Vol. 36 (2005) ACTA PHYSICA POLONICA B No 4

GDR IN HOT NUCLEI: NEW MEASUREMENTS*

F. Camera[a], M. Kmiecik[b], O. Wieland[a], G. Benzoni[a], A. Bracco[a]
S. Brambilla[a], F. Crespi[a], P. Mason[a], A. Moroni[a], B. Million[a]
S. Leoni[a], A. Maj[b], J. Styczeń[b], M. Brekiesz[b], W. Męczyński[b]
M. Ziębliński[b], F. Gramegna[c]v, S. Barlini[c], V.L. Kravchuk[c]
A.L. Lanchais[c], P.F. Mastinu[c], M. Bruno[d], M. D'Agostino[d]
E. Geraci[d], A. Ordine[e], G. Casini[f] and M. Chiari[f]

[a] Dept. of Physics, University of Milan and INFN Section of Milan, Milano, Italy
[b]H. Niewodniczański Institute of Nuclear Physics, PAN, Kraków, Poland
[c]Laboratori Nazionali di Legnaro, I.N.F.N., Legnaro (Padova), Italy
[d]I.N.F.N. and Dipartimento di Fisica dell'Universitá di Bologna, Bologna, Italy
[e]I.N.F.N. Sezione di Napoli, Napoli, Italy
[f]I.N.F.N. Sezione di Firenze, Firenze, Italy

(Received December 16, 2004)

The measured properties of the Giant Dipole Resonance in hot rotating nuclei are successfully described with the model of thermal fluctuations, even though there are still some open problems especially at very low ($T < 1.2$ MeV), very high ($T > 2.5$ MeV) temperatures and missing data in some mass regions. Recent experimental works have addressed more specific problems regarding the nuclear shape and its behaviour in very particular and delimited phase space regions. In this paper will be discussed new exclusive measurements of the GDR γ decay in heavy ^{216}Rn nuclei (where the shape of nuclei surviving fission have been probed) and some preliminary data on the ^{132}Ce nuclei at very high excitation energy.

PACS numbers: 24.30.Cz, 27.80.+w

1. Introduction

The Giant Dipole Resonance is a collective excitation state which has been extensively studied. Macroscopically, it is described as an oscillation of protons against neutrons while, microscopically, a GDR state is a coherent

* Presented at the XXXIX Zakopane School of Physics — International Symposium "Atomic Nuclei at Extreme Values of Temperature, Spin and Isospin", Zakopane, Poland, August 31–September 5, 2004.

