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STUDY OF HOT NUCLEI THROUGH THE GIANT DIPOLE RESONANCE DECAY

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ABSTRACT

The saturation of the giant dipole resonance γ multiplicity in hot nuclei at excitation energies above 300 MeV is confirmed by two experiments : ^{36}Ar+^{90}Zr at 27 MeV/A and ^{36}Ar+^{98}Mo at 37 MeV/A performed at GANIL by using the MEDEA multidetector. A significant decrease of the GDR γ yield is observed when the bombarding energy is increased from 27 MeV/A to 37 MeV/A. This decrease is qualitatively in agreement with a dynamical calculation yielding a larger equilibration time for the hot system formed at 37 MeV/A than for the system formed at 27 MeV/A.

1. Introduction

One of the most exciting results of recent heavy ion physics is the possibility to create and study hot nuclei formed through complete and incomplete fusion reactions. Numerous studies measuring evaporation residues, fission fragments, emitted light particles, and intermediate mass fragments have been performed in the aim to understand the behavior of nuclear matter under such extreme conditions. More recently, the measurement of high energy γ-rays has yielded information on the dissipation mechanism in energetic heavy ion collisions and the study of the giant dipole resonance (GDR) in hot nuclei through its gamma decay has addressed the question of the persistence of collective motion at high excitation energies.

The GDR is characterized by its centroid energy, width and strength and the evolution of these observables as a function of excitation energy has been a subject of numerous experimental studies. The most complete systematics has been obtained on the medium mass nuclei in the vicinity of A≈115. As a function of excitation energy, the centroid energy of the GDR seems to remain stable, at about 15 MeV[1]. At moderate excitation energies, below 130 MeV, the width increases from 4.8 MeV to about 12 MeV due both to the increase of maximum angular momentum populated in the reaction[2] and to thermal effects as demonstrated by studies where the GDR was measured in excited nuclei with a very low angular momentum populated by inelastic α scattering[3]. Above 130 MeV, divergent results concerning the width of the GDR have been reported. Experiments by Bracco et al.[4] and more recently Hoffman et al.[5] lead to the conclusion of the saturation of the width at a value around 12 MeV while Yoshida and co-workers fitted their results with a continuously increasing width[6]. While the γ-ray multiplicity from the GDR increases up to 300 MeV in agreement with 100% of sum rule strength, this seems no longer to be the case at higher energies, where a saturation of the γ yield has been observed[6,7,8]. Several theoretical models have been proposed to explain the observed saturation, either by a rapid increase of the GDR width with temperature[9,10,11], by a long coupling time of the GDR to the compound nucleus[12,13] or by an appearance of a low lying GDR component at high temperature[14].

In order to study the GDR at very high temperatures, near the critical temperature expected for the liquid gas phase transition, the GDR γ rays were measured in two experiments performed at GANIL (France) by using the MEDEA multidetector[15]. The first concerned the reaction ^{36}Ar+^{90}Zr at 27 MeV/A and the results have already been published[8,16]. The second experiment, ^{36}Ar + ^{98}Mo, was performed at a considerably higher bombarding energy, 37 MeV/A, allowing to study the evolution of the γ-ray yield with increasing bombarding energy. In the following, the disappearance of the GDR at high excitation energies will be discussed in the light of these two experiments.

2. Experiments and results

Hot nuclei were formed in incomplete fusion reactions of ^{36}Ar+^{90}Zr at 27 MeV/A and ^{36}Ar+^{98}Mo at 37 MeV/A. Gamma rays and light charged particles were measured with the MEDEA multidetector consisting of a ball of 180 barium fluoride (BaF_2) detectors covering an angular range between 30°and 170° with a solid angle of 3.37π. The system is completed by a forward phoswich wall covering the angles between 10° and 30°. To allow for the simultaneous measurement of γ–rays and light charged particles, the entire system operates under vacuum inside a large scattering chamber. Fusion-like residues were detected in two parallel plate avalanche counters (PPAC) located in front of the phoswich wall covering between 6° and 22° on either side of the beam. In the experiment at 37 MeV/A only one PPAC was used in order to have a better coverage for the phoswich detectors to measure light charged particles emitted from the projectile-like source. The trigger was given by one PPAC firing in coincidence with at least one BaF_2 detector.

