Influence of dissipation on the population and decay of compound nuclei

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Abstract

The importance of nuclear dissipative effects in the formation and decay of compound nuclei is investigated with the $\gamma$-ray decay of the giant dipole resonance built on highly excited states. These studies show evidence for long formation times ($\sim 10^{-20}$s) in heavy, almost symmetric systems. Enhanced $\gamma$-ray emission is observed in the decay of fissile nuclei because of the dynamical hindrance of fission. This effect allows the study of hot nuclei prior to fission and it also influences the spin distribution leading to evaporation residues.

1. INTRODUCTION

It is well established that dynamical effects play an important role in the fusion of heavy nuclei. Under certain conditions (heavy, nearly symmetric reactants) the fusion cross section is greatly over-predicted by simple static one dimensional potential models. In these cases it is not sufficient to exceed the one dimensional potential barrier in order to fuse, but an "extra push" energy is required [1]. Swiatecki and collaborators included dissipative dynamics in their calculations of heavy ion fusion reactions and could reproduce measured fusion cross sections [2].

Once the reactants pass inside a saddle point in the complex multi-dimensional configuration space describing the reaction, fusion is considered to have occurred, and evolution toward equilibrium begins. While dynamical effects could influence this evolution, the time scale for the equilibration has generally been assumed to be so fast compared to any decay processes relevant to the compound system (especially at the moderate excitation energies reached in near barrier reactions) that any such dynamical influences can be ignored. Once the equilibrated compound system is reached, the Bohr independence hypothesis should apply, so that the subsequent decay is correctly treated by a conventional statistical model, and is therefore independent of the way the system was formed.

However, recent neutron multiplicity measurements of fusion reactions of nearly symmetric systems near the Coulomb barrier have raised the possibility that dynamics could influence the decay of the fused system in a way that seems to violate the independence hypothesis [3, 4]. When the compound nucleus is formed...
using projectile target combinations with different mass asymmetries, at the same excitation energy and the same angular momentum, differences in the neutron multiplicity were observed.

While these observations of entrance channel effects are still controversial, and not adequately understood, dissipation is known to influence the decay of compound nuclei when fission is involved. Again, this effect was first observed in experimental studies of neutron multiplicities. In heavy fissile systems more neutrons were evaporated prior to fission than predicted by statistical models [5]. This enhancement has been explained with dissipation which slows down the fission process allowing for additional particle and \( \gamma \)-ray emission before fission [6].

We will describe experiments that use a different probe to study the influence of dissipation on both the formation and the decay of the compound nucleus. The \( \gamma \)-ray decay of the giant dipole resonance (GDR) built on highly excited states turns out to be a very sensitive tool to study any dissipative effects. It was shown early on in the study of \( \gamma \)-ray spectra in the GDR region that \( \gamma \) rays from the GDR are emitted predominantly during the first few decay steps of the compound nucleus [7], thus it should be sensitive to effects during the formation and first stages of the decay. In addition, the \( \gamma \)-ray spectrum exhibits a splitting of the GDR for deformed nuclei which can be related in a straightforward way to the shape of the nucleus. This is important because the fusion and the fission process involve dramatic changes in the shape of the nucleus.

The experiments described here were performed with the HHlRF tandem accelerator at Oak Ridge National Laboratory. High energy \( \gamma \)-rays were measured with 76 \( \text{BaF}_2 \) detectors arranged in four arrays of 19 crystals each. Details of the experimental set-ups can be found elsewhere [8, 9].

2. COMPOUND NUCLEUS FORMATION

In order to search for formation time effects in the fusion of heavy ions, we studied the compound nuclei \(^{164}\text{Yb}, \ 160\text{Er}\) and \(^{110}\text{Sn}\). We will concentrate here on the almost symmetric reaction \(^{64}\text{Ni} + ^{100}\text{Mo}\) and the reference (asymmetric) reaction \(^{16}0 + ^{148}\text{Sm}\), both leading to the compound nucleus \(^{164}\text{Yb}\). When both reactions form the compound nucleus at the same excitation energy and spin, the resulting \( \gamma \)-ray spectra should be identical, if the formation time is short compared to the decay times.

