

Evidence for the Jacobi shape transition in hot ^{46}Ti

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The γ -rays from the decay of the GDR in the compound nucleus reaction $^{18}\text{O}+^{28}\text{Si}$ at bombarding energy of 105 MeV have been measured in an experiment using a setup consisting of the combined EUROBALL IV, HECTOR and EUCLIDES arrays. The shape of the rotating compound nucleus, ^{46}Ti , is expected to undergo the Jacobi transition around spin $28\hbar$. A comparison of the GDR lineshape data with the predictions of the thermal shape fluctuation model, based on the most recent rotating liquid drop LSD calculations, shows evidence for such Jacobi shape transition. In addition to the previously found broad structure in the GDR lineshape region at 18–25 MeV caused by large deformations, the presence of a low energy component (around 10 MeV), due to the Coriolis splitting in prolate, well deformed shape has been identified for the first time.

1. INTRODUCTION

The Jacobi shape transition, an abrupt change of nuclear shape from an oblate ellipsoid non-collectively rotating around its symmetry axis, to an elongated prolate or triaxial

shape, rotating collectively around the shortest axis has been predicted to appear in many nuclei at angular momenta close to the fission limit [1,2]. Signatures of the presence of elongated shapes can be found, among others, in the γ -decay of the Giant Dipole Resonance (GDR), in the giant back-bend of the $E2$ γ -transition energies [3] and in the angular distribution of the emitted charged particles.

Until now, however, a firm experimental evidence for the Jacobi shape transition in nuclei could not be established. Some indications of such elongated shapes were obtained in the studies of the GDR decay from $^{45}\text{Sc}^*$ [4] and $^{46}\text{Ti}^*$ [5] compound nuclei. In the case of $^{45}\text{Sc}^*$, the GDR measurement was inclusive, while for $^{46}\text{Ti}^*$ it was more exclusive, namely it was associated with various γ -multiplicity values. However, in both studies other explanations, as for example contribution from fission could not be completely ruled out.

In order to address in more detail the problem of the Jacobi shape transition focusing on the GDR γ -decay, a new highly selective experiment for $^{46}\text{Ti}^*$ was performed. To obtain high energy γ -ray spectra associated with fusion-evaporation reaction and free from contribution of fission products and/or other non-fusion reactions, the restrictive conditions of gating on well-known discrete lines of the evaporation residual nuclei were applied.

In this paper we report on some new results concerning the measurement of the high energy γ -rays with very stringent conditions selecting the highest part of the spin distribution.

The following section describes the experiment and the data analysis. The discussion of the results presented here focuses for the first time on the importance of the Coriolis splitting of the GDR components at the high rotational frequencies that can be reached only in light nuclei.

2. THE EXPERIMENT

The experiment was performed at the VIVITRON accelerator of the IReS Laboratory, Strasbourg (France), using the EUROBALL IV Ge-array coupled to the HECTOR array [6] and the charged particle detector EUCLIDES. The ^{46}Ti compound nucleus was populated in the $^{18}\text{O}+^{28}\text{Si}$ reaction at 105 MeV bombarding energy. The excitation energy of the ^{46}Ti nuclei was 86 MeV and the maximum angular momentum $l_{\text{max}} \approx 35 \hbar$. For this experiment, the EUROBALL consisted of 26 germanium clover and 15 cluster detectors (all with the BGO anti-Compton shields), and 75% of the Inner-ball (83 BGO crystals) which together with the germanium detectors resulted in 65% efficiency for the multiplicity determination. The 8 large volume BaF_2 detectors of the HECTOR were placed in the forward hemisphere, together with 4 small BaF_2 detectors which provided a good time reference signal. The EUCLIDES consisted of 40 silicon telescope detectors covering approximately 90% of the solid angle. Only events having at least 2 Compton suppressed Ge signals and one high-energy γ -ray were accepted. A total number of 10^8 events were collected, in which the γ -ray energy in any BaF_2 detector was larger than 4 MeV.

