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# The GDR in Hg and Eu nuclei from selected decay chains

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The $\gamma$-decay of the GDR in hot Hg and Eu isotopes has been measured in coincidence with selected low-energy $\gamma$-transitions of the evaporation residues.

In the Hg case, the GDR width at finite temperature and at different spins was studied by analyzing simultaneously with the statistical model the high-energy $\gamma$-ray spectra associated with different residual nuclei and the fractions of residue cross-sections. The measured GDR width was found in good agreement with the predictions of the thermal fluctuations model.

In the case of Eu, we have measured the high-energy $\gamma$-rays in coincidence with low-energy $\gamma$-transitions from different nuclear configurations of $^{143}$Eu in order to search for the GDR decay built on a superdeformed state. The analysis of the data shows a possible evidence of this state. The measured intensity indicates that the superdeformation survives only few MeV above the yrast line.

## 1. Introduction

The properties of hot rotating nuclei have been extensively explored making use of the simplest nuclear collective mode, the Giant Dipole Resonance (GDR). These studies, which started almost two decades ago, developed very rapidly and many theoretical and experimental works are now available. However, most of the performed experiments are rather 'inclusive', namely the nuclear and GDR properties extracted from the data reflect an average over the whole phase space (E*,I) available for the decay of the compound nucleus. Only in recent years, as the experimental techniques have progressed, it was possible to perform more 'exclusive' experiments in which the GDR properties have been measured, for example, relative to the excitation energy [1] or to the angular momentum [2–4] yielding important new informations on the average nuclear shape at finite temperature and spin, on the role of thermal fluctuations and on the damping mechanisms of the GDR at finite temperature [5].


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In this paper we present two new 'exclusive' studies of the GDR in Hg and Eu nuclei. These are new especially for the used experimental technique: the high-energy $\gamma$-rays emitted by the decay of the GDR were measured in coincidence with discrete $\gamma$-transitions emitted by the compound nucleus at the very end of the decay. This type of 'exclusive' experiments allows to accurately tag the fusion reaction (by gating on the residues) both at low and high spins and to correlate the GDR emission with selected residues (as for the Hg experiment) or with different nuclear configurations in the same residue (as for the Eu experiment).

In the case of Hg, described in section 2, the objective is the measurement of the GDR width at finite temperature at different spins and the comparison with the model predictions. The thermal shape fluctuations model for this mass region and at moderate temperature (T$\approx$1.5 MeV) predicts that even at high spins (I$>$ 30 $\hbar$) the average deformation is rather small. This is in contrast with what we know at T = 0 where superdeformed bands have been found. In addition, because several spectra associated to different residual nuclei were measured, a very stringent test of the statistical model analysis procedure, which is at the basis of the studies of GDR in hot nuclei, is also provided by this work.

The goal of the Eu experiment is the search for the $\gamma$-decay of the GDR built on a superdeformed state (SD) in $^{143}$Eu. The decay of the GDR on a superdeformed nuclear state has been advocated as one of the important mechanisms to explain the intense feeding of superdeformed bands [6]. In addition, it is interesting to try to establish how high in excitation energy superdeformed configurations exist and the GDR decay is expected to be a very good probe for answering this question. Details about this experiment are given in section 3.

## 2. GDR in hot $^{194}$Hg

The aim of this experiment is the study of the angular momentum effects in the total width of the GDR. Previous studies, made with less exclusive techniques, relative to $^{106-110}Sn$ and $^{176}W$ [2] at moderate temperature (T<2 MeV) have shown that the behaviour of the GDR width at fixed temperature as a function of the angular momentum of the compound nucleus depends on the interplay between the maximum (equilibrium deformation) and $\sigma_\beta$ (the variance) of the shape distribution in the framework of the thermal fluctuations theory or, in other words, on the average deformation of the nucleus $<\beta>$.