In incomplete fusion reactions the linear momentum transfer (LMT), the mass of the composite system and its excitation energy can be obtained from the recoil velocity by applying a massive transfer model[17]. The time-of-flight spectrum measured for the heavy residues in both reactions is broad showing that a wide range of LMTs and thus excitation energies is populated. The mean LMTs obtained are 75% and 60% for the reactions at 27 and 37 MeV/A, respectively.

Table 1 Temperatures and excitation energies obtained from the analysis of the proton and alpha particle spectra (see text).

	^{36}Ar+^{90}Zr, 27 MeV/A		^{36}Ar+^{98}Mo, 37 MeV/A	
v_R/v_{CM}	0.50	0.70	0.45	0.65
T_{app} (proton)	4.65	5.20	5.3	5.5
T_{app} (alpha)			5.8	6.2
T_{init} (proton)	6.0	6.8	6.9	7.1
T_{init} (alpha)			6.7	7.1
E* (A/11)	350	500	470	530

While at low bombarding energies, below 20 MeV/A, the massive transfer model gives a reasonable account of the mean excitation energy, at higher energies, it fails due to an inadequate treatment of pre-equilibrium emission. Therefore, to estimate temperatures of the hot nuclei formed, the spectra of light charged particles were analyzed in terms of a moving source fit. Three different sources were considered : a compound nucleus source, a projectile-like source and an intermediate velocity source which simulates the pre-equilibrium emission. The results concerning the compound nucleus source are presented in table 1 for both reactions. In each case two bins are selected in the time of flight spectrum of the residues characterized by the reduced residue velocity v_R/v_{CM}. The temperature extracted from the moving source fit is an apparent temperature averaged over the whole decay chain. The ratio between the apparent and initial temperature depends strongly on the type of the decay particle. In the literature this ratio is reported to be 1.3 and 1.15 for protons and alpha particles, respectively[18]. Applying these ratios yield very similar values for the initial temperatures obtained from both proton and alpha spectra as can be seen in table 1 for the reaction at 37 MeV/A. In the case of 27 MeV/A only proton spectra were analyzed.

To infer excitation energies the Fermi gas formula was used with a level density parameter of A/11 and A=115. The excitation energy strongly depends on the level density parameter and the values reported here must be considered with large error bars. However, it can be concluded that the two reactions produced hot nuclei with mean excitation energies around 500 MeV. In both reactions a wide range of excitation energies is populated allowing to study the GDR as a function of excitation energy. Moreover, the measurement of the two reactions at different bombarding energies with the same experimental setup yields accurate information on the dependence of the γ–yield on the bombarding energy.

Figure 1 shows a gamma spectra measured in coincidence with fusion-like residues at 37 MeV/A bombarding energy. At low energies γ–rays emitted by the compound nucleus at the end of the decay chain give rise to a steep exponential decay. At about 15 MeV, a bump can be seen corresponding to γ-rays from the decay of the GDR excited in nuclei of mass around 115. The high energy part of the spectrum (above 35 MeV) is due to the nucleon-nucleon bremsstrahlung taking place during the first stages of the collision process. Before analyzing the GDR, the bremsstrahlung component must be subtracted from the γ-spectra. This component is generally well reproduced by an exponential with a slope parameter depending on the bombarding energy[19]. An exponential fit to the spectrum at $E_\gamma > 35$ MeV is shown in the figure by a dashed line.

