Towards Limiting Temperatures in Nuclei: The Behavior of Collective Motion

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Gamma rays emitted from hot nuclei with mass around 115 and excitation energies between 350 and 550 MeV, formed in the $^{36}Ar+^{90}Zr$ reaction at 27 MeV/nucleon, have been measured. The γ-ray yield from the decay of the giant dipole resonance in these nuclei remains constant over the excitation energy range studied. This quenching of the γ multiplicity cannot be explained by a continuous increase with temperature of the width of the resonance. Better agreement with the data is obtained by assuming a cutoff of γ emission from the resonance above an excitation energy of 250 MeV. The existing data do not show entrance channel effects.

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The possibility to create nuclei heated to temperatures approaching their limit of existence allows us to study the evolution of the collective motion of nucleons in nuclei towards chaotic behavior at extreme excitation energies. The properties of the highly collective giant dipole resonance (GDR) should provide the best experimental fingerprint of such an evolution since they can be measured through γ decay. A large body of data exists concerning the properties of the GDR in nuclei of mass $A \approx 110$ up to approximately 300 MeV excitation energy [1]. At these moderate energies the position of the GDR remains nearly constant at its ground state value (i.e., ≈ 16 MeV). Its width increases from the ground state value of 5 MeV up to approximately 11 MeV at $E^*=130$ MeV [2]. At higher excitation energies experimental results have been reproduced either supposing a saturation of the width [3,4], or by a width continuously increasing with temperature [4–6]. Finally, the γ yield from GDR decay is consistent with 100% of the energy weighted sum rule (EWSR) up to $E^*=300$ MeV. Above 300 MeV, experimental results [5,7] are more fragmentary, but show a saturation of the γ yield from the GDR decay. Several reasons have been invoked: a strong increase of the width of the GDR with temperature [5,8,9], hindrance of the γ emission due to the time necessary to couple the GDR to the compound nucleus (preequilibrium effects) [10], or a loss of collectivity of very hot nuclei [7,8].

In the present work γ spectra were measured in coincidence with nuclei of mass around 115 with excitation energies between 350 and 550 MeV. It will be shown that a continuous increase of the GDR width with temperature does not allow one to reproduce the entire γ spectra, but that other types of mechanisms leading to a quenching of the γ yield at high excitation energies must be invoked.

In order to produce hot nuclei through incomplete fusion reactions, a 300 $\mu g/cm^2$ ^{90}Zr target was bombarded with the 27 MeV/nucleon ^{36}Ar beam from the GANIL facility. Gamma rays and light charged particles were detected with the MEDEA multidetector [11], which is a detector ball consisting of 180 barium fluoride (BaF_2) crystals that cover the angular range between 30° and 170°. An unambiguous separation of γ rays from neutrons and light charged particles was achieved by the combination of a pulse shape analysis and time of flight measurement. The detectors were calibrated in energy with the 4.4 and 6.1 MeV γ rays from AmBe and PuC sources, respectively. The light charged particle calibration was deduced from the γ calibration using the procedure of Ref. [12]. Fusionlike residues were detected in two parallel plate avalanche counters covering between 6° and 22° on either side of the beam. These counters yielded energy-loss and time-of-flight information which allowed us to select fusionlike residues. The trigger requirement was given by one parallel plate counter firing in coincidence with at least one BaF_2 detector. This requirement eliminates the cosmic-ray contamination from the γ spectra.

Through the incomplete fusion mechanism a wide range of residue velocities, and thus of linear momentum transfers and excitation energies, is populated in the reaction. Here, the data have been sorted into three bins according to the ratio $v_R/v_{\mathrm{c.m.}}$ between the velocity of the detected recoil and the velocity of the center of mass. The mean velocities of each bin are $0.52v_{\mathrm{c.m.}}$, $0.69v_{\mathrm{c.m.}}$, and $0.92v_{\mathrm{c.m.}}$, corresponding, according to the massive transfer model [13], to excitation energies of 360, 480, and 630 MeV and initial masses of 105, 113, and 122,

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TABLE I. Multiplicities, temperatures, and velocities of the compound nucleus source (CN) extracted from the moving source fits. The errors indicated are only those due to the fitting procedure.

$v_R/v_{\rm c.m.}$	$M_{\rm CN}$	$T_{\rm CN}$ (MeV)	$v_{\rm CN}/v_{\rm c.m.}$
52%	1.67 ± 0.08	4.64 ± 0.15	0.59 ± 0.03
69%	1.89 ± 0.10	5.21 ± 0.20	0.78 ± 0.04
92%	2.00 ± 0.11	5.35 ± 0.20	0.82 ± 0.04

respectively.

