The Gamma Decay of the GDR
Under Extreme Conditions

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Abstract. The study of the $\gamma$ decay from the giant dipole resonance (GDR) at finite temperature and far from stability allows to obtain information on the properties of nuclei in different regimes. Exclusive measurements of $\gamma$ -decays with fusion reactions were made at LNL (INFN) in order to address different physical problems. First, the measurement of the temperature dependence of the GDR width up to $T = 4$ MeV in the mass region $A=130$ will be shown together with its interpretation in terms of thermal shape fluctuation calculations. Secondly, a measurement of the isospin mixing for nuclei in the mass region $A = 80$ at temperature around $T=2$ MeV is described. Finally the search for the pygmy dipole resonance in the neutron rich $^{68}$Ni nucleus, produced by fragmentation at GSI, will be presented. Coulomb excitation at 600 MeV/nucleon was employed and the $\gamma$ -rays were detected with the RISING array.

Keywords: giant dipole resonances; hot nuclei; statistical model; pygmy dipole resonance.

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DAMPING MECHANISM OF THE GDR IN HOT NUCLEI

The Giant Dipole Resonance (GDR) is a collective excitation of the nucleus in which protons and neutrons oscillate with opposite phase and can be present both in the ground and excited states. By studying the $\gamma$ -decay of the GDR it is possible to investigate highly excited nuclei and to explore the basic nuclear structure properties at finite temperature and angular momentum, such as nuclear shapes and thermal effects. In particular, the dependence of the GDR width on temperature and angular momentum provides information on the evolution of the nuclear shapes and on the damping mechanism of this collective state.

In general, the measured GDR width is well described within the thermal fluctuation model (TFM) for $T < 2$ MeV, at higher temperature the situation is more complex, also due to the presence of sizable pre-equilibrium emissions which significantly cool down the nuclear system before it thermalizes. Experimental data are required which do not contain pre-equilibrium contributions, because its subtraction is model dependent.

An experimental campaign focused to the measurement of the width of the GDR built on excited nuclei with mass $A\sim130$ and with temperature in the interval 2-4 MeV was performed at INFN Legnaro National Laboratory (LNL), making use of the GARFIELD-HECTOR array [1]. High energy $\gamma$-rays from the decay of the GDR were
Two different reactions were employed, producing the same \( ^{132}\text{Ce} \) compound nucleus at excitation energy 100, 150 and 200 MeV: a symmetric one, using a \( ^{64}\text{Ni} \) beam at 300, 400 and 500 MeV on a \( ^{68}\text{Zn} \) target, and an asymmetric one with an \( ^{16}\text{O} \) beam at 130 and 250 MeV on a \( ^{116}\text{Sn} \) target. For the two reactions at the highest bombarding energy the excitation energy deduced from kinematics is the same (200 MeV). While the \( \alpha \)-particle spectra corresponding to the \( ^{64}\text{Ni} \)-induced reaction show a spectral shape in agreement with a statistical emission from a fully thermalized compound system (red curve), in the case of the \( ^{16}\text{O} \) beam a sizable pre-equilibrium contribution is observed, see figure 1. As a consequence, the study of the GDR width at different temperatures was restricted to the symmetric \( ^{64}\text{Ni} \)-induced reaction, which does not require any correction related to pre-equilibrium effects. Figure 2 shows the high energy \( \gamma \)-ray spectra measured in coincidence with the recoiling residual nuclei from the symmetric reaction induced by the \( ^{64}\text{Ni} \) beam at 3 different excitation energies. The full lines give the best fitting statistical model calculations folded with the response function of the BaF\(_2\) array (for details see [1]).

![Figure 1](image1.png)

**FIGURE 1.** \( \alpha \)-particle spectra for the \( ^{64}\text{Ni} \)-induced reaction (\( E_{\text{lab}}=500 \) MeV) (left panel) and for the \( ^{16}\text{O} \)-induced reaction (\( E_{\text{lab}}=250 \) MeV) (right panel) and the corresponding statistical model calculations.

![Figure 2](image2.png)

**FIGURE 2.** The measured (points) and calculated (lines) high energy \( \gamma \)-ray spectra for \( ^{132}\text{Ce} \) at excitation energy of 200, 150 and 100 MeV [1].