On the basis of these findings one expects that for heavier nuclei (as for example A=190) the average nuclear deformation for T<2 MeV should not change appreciably with angular momentum and consequently the width is not expected to change with spin. This behaviour is in contrast with the behaviour at T = 0 where at high spins superdeformed configurations were found. The first studies, made almost a decade ago with less efficient apparata [7,8], were not able to address this question but already pointed to the importance of selecting the fusion channel because of possible contaminations as for example due to fission.

The experiment was performed at the tandem accelerator laboratory of the Niels Bohr Institute (Risø, Denmark). The reactions were $^{30}$Si (142 MeV) + $^{164}$Dy = $^{194}$Hg. The thickness of $^{164}$Dy target was 0.75 mg/cm$^2$. The corresponding excitation energy for the compound is 60 MeV, the temperature is 1.3 MeV and the maximum angular momentum 41 $\hbar$.

The experimental apparatus was a combination of the Nordball detector array (17 Compton-suppressed HpGe detector + a 30 element multiplicity filter) with the HECTOR detector array. The latter consists of 8 large volume $BaF_2$ detectors for the measurement of high-energy $\gamma$-rays. The multiplicity filter covered a solid angle of $\approx 2\ \pi$. The detection efficiency for high-energy $\gamma$-rays was $\approx 1$ % at 15 MeV, similar to that for the detection of low-energy $\gamma$-rays. The gain of each large volume $BaF_2$ detector has been monitored continuously during the experiment using a LED source and corrected during the off-line analysis [9]. The collected events consisted of coincidence of a high-energy $\gamma$-ray ($E_\gamma > 3$ MeV), with at least one low energy $\gamma$-ray measured with HpGe detectors and two or more $\gamma$-rays measured in the multiplicity filter. High-energy $\gamma$-ray spectra in coincidence with low-energy transitions were obtained for two fold-sum energy windows measured with the multiplicity filter.

All measured spectra and relative cross sections were analysed within the framework of the statistical model. Because of the channel selection a Monte Carlo approach has been necessary. In figure 1 the fractions of residue cross sections, deduced from the HpGe spectra, in coincidence with a $\gamma$-ray with an energy $E_G$ or higher are shown. In the left panel the data relative to the fold window 2-5 (corresponding to an average spin of 24 $\hbar$) are shown while on the right one the data relative to fold higher than 6 (corresponding to an average spin of 36 $\hbar$) are displayed. The lines represent the results of the Montecarlo statistical model calculations. All channels are rather well predicted, within 10%, in the two different spin windows. The same is true for the total case.

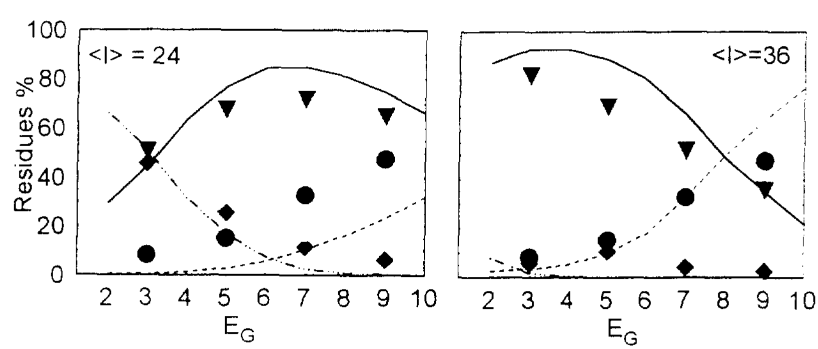


Figure 1. Fractions of residue cross-sections in coincidence with a $\gamma$-ray with energy $E_G$ or higher. The left panel is relative to the case at $I \simeq 24\hbar$ while the right one is relative to $I \simeq 36\hbar$. The lines are the results of statistical model calculations of Montecarlo type. The dashed lines and the filled points are relative to $^{191}$Hg, the continuous lines and the filled triangles to $^{190}$Hg and the dot-dashed lines and filled diamonds to $^{189}$Hg.