A complementary characterization of the hot nuclei can be obtained through the study of the light charged particle spectra. For each velocity bin, proton spectra were extracted for several angles in the range covering $69° < \theta_{\rm lab} < 160°$, and analyzed in terms of a moving source fit. Only two sources, a compound nucleuslike source and an intermediate velocity source simulating preequilibrium emission, were necessary to fit the data over the angular range studied. The parameters of the compound nucleus source are given in Table I. The multiplicity of emitted protons, apparent temperature, and velocity of the compound nucleus source increase with increasing residue velocity, confirming that larger residue velocities allow us to focus on hotter and hotter nuclei. Moreover, the compound nucleus source velocity is in reasonable agreement with the measured residue velocity. The temperature increases strongly when going from the first to the second velocity bin, and less for the highest bin. The initial temperature of the compound nucleus was inferred from the apparent temperature obtained from the moving source fit using the relationship obtained in the literature for protons: $T_{\rm init} = 1.3T_{\rm app}$ [14]. Discounting the highest velocity bin, the best agreement between the excitation energies deduced from the temperature measurements and those from the velocity measurement is obtained by using a level density parameter $a = A/K$ with $K = 11$ MeV. By using this value an excitation energy of 550 MeV is deduced for the highest velocity bin, clearly lower than the value given by the massive transfer model. The excitation energies quoted in the following will be 350, 500, and 550 MeV, corresponding to $K = 11$ MeV. This value is in reasonable agreement with recent theoretical calculations [15] which predict an increase of the level density parameter for Sn nuclei from $K = 8.5$ MeV at zero temperature to $K = 12$ MeV above $T = 5$ MeV. The combination of the residue and particle measurements clearly establish that increasing residue velocities correspond to increasing excitation energies and that hot nuclei with excitation energies well in excess of 300 MeV are populated in the present reaction.

Figure 1 shows γ spectra measured at 90°, where the Doppler shift is negligible, in coincidence with fusion events for the three excitation energy bins, normalized over 4π. The remarkable feature of these spectra is the pronounced bump observed around 15 MeV due to the

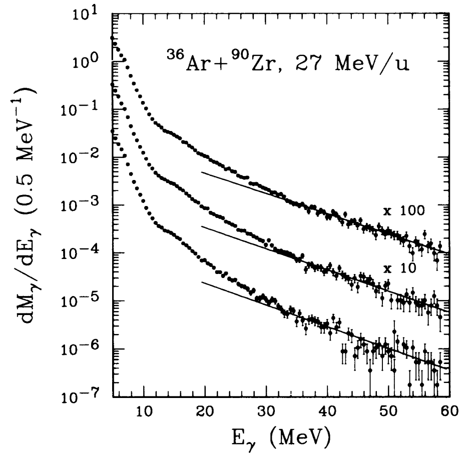

FIG. 1. Normalized γ spectra measured for three excitation energy bins at 350 MeV, 500 MeV ($\times$10), and 550 MeV ($\times$100). The solid lines are a fit to the high energy component of the spectra ($E_\gamma > 35$ MeV).

γ decay of the GDR. At low energies statistical γ rays emitted by the compound nucleus at the end of its decay chain give rise to a steep exponential decay. The high energy γ yield can be represented by an exponential function, fitted to the spectrum for $E_\gamma > 35$ MeV. The slope parameter for all three bins is 9.5±1.0 MeV, which is in good agreement with the known systematics for nucleon-nucleon bremsstrahlung [16]. Moreover, the high energy γ yield increases with increasing residue velocity, in agreement with a simple geometrical picture in which the highest momentum transfers correspond to the most central collisions for which the number of nucleon-nucleon collisions is largest.

To investigate the evolution of the γ decay from the GDR as a function of excitation energy, the bremsstrahlung component, assumed to have an exponential shape over the entire energy range, was subtracted from the spectra. Such an assumption is justified by theoretical calculations performed down to E_γ=20 MeV [17]. The γ multiplicity was then integrated between 12 and 20 MeV, corresponding approximately to the range of GDR transitions in the spectra. The integrated multiplicities are $(3.5 \pm 0.2) \times 10^{-3}$, $(3.8 \pm 0.2) \times 10^{-3}$, and $(4.1 \pm 0.4) \times 10^{-3}$ for 350, 500, and 550 MeV, respectively, and can be considered constant within the error bars.