Figure 1 shows two measured high-energy γ -ray spectra. The first, displayed by the histogram, corresponds to the selection of γ -fold in the interval 11–20, as measured in the Innerball. The second spectrum, showed with filled squares, was obtained with the

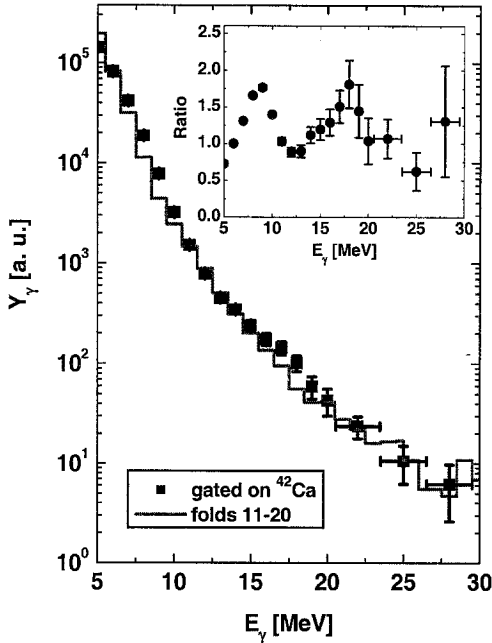


Figure 1. Two high-energy γ -ray spectra measured with the HECTOR BaF₂-detectors: one is gated by the Innerball folds 11–20 (histogram) and the other is additionally gated by the discrete transitions in ^{42}Ca measured in the EUROBALL Ge-detectors (filled squares). The inset shows the ratio of these two spectra.

additional simultaneous selection of clean and well resolved low energy γ -ray transitions of ^{42}Ca in the Ge-detectors of the EUROBALL array. This particular residual nucleus was expected to be populated only in the decay from the highest spin region of the compound nucleus and, therefore, by gating on it we obtained data corresponding to the highest spins and free from fission contaminations. The two spectra, normalized at $E_\gamma = 6$ MeV, show differences in the two regions: around $E_\gamma = 9$ MeV and around $E_\gamma = 17$ MeV, where evident yield excesses were found in the germanium gated spectrum. These excesses are better evidenced in the inset to Figure 1, which shows the ratio of the two measured spectra.

3. THE STATISTICAL MODEL ANALYSIS

The statistical model analysis was made for the high energy γ -spectrum gated by the discrete transitions in ^{42}Ca . This spectrum, being associated with a selected evaporation channel, was analyzed using the CASCADE code based on the Monte-Carlo technique. This, in fact, allows to select only those decay chains which lead to the population of a specific residual nucleus.

The used Monte Carlo version of the CASCADE code, previously employed for the analysis of the heavier mass data [7,8], was implemented for this mass region by choosing the most appropriate values of the statistical model parameters (e.g. level density was assumed to be in accordance with Reisdorf prescription [9], the yrast line was taken from the experiment and extrapolated by the liquid drop values).

In the left panel of the Figure 2, the best fit to the experimental data is shown with the

full line together with the data (filled squares). It corresponds to a GDR strength function consisting of 3 components at $E_{GDR} = 10.8, 18$ and 26 MeV exhausting approximately the entire EWSR strength. In particular, the need of a low energy component at ≈ 10 MeV

