PROPERTIES OF HOT NUCLEI STUDIED BY THE GDR γ-DECAY IN EXCLUSIVE EXPERIMENTS *

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Three topics concerning the γ-decay of the Giant Dipole Resonance in hot rotating nuclei from recent exclusive experiments with the HECTOR array are discussed. The first is the dependence of the GDR width in Sn nuclei as a function of angular momentum at constant temperature. The second is the search for γ-decay of the GDR build on superdeformed configurations in the ^{143}Eu nucleus. The third is the study of reaction entrance channel effects in the decay of the compound ^{170}W nucleus.

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1. Introduction

The γ-decay of the Giant Dipole Resonance (GDR) in rotating compound nuclei has provided valuable information on the nuclear structure at finite temperature, especially when the GDR properties were correlated with other, simultaneously measured, nuclear quantities. In this contribution some recent results from such exclusive GDR experiments are presented.

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In particular we focus on experiments where the high energy γ-rays from the GDR-decay were measured in coincidence with other reaction products. All the selected experiments were performed at the TANDEM+Booster accelerator facility of the Niels Bohr Institute in Risø. The heart of the experimental set-up was the HECTOR array [1]. It consists of 8 large volume BaF_2 crystals, used for measuring high energy γ-rays from the GDR decay. HECTOR was equipped with the efficient multiplicity filter HELENA (38 small BaF_2 crystals) for measuring the multiplicity of low energy γ-transitions to give information on the angular momentum of the decaying nucleus. In some experiments two position sensitive Parallel Plate Avalange Counters (PPAC) were employed, for the determination of the direction and of time of flight of the recoiling nuclei. In other experiments HECTOR+HELENA were coupled to high resolution germanium arrays NORDBALL (20 germanium detectors with anticompton BGO shields) or PEX (Pre-Euroball eXperiments), in which the discrete line γ-transitions were measured in coincidence with the high energy γ-rays from HECTOR. PEX consisted of 4 large germanium cluster detectors, each composed of seven hexagonal-faced hyperpure germanium crystals separately encapsulated, and surrounded by a large BGO anti-Compton shield. In the case of the PEX experiment described in section 4 the energy deposited by the evaporated charged particles, protons and α's, was measured with a Si-Ball array, consisting of a dodecahedral silicon wafer [2] of 31 elements surrounding the target. Coincidences between events from all of detector types were collected, and in the off-line analysis all the relevant possible combinations of coincidence matrices were created.

In this paper we discuss some of the results obtained in these experiments with focus on chosen topics: *(i)* the damping mechanisms of the GDR in hot nuclei (Section 2); *(ii)* the search of the GDR-decay in superdeformed nuclei (Section 3); and *(iii)* the study of the "entrance-channel effect" in compound nucleus formation (Section 4).

2. Origin of the GDR width increase in heated nuclei

One of the most interesting problems concerning the physics of hot nuclei are the damping mechanisms which give rise to the measured width of the giant dipole vibration. In particular, by exploring the dependence of the GDR width as a function of another nuclear parameter (as for example temperature or angular momentum) one can learn more about the mechanisms that affect the damped motion. The main mechanisms expected to contribute significantly to the observed GDR width of hot nuclei are collisional damping and thermal shape fluctuations.

The collisional damping arises from the mixing of giant resonant state (microscopically described as $1p$–$1h$ excitations) with more complicated states at the same energy. At finite temperature there are two different predictions for the collisional damping, one giving results basically independent of temperature (see [3, 4]), in contrast to the other, which gives a marked temperature dependence (see [5]).

Thermal shape fluctuations may be understood in simple terms by assuming that the nuclei at finite temperatures form an ensemble of shapes, in which each shape is populated with a probability given by a Boltzmann factor. To understand the role played by thermal fluctuations in the GDR width it is important to include the coupling of the dipole oscillation to the quadrupole nuclear deformation. In a spherical nucleus the GDR strength can be well described by a Lorentzian function, with a width equal to the intrinsic GDR width. In a deformed nucleus, the GDR strength splits into different components as a result of the different GDR resonance frequencies along the longer and shorter axes. At higher temperatures the nucleus is characterised by a distribution of deformations, with superposition of the different GDR strength functions. This gives rise to an effective strength function with a larger width. Since the deformation of the heated nucleus, once the role of the shell structure has been weakened, is expected to increase with rotation (centrifugal flattening), one expects that the effective GDR width will be proportional to the angular momentum. In addition, since the extent of thermal shape fluctuations increases with the temperature, one also expects a width increase at higher temperatures. Consequently it is important to try *to disentangle temperature and angular momentum effects* when discussing the GDR width.

