Giant Dipole Resonance in the Hot and Thermalized ^{132}Ce Nucleus: Damping of Collective Modes at Finite Temperature

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The γ decay of the giant dipole resonance (GDR) in the ^{132}Ce compound nucleus with temperature up to ≈ 4 MeV has been measured, using the reaction ^{64}Ni + ^{68}Zn at $E_{\mathrm{beam}} = 300$, 400, and 500 MeV. The γ and charged particles measured in coincidence with recoils are consistent with a fully equilibrated compound nucleus emission. The GDR width, obtained with the statistical model analysis, is found to increase almost linearly with temperature. This increase is rather well reproduced within a model including thermal shape fluctuations and the lifetime of the compound nucleus.

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The study of the properties of the giant dipole resonance (GDR) at high temperature and angular momentum is one of the central topics in nuclear structure as it provides insight into the behavior of nuclei under extreme conditions. The wealth of experimental data on this subject covers in most cases an interval of temperatures up to ≈ 2.5 MeV and is mainly based on the study of the γ decay from fusion-evaporation reactions. These data have been shown to provide an important testing ground for the theoretical models. In particular, the change of the GDR width with angular momentum and temperature reflects the role played by quantal and thermal fluctuations in the damping of the giant vibrations [1–7]. While, in general, the experimental results at $T < 2$ MeV are rather well understood within the thermal fluctuation model (TFM) [8], at a temperature higher than 2.0 MeV the situation is more complex. In fact, the most recent works [9,10] have raised the very important question on whether the thermalization process at very high excitation energies ($E^* > 150$ MeV) is properly known and, consequently, if the temperature of the γ-ray emitting systems can be determined correctly. This very relevant remark was pointed out and discussed in connection with the measurements of γ rays and light charged particles (LCP) in Sn isotopes at temperature up to ≈ 2.5 MeV using the reaction ^{18}O + ^{100}Mo with $E_{\mathrm{beam}} = 122$–217 MeV. The analysis of the LCP spectra has shown that the preequilibrium contribution is sizable, corresponding, in the case of the highest bombarding energies, to a loss of excitation energy of approximately 20%. Another very interesting aspect of the works of Kelly *et al.* concerns the reinterpretation of the previous GDR experiments performed by other groups at $T > 2.0$ MeV using different projectile and target combinations [9–15]. This reinterpretation, motivated by the effort of a better definition of the initial excitation energy affecting the GDR analysis, provided a picture of the temperature dependence of the GDR width no longer consistent with the saturation effect previously observed. More specifically, before the Kelly *et al.* analysis there was some evidence that beyond the bombarding energy at which the angular momentum saturates the GDR width increases slowly, and this was interpreted as due to only one mechanism, namely, that of thermal shape fluctuations driven by temperature. In contrast, the results of Kelly *et al.* [9] showed a continuous increase of the GDR width when the values of the excitation energies were corrected for the preequilibrium emission. It is clear from the above considerations that the behavior of the GDR at the highest temperatures ($T > 2.0$ MeV) is presently an open question and more complex than expected. A better investigation of this problem requires data without preequilibrium contribution whose subtraction is model dependent. Therefore the present work uses experimental conditions allowing one to deduce directly from two observables (charged particles and γ rays) the excitation energy of the compound nucleus.

The present work reports on an experiment concerning the GDR in the mass $A \approx 130$ region at temperature in the interval $T = 2$–4 MeV using the symmetric reaction ^{64}Ni + ^{68}Zn leading to ^{132}Ce. The used bombarding energies of 300, 400, and 500 MeV correspond to the kinematical value of excitation energies $E^* = 100$, 150, and 200 MeV. In the experiment LCP, γ rays, and heavy recoiling nuclei were measured in coincidence. In addition we measured with the same experimental conditions the LCP, γ rays, and heavy recoiling nuclei produced in the asymmetric mass entrance channel reaction $^{16}O + ^{116}Sn$, which should lead to the same compound ^{132}Ce at $E^* =$ 100 and 200 MeV, as deduced from kinematics. This last reaction was used to define and compare the preequilibrium contribution, which was predicted in a similar case by Kelly *et al.* The present experiment is designed to add valuable information on the behavior of the GDR width at very high excitation energies in nuclei with spherical ground states as in the case of Sn isotopes with similar masses ($A \approx 110$–120). In the latter case, a continuous increase of the width with temperature was seen after a proper characterization of the excitation energies.