superposition of many p–h states. Experimentally, the GDR can be observed as an increase in the photo-absorption/photo-emission cross section between 10–20 MeV. The strength function of a GDR state built on ground state nuclei can be parametrised as a superposition of three lorentzians associated to the vibration along the three principal axis. The centroid of each component is inversely proportional to the length of the oscillation axis, consequently, the more the nucleus is deformed, the more splitted will be the GDR strength function. At zero temperature, the width of each component (damping width) is between 3–5 MeV and reflects the damping of such collective and ordered state to more complicated np–nh states [1]. It has been theoretically predicted [1,2] and experimentally observed [1,3] that the GDR state can be built not only on nuclei in their ground state but also in excited states and, in particular, on compound nuclei. As the coupling of the GDR to the quadrupole deformation remain the same as it is at zero temperature, the GDR is an unique tool to study nuclear structure in hot rotating nuclei. The major difference between the GDR properties in hot and ground-state nuclei concerns its width. In fact, it has been experimentally observed that the GDR width in exited nuclei is larger than the width measured in ground states (generally indicated as Γ_0) [4, 5]. Theoretically, the increase of the width has been interpreted as due to both angular momentum (as it can deform the nucleus) and excitation energy, and it is well described in the framework of the thermal fluctuations model (TFM) [6, 7]. It is important to stress that the observed increase of the width with temperature is not an additional damping mechanism of the GDR but an effect only due to the "hot and rotating" environment in which the collective state happens to be. In the TFM model, the hot rotating nucleus does not have a fixed shape and orientation but feels a whole distribution of shapes with a probability proportional to the Boltzmann term $\exp(-F/T)$ where F is the free energy and T the nuclear temperature. The measured GDR is consequently a weighted average of the GDR built on this ensemble of shapes. In the last 10–15 years, a large amount of experimental data on the GDR in hot rotating nuclei has been accumulated in a wide interval of masses, temperature and spin. The thermal fluctuations model has interpreted successfully most of the experimental data with the exception of the data at low temperature one ($T < 1.2$ MeV) where the model seems to systematically overestimate the disappearance of shell effects. Besides, the model has not yet been tested in heavy and light masses (the available data scan a mass range between $A = 44$ to $A = 208$) where very high rotational frequency or fission competition mechanism might change the ensemble of shapes and the overall fluctuations scenario. Another open problem regarding GDR in hot nuclei regards the behaviour of its width at very high temperatures ($T > 2.5$ MeV) where the present data cannot distinguish between different model predictions. Because of the general success of the TFM model, it has been proposed recently a universal correlation law between the GDR width and the average quadrupole deformation which successfully describes all the available data where shell effects do not play a significant role [7], with the exception of only one case [8]. In a mass-spin-temperature region where the properties of the GDR are well understood, one can use such a collective state as a powerful probe to sample nuclear shape in region which cannot be studied by standard techniques like, for example, discrete spectroscopy. In fact, in the search of highly deformed structures like hyper-deformation or in the search of the Jacobi shape transition where it could be difficult to observe long series of regular spaced discrete lines, the identification of a highly splitted GDR strength function might be easier to observe and complementary to the discrete spectroscopy. The feeding mechanism of super- and hyper-deformed structures (SD–HD) can also be successfully studied using the GDR as a probe. In fact, the measurement of a SD-GDR in coincidence with a SD-discrete-band [9, 10] may explain the not-yet-understood problem of the unexpectedly high yield of SD structures. As an example, in the $A \simeq 45$ mass region, there has been a long series of experiments to identify the Jacobi shape transition using the GDR as a probe [11–13]. In the contribution of Kmiecik [14] to this conference, the data relative to a HECTOR–EUROBALL experiment are presented and evidence of such shape transition and a preferential feeding of the GDR to highly deformed structures is discussed.

In our paper, the results of a series of experiments performed using the HECTOR array addressing to some open problems previously discussed will be presented. In particular, the first chapter will show data on ^{216}Rn to check TFM in such almost unexplored mass region. In the dataset, it has been selected the highest angular momentum populated by the reaction to measure the shape of ^{216}Rn nuclei which survive fission. In the second chapter will be presented some preliminary data on the measurement of the GDR strength function and width at very high temperature $T > 2.5$ MeV. For the first, time a very symmetric and asymmetric reactions have been used to produce the same compound nucleus for which fusion residues, charged particles and γ-rays have been measured simultaneously.

2. GDR in ^{216}Rn: Probing nuclear shape close to fission limit

As discussed in the introduction, the TFM model has been successfully tested only up to the mass $A = 208$. For heavier masses, there has been only one measurement [15] and the GDR width could not be fully experimentally extracted. Measurements in such mass region are extremely important as the shape ensemble the hot nucleus samples is somehow limited by fission.

Besides, as the GDR couples to quadrupole shape, one can obtain information about nuclear shape along the fission path and, in particular, by selecting nuclei populated at very high spin, measure the shape of those species which survive fission.