The first data from systematic studies made for Sn nuclei [6, 7] in heavy ion fusion reaction show that the GDR width increases as a function of the excitation energy. The width increases from the ground state value (5 MeV) up to the value of about 11 MeV at $E^* = 130$ MeV and from there it essentially remains constant. However, since these data were obtained in inclusive experiments for different bombarding energies, where both the temperature and mean angular momentum were increasing, it was not clear at that time whether the width increase mainly was induced by temperature or by angular momentum. In [6, 7] it was suggested that the dominant part of this effect must be caused by angular momentum, since the increase and saturation of the width is correlated with the increase and saturation of the angular momentum. Nevertheless the need for other experiments, in which the effects of the temperature and the angular momentum could be clearly separated, was evident. More recently, results for the GDR width were obtained in experiments where the Sn compound nucleus was formed at specific excitation energies and corresponding narrow angular momentum intervals. In that case the temperature associated to the selected angular momentum intervals was almost constant (only changing by the amount related to the energy bound in rotation). These results [8, 9] are shown in the left part of Figure 1 as filled squares. It is seen how the GDR width increases from 8.5 MeV at $\langle I \rangle = 24\,\hbar$ up to 13 MeV at $\langle I \rangle = 54\,\hbar$. In order to find out, whether this increase is due to an increase of the intrinsic width or to deformation effects, we made use of angular distribution measurements. As was shown in [8], if the increase of the intrinsic GDR width is the main source of the GDR strength function broadening, the magnitude of the A_2-coefficient in the $W(\Theta)$ angular distribution function for the low energy component should be either unchanged or slightly decreased. This is because the overlap between the high energy and low energy GDR components, which have different A_2-coefficients, will be larger. If the broadening is due to a larger nuclear deformation, the magnitude of A_2-coefficient for the low energy component should increase. This is because the overlap between the different GDR components is smaller. The right hand side of figure 1 shows the corresponding magnitudes of the A_2-coefficient. We can see that the A_2 increases with spin in a very pronounced way. It can be concluded that the combined measurement of the strength function and of the A_2 indicates that the increase of the width is mainly caused by the increase of the equilibrium deformation of the ensemble induced by angular momentum.

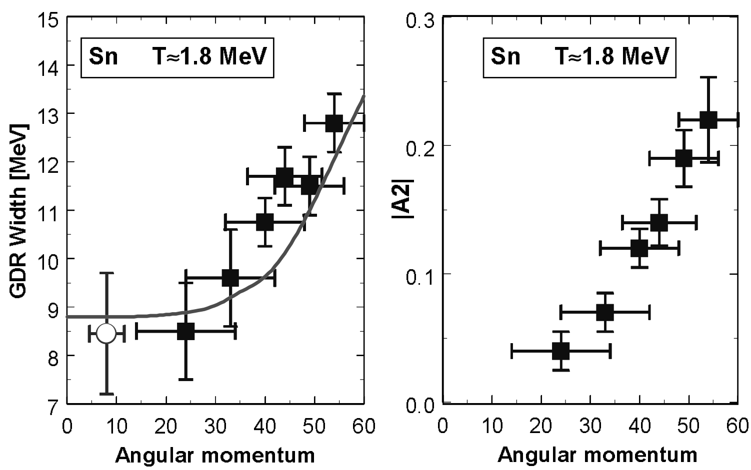

Fig. 1. Left: The measured values of the GDR width in Sn nuclei at $T \approx 1.8$ MeV from fusion reactions (solid squares) and from the inelastic scattering of α-particles (open circle). Right: The absolute value of the A_2-coefficients obtained for the low energy GDR component in the fusion reaction experiments.

In another type of experiments, using inelastic scattering of α-particles [10], the GDR width in Sn nuclei was measured as a function of temperature for constant and low ($I < 10\,\hbar$) spin. Also in that case a significant increase of the GDR width from 5 MeV at $T = 1$ MeV up to 13 MeV at $T = 3$ MeV was found. The experimental point, corresponding to the temperature $T = 1.8$ MeV, is shown in the figure 1 (left hand side). One see that this value is the same as that at spin $24\hbar$ obtained in our fusion reaction measurement. Consequently, the general behaviour of the GDR width with spin at constant temperature is suggesting that below a certain critical angular momentum thermal fluctuations wash out the effect of the angular momentum responsible for the increase of the equilibrium deformation [9]. In particular, when the equilibrium deformation is smaller than the variance of the distribution of shapes in an ensemble, the observed effective width is proportional to the variance. In contrast, when the equilibrium deformation is larger than the variance, the width is proportional to the equilibrium deformation (whose rate of increase is inversely proportional to the moment of inertia). Indeed, thermal shape fluctuation predictions for the GDR width in the adiabatic limit [9,11], as indicated by solid line in figure 1, show this behaviour and are in rather good agreement with the data. In these calculations the intrinsic GDR width was equal to the ground state value. The same calculations [11] were able to describe the temperature dependence of the GDR width measured in [10], pointing that the observed increase is due to increasing effect of thermal shape fluctuations. Consequently one can conclude that the collisional damping, giving rise to the intrinsic GDR width, is almost independent of temperature.