Figure 3 shows the extracted values of the GDR width in comparison with results of theoretical predictions based on the TFM of the nuclear shape. It is found that the predicted increase does not reproduce the present experimental data at \( T > 2.5 \) MeV. The explanation for this discrepancy is related to the fact that the effect of the lifetime of the compound nucleus plays a role at these temperatures. In fact, taking also into account the compound nucleus lifetime (calculated within the statistical model) a much better agreement between data and theory is obtained, as shown in figure 3 by the thick line.
One can conclude that, in agreement with the expectation of the theory, for $T > 2$ MeV there is no room for a significant increase of the intrinsic width $\Gamma_0$ with temperature, unless one unrealistically neglects the CN lifetime contribution to the total width.

**ISOSPIN MIXING AT HIGH TEMPERATURE IN N=Z NUCLEUS**

The problem of the mixing of states with isospin $I \neq I_0$ in $N \approx Z$ nuclei, related to the isospin symmetry and its breaking mainly by Coulomb interaction, has attracted renewed interest both, at zero and finite temperature. In particular, at high excitation energy restoration of the isospin symmetry should occur. The isospin mixing probability is related to the ratio of the spreading width of the Isobaric Analog State (IAS) with the statistical decay width of the compound nucleus. The restoration of the isospin symmetry can be understood on the ground of simple kinetic arguments, if the compound nucleus decays on a time scale which is shorter than the time needed for a well-defined isospin state to mix with states with different isospin, then the isospin symmetry is partially or totally restored [3,4]. While the spreading width of IAS is expected not to depend on temperature, the decay width of the compound is known to increase with temperature so that these two effects result in a decrease of the isospin mixing probability. So far the temperature dependence of the isospin mixing has been extensively investigated only in light nuclei ($30 < A < 60$) [5].

The present experiment was performed at LNL with beams of $^{40}$Ca and $^{37}$Cl at 200 and 154 MeV onto $^{40}$Ca and $^{44}$Ca targets, respectively, leading to the formation of $^{80}$Zr and $^{81}$Rb compound nuclei at the same excitation energy. The method of comparing the $\gamma$-decay of a compound nucleus formed in $I = 0$ or $I \neq 0$ state is well established [4,5]. Indeed E1 transitions from GDR decay are strongly inhibited due to the isovector nature of the E1 dipole. The comparison is essential to eliminate uncertainties in the width and position determination of the GDR. The measurements were based on the complex setup described in the previous section.
The γ-ray yield for the $^{40}\text{Ca} + ^{40}\text{Ca}$ and $^{37}\text{Cl} + ^{44}\text{Ca}$ reactions were measured, both leading to a compound system with the same excitation energy of $E^* = 85\text{MeV}$ and mass $A \approx 80$. In Fig. 5 two data-sets for γ-yields are shown one inclusive and the other one corresponding to events in coincidence with evaporative residues (lower curves). In addition, preliminary statistical model calculations are shown for full and no isospin mixing. This comparison points that in $N = Z$ nuclei with $A = 80$ and $T \approx 2\text{ MeV}$ there is to some extent isospin restoration. These nuclei are unstable and difficult to populate at zero temperature. The further work on this experiment is expected to provide information on how the Coulomb interaction is affecting the spreading width of the IAS.

**PYGMY DIPOLE RESONANCE IN THE NEUTRON RICH $^{68}\text{Ni}$**

The evolution of the GDR strength from stable to exotic, weakly bound, nuclei with extreme neutron to proton ratio, in connection with the existence of the so called Pygmy Dipole Resonance (PDR) or soft mode is presently of high interest. This mode of excitation arises from the vibration of the less tightly bound valence neutrons against the residual core and according to different type of calculations, it is expected to appear as a redistribution of the strength towards lower excitation energies, well below the giant resonance region. It is also found that the details of this redistribution depend significantly on the effective forces used in the calculations. Moreover, the pygmy resonance strength can have a striking impact on the calculated r-abundance of the elements since it can significantly change the neutron capture process in the r-process nucleosynthesis. For nuclei far from stability the pygmy dipole resonance was investigated with Coulomb break up reactions for the $^{20-22}\text{O}$, $^{26}\text{Ne}$ and $^{132-134}\text{Sn}$ nuclei.
In this context Coulomb excitation followed by $\gamma$ decay was instead measured, similarly to the case of the study of the response below 8 MeV in $^{20}$O [9].