We used the semi-classical dissipative collision code HICOL [10] which is based on Swiatecki's model in order to calculate formation times of the systems. Figure 1 shows results of HICOL calculations for the evolution of the quadrupole moment (a) and the excitation energy (b) as a function of time for several reactions forming \(^{164}\text{Yb}\) and \(^{110}\text{Sn}\). Both more asymmetric reactions, \(^{16}0 + ^{148}\text{Sm}\) and \(^{18}0 + ^{92}\text{Mo}\) equilibrate very quickly (\(-10^{-21}s\)), whereas the reaction \(^{64}\text{Ni} + ^{100}\text{Mo}\) is predicted to have a large formation time (\(-10^{-20}s\)). Figure 1 also shows that the influence of dissipation is not only a function of the asymmetry but it also depends strongly on the total mass of the compound system. \(^{110}\text{Sn}\) formed with the reaction \(^{50}\text{Ti} + ^{60}\text{Ni}\) equilibrates quickly although it is even more symmetric than the \(^{64}\text{Ni} + ^{100}\text{Mo}\) reaction, because the composite system is not as heavy. These formation times have to be compared to typical neutron evaporation times which are \(\sim 2 \times 10^{-20}s\) at the relevant excitation energies (\(\sim 50\text{ MeV}\)).

Before comparing the \( \gamma \)-ray spectra, it is very important that the \( \gamma \)-rays are
indeed coming from nuclei with the same excitation energy and spin. We used 55 detectors of the Spin Spectrometer [11] in order to measure the total $\gamma$-ray multiplicity. The initial spin distribution was then reconstructed with simulations with the evaporation code EVAP [12] and with GEANT3 [13].

The $\gamma$-ray spectra corresponding to a spin range of 10$\hbar$ - 35$\hbar$ for the $^{16}$O (a) and $^{64}$Ni (b,c) induced reactions are shown in Fig. 2 as histograms. The solid lines correspond to calculations using the statistical model code CASCADE [14]. The initial spin distributions were taken from the EVAP simulations. The GDR parameters extracted from a fit to the $^{16}$O data were $E_1 = 12.2 \pm 0.2$ MeV, $I_1 = 4.9 \pm 0.5$ MeV, $E_2 = 15.7 \pm 0.5$ MeV, and $\Gamma_2 = 6.9 \pm 1.0$ MeV, consistent with previous measurements in this mass region and excitation energy [15]. However, it is obvious that these parameters can not reproduce the $\gamma$-ray spectrum produced in the $^{64}$Ni induced reaction (b).

The right side of Figure 2 shows the fit quality of the $^{16}$O data (d) and the large discrepancy for the $^{64}$Ni data (e) in a linearized plot. To create this plot, the data as well as the calculations were divided by the same spectra calculated using a constant dipole $\gamma$-ray strength function.

Before one can attribute the observed differences to different formation properties, one has to exclude other possibilities. The main concern is that the $^{64}$Ni data contains contributions from mechanisms other than fusion-evaporation reactions. The cross section for deep inelastic reactions is comparable to the fusion cross section [16], however the excitation energy and spin of the fragments is so low [10], that the contributions to the $\gamma$-ray spectra are negligible (< 1% above 9 MeV). Contributions from fission, due to excited fission fragments could also be excluded since at the present excitation energy only $\sim 0.2$% fission cross section is predicted by statistical model calculations and no fission has been observed [17, 16].

We thus explore the possibility that differences are indeed due to the long formation times in the $^{64}$Ni reaction. As mentioned before, this formation time is comparable to the mean time for neutron evaporation. If indeed neutrons and $\gamma$ rays are emitted during this prolonged formation time, a modification of the
Fig. 2: Comparison of the \( \gamma \)-ray spectra from \(^{164}\)Yb following the reaction \(^{16}\)O + \(^{148}\)Sm (a) and \(^{64}\)Ni + \(^{100}\)Mo (b),(c). The solid curves are calculations using the code CASCADE as explained in the text. The right side shows linearized plots of the \( \gamma \)-ray spectra from the \(^{16}\)O (d) and \(^{64}\)Ni (e),(f) induced reactions.

resulting emission spectra compared to those measured with \(^{16}\)O + \(^{148}\)Sm is not surprising.

In order to get some qualitative idea of the effects which might be expected, we have attempted to model this non-equilibrium decay picture using a step-wise application of the equilibrium statistical model in the form of the code CASCADE. According to HICOL calculations, key parameters (thermal energy, composite system shape, etc.) of the statistical model are changing during the formation time. We treat this by dividing the formation time into time steps, using fixed statistical model parameters obtained from the appropriate time averaged HICOL result for each step. We allow decays to occur within the time step, and obtain the input population distributions for each step from the results of the preceding steps. The final step is a conventional equilibrium statistical calculation with decay proceeding without a time cutoff. For present purposes the simplest (i.e. two-step) implementation of this scheme is adequate as an illustration. We take the mean excitation energy (30 MeV) and deformation parameters from the HICOL calculation. The GDR parameters derived from the HICOL results are \( E_1 = 9.2 \) MeV and \( E_2 = 18.0 \) MeV. The corresponding widths are estimated as \( \Gamma_1 = 3.0 \) MeV and \( \Gamma_2 = 6.0 \) MeV. A level density parameter of \( A/15 \) was chosen, guided by calculations for superdeformed shapes. The first (formation) step extends for
\[ \sim 2 \times 10^{-20} \text{s}. \] Due to the large number of parameters in this calculation it is difficult to extract an uncertainty of the formation time. We estimated an error of 
\[ +1 \times 10^{-20} \text{s}. \] The resulting populations in excitation energy and spin were treated as input populations for the next (fully equilibrated) step, which was treated within the regular statistical model, using the standard parameters mentioned earlier. Results of these calculations are shown in Fig. 2 (c) and (f). The total \( \gamma \)-ray spectrum (solid) is a sum of two contributions: \( \gamma \)-rays emitted during the formation time (dashed) and \( \gamma \)-rays from the compound nuclei (dot-dashed).