3. GDR decay in superdeformed nuclei

The existence of the nuclear superdeformation, characteristic of a nucleus having an ellipsoidal shape with the long to short axis ratio 2:1, has been verified in many nuclei. However, the population of the superdeformed configurations is not yet understood in detail. It has been suggested [12] that the decay of GDR might play a major role, due to the large splitting of the components.

For a superdeformed nucleus the low energy component of the GDR is expected at 9–10 MeV in medium heavy nuclei. For the GDR built on yrast or low lying superdeformed states, the strength function of this component, if lying below the neutron binding energy (10–11 MeV), enhances the γ-decay to these SD states, competing favourably with the neutron decay. Consequently, one would expect an increase of GDR strength around 10 MeV, when gating on superdeformed transitions.

The sensitivity of standard equipment is in general not sufficient to address this question directly, namely by measuring the high energy γ-rays from the GDR decay in coincidence with the discrete transitions along the superdeformed bands. In the case of ^{143}Eu it was possible to search in a more indirect way for a signal from the γ-decay of the GDR in a superdeformed configuration by use of some of the peculiar features known for this nucleus.

In particular, the low spin structure of this nucleus is characterised by coexistence of two configurations, one almost spherical and the other showing triaxial deformation. At high spins, a rather intense population of superdeformed bands (yrast and excited in the continuum region) has been found [13–15]. In addition it was shown [15], that both the yrast and the intense superdeformed quasi-continuum decay to the spherical states *only*, by-passing the triaxial shape. Consequently, by comparing the high energy spectra gated by γ-transitions among spherical states (fed both by normally deformed and SD continuum) and gated by γ-transitions among triaxially deformed states (fed only by normally deformed continuum), one expects to see the contribution from the γ-decay of the GDR in superdeformed states.

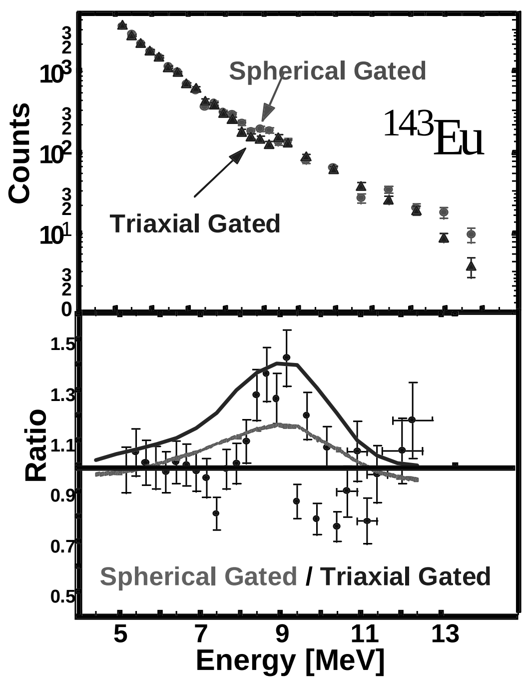

Fig. 2. Top: High energy γ-ray spectra gated by transitions between spherical (circles) and triaxial (triangles) states in ^{143}Eu. Bottom: Ratio between the two spectra shown in the top panel. The lines are from statistical model calculations using two different sets of level density parameters.

Such spectra, obtained [16] in the reaction 165 MeV ^{37}Cl on ^{110}Pd are presented in Figure 2 (upper part). The lower part of this figure shows the ratio of the spectra and comparisons with the statistical model. The calculations were made for 2 sets of level density parameters [16, 17]. Indeed, in spite of the statistical uncertainties, this ratio shows an excess of counts exactly in the region where one expects to find the low energy component of the GDR built on superdeformed configurations. One can also notice that this excess falls between the 2 statistical model predictions. Also short experimental runs were performed for excitation energy 4 MeV lower (the bombarding energy of ^{37}Cl was 160 MeV) and 4 MeV higher (170 MeV) [18], in order to see whether this effect will persist. The statistics was smaller, but one can indeed see that this effect exist, further confirming the observation. The bump is smaller for the lower excitation energy. For the higher excitation energy it is similar to the one found at 165 MeV bombarding energy. It is indicated that the high energy cut-off for the low energy GDR component seems to shift towards higher γ-energies with the bombarding energy. This is not yet understood, but may be related to an increase in available phase space (both in excitation energy and angular momentum) for the superdeformed configurations.