One of the cleanest way to select compound nuclei populated at high spin is the use of high spin isomeric states which are present in such mass region. In particular, ^{211}Rn and ^{212}Rn have two isomers at spin $63/2\,\hbar$ and $30\,\hbar$, respectively [16]. By measuring high energy γ-rays emitted in coincidence with such high-spin isomers it is possible to have a very clean tag to select only compound nuclei which survive fission and remain populated at very high-spin. For this purpose, the reaction ^{18}O (96 MeV) + ^{198}Pt was chosen. The main decay channels consist in the emission of 4 to 6 neutrons populating $^{210-212}$Rn; the lightest Rn isotope is predominantly populated at low spin while ^{212}Rn is mostly populated at spin higher than $35\,\hbar$. In the experiment, the HECTOR [17] array was used. A Mylar recoil catcher was placed 40 cm after the target, around the catcher and shielded from target; a BGO Compton shield was placed and used to detect the isomer delayed γ-emission. The measurement was done at the INFN Legnaro Laboratories, details of the experimental setup are described in Ref. [16].

The multiplicity of low energy γ rays around the target in coincidence with the isomer-states is of the order of only 5 (the average value measured in the reaction is of the order of 13–15) indicating that the isomers are populated in the reaction and stopped in the catcher which collects the rest of the decay. Fig. 1 shows the measured high energy γ-rays spectra. Panels (a) and (b) show the spectra in coincidence with the folds interval 5–8 and 9–30, respectively. Panel (c) shows the γ-ray spectra in coincidence with the isomer. In all plots, the continuous gray line shows the results of a statistical model calculation performed using the Monte Carlo version of cascade [18].

As can be seen, the statistical model calculations reproduce well the measured spectra in all cases. The corresponding GDR centroids and widths are listed in Table I. Even though the GDR centroids and widths are very similar in the three cases, the high energy γ-ray spectra are not. In panel (c) the thick dark line shows the calculation which reproduce the total un-gated spectra while the thin one shows the calculation where ^{212}Rn residues and spin larger than $35\,\hbar$ are required. As it can be seen from Table I, the measured values of the GDR width in this case are found: *(i)* larger than in the ground state nuclei (almost by factor of two); *(ii)* independent on the angular momentum of the compound system. The observed difference between the measured GDR width and that in ground state nuclei in the same mass region is of the same magnitude as that one found in lighter nuclei and interpreted in terms of thermal fluctuations of a hot compound system, while point *(ii)* indicates that the average deformation of the nucleus is not

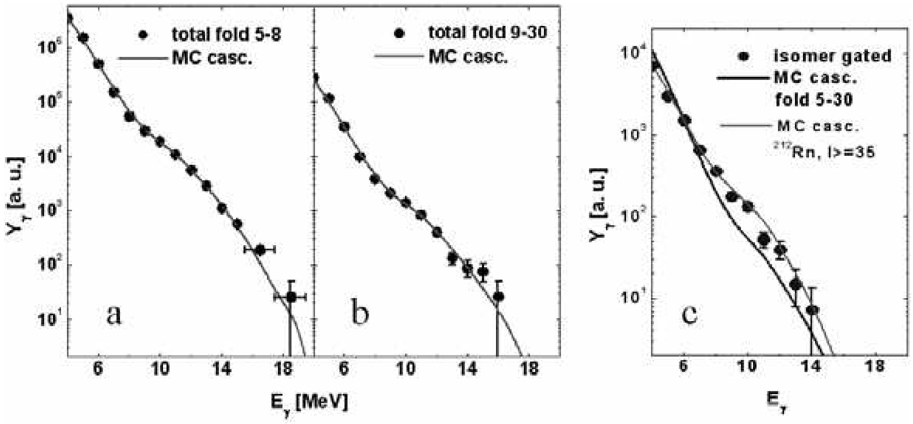

Fig. 1. The high energy spectra measured in the compound fusion reaction ^{18}O + ^{198}Pt at 96 MeV. Panels (a) and (b) show the spectra measured for low energy coincidence folds 5–8 and 9–30 corresponding to an average spin of 23 and 29 $\hbar$, respectively. Panel (c) shows the high energy γ-ray spectrum measured in coincidence with the isomer stopped in the catcher. In all panels, the thin light continuous lines show the results of the statistical model calculations. In panel (c) the calculations have been done requiring ^{212}Rn as a residue and compound nucleus with a spin higher than 35 $\hbar$. The thick line shows the results of the calculations where such conditions are lifted.