Statistical calculations using the code CASCADE [18] were performed at different excitation energies assuming $E_{\rm GDR} = 76.5A^{-1/3}$ MeV, $\Gamma_{\rm GDR} = 12$ MeV, and $S_{\rm GDR} =$ 100% EWSR, for the energy, width, and strength of the GDR. Such calculations, with a saturated width and 100% EWSR, allowed us to reproduce the γ spectra at lower excitation energies [1]. The temperature dependent level density parameter from [15] was used. The calculations were folded with the detector response. The calculation at 500 MeV is compared to the data in Fig. 2.

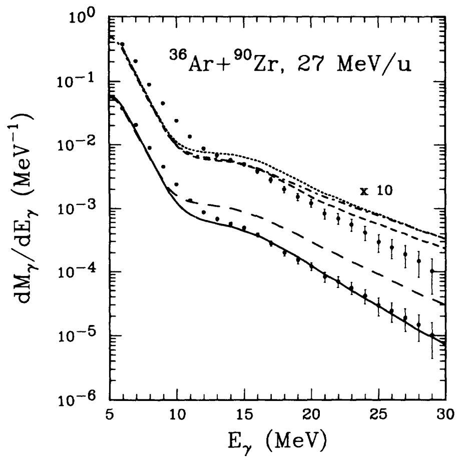

FIG. 2. Upper part: Comparison of the experimental data for the 500 MeV bin after bremsstrahlung subtraction (points) with CASCADE calculations including two prescriptions for a continuously increasing GDR width proposed by Chomaz [8] (dash-dotted line) and Smerzi *et al.* [9] (dashed line), and with a calculation using $\Gamma_{\text{GDR}} = 4.8 + 0.0026E^{*1.6}$ MeV [2] (dotted line). For details of the calculations see Ref. [19]. Error bars in the experimental spectrum include statistical errors and uncertainties due to different assumptions on the slope parameter and normalization of the brehmsstrahlung component. Lower part: Same experimental spectrum compared with a CASCADE calculation with 100% EWSR (dashed line) and a calculation with a cutoff of the GDR γ emission above $E^* = 250$ MeV (full line). Both calculations were performed with $\Gamma_{\text{GDR}} = 12$ MeV.

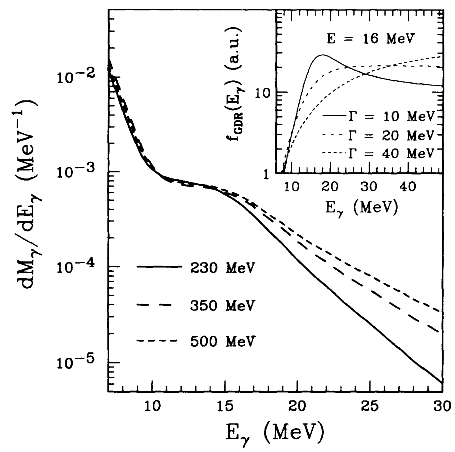

FIG. 3. CASCADE calculations performed at three excitation energies using $\Gamma_{\text{GDR}} = 4.8 + 0.0026E^{*1.6}$ MeV. Inset: Evolution of $f_{\text{GDR}}(E_\gamma)$ as a function of Γ_{GDR} (see text).

The calculations clearly overshoot the data in the GDR region. Moreover, the calculated multiplicity increases strongly with excitation energy, in contrast to the experimental results. It should be noted that the choice of a different level density parameter can change the calculated yields slightly but does not affect the above conclusions [19].

The saturation of the GDR γ yield at high excitation energies clearly confirms the earlier results of Refs. [5,7]. It was proposed [5,8,9] that the observed saturation could be related to a strong increase of the width of the GDR with excitation energy. Indeed, increasing the width of the GDR will spread the γ rays over a larger energy range and thus lead to a quenching of the yield between 12 and 20 MeV. This is depicted in Fig. 3 which displays the result of CASCADE calculations at three excitation energies, using a width which varies along the decay chain as $\Gamma_{\text{GDR}} = 4.8 + 0.0026(E^*)^{1.6}$ [2]. The point we wish to stress is that the saturation of the yield around the GDR centroid is obtained at the expense of an increase at higher energies. This is simply understood from the statistical dipole photon emission rate:

$$R_\gamma dE_\gamma = \frac{\rho(E_2)}{\rho(E_1)} f_{\text{GDR}}(E_\gamma) dE_\gamma,$$

where

$$f_{\text{GDR}}(E_\gamma) \propto E_\gamma^2 \frac{\Gamma_{\text{GDR}} E_\gamma^2}{(E_\gamma^2 - E_{\text{GDR}}^2)^2 + \Gamma_{\text{GDR}}^2 E_\gamma^2}.$$