4. Entrance channel effects

Within the last 15 years, several experimental data, mainly concerning the highest spins and massive projectiles, have indicated the existence of an entrance channel effect in the decay of the same compound nuclei(*e.g.* [20, 21]). Thoenessen [19] suggested that these effects may result from the entrance channel dependent formation time of the compound nucleus. For the mass-asymmetric target-projectile combination the formation time is short, and the particles are evaporated from the fully equilibrated system. For the mass-symmetric entrance channel, however, the time could be so long, that particles (and GDR γ-rays) may be emitted before equilibration is reached. This would mean that the compound nuclei in the reactions are different: they can have different excitation energy and angular momentum distributions. Guided by these ideas, we have investigated this problem experimentally, by measuring the decay properties of the ^{170}W compound nucleus, formed in different reactions (^{48}Ti on ^{122}Te and ^{60}Ni on ^{110}Pd), but at "identical" excitation energies and angular momenta [22]. For comparing the available excitation energies of the fully equilibrated systems created in both reactions, we used the average numbers of emitted neutrons [22]. This quantity shows which neutron evaporation channel is, in average, dominant at a given angular momentum, and is related to the available energy for the decay process. Figure 4 shows such quantities for both, asymmetric and more symmetric, reactions leading to ^{170}W with the excitation energy $E^* =$

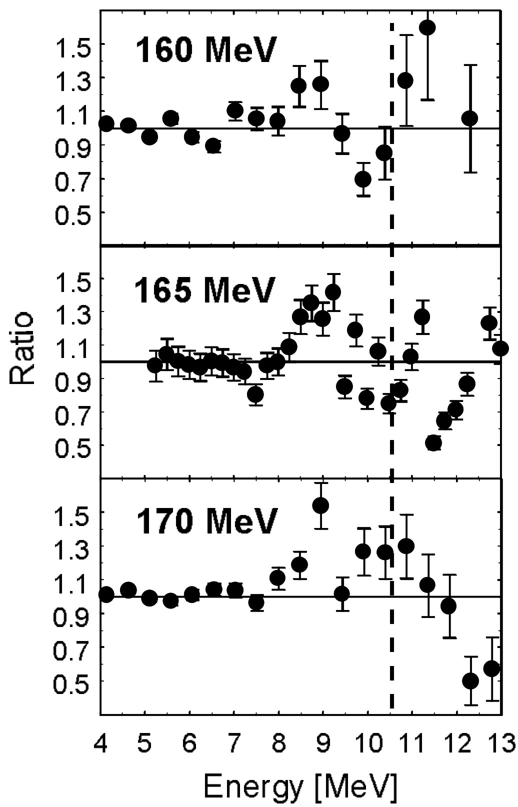

Fig. 3. Same as in the bottom part of Fig. 2, but for 3 bombarding energies: 160 MeV (top), 165 MeV (middle) and 170 MeV (bottom). The vertical dashed line indicates the γ-ray energy equal to the neutron binding energy.

61 MeV and with the angular momentum distribution having $L_{\max} = 68\ \hbar$ (according to the recent model of Winther [23]). They were extracted from the relative evaporation residue cross-sections, obtained from the discrete line intensities, and plotted as a function of γ-fold (which is proportional to the angular momentum of the decaying nucleus). The average number of emitted neutrons is extracted for pure neutron evaporation channel xn, for α, xn channels and for γ, xn channels, that involve γ-rays with energy higher than 7 MeV (mostly from the GDR decay). One can observe a gradual decline of all measured quantities with increasing fold as expected, reflecting the spin dependent energy of the yrast line. In the case of pure neutron evaporation channel the values for both reactions are very similar both in magnitude and behaviour. The error bars for the $\langle\gamma, xn\rangle$-quantities are large, but within the covered fold range these quantities are also similar. For the

α, xn channel, however, one can notice that above fold 8 (corresponding to the average angular momentum $\langle I \rangle \approx 40\ \hbar$) an apparent discrepancy can be observed, increasing with the γ-ray fold. This "α-effect" can be explained by assuming a higher fraction of α-particles in the more symmetric system is emitted during the formation phase, thus removing more energy by the α particles. An alternative explanation of this observation could be that emission of α particles from nuclei with very elongated shapes, will compete more favourably with the fission process in the case of longer fusion times. Such pre-equilibrium "α-cooling" effect may cause the residues to be populated at higher spin, than given by the conventional fission limit for angular momenta. The population cross-section after α emission will have a longer tail extending up to higher angular momenta, where more energy is bound in the rotation, and therefore the effective excitation energy will be smaller. The fold dependence of this difference could be ascribed to the dependence of the formation time on the angular momentum.