In the left panel of figure 2, the high-energy $\gamma$-ray spectra in coincidence with each residues are displayed for the $I \simeq 24\hbar$. In the panel, the spectrum associated to $^{191}$Hg (filled points) has a enhanced contribution of high energy gamma rays while in the one associated to $^{189}$Hg (filled squares) such a contribution is nearly zero. This is due to the fact that the compound has a definite energy to distribute between neutrons and $\gamma$, and consequently if more neutrons are emitted less energy is left for $\gamma$-rays.

In the statistical model calculations performed to reproduce all the measured spectra a single Lorentzian analysis with 100% of EWSR was carried out. The value of the GDR centroid was fixed at 14 MeV and the GDR width was varied to reproduce, simultaneously, the total spectrum and those associated to the different final channels. The experimental data and the corresponding statistical model calculations are shown in the central and right panels of figure 2. A width of 6.5 MeV was obtained for the total spectrum (gated by all lines) and a width of 6.5 and 5.5 was found for the $I \simeq 24$ and $I \simeq 36$ case, respectively.

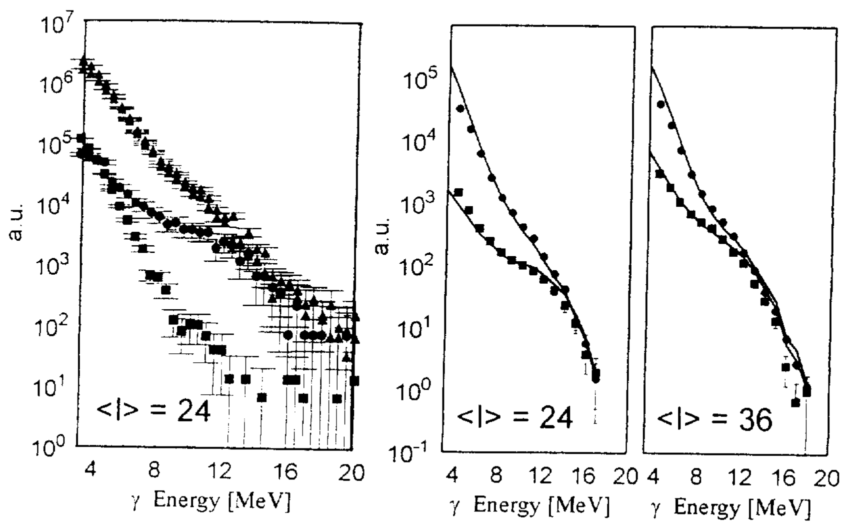


Figure 2. The measured high energy gamma ray spectra in coincidence with different residues relative to the case at $I \simeq 24\hbar$ is shown in the left panel. The filled squares indicate the high energy spectrum in coincidence with $^{189}$Hg, the filled triangles with $^{190}$Hg and the filled points with $^{191}$Hg. The normalization of the spectra is relative to the population of each residue. In the central and right panels the high energy spectra in coincidence with all HpGe discrete lines (filled points) and with $^{191}$Hg (filled squares) are displayed. The central panel is relative to the fold-sum energy window with an average spin of $I \simeq 24$ while the right one has an average spin of $I \simeq 36$.

Theoretical calculations of the GDR strength function were performed assuming an adiabatical coupling of the GDR vibration to the quadrupole deformation. The GDR strength function for a fixed deformation and orientation was assumed to be a superposition of three Lorentzians (each representing the oscillation over one of the three principal axes). The GDR centroid for each Lorentzian has been obtained from the Hill Weeler formula [10] and the correspondent width by the relation $\Gamma = \Gamma_0(E_k/E_{GDR})^\delta$ where $\Gamma_0$=4