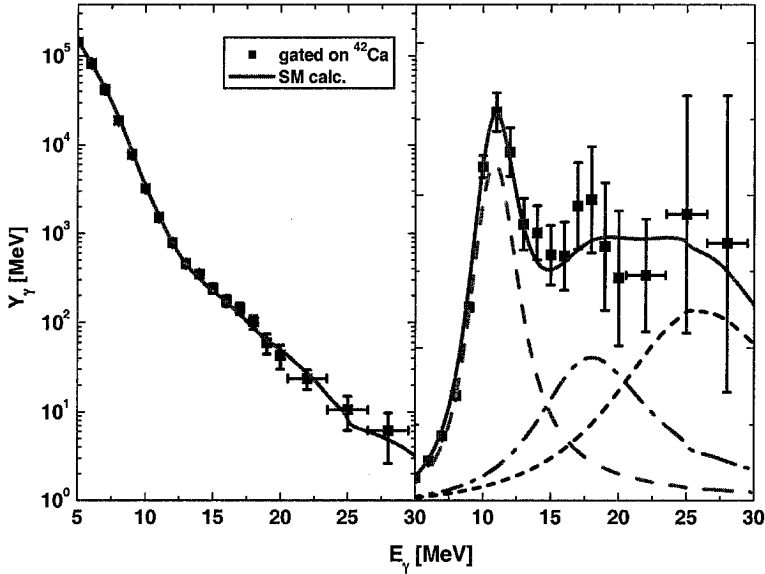


Figure 2. Left panel: The high-energy γ -ray spectrum gated by the ^{42}Ca transitions and by high fold region (already shown in Fig. 1), in comparison with the best fitting statistical model calculations (full drawn line) assuming a 3-Lorentzian GDR lineshape with energies: $E_{GDR} = 10.8(1), 18(1)$ and $26(2)$ MeV; widths: $\Gamma_{GDR} = 4.0(5), 10(1)$ and $16(3)$ MeV; and strengths: $\sigma_{GDR} = 0.35(5), 0.38(10)$ and $0.7(2)$. Right panel: The deduced experimental GDR strength function (full drawn line, see text for explanation) together with best fitting 3-Lorentzian function and its individual components.

is consistent with the fact that this spectrum has an yield excess as compared to a more inclusive spectrum (see the inset to Figure 1). The quality of the fit can be judged more clearly by inspecting the right panel of Fig. 2. This figure shows the GDR strength function data, represented by the quantity $F_{3L}(E_\gamma) * Y_\gamma^{exp}(E_\gamma) / Y_\gamma^{cal}(E_\gamma)$. In that expression $Y_\gamma^{exp}(E_\gamma)$ and $Y_\gamma^{cal}(E_\gamma)$ are the experimental and calculated spectra, respectively, shown in the left panel of Fig. 2. The best fit GDR strength function, $F_{3L}(E_\gamma)$, consists of 3-component Lorentzian function with parameters (energy, width and strength) taken from the best fit to the experimental spectrum. $F_{3L}(E_\gamma)$ and its individual components are also plotted in the figure. It should be noted, that the best fit line $F_{3L}(E_\gamma)$ corresponds to the effective nuclear shape probed by the GDR oscillations.

4. DISCUSSION

The most striking feature of our results is the presence of the excess of the γ -yield at ≈ 10 MeV, identified for the first time in this mass region. A possible explanation can be related to a mechanism such as the Coriolis splitting of the GDR lineshape controlled by the rotational frequency of the rotating nucleus. In fact, only in those light nuclei one can reach the highest values of the rotational frequency (2–3 MeV in the spin interval 20–30 $\hbar$) and in this particular experiment we are able to select them much better than in the previous rather inclusive works. Therefore, we have investigated in detail the effect of the Coriolis splitting in the GDR lineshape as a function of the spin (rotational frequency) and the quadrupole deformation type (γ) and the size (β).

The expressions connecting the GDR vibrational frequencies to the rotational frequency [10,11] of the nucleus are reported in Table 1.

Table 1

In this table we denote with ω the rotational frequency while ω_1 , ω_2 and ω_3 are the vibrational frequencies along the axis in the intrinsic frame of the nucleus. The expressions for the relative strengths of the 5 components are taken from [12].