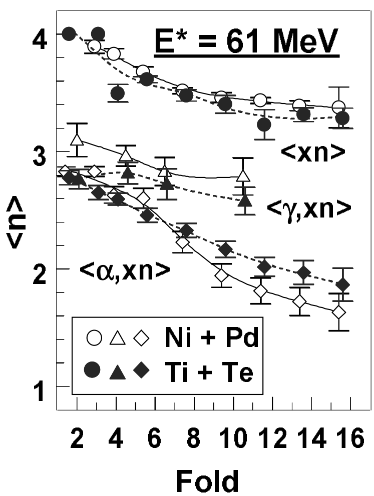

Fig. 4. Average number of emitted neutrons, as a function of γ-ray fold. Open points are for nickel induced reaction, solid — for titanium. The $\langle xn \rangle$ indicates the results for pure xn evaporation channel, the $\langle \alpha, xn \rangle$ — channels involving emission of 1 α-particle and neutrons, the $\langle \gamma, xn \rangle$ — channels involving emission of a high energy (>7 MeV) γ-ray with neutrons or α-particles.

Since the γ-decay of the GDR was proven to constitute a good probe for the time scales of nuclear processes [24], it would be very interesting to study the GDR shape in both reactions, in the cases that GDR decay appears in the xn or in the α, xn channels. One could expect, that GDR strength function can provide information on the temperature and the shape of decaying nucleus. Figure 5 shows the high energy γ-ray spectra, gated by discrete transitions in residua formed in the pure neutron xn and in α, xn evaporation channels. However, even in the more efficient xn channel the statistics is small, the spectrum stops at 14 MeV. One may not notice the difference between the reactions. The calculations performed with the Monte-Carlo version of the CASCADE evaporation code are also shown in the figure. A good agreement in the slope of the statistical part of the spectra is seen. One can also notice that the slope for the α, xn channel is larger, indicating a lower effective temperature, which may be due to the fast emission of α-particles.

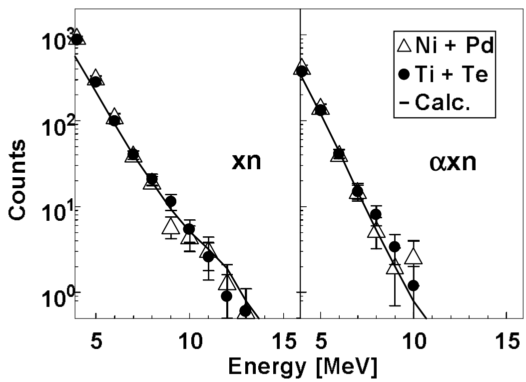

Fig. 5. High energy γ-ray spectra gated by discrete transitions in $3n$, $4n$ and $5n$ evaporation residua (left); compared to αn, $\alpha 2n$ and $\alpha 3n$ evaporation residua (right).

5. Summary

In the 3 different topics discussed above we try to show that exclusive GDR experiments can indeed provide sensitive tools for studying the properties of hot rotating nuclei and the dynamics of the nuclear reactions. By disentangling the angular momentum effects from the thermal effects, it was possible to prove, that the behaviour of the GDR width as a function of angular momentum results from the interplay between spin induced deformation effects and temperature induced shape fluctuations. In addition, the comparison to the thermal shape fluctuation model suggest that the effect of collisional damping is almost independent on temperature.

In a very exclusive measurement it was possible to select in a very unique way decays that could be attributed to the GDR build on the superdeformed configurations, which in turn is responsible for the enhanced population of SD states generally observed.

As far as the problem of entrance channel is concerned, one could see a small, but significant effect for the highest angular momenta in the α, xn evaporation channel only. This effect could be ascribed to a longer formation time of a more symmetric entrance channel. The statistics of the high energy spectra is, unfortunately, too low to provide any firm conclusion on the GDR shape in these evaporation channels.

These results also point to a conclusion, that experiments with more efficient detection systems are needed, to completely resolve the interesting problems mentioned in this paper.

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