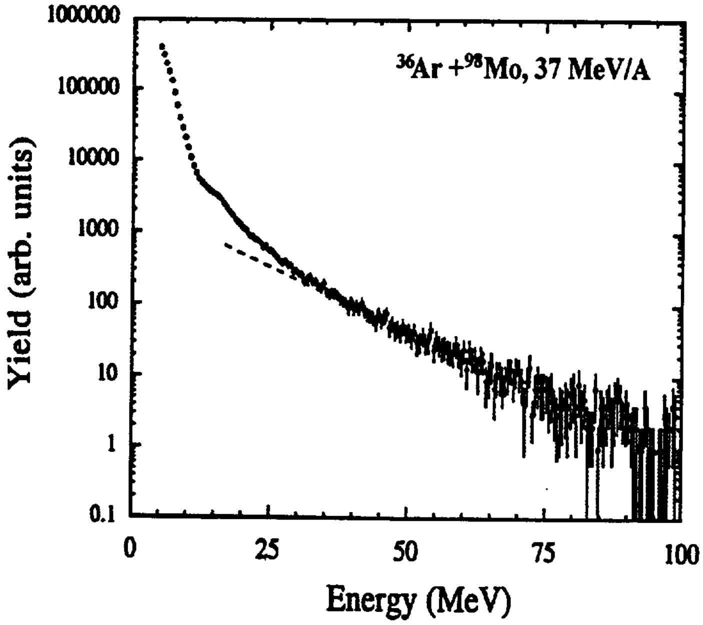

Figure 1 Gamma spectrum measured for the reaction ^{36}Ar+^{98}Mo at 37 MeV/A in coincidence with fusion-like residues. The dashed line corresponds to the estimated contribution from the bremstrahlung.

3. Saturation of the GDR yields measured in different experiments

A quantitative analysis of the GDR γ emission calls for comparison with statistical calculations since γ-rays from the GDR can be emitted at all steps of the decay chain of the hot nucleus. Generally such calculations are carried out using the statistical decay code CASCADE[20]. This code treats the statistical emission of γ-rays, neutrons, protons and α-particles from an equilibrated compound nucleus with a given initial excitation energy and angular momentum. In these calculations a Lorentzian line shape is assumed for the GDR. Such calculations assuming 100% of sum rule strength and a width of 12 MeV for the GDR nicely fit the measured γ-spectra at excitation energies below 300 MeV[1]. Similar calculations were carried out for the reaction ^{36}Ar+^{90}Zr at 27 MeV/A[16]. However, in this reaction giving rise to hot nuclei with excitation energies ranging from 350 MeV to 550 MeV, the calculations largely overestimated the GDR γ-yield.

Moreover, the spectra measured for different linear momentum transfer bins corresponding to different excitation energies were identical, in contradiction with what is expected from the statistical decay for which the GDR γ-multiplicity increases with increasing excitation energy. These observations lead to a conclusion of a saturation of the GDR γ-yield at excitation energies above 300 MeV and were in agreement with the results reported in ref.[6,7] for similar systems.