The experiment was performed at the Legnaro National Laboratory of INFN using a setup consisting of an array for fragment and light charged particle detection (GARFIELD [16]) combined with 8 large volume BaF_2 detectors for high energy γ-ray detection (HECTOR [17]) and two position sensitive parallel plate avalanche counter telescopes (PSPPAC) [16]. The BaF_2 detectors, positioned in the GARFIELD chamber at ≃30 cm from the target at 125° and 160°, have a time resolution of ≃1 ns. The neutron events were rejected using time-of-flight information. The GARFIELD array measured light charged particles and fragments. It consists of a large drift chamber, divided into 24 sectors. Each sector is then subdivided in 4 pseudotelescopes formed by ΔE gas microstrip detectors coupled to CsI(Tl) crystals. The detection and identification of charged particles at 30°–85° used the ΔE-E and drift time signals. The BaF_2 detectors were calibrated using standard γ-ray sources and the 15.1 MeV γ rays from the reaction $d(^{11}B, n\gamma)^{12}C$ at 19.1 MeV. An electronic threshold of ≈4 MeV was set for γ rays. The GARFIELD detectors were calibrated using elastic scattering of ^{12}C and ^{16}O with energies from 6 to 20 MeV/A. The identification threshold for LCP and fragments was about 900 keV/A. For all the reactions, the same tagging conditions, deduced from the PSPPAC's identification of the recoiling residues, were used for both the light charged particles and the γ rays.

Figure 1 shows selected α-particle spectra measured in coincidence with the heavy recoiling residual nuclei for $^{16}O + ^{116}Sn$ at $E_{beam} = 250$ MeV (top row) and $^{64}Ni +$ ^{68}Zn at $E_{beam} = 500$ MeV (bottom row). The excitation energy deduced from kinematics is the same in both cases. In the left panels the spectra measured at different center of mass angles, normalized in the region of the maximum yield, are displayed. The spectral shape of the α particle changes pronouncedly by varying the detection angle for the O-induced reaction, while it is basically unchanged for the Ni-induced reaction. This behavior of the angular distribution for the O-induced reaction reflects the presence of a sizable preequilibrium contribution in the emission of the compound nucleus as deduced from the strongly forward focused α-particle yields. In order to verify this explanation, statistical model calculations were made and normalized to the low energy part of the barrier. This is shown together with the data in the right panels of Fig. 1. The α-particle spectrum of the Ni-induced reaction is very well reproduced by the calculation implying emission from a fully thermalized compound system. In contrast, the statistical model calculations cannot describe the large extra yield measured with the O-induced reaction, and a more complete analysis including other contributions such as those from a nonequilibrated thermal source is necessary to understand the data. Therefore, the study of the GDR problem in the present Letter is restricted to the data

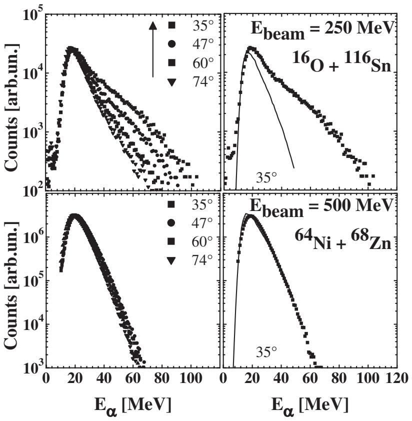

FIG. 1. Left panels: Measured α spectra in the c.m. system at different angles. The lower panels show the data taken with the ^{64}Ni beam ($E_{lab} = 500$ MeV) and the upper panels show data with the ^{16}O beam ($E_{lab} = 250$ MeV). The right panels show the spectra specifically at 35°. The continuous lines show the statistical model calculations [37,38].

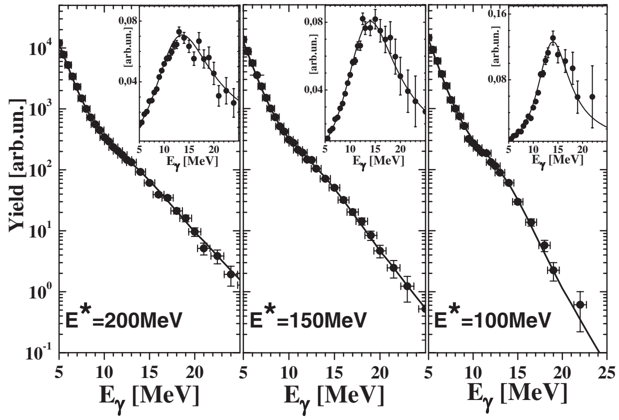

FIG. 2. The measured (solid points) and calculated statistical model (solid line) high energy γ-ray spectra for ^{132}Ce at $E^* =$ 200, 150, and 100 MeV. The calculations assume a fully thermalized CN and an average spin $\langle J \rangle$ of $45\hbar$. In the inset, $F(E_\gamma) Y_\gamma^{expt}(E_\gamma)/Y_\gamma^{calc}(E_\gamma)$ (see text) is plotted and the lines are the best fitting single component Lorentzian functions.

obtained with the Ni-induced reaction corresponding to a symmetric mass entrance channel system. Extensive analyses of the LCP spectra for both symmetric and asymmetric reactions will be the subject of a future paper [18,19].