The main difference in the spectral shape between the regular statistical model and including the formation time effect is not additional \( \gamma \)-rays from the formation phase, as can be seen in Fig. 2 (f). The main effect depends on the fact that the branching ratio for emission of high-energy \( \gamma \)-rays (i.e. \( E_{\gamma} \), near the GDR peak) is a strongly increasing function of increasing excitation energy. The reduced effective excitation energy during the formation time therefore results in a reduced high energy \( \gamma \)-ray yield during the initial step. The cooling of the compound nucleus due to particle evaporation during the formation stage results in a lower mean energy of the compound system, and hence a modification of the \( \gamma \)-ray spectrum resulting from the compound system after full equilibration.

3. COMPOUND NUCLEUS DECAY

The observation of the delayed onset of fission or fission hindrance in neutron multiplicity measurements\[51 has also been observed in \( \gamma \)-ray experiments\[18\] and several theoretical models are trying to explain the origin of this effect\[19, 20, 21\]. We will not discuss the effect itself here, but rather concentrate on the implications of this hindrance in a mass region and excitation energy where only a part of the total fusion cross section leads to fission. Measurements of \( \gamma \)-ray – fission coincidences probe the small range of angular momenta where fission is dominant\[22\]. The enhancement of \( \gamma \)-rays prior to fission allows the study of hot nuclei at large angular momenta. In addition, changing the properties of fission in the decay models might influence the population resulting in evaporation residues. We studied the reaction \( {^{16}O + ^{159}Tb} \) at an excitation energy of 123 MeV and measured \( \gamma \)-rays in coincidence with evaporation residues and fission fragments.

3.1. Nuclear shape at high spins

In the reaction \( {^{16}O + ^{159}Tb} \) at 123 MeV excitation energy only the population with angular momenta larger than \( \sim 50 \hbar \) leads to fission (see also Figure 4). Figure 3 shows the \( \gamma \)-ray spectra measured in coincidence with evaporation residues (a) (thus gating on the lower part of the spin distribution) and in coincidence with fission fragments (b,c). The solid lines correspond to results from \( \text{CASCADE} \) calculations.

The GDR energies for the compound system (\( E_1 = 12.4 \text{ MeV}, E_2 = 15.3 \text{ MeV} \) and widths (\( \Gamma_1 = 8.0 \text{ MeV}, \Gamma_2 = 10.5 \text{ MeV} \) were taken from previous experiments at somewhat lower energies and were extrapolated to what would be expected at 123.4 MeV excitation energy\[15\]. The calculations in coincidence with evaporation residues can describe the data very well.

The total calculated \( \gamma \)-ray spectrum in coincidence with fission fragments is a
Fig. 3: Experimental γ-ray spectra (histogram) from the decay of $^{175}$Ta ($E_{\text{beam}} = 160$ MeV) in coincidence with evaporation residues (a) and fission fragments (b) and (c). The smooth curves are fits corresponding to calculations using CASCADE with GDR parameters for normal deformed shapes (a) and (b) and shapes with large deformation (c). The calculations in coincidence with fission fragments include dissipation effects and are a sum of pre-fission (dot-dashed) and post-fission (dashed) γ-rays. Linearized presentation of the data from (b) (dashed) and (c) (solid) are shown in (d). Part (e) presents calculations of a sum (solid) of normal deformation (dashed) and large deformation (dot-dashed).

Calculations using standard statistical model parameters could not describe the strength of the data in the region of the compound nucleus GDR. The overall strength could only be reproduced by including the fission hindrance as described in Ref. [23] into the statistical model code. The fit with a nuclear dissipation coefficient of $\gamma = 10$ is shown in Fig. 3 (b). Although the strength can be well described, the spectral shape, particularly in the 8 - 11 MeV energy range, can still not be fitted. Therefore, the GDR parameters for the decay from the highest partial waves were adjusted in order to provide a best fit to the γ-ray - fission coincidence data. This fit is shown in Fig. 3 (c). The fit requires a large splitting of the GDR energies ($E_1 = 9.5 \pm 0.5$ MeV, $\Gamma_1 = 5 \pm 1.0$ MeV and $E_2 = 15.0 \pm 1.0$ MeV, $\Gamma_2 = 7.0$ MeV).
\( \pm 2.0 \text{ MeV} \) that corresponds to a nuclear deformation of \( \beta = 0.55 \pm 0.11 \).