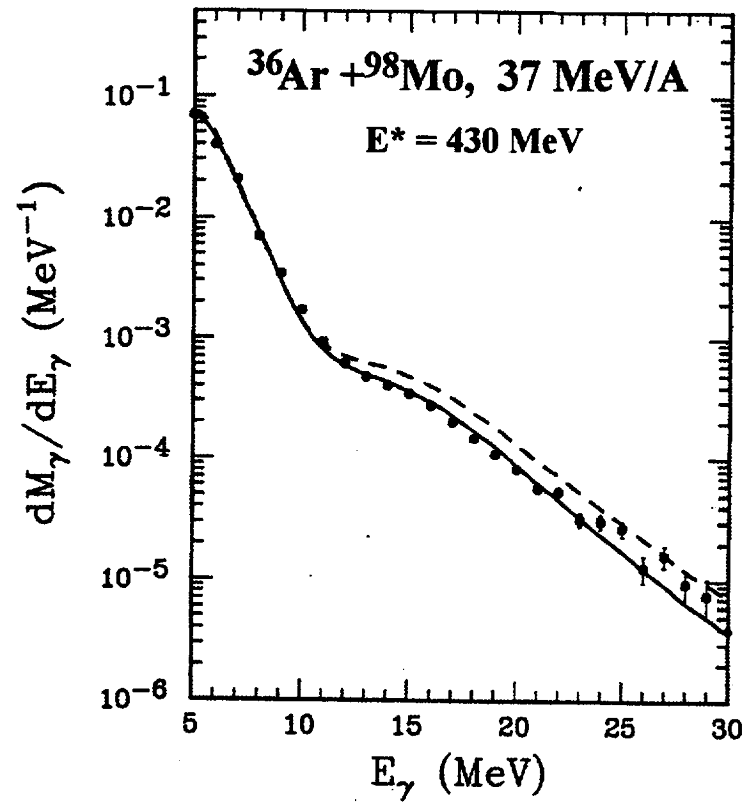

Figure 2 Gamma spectrum after the bremsstrahlung subtraction for the 430 MeV excitation energy bin in the ^{36}Ar+^{98}Mo reaction at 37 MeV/A. The spectrum is compared with CASCADE calculations including a cutoff above 200 MeV (solid line) and above 250 MeV (dashed line).

In the case of ^{36}Ar+^{90}Zr at 27 MeV/A, it was demonstrated in ref.[8] that the hypothesis of a continuously increasing GDR width would indeed lead to a suppression of the GDR γ multiplicity in the region between 12 and 20 MeV but would enhance the GDR γ yield at higher energy between 20 and 35 MeV, in contradiction with the data. In order to reproduce the data the assumption of a complete suppression of the GDR above 250 MeV excitation energy was necessary. In the case of ^{36}Ar+^{98}Mo at 37 MeV/A, CASCADE calculations were also carried out by introducing a sharp suppression of the GDR γ-emission above a given excitation energy. In these calculations a constant width of 12 MeV for the GDR was used along the whole decay chain. The result of the calculation is compared to the γ-spectrum measured for a residue velocity bin corresponding to 430 MeV excitation energy in fig. 2. The solid line corresponds to a cutoff of the GDR γ emission above 200 MeV and nicely reproduces the spectrum, while the dashed line corresponding to the cutoff above 250 MeV clearly overestimates the measured GDR yield. The fact that the cutoff energy in the case of the reaction at 37 MeV/A is clearly lower than the one needed to fit the data at 27 MeV/A indicates a dependence of the

GDR saturation energy on the entrance channel and particularly on the bombarding energy.

Since the main bulk of the GDR γ yield is concentrated between 12 and 20 MeV for the studied systems, the GDR γ yield measured in different experiments can be compared by integrating the γ spectrum between these two energies after bremsstrahlung subtraction. The integrated γ multiplicities as a function of excitation energy are presented in fig. 3 for different experiments yielding compound nuclei of masses around 115. At low excitation energies, below 200 MeV, the GDR γ yield clearly increases with increasing excitation energy. In the data obtained for excitations energies above this value, the GDR γ yield no longer increases with increasing excitation energy. However, the saturation value of the gamma multiplicity is different for different experiments. In particular, a strong decrease is observed between the two experiments performed with the MEDEA detector at 27 and 37 MeV/A bombarding energies. At 27 MeV/A the integrated multiplicity is about 4 10^{-3} while at 37 MeV/A this value is only about 2.6 10^{-3}.

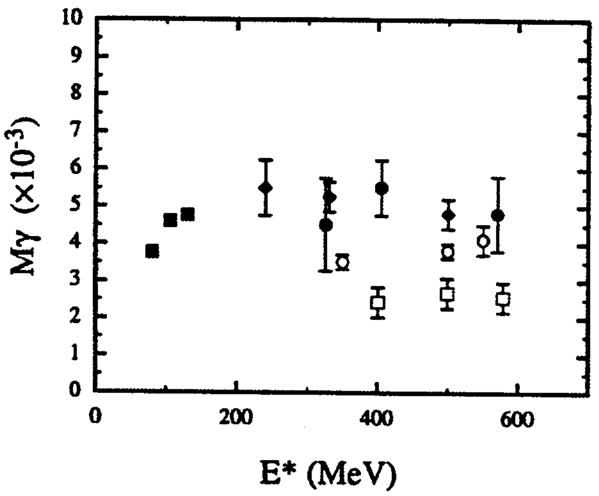

Figure 3 Integrated yields between 12 and 20 MeV for $^{32}S+^{100}Mo$ at 4.7, 5.6 and 6.6 MeV/A (full squares), $^{40}Ar+^{92}Mo$ at 21 MeV/A (full diamonds) and $^{40}Ar+^{92}Mo$ at 26 MeV/A (full circles) from ref.[21] and $^{36}Ar+^{90}Zr$ at 27 MeV/A (open circles), $^{36}Ar+^{98}Mo$ at 37 MeV/A (open squares) from ref.[16] and from this work.