TABLE I

The GDR parameters for hot rotating ^{216}Rn obtained from the fit to the experimental data.

Data	Fold 5–8	Fold 5–30	Fold 9–30	Isomer gated
CN spin [$\hbar$]	23	26	29	> 35
GDR centroid [MeV]	13.2 ± 0.1	13.2 ± 0.1	13.2 ± 0.3	13.2 ± 0.5
GDR width [MeV]	7.0 ± 0.3	7.0 ± 0.3	7.0 ± 0.4	7.3 ± 1

changing significantly with the spin. Such a scenario is theoretically confirmed as it can be seen in the potential energy maps of ^{216}Rn calculated using the LSD model [19]. In such calculations, the ^{216}Rn equilibrium and average shape remains almost spherical up to 40 $\hbar$. For higher spin, the fission channel totally dominates. Fig. 2 shows the measured GDR width compared to the prediction of the TFM scenario in which the free energy is calculated using the LSD model [16, 19] (dashed line). The dotted line represents the prediction of the scaling law of Ref. [7]. In both cases, the predictions agree significantly well with the experimental data indicating that the TFM approach can be successfully extended up to mass $A = 216$ (where fusion-fission competition is remarkably strong) for all angular momenta.

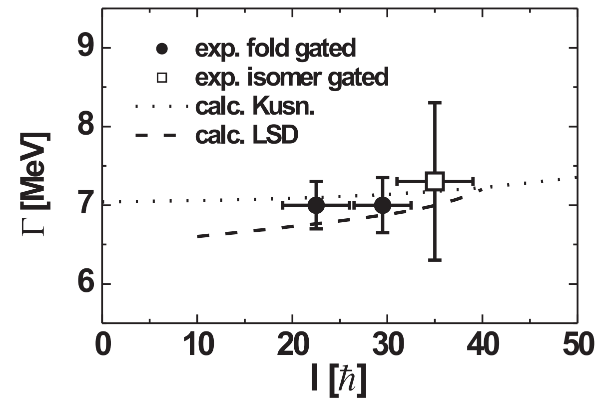

Fig. 2. The measured GDR width compared to the results of the thermal fluctuations model [16–19] and the calculation of Kusnezov *et al.* of Ref. [7].