The calculations of Figure 3 (b) and (c) are shown in a linear presentation in part (d) as dashed and solid lines respectively. When compared with the calculation using GDR parameters corresponding to a normal deformed system (dashed), the data clearly show missing strength around 9 MeV. However, the calculation with the large GDR splitting (solid) provides a good description of the data.

The value of \( \beta = 0.55 \pm 0.11 \) extracted in our analysis is the largest deformation thus far obtained from the decay of the GDR built on highly excited compound nucleus states. The pre-fission \( \gamma \) decay samples a hot (temperature, \( T = 1.8 \text{ MeV} \)) system in a relatively narrow range of very high angular momenta (\( J \approx 60 - 80 \hbar \)). The large deformation certainly implies that the excited system sampled by the GDR decay in this angular momentum range has a very extended shape. In order to compare our data quantitatively with theoretical predictions, a full thermal fluctuation analysis as described by [24, 25] has to be performed. However, free energy surfaces which are necessary for those calculations are not available for the nuclei populated in the present reaction.

However, guided by calculations of free energy surfaces in Dysprosium isotopes, [26] we speculate that the observed splitting might be due to the existence of a stable minimum at large deformation which is entirely due to macroscopic effects (Jacobi instability) and is largely unaffected by increasing temperature, at least to \( T \approx 2.3 \text{ MeV} \) [27]. These macroscopic results are obtained from the rotating liquid drop (RLD) model [28]. The critical spin above which \(^{175}\text{Ta}\) is predicted by the RLD to rapidly evolve from the normal, moderately deformed, oblate shape to a superdeformed triaxial, but nearly prolate shape, is \( J_c = 79\hbar \). This minimum survives only over a narrow range of spins (\( \Delta J = 5\hbar \)), over which we can expect, a broad, rather flat free energy surface with a minimum at a deformation \( \beta \approx 0.6 \), or larger. Explicitly, for \(^{175}\text{Ta}\) the RLD predicts a minimum with a major to minor axis ratio of \( \sim 2.2/1 \) at \( \sim 80 \hbar \), coexisting with a moderately deformed (axis ratio 1.2/1) oblate minimum.

We thus tried to describe the data as a mixture of normal deformation and a very large deformation, guided by the above discussion. The GDR parameters for the normal deformation were chosen as before with reduced widths (\( \Gamma_1 = 6.0 \text{ MeV}, \Gamma_2 = 8.5 \text{ MeV} \)) to account for the smaller effective excitation energy at these high spins and the smaller angular momentum range. The GDR energies for the large deformation were taken to be \( E_1 = 8.5 \text{ MeV} \) and \( E_2 = 17.5 \text{ MeV} \), which yield the same mean resonance energy and corresponds to an axis ratio of \( \sim 2.1/1 \). The widths were \( \Gamma_1 = 5 \text{ MeV} \) and \( \Gamma_2 = 7 \text{ MeV} \). Figure 3 (e) shows that the sum (solid) of the normal (dashed) and very large (dot-dashed) deformed contributions compared to the data in a linearized plot can describe the data rather well.

It should be mentioned that in an independent study, \( \gamma \)-ray spectra from the decay of the GDR built on highly excited states in \(^{45}\text{Sc}\) show effects which can also be explained with the existence of prolate deformed shapes due to the Jacobi instability [29].

### 3.2. Evaporation residue population

The version of CASCADE, modified to include the reduction of the fission probability due to nuclear dissipation, that was applied for the analysis of the \( \gamma \)-ray data can also be used to calculate the spin distribution leading to fission and evaporation residues. Since fission is a major decay channel and it is strongly
modified due to the dissipation it might be conceivable, that it also influences the population distribution for evaporation residues [30].

This might be important for statistical model calculations of the population of superdeformed bands. Experimentally it has been determined that the population of superdeformed bands is unexpectedly large (1 - 2% of the total population) and that they are populated only over a narrow region of the highest spins of the evaporation population [31]. In most cases the high-spin limit of the evaporation residue population is determined by the competition with fission (fission cut off). A number of aspects of the feeding of superdeformed bands have been investigated theoretically [32], but one aspect that has not been explored is how the high-spin cut off due to fission might be influenced by dynamical effects in the fission process.

In Figure 4, we show the influence of dissipation on the population distribution as a function of spin. The total fusion cross section (solid) is partitioned between the fission and evaporation residue cross section. The distribution of fission cross section including dissipation (short-dashed) is shifted to lower spins compared to the standard calculation (dotted), whereas