GDR rotational frequency		Strength
$\omega = 0$	$\omega > 0$	
ω_1	ω_1	$\frac{1}{\omega_1}$
ω_2	$\Omega_2 + \omega$	$\frac{1}{\Omega_2} \frac{(\Omega_2 - \omega)^2 - 0.5(\omega_2^2 + \omega_3^2)}{2\sqrt{\Delta}}$
	$\Omega_2 - \omega$	$\frac{1}{\Omega_2} \frac{(\Omega_2 + \omega)^2 - 0.5(\omega_2^2 + \omega_3^2)}{2\sqrt{\Delta}}$
ω_3	$\Omega_3 + \omega$	$\frac{1}{\Omega_3} \frac{-(\Omega_3 - \omega)^2 - 0.5(\omega_2^2 + \omega_3^2)}{2\sqrt{\Delta}}$
	$\Omega_3 - \omega$	$\frac{1}{\Omega_3} \frac{-(\Omega_3 + \omega)^2 - 0.5(\omega_2^2 + \omega_3^2)}{2\sqrt{\Delta}}$
$\Omega_2 = \frac{\omega_2^2 + \omega_3^2}{2} + \omega^2 + \sqrt{\Delta}$ $\Omega_3 = \frac{\omega_2^2 + \omega_3^2}{2} + \omega^2 - \sqrt{\Delta}$ $\Delta = \frac{1}{4}(\omega_2^2 - \omega_3^2)^2 + 2\omega^2(\omega_2^2 + \omega_3^2)^2$		

Figure 3 shows the calculated GDR lineshapes for ^{46}Ti to emphasize how they evolve as the functions of I and β for the cases of prolate, oblate and triaxial shapes. One can clearly note that the Coriolis splitting is not affecting the oblate shapes ($\gamma = 60^\circ$). In contrast, it produces strong effects, increasing as a function of spin, in the case of triaxial

($\gamma = 30^\circ$) and especially prolate shapes ($\gamma = 0^\circ$). In particular, it produces a rather strong and narrow peak at ≈ 10 MeV for prolate and triaxial deformations with $\beta \geq 0.4$ which is similar to that we have observed in our experimental data.

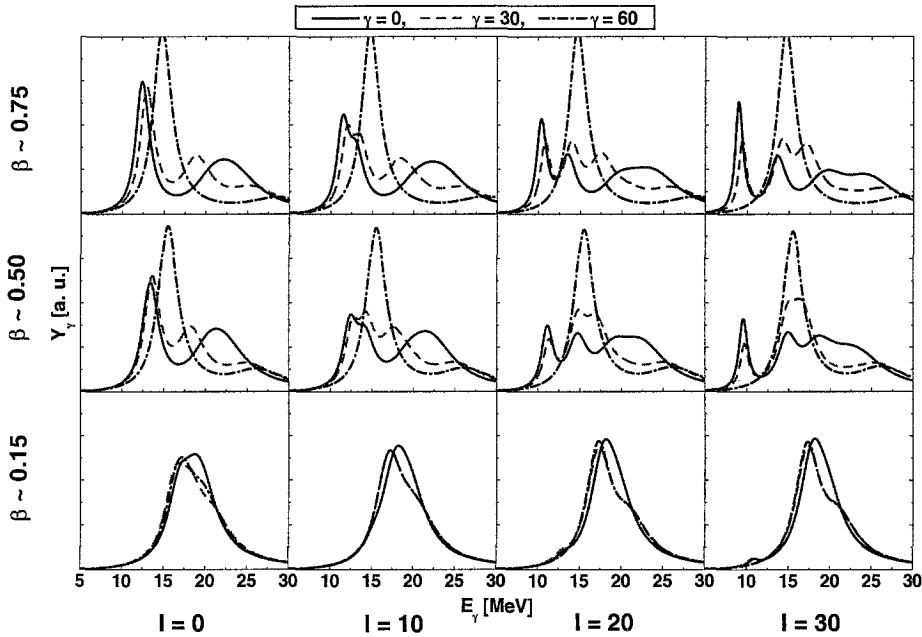


Figure 3. Calculated GDR lineshapes for ^{46}Ti assuming different types of deformation (prolate $\gamma = 0^\circ$, full drawn line; triaxial $\gamma = 30^\circ$, long-dashed line; $\gamma = 60^\circ$ oblate, dashed-dotted line) for different values of spin and quadrupole deformation size. This is to illustrate the effect of the Coriolis splitting giving rise, at highest rotational frequencies and prolate and triaxial deformations, to a component around 10 MeV.

