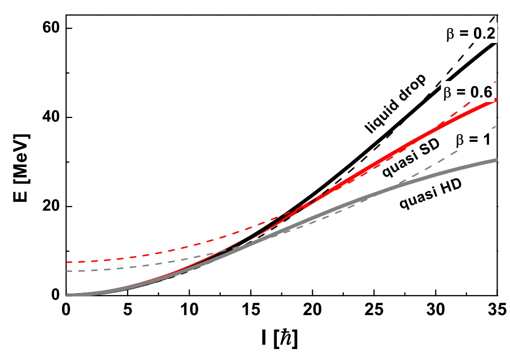

Fig. 5. The yrast lines implemented in the calculations (from Ref. [14]).

The yrast line, denoted quasi-superdeformed ("quasi SD"), corresponds to the spin region $I = 15$–$30\,\hbar$ for the yrast line of the rigid body with deformation parameter $\beta \approx 0.6$. Actually, the yrast line with the same deformation parameters was deduced from a reasonable description of the α-particle decay of ^{44}Ti [5]. The calculations with this parameterization, shown as "SD", reproduce the experimental spectra for $Z = 18$ and $Z = 19$ while the spectra associated with $Z = 20$ still deviate significantly from the model results. In order to improve the agreement for $Z = 20$ we have been forced to assume an even more deformed yrast line. In this calculation, the yrast line labeled in Fig. 5 "quasi HD" was used [this label was used as the corresponding line resembles the yrast line for the rigid body with a deformation parameter $\beta \approx 1$ (for $I = 15$–$30\,\hbar$)]. However, the "HD" calculations (shown in Fig. 4) underestimate the experimental data of energy distributions in this case, pointing to deformations between $\beta = 0.6$ and 1, while the simulated angular correlations agree completely with the data.

4. Discussion of the results

A possible explanations of such an anomalously large deformation, that may seem unrealistic, can be related to the time scale of the evaporation process.

When many particles are evaporated, the time needed for this process can be long enough, such that it is sufficient for the residual nucleus to adjust its initial "Jacobi shape" (with $\beta \approx 1$) to smaller deformations ($\beta \approx 0.6$) at lower temperatures and spins. The effective level density of the final states has to be described by a different deformation as for the initial Jacobi shapes, *i.e.* by the quasi-superdeformed yrast line.

However, for $Z = 20$, with only a single α-particle emission, the process time may be too short to change the shape. Therefore, the yrast line describing such nucleus may lie between the quasi-hyperdeformed yrast line (with $\beta \approx 1$), describing the initial Jacobi shapes, and a quasi-superdeformed yrast line (with $\beta \approx 0.6$), describing the final states. The deformation of a nucleus visualised in the spectra of α-particles emitted during the process of changing the shape of a nucleus may be considered to be *"dynamical hyperdeformation"*. Similar result was in fact observed in the α-particle spectra from the decay of ^{59}Cu [16].

Another explanation related to the evaporation time scale may be considered, inspired by the angular distributions of charged particles measured by the EUCLIDES array during the HECTOR + EUROBALL experiment [3].

The angular distributions measured in the laboratory frame for different fold windows were normalized to the one measured at fold region 5–10, and converted to the center of mass. Fig. 6 shows such relative angular distributions of protons and α-particles for different fold regions, obtained in coincidence with the low energy transitions in ^{42}Ca simultaneously measured in EUROBALL Ge-array. In the case of protons one can see that for the highest folds (highest average spin) the distribution becomes symmetric around 90°, as expected for evaporation from the collectively rotating, deformed nucleus.

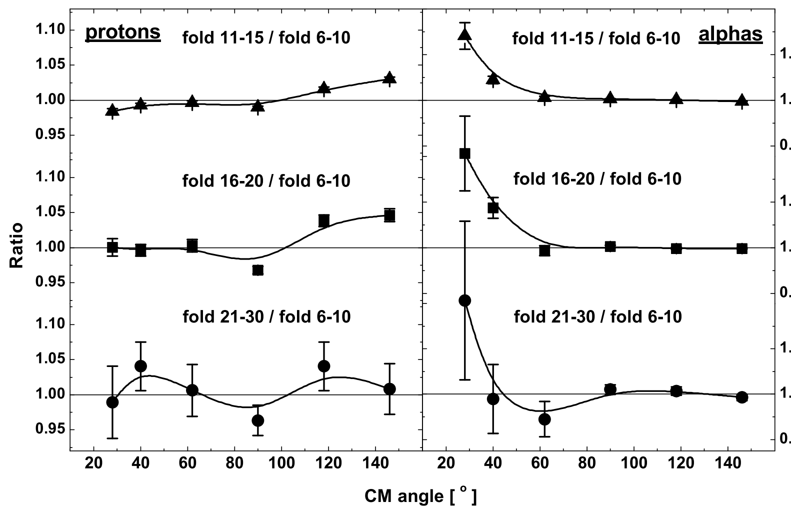

Fig. 6. The angular distributions of protons and α-particles, measured using the EUCLIDES array. The experimental data are represented with points. The solid lines are to guide the eye.

In contrast, for the α-particles the angular distributions obtained are not symmetric and show forward peak at high spins. This suggests a *pre-equilibrium emission* of α-particles, or perhaps even an incomplete fusion process. Such equilibration process, taking place especially for a mass-symmetric reaction and at highest spins, is usually characterized by extended, "di-nuclear" systems and by relatively long times (up to 10^{-19} s) [18]. If an α-particle is emitted during this equilibration process, its emission may in a natural way be described by the large deformations (with $\beta \approx 1$) of the "di-nuclear" systems. Similar effect may also have been observed in the much heavier symmetric fusion reaction ^{64}Ni + ^{64}Ni leading to hyperdeformed quasi-continuum states in the $A = 125$ region [19].

5. Summary

The deformation effects in ^{46}Ti were investigated in high energy γ-ray GDR decay as well as with the α-particle energy and angular distribution measurements. All of them show large deformation of the ^{46}Ti compound nucleus at high spins as predicted by the theoretical calculations of Fig. 1 performed within the LSD model [1, 2] and consistent with the SD bands recently discovered in this light-mass region [6–8].

The obtained angular distributions confirm the results of the measurements of the α-particle energy spectra. The α-particles emitted from hot rotating ^{46}Ti compound nuclei point to large deformations ($\beta \approx 0.6$) involved in the evaporation process. In the case of a single α-particle emission an even larger deformation ($\beta \approx 1$) is suggested. This may be interpreted as an effect of *dynamical hyperdeformation* or *pre-equilibrium emission* of an α-particle from a "di-nuclear system".

The high energy γ-ray spectra measured in the HECTOR + EUROBALL experiment definitely show a strongly fragmented structure with the low energy component growing with increasing spin and a broad part at higher energies. Such line-shape of the GDR corresponds to the expected Jacobi shape transition including the enhanced splitting by the Coriolis interaction at high spin. In addition, it was found that the low energy GDR component seems to feed preferentially the superdeformed band in ^{42}Ca [20, 21]. This suggests that the very deformed shapes after the Jacobi shape transition in the hot compound nucleus remain during the evaporation process, especially if it proceeds via the single α-particle emission channel, feeding ^{42}Ca.

Clearly, the Jacobi shape transition in the compound nucleus plays an important role in population of very elongated rapidly rotating cold nuclei, as was proposed in [22].

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