In this equation the factor $\rho(E_2)/\rho(E_1)$ is the ratio of the level densities between the final and initial states differing by an energy $E_\gamma = E_1 - E_2$. The inset of Fig. 3, which displays $f_{\text{GDR}}(E_\gamma)$ for different values of Γ_{GDR}, clearly shows that the γ yield is shifted to higher energies for increasing values of Γ_{GDR}. Therefore, in the high energy region, the increase of the GDR width does not introduce a quenching but rather an increase of the γ multiplicity. Moreover, the slope of the γ spectrum in this region should decrease with excitation energy due both to the behavior of the level density ratio with increasing temperature and to the broadening of the GDR strength. These effects are not seen in the experimental data. In fact, the three measured γ spectra, after bremsstrahlung subtraction, are identical within the error bars above 12 MeV.

CASCADE calculations performed following three prescriptions proposed in the literature [2,8,9] for a continuous increase of the GDR width are compared to the data at 500 MeV excitation energy in Fig. 2. Two of the calculations give a reasonable account of the γ yield between 12 and 20 MeV. However, in all cases, the assumption of an increase of the width leads to an overprediction of the γ multiplicity in the high energy region above 20 MeV. This conclusion cannot be modified by changing the slope or normalization of the subtracted bremsstrahlung component, as shown by the error bars of the spectrum which include uncertainties on the bremsstrahlung subtraction. Only the assumption of a complete absence of the bremsstrahlung component, which would be in contradiction with all known systematics, could lead to agreement between the data and the calculations. In conclusion, the GDR γ emission must be hindered by another mechanism than the increase of the width.

The simplest way to simulate the complete γ spectrum above 12 MeV is to introduce a sharp suppression of the γ emission above a given excitation energy. Such a calculation using a constant width of 12 MeV for the GDR, and a cutoff excitation energy of 250 MeV allows us to reproduce the γ spectra above 12 MeV measured for the three excitation energy bins, as shown for 500 MeV excitation energy in Fig. 2. The use of a smooth cutoff as a function of the temperature gives similar results, showing that the precise shape of the cutoff cannot be inferred from the present data.

In Ref. [10] it was proposed that in a compound nucleus the dipole excitations need a certain time to be equilibrated during which the GDR γ emission will be hindered. This is expected to induce a decrease of the GDR γ yield above 200 MeV excitation energy in the Sn nuclei and, indeed, applying such a theory gives a reasonable account of the data [19] with a result similar to that using a sharp cutoff above 250 MeV. However, it has been shown [20] that in the framework of this model, the use of a system with different N/Z ratios for the projectile and target would lead to an enhancement of the GDR γ yield compared to a symmetric N/Z system. Indeed, in the former case the asymmetry in N/Z ratios induces dipole oscillations in the entrance channel and thus preequilibrium GDR γ decay can contribute to the measured γ spectra. In the present experiment the integrated γ yield between 12 and 20 MeV is close to the value measured for the ^{40}Ar $+^{92}$Mo reaction at 26 MeV/nucleon reported in Ref. [5]. In this reaction, projectile and target have almost identical N/Z ratios, contrarily to the present experiment. This absence of entrance channel dependence casts some doubt on the possibility of consistently explaining the saturation of the GDR γ yield by preequilibrium effects.

In Refs. [7,8] it was suggested that the observed saturation could be due to a loss of collectivity at high temperature. Another possibility could be that the GDR is replaced by some one-particle–one-hole strength around 8 MeV as one approaches very high excitation energies. This tendency can be found in random phase approximation calculations at high temperatures [21]. Note that a large discrepancy between the CASCADE calculations and the experiment is observed between 8 and 12 MeV. An analogous phenomenon can be found in the results of Ref. [7]. This discrepancy could be an experimental indication of such a low-lying component. However, before any definite conclusion about the origin of this component in the γ spectrum can be drawn, more experimental work and new theoretical predictions are called for.

In summary, γ rays were measured in coincidence with well characterized hot nuclei at excitation energies above 300 MeV. The γ yield above 12 MeV from the GDR decay is constant as a function of excitation energy. We have shown that an increase with temperature of the width of the GDR could account for the integrated γ yield between 12 and 20 MeV but is unable to reproduce the spectra above 20 MeV. To reproduce the data a quenching of the γ emission at excitation energies above approximately 250 MeV must be supposed. The fact that the N/Z asymmetry in the entrance channel has no effect on the GDR γ yield suggests that preequilibrium γ-emission effects cannot be invoked. The investigation of possible reasons for this quenching, such as a loss of collectivity of very hot nuclei or a shift towards lower energies of the GDR strength at high temperatures, calls for new theoretical developments.

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