3. GDR in very hot nuclei

As discussed in the previous chapters, in nuclear systems with temperatures up to 2–2.5 MeV, the increase of GDR width relative to its ground state value Γ_0 has been interpreted as an effect only due to the "hot and rotating" environment in which the GDR happens to be. In fact, a hot environment *(i)* induces an averaging on the shape sampled by the GDR and *(ii)* makes shell effects vanish. In such a scenario, rotation easily deforms the nucleus splitting GDR components and increasing its total width. As a consequence of the TFM approach, the GDR intrinsic width Γ_0 does not strongly depends on nuclear temperature. As the nuclear temperature increases, different phenomena could start playing an important role. In fact, in very hot nuclei *(i)* the time needed to build a GDR state can be comparable or longer than the particle emission timescale, inducing a limit in the temperature at which such a collective oscillation could exist [1, 20] and *(ii)* the time needed for the GDR to couple to the quadrupole deformation might be comparable or longer relative to the shape fluctuations time, inducing the phenomenon of motional narrowing [1, 21]. In such energy and temperature range, other approaches different than TFM have been proposed where Γ_0 is expected to increases with temperature. Experimental measurements of the GDR widths at high temperatures started almost two decades ago mostly in the Sn region showing a saturation of the width for excitation energies larger than $E^*/A = 1$ [22–24]. Recently, in a new set of measurements, in which the coincidence fold and charged particles have been measured together with high energy γ-rays (even though not in coincidence), a pre-equilibrium emission has been observed stronger than expected. The re-analysis of the old datasets, taking in consideration such pre-equilibrium emission, has shown a completely different scenario where the GDR width increases with temperature and does not saturate at least until 3–4 MeV of temperature [25]. To understand the role of the pre-equilibrium emission in the cooling process of the compound nuclei, we have measured the decay of the GDR in the ^{132}Ce* nuclei for different entrance channels and excitation energy. In the experiment, the high-energy γ-rays were detected with 8 large BaF_2 detectors of the HECTOR [17] apparatus, the residues were measured by a PSPPACs system covering the angles between 4° and 12° while the light charged particles were registered using one section of the GARFIELD detector array [26] (see the contribution of Gramegna to this conference [27]). The GARFIELD array [26] consists of two large drift chambers with a microstrip structure composed of 180 trapezoidal pads placed inside. Each of such pads provides signals of the incoming light charged particles. In the same gas volume there are 180 CsI(Tl) which provide the measurement of the residual energy. By the combined use of the $E - \Delta E$ and time signals, it is possible to detect and to identify the light charged particles emitted between 30° to 90°. The PSPPAC system consists of two position sensitive PPACs and a foil between them. The thickness of the foil is chosen to stop only the fusion like particles and let the scattered beam or the project-like particles to pass through. Consequently, the anti-coincidence between the two PSPPACs, together with the measurement of the time of flight, cleanly selects only the fusion residues. The hot and rotating ^{132}Ce nucleus was formed using two different entrance channels, one symmetric (^{64}Ni + ^{68}Zn at $E_{\rm beam}$ = 300, 400 and 500 MeV) and the other very asymmetric (^{16}O + ^{116}Sn at $E_{\rm beam}$ = 250 and 130 MeV), in order to investigate the role of the pre-equilibrium emission. It is important to note that the ^{64}Ni+^{68}Zn reaction at $E_{\rm beam} = 500$ and 300 MeV leads to the same nominal excitation energy of the compound nucleus formed in the ^{16}O + ^{116}Sn reaction at 250 and 130 MeV, respectively. The plots of Fig. 3 show the high energy γ-ray spectra measured in the ^{64}Ni and ^{16}O reactions normalised at 6–7 MeV. The expected increase of the γ-rays yield between 10–16 MeV with the beam energy is clearly evident in both plots of Fig. 3. A direct comparison of the two reactions shows that the oxygen induced compound has a higher yield than the Ni induced one and a stronger pre-equilibrium emission. The reason of such effect might be due to the strong N/Z asymmetry of the two reactions (1.29–1.27 for the Ni induced reaction and 1–1.32 for that induced by oxygen). This effect has already been observed [28] and interpreted as a prompt dipole emission coming from the earliest stages of the reaction. Full statistical model calculations are in progress for the extraction of the GDR parameters (EWSR, centroid and width).

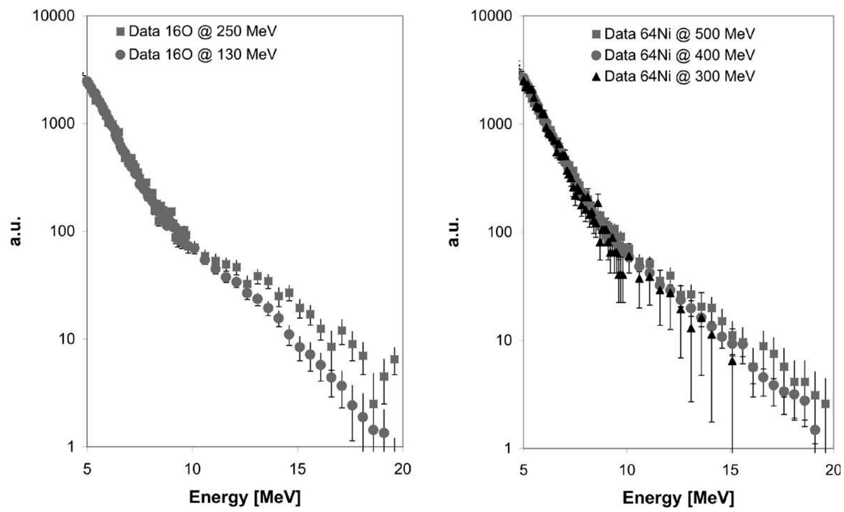

Fig. 3. The measured high energy γ-rays using ^{64}Ni (right panel) and ^{16}O (left panel) projectile. The yield in the GDR region increases with the beam energy.