The γ-ray spectra measured in coincidence with the recoiling residual nuclei are shown in Fig. 2 (symbols) together with the best fitting statistical model calculations (solid line) [20,21]. The calculations were folded with the response function of the BaF_2 array calculated using the GEANT [22] libraries and were then normalized at around 8 MeV. The width was obtained from the best fit to the data using a χ^2 minimization procedure between 12 and 22 MeV. Because of the exponential nature of the spectra, the χ^2 of this fit is dominated by the low energy part and it is relatively insensitive to the high energy region. Consequently, the best fitting GDR parameters were chosen to be those minimizing the χ^2 divided by the number of counts as, for example, in Ref. [12].

A single Lorentzian strength function centered at $E_{\mathrm{GDR}} \approx 14$ MeV (lower than the $T = 0$ MeV value) as in [23] and a value of the energy-weighted sum rule (EWSR) corresponding to $\approx$100% of the Thomas-Reiche-Kuhn sum rule were used. In order to display the spectra on a linear scale to emphasize the GDR region, the quantity $F(E_\gamma)Y_\gamma^{\mathrm{expt}}(E_\gamma)/Y_\gamma^{\mathrm{calc}}(E_\gamma)$ was plotted in the insets of Fig. 2. $Y_\gamma^{\mathrm{expt}}(E_\gamma)$ is the experimental spectrum and $Y_\gamma^{\mathrm{calc}}(E_\gamma)$ the best fit calculated spectrum, corresponding to the single Lorentzian function $F(E_\gamma)$. The resonance width and centroid were treated as free parameters of the fit. For the level density description the Reisdorf formalism of Ignatyuk [24,25] was used with a value of the level density parameter a (MeV^{-1}) between $A/10$ and $A/9$ for $E^* < 100$ MeV. At higher excitation energies we used a level density parameter, as deduced from [26,27], which decreases linearly to $A/11$ up to $E^* < 170$ MeV and saturates down to $A/12.5$ for $E^* > 170$ MeV.

Since at these experimental bombarding energies there is a saturation of the angular momentum of the compound nucleus (CN), an average value of $\langle J \rangle = 45\ \hbar$ and maximum of $L_{\max} = 70\hbar$ was used for all the present calculations. The best fitting values deduced from the analysis of the GDR region correspond to a width $\Gamma_{\mathrm{GDR}} = 8 \pm 1.5$, 12.4 ± 1.2, and 14.1 ± 1.3 MeV at $E^* = 100$, 150, and 200 MeV, respectively. Note that the statistical model calculation of the α spectra at bombarding energy of 500 MeV of Fig. 1 (right-bottom panel) was made with the same excitation energy values.

The nuclear temperature of the compound nucleus associated with the GDR decay was calculated with the expression $T = 1/[d(\ln(\rho))/dE]$, as discussed in Refs. [28,29], where ρ is the level density. The resulting value for the present data is not substantially different from the one calculated using the relation $T^2 = [(E_x - E_{\mathrm{rot}} - E_{\mathrm{GDR}})/a)]$, where E_{rot} is the rotational energy. To take into account that the γ rays from the GDR region (12–25 MeV) are emitted at different steps of the CN decay, one has to make a weighted average for the temperature. Before doing this we have investigated the excitation energy interval to be taken for the average by examining how the sensitivity to the GDR width changes in the various steps on the decay. We noted that a considerable change (outside the error bars) of the GDR width in the low temperature part of the CN decay does not affect the fit to the data. Therefore at the present excitation energies the performed average corresponds to approximately 50% of the total yield. The obtained values for the average temperature are 1.9, 2.8, and 3.7 MeV, for $E_{\mathrm{beam}} = 300$, 400, and 500 MeV, respectively.

The measured values of the GDR width are shown in Fig. 3. The error bar in the width is the statistical error connected to the χ^2 minimization. The horizontal bar represents the average temperature range associated to 75% (lower value) and 25% (upper value) of the gamma yield. The neglected yield in the average represents the decay at the end of the CN cascade that is not sensitive to the GDR width because of its spectra shape. In the same figure we show the existing data at lower temperature, which correspond to reactions leading to fully thermalized compound nuclei [30,31].