In order to interpret the obtained GDR strength function data in the entire measured γ -ray energy region (5–30 MeV), we use the same approach as has been adopted in almost all experiments concerning the GDR in hot and rotating nuclei [13–15]. This is based on the thermal shape fluctuation model which predicts the GDR strength function corresponding to the shape ensemble probed by this collective excitation mode.

In the present case we have obtained the shape ensemble distributions (proportional to the Boltzmann factor $\exp(-F/T)$, where F is the free energy and T is the temperature) for the relevant total excitation energy (85 MeV) and for different spins using the new parametrization of the liquid drop model LSD [2].

Those calculations show that the equilibrium shape of ^{46}Ti undergoes the Jacobi transition from an oblate to a triaxial and a prolate shape for $I = 28 \hbar$. For the comparison with the experimental data at the highest spins populated in the reaction, we select the

calculations for the spin interval $28\text{--}34 \hbar$ (this corresponds to an average temperature $T = 2 \text{ MeV}$ and rotational frequency $\omega = 2.8 \text{ MeV}$). The calculations neglect shell effects, which are not expected to be important in this temperature region. The resulting GDR strength function, obtained as a weighted average (with the weight given by the Boltzmann factor) of strength functions calculated at each β, γ point (including also Coriolis effects), is displayed with the full line in Fig. 4 and compared with the experimental data. The remarkable good agreement between the theoretical predictions and the present experimental results is very much in favour of the presence of the Jacobi transition. More evidence for this transition is also given by the fact that the peak at $\approx 10 \text{ MeV}$ can originate only in the presence of a fast rotation in nuclei of prolate or triaxial shapes (see discussion at the beginning of the section). In fact, for oblate shapes, typical for the equilibrium deformation at rotational frequencies lower than the critical value for the Jacobi transition, the Coriolis splitting is always absent.

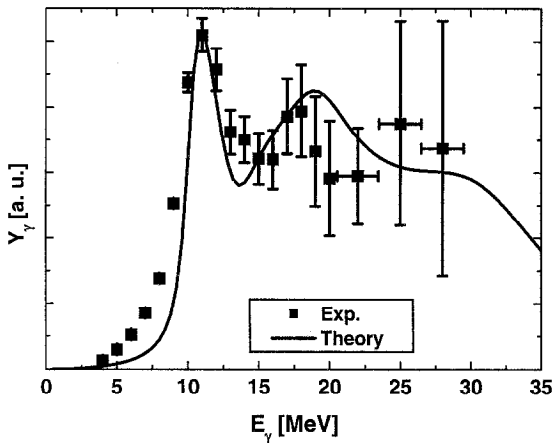


Figure 4. The full drawn line shows the theoretical prediction (at $\langle T \rangle \approx 2 \text{ MeV}$ and in the spin region $28\text{--}34 \hbar$) of the GDR lineshape in ^{46}Ti obtained from the thermal shape fluctuation model based on free energies from the LSD model calculations [2]. The filled squares are the experimental data shown also in the right panel of Figure 2.

A further signature for the Jacobi transition is the presence of two other broad components in the strength function at higher energies. One component, at $\approx 17 \text{ MeV}$, is clearly seen in the present data, while the other which is very broad (at $20\text{--}30 \text{ MeV}$) can only barely be identified because of the very limited statistics at these high energies in the present very exclusive spectrum.

In summary, the present work on the GDR γ -decay in the hot rotating nucleus, ^{46}Ti , shows evidence for the expected Jacobi shape transition. It is based on the observation of two particular features in the measured GDR strength function. The first, already found in the previous works [4,5], is the presence of a high energy component related to large deformations. The second feature, identified for the first time in the present experiment, is the appearance of a GDR component at $\approx 10 \text{ MeV}$ (in region where the statistics is very high), which is interpreted as due to the Coriolis splitting of the lowest vibrational frequency (which corresponds to the dipole vibration along the long axis of the well deformed prolate or triaxial shape) and consequently shifting down a part of the

strength. This shows the importance of the selection of high rotational frequencies and of a good tagging on fusion-evaporation events in the investigations of nuclear shapes through the GDR γ -decay.

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