4. Conclusion

In this paper, two new measurements of the GDR in hot rotating nuclei have been presented. The first on ^{216}Rn has provided experimental data in a mass region not yet experimentally explored and has shown that the thermal fluctuations model is able to successfully describe GDR observables in this mass region, also in the case where only highly rotating nuclei surviving fission are selected. The second set of data, although not fully analysed yet, has explored the GDR properties in very hot $A \simeq 132$ nuclei. The data, taken at different beam energies using nickel and oxygen beams producing the same compound system, show strong entrance channel effects and a possible evidence on the presence of a prompt dipole emission coming from the earliest stages of the reaction.

This work was partially supported by the Polish State Committee for Scientific Research (KBN) Grant No. 2 P03B 118 22.

REFERENCES

[1] P.F. Bortignon, A. Bracco, R.A. Broglia, Harwood Academic Publishers, Amsterdam 1998, volume of Contemporary Concepts in Physics.

[2] D.M. Brink, Ph.D Thesis, University of Oxford.

[3] J.O. Newton *et al., Phys. Rev. Lett.* **46**, 1383 (1981).

[4] A. Bracco *et al., Phys. Rev. Lett.* **47**, 3748 (1995).

[5] F. Camera *et al., Nucl. Phys.* **A572**, 401 (1994).

[6] E. Ormand *et al., Phys. Rev. Lett.* **77**, 607 (1996); *Nucl. Phys.* **A614**, 217 (1997); *Nucl. Phys.* **A618**, 20 (1997).

[7] D. Kusnezov, E. Ormand, *Phys. Rev. Lett.* **90**, 042501-1, (2003) and reference therein.

[8] S.K. Rathi *et al., Phys. Rev.* **C67**, 024603 (2003).

[9] B. Herskind *et al., Phys. Rev. Lett.* **59**, 2416 (1987).

[10] A. Bracco *et al., Nucl. Phys.* **A687**, 237c (2001).

[11] M. Kicinska-Habior *et al., Phys. Lett.* **B308**, 225 (1993).

[12] A. Maj *et al., Nucl. Phys.* **A687**, 192 (2001).

[13] A. Maj *et al., Nucl. Phys.* **A731**, 319 (2004).

[14] M. Kmiecik *et al.*, *Acta Phys. Pol. B* **36**, 1169 (2005), these proceedings.

[15] T. Tveter *et al., Phys. Rev. Lett.* **76**, 1035 (1996).

[16] M. Kmiecik *et al., Phys. Rev.* **C70**, 064317 (2004).

[17] A. Maj *et al., Nucl. Phys.* **A571**, 185 (1994).

[18] K.-H. Schmidt *et al., Phys. Lett.* **B168**, 39 (1986).

[19] K. Pomorski, J. Dudek, *Phys. Rev.* **C67**, 044316 (2003).

[20] P.F. Bortignon *et al., Phys. Rev. Lett.* **67**, 3360 (1991).

[21] E. Ormand *et al., Phys. Rev. Lett.* **69**, 2905 (1992) and reference therein.

[22] A. Bracco *et al., Phys. Rev. Lett.* **62**, 2080 (1989).

[23] G. Enders *et al., Phys. Rev. Lett.* **69**, 249 (1992).

[24] H.J. Hoffman *et al., Nucl. Phys.* **A571**, 301 (1994).

[25] M.P. Kelly *et al., Phys. Rev. Lett.* **82**, 3404 (1999).

[26] F. Gramegna *et al., Nucl. Instrum. Methods* **A389**, 474 (1997).

[27] F. Gramegna *et al.*, *Acta Phys. Pol. B* **36**, 1155 (2005), these proceedings.

[28] D. Pierroutsakou *et al., Eur. Phys. J.* **A17**, 71 (2003) and reference therein.