The data for the Ce isotopes are also compared with theoretical predictions based on the TFM of the nuclear shape. Within this model, the GDR strength function is calculated by averaging the line shape corresponding to the different possible deformations. The averaging over the distribution of shapes is weighted with a Boltzmann factor $P(\beta, \gamma) \propto \exp[-F(\beta, \gamma)/T]$, where F is the free energy and T is the nuclear temperature [2,32,33]. At each deformation point the intrinsic width Γ_0 of the resonance was chosen equal to the zero temperature value, namely, 4.5 MeV, as it was generally done to reproduce the existing

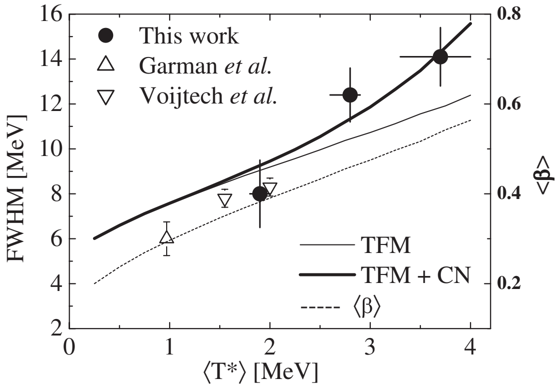

FIG. 3. Comparison between measured (solid circles) and calculated GDR widths at $\langle J \rangle = 45\hbar$. The thin continuous line shows the thermal shape fluctuations simulation, while the thick continuous line includes also the CN lifetime. The data from Garman *et al.* [30] (up-pointing triangle) correspond to an angular momentum value between $\langle J \rangle \approx 8\hbar$ and $16\hbar$, while those of Voijtech *et al.* [31] (down-pointing triangles) to $\langle J \rangle \approx 23\hbar$ and $27\hbar$. The dashed line shows the average deformation $\langle \beta \rangle$ calculated by the TFM [7,33] (scale on the right axis).

majority of data at $T < 2.5$ MeV. This calculation is shown with a thin continuous line in Fig. 3. One can note that the predicted increase does not reproduce the present experimental data at $T > 2.5$ MeV. In addition, the predicted increase follows rather well the deformation increase of the compound nucleus induced by temperature. This is also shown in Fig. 3 where the average deformation of the nucleus obtained by the TFM is shown with a dashed line (scale on the right vertical axis). A possible explanation for the discrepancy between the data and the TFM at $T > 2.5$ MeV could be related to the fact that the lifetime of the compound nucleus could play a role at these temperatures. This question was originally addressed by Chomaz *et al.* [33–35] who showed the importance of this effect at temperature higher than 2.5 MeV. The present calculation within the TFM including also the compound nucleus lifetime is shown in Fig. 3 with a thick solid line. The CN total lifetime values were calculated with the statistical model. A change of the level density parameter between $A/10$ to $A/12$ as discussed in Ref. [33] implies a change of the order of 0.5 MeV at $T = 3.5$ MeV. These values were included in the calculations by adding them to the GDR intrinsic width Γ_0 before performing the averaging over shapes [34,35]. In this case a remarkable agreement between the experimental data and the predictions is found. We have also performed a statistical model calculation including the temperature dependence of the GDR width given by the thick line of Fig. 3, and this gives a good fit to the data. From the present comparison, one can also note that, in agreement with the expectation of the theory [1], for $T > 2$ MeV there is no room for a significant increase of the intrinsic width Γ_0 with temperature [36], unless one unrealistically neglects the CN lifetime contribution to the total width.

In conclusion, the analysis of the data shows that the GDR width does not saturate at $T > 2.5$ MeV but increases steadily with temperature at least up to 4 MeV. This behavior is consistent with the one found for the Sn isotopes [9]. However, in the Sn work the data were corrected for the preequilibrium emission at variance with the present case where no corrections on the excitation energy were necessary and for which the excitation energy was deduced from the analysis of both LCP and γ rays measured in coincidence with heavy recoiling nuclei. The consistent behavior of the GDR width with increasing temperature found in the two mass regions of Sn and Ce in the interval $T = 2.5$–4 MeV sheds more light on the interesting problem of the damping mechanisms of collective modes at finite temperature. Deformation effects and the intrinsic lifetime of the compound nucleus are the two combined mechanisms, which explain the measured increase of the width with temperature. Exclusive studies of this type should therefore be pursued also in other mass regions including more exotic ones, or in other rotational frequency regimes to further test nuclear structure under extreme temperature conditions and to learn more about nuclear deformation.

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