Here the measurement of the $\gamma$-decay following Coulomb excitation of a $^{68}$Ni beam at 600 MeV/nucleon, energy at which the dipole excitation dominates over the other excitation modes, is presented. The experiment was performed at the GSI Laboratory, where $^{68}$Ni was produced from the fragmentation of $^{86}$Kr beam at 900 MeV/A from the UNILAC-SIS. The primary beam was focused on a Be target 4 g thick and the $^{68}$Ni ions were selected using the Fragment Separator (FRS) facility. The $\gamma$-ray emission and particle identification after Coulomb excitation of $^{68}$Ni was measured and tracked using the RISING set-up [10]. The measured high energy $\gamma$-rays spectra in HPGe cluster detectors and in large volume BaF$_2$ scintillators of the RISING setup are shown in figure 8. The experimental conditions are such that only Coulomb excited events are selected and nuclear contributions are strongly suppressed. A peak structure at $E_\gamma \approx 11$ MeV is observed in all $\gamma$-ray Doppler corrected spectra corresponding to detectors at different angles. In figure 6, the lines superimposed to the experimental spectra correspond to accurate Monte Carlo simulations (with GEANT) of the set-up for a 11 MeV $\gamma$-ray incident in the corresponding detectors.

![Graphs showing HPGe and BaF2 yield for $^{68}$Ni](image)

**FIGURE 6.** The high-energy $\gamma$-ray spectra measured in the BaF$_2$ detectors (right) and in the HPGe cluster detectors (left) are shown. The continuous line superimposed to the experimental spectra are the results of GEANT simulation of the peak line shape $\gamma$-ray at 11 MeV.

From the measured $\gamma$-ray spectra the radiation having a statistical nature was subtracted. Such statistical spectrum, in the energy interval from 2 MeV and up to around 6 MeV, contains the contribution also from the Au target. In addition, for $\gamma$ rays below 2 MeV there are contributions (Lorentz boosted) from low energy X-rays, present in the fast-beam environment. The cross section for the ground state $\gamma$-decay following Coulomb excitation of the projectile is directly proportional to the photonuclear cross section multiplied by the ground state decay branching ratio and by the virtual photon flux (calculated following the Weizsäcker-Williams method [11]). In order to determine the strength of the measured PDR peak the unfolding of the measured spectra was performed. First the cross section for Coulomb excitation and $\gamma$-decay for a E1 distribution given by the sum of two Lorentzians one for the GDR (centered at $E_\gamma \approx 16$ MeV) and the other for the PDR (centered at $E_\gamma \approx 11$ MeV) was calculated with the above described formalism. Then the result was folded with the detector response function. Finally an iteratively seeking, varying strength, position and width of the resonances, was applied to obtain the best fit to the data. The results
are displayed in figure 7. A PDR strength of approximately 5% of the total GDR strength was found. The PDR yield is enhanced with respect to the GDR yield due to the fact that the photon flux, the $\gamma$-decay branching ratio and the detection efficiency all decreases with energy (for details see [12]).

![Figure 7](image.png)

**FIGURE 7.** The high-energy $\gamma$-ray spectrum measured in the BaF$_2$ detectors is shown as points. The continuous line superimposed to the experimental spectrum is the results of the calculated cross section with both the GDR and PDR contributions [12]. The dotted line is the contributions of the GDR only and the dashed line contains only the PDR contribution.

In summary in this experiment high energy $\gamma$-rays from Coulomb excitation of $^{68}$Ni at 600 MeV/nucleons were measured. An extra strength at around 11 MeV as compared to that of the GDR tail was observed at different detection angles. This extra strength corresponds to approximately 5% of the TRK-EWSR strength. Theoretical predictions based on different approaches provide values in the interval 4 - 8% for the PDR strength in $^{68}$Ni. The present result opens new perspectives for other experiments concerning more and deeper investigations of this problems, particularly using higher resolution detectors and higher intensity exotic beams.

**REFERENCES**