MeV, $E_{GDR}$=13.5 MeV and $\delta$=1.9. The total GDR strength function was obtained by summing the strength function associated to all possible deformations and orientations weighted by the Boltzmann term $exp(-F/T)$ where F is the free energy and T the temperature. The free energy was calculated using the standard Nilsson-Strutinsky procedure in a $(J_z, T)$ fixed environment [11,12]. The left panel of figure 3 shows how the average deformation $<\beta>$, the equilibrium deformation $\beta_{eq}$ and the variance of the shape distributions $\sigma_\beta$ change with angular momentum. No significative dependence of $<\beta>$ on spin is found and this is connected to the fact that the equilibrium deformation remains smaller than $\sigma_\beta$. The GDR width is predicted to be constant with spin and this is well confirmed by the experimental data.

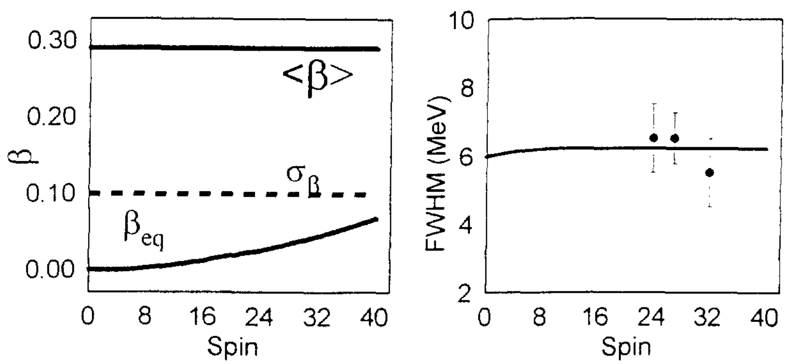


Figure 3. The right panel shows the measured FWHM for $^{194}$Hg at T=1.3 MeV as a function of angular momentum and the theoretical prediction calculated using the thermal fluctuations model described in the text. In the left panel the calculated equilibrium deformation, the variance of the spin distribution and the average deformation are displayed

The present data show that the GDR width follows the same behaviour with spin as the average deformation $<\beta>$. However, it is important to stress that the GDR line shape calculated with this approach is different than that calculated at a fixed $<\beta>$ value. Besides, the nuclear moment of inertia $\Im$ plays an important role in the determination of the GDR width. In fact, in heavy nuclei like $^{194}$Hg or $^{176}$W (where a similar behaviour has been calculated and observed) a large $\Im$ sensibly reduces the effect of oblate flattening induced by rotation. In medium mass nuclei, instead, where $\Im$ is sensibly smaller, higher deformations can be reached and a stronger spin dependence of the GDR width has been observed [2].

## 3. GDR in $^{143}$Eu

In this section we discuss the first experiment aiming at searching a signal of the $\gamma$-decay of the GDR in the superdeformed $^{143}$Eu. At low spin, due to the coexistence of both spherical (ND) and triaxially deformed (TD) shapes [13] [14], this nucleus has a very complex and irregular level scheme. At high spin it becomes superdeformed (SD). This nucleus is also characterized by a very intense continuum of E2 type that was found to originate from superdeformed configurations [15].

Both the superdeformed yrast band and the excited superdeformed states of the E2 continuum follow decay routes leading to g.s. that populate low spin states of the spherical shape only (ND) [15]. It is therefore expected that one should see the $\gamma$-decay of the GDR built on superdeformed states by comparing high-energy spectra gated by low spin transitions of the spherical shape (partly populated by transitions from superdeformed states) with those gated by low spin transitions of the triaxial shape (not populated by the superdeformed states).

The experiment was performed at the Tandem Accelerator Laboratory of the Niels Bohr Institute in Risø, (Denmark), using the same set up described in section 2. The $^{37}$Cl beam, at the incident energy of 165 MeV, impinged on a two stacked targets of $^{110}$Pd (97.3% pure and 510 and 550$\mu$g/cm$^2$ thick). The compound nucleus $^{147}$Eu was formed at an excitation energy of 79 MeV. The maximum angular momentum is predicted to be 62$\hbar$ by the Swiatecki model [16] and 68 $\hbar$ by the model of Winther, in which the excitation of collective modes is taken into account in the formation process ([17]). Figure 4 shows the ratio of the high-energy $\gamma$-ray spectrum gated by ND transitions (fed by the decay of superdeformed configuration) with the spectrum gated by TD transitions (not fed by the decay of superdeformed states). This ratio corresponds to the fold interval 6-10 measured with the multiplicity filter.