Such a strong bombarding energy dependence could be explained by different times required for the GDR mode to equilibrate in the hot system formed through different entrance channels. In order to study the dynamical effects in these reactions calculations, where the entrance channel dynamics were coupled to stochastic mean-field simulations, were carried out. In these calculations the dynamical evolution is given by the Boltzmann-Nordheim-Vlasov (BNV) equation and the stochastic simulation of the fragment formation in the spinodal region is carried out in the Boltzmann-Langevin approach[22,23]. In the case of both reactions, $^{36}Ar+^{90}Zr$ at 27 MeV/A and $^{36}Ar+^{98}Mo$ at 37 MeV/A, a strong pre-equilibrium emission is observed. During this phase the system looses rapidly its energy and mass. After about 80-100 fm/c the fast pre-equilibrium emission diminishes and the system enters the spinodal region where a competition between fragmentation of the system and survival of a heavy composite nucleus occurs. In both reactions, at small impact parameters, a heavy fusion-like nucleus survives and the system stabilizes. However, the time during which the system remains in the spinodal region is about 200 fm/c for $^{36}Ar+^{98}Mo$ at 37 MeV/A while it is only about

150 fm/c for ^{36}Ar+^{90}Zr at 27 MeV/A corresponding to excitation energies of 320 MeV and 360 MeV and masses of 104 and 108 for the composite systems, respectively. If one assumes that the GDR cannot be established in the instability region due to constant density fluctuations, then the GDR vibration could appear at lower excitation energy at 37 MeV/A than at 27 MeV/A.

Table 2 Comparison between calculated and experimental GDR γ yields (see text).

	Calculation	Experiment
^{36}Ar+^{90}Zr, 27 MeV/A	4.9 10^{-3}	3.8 10^{-3}
^{36}Ar+^{98}Mo, 37 MeV/A	4.3 10^{-3}	2.6 10^{-3}

To predict the GDR γ multiplicity in this scenario CASCADE calculations were performed using as input the masses and excitation energies quoted above from the dynamical calculation and the γ spectra obtained were integrated between 12 and 20 MeV. The resulting multiplicities are compared to experimental values in table 2. The calculation shows a decrease of the GDR γ yield when the bombarding energy increases, in agreement with the experimental trend. However, in both cases, the calculated multiplicity overpredicts the measured one. The excitation energies given by the dynamical calculation, 360 and 320 MeV, are larger than the observed saturation energies 250 and 200 MeV, for the reactions at 27 and 37 MeV/A respectively, which explains the larger GDR γ multiplicities obtained from the calculation.

4. Conclusions

The saturation of the giant dipole resonance γ decay from hot nuclei having excitation energies above 300 MeV is confirmed by two experiments ^{36}Ar+^{90}Zr at 27 MeV/A and ^{36}Ar+^{98}Mo at 37 MeV/A performed at GANIL using the MEDEA multidetector. In the incomplete fusion reactions a wide range of excitation energies was populated and the GDR γ yield was studied as a function of excitation energy. Both experiments show a constant GDR γ multiplicity over an excitation energy range from about 300 to 500 MeV. However, a very intriguing feature is that in the case of the reaction at 37 MeV/A, the GDR γ yield is significantly lower than in the case of 27 MeV/A. This decrease as a function of bombarding energy could be explained by a longer equilibration time of the GDR with the hot system leading to a lower effective excitation energy for the onset of the vibration. This is qualitatively supported by a dynamical calculation coupling the Boltzmann-Nordheim-Vlasov equation to a stochastical simulation of fragment formation in the spinodal region. This calculation predicts a lower excitation energy for the remaining heavy fragment at the exit of the instability region for the reaction at 37 MeV/A. However, in the case of both reactions, the GDR γ yield calculated by the CASCADE code using as an input the excitation energies and masses from dynamical calculation overestimates the measured yields.

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