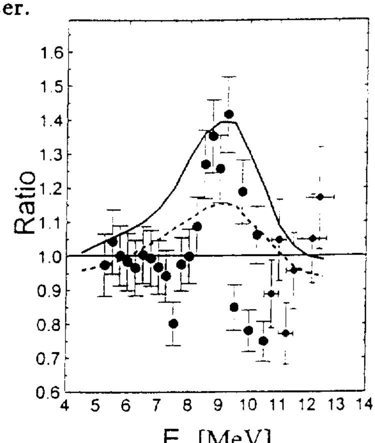


Figure 4. The measured ratio between the high-energy spectra in coincidence with ND and TD discrete transitions. The curves are the statistical model calculations. The short dashed line is relative to the case where level density parameter a=A/8 MeV$^{-1}$ was used for both superdeformed and normal configurations, while the continuous line corresponds to a=A/10 MeV$^{-1}$ for the superdeformed contribution.

The measured ratio deviates from one (by approximately 15-30 %) between 7 to 10 MeV, region where one expects to find the low energy component of the GDR built on a superdeformed nucleus. Effects related to the population of different spin regions are not very likely because the two type of transitions have very similar fold distributions [18].

The two curves in figure 4 are calculated ratios obtained with the statistical model. The E1 spectrum associated to the case in which the nucleus is not superdeformed is calculated using a single Lorentzian strength function centered at 15 MeV and with a width varying from 5 to 8 MeV as a function of excitation energy. The E1 spectrum associated to the superdeformed configuration was calculated using a two Lorentzian strength function (with 33% of the EWSR in the low energy component) in the region U = 0-15 MeV, I = 40-55 $\hbar$ (where U is the energy above yrast and I the spin) and a single Lorentzian function in all the other regions of the phase space sampled by the compound nucleus decay (cf. [19] for more details). Two values were used for the level density parameter of the superdeformed E1 decay. One is a=A/8 $MeV^{-1}$ (dashed line) and the other a=A/10 $MeV^{-1}$ (solid line).

It is interesting to point out that, even though the transition probability for the E1 decay for a SD nucleus is a factor of 4 to 10 times larger than that of the ND nucleus. the overall enhancement is only of the order of 15 to 30 %. This is because the superdeformation exists only in a very small area of the phase space, extending only few MeV above yrast.

## 4. Conclusion

The high-energy $\gamma$-rays emitted in the decay of hot Hg and Eu nuclei have been measured in coincidence with discrete $\gamma$ transitions.

In the Hg case, the width of the GDR was obtained analyzing simultaneously both the measured cross section and the residue-gated spectra. The GDR width was found to be independent of angular momentum in agreement with the theoretical prediction of the thermal fluctuations model. This result, together with those obtained in lighter mass regions, gives a strong support to the model of thermal fluctuations as the main damping mechanism of the GDR at finite temperature. A particularly interesting aspect of this model is the role of the moment of inertia in the oblate flattening of the nucleus induced by angular momentum, which is predicted to be small for large moment of inertia. The measured dependence of the GDR width on angular momentum supports this point.

In the Eu case, the comparison between the high-energy spectrum in coincidence with discrete transitions from the quasi spherical shape (partly populated by SD decay) with the spectrum in coincidence with discrete transitions from the triaxial shape (not populated by SD decay) and the comparison with statistical model predictions seem to indicate contributions from the decay of the GDR on a superdeformed nucleus near the yrast line. However, higher statistics are needed to confirm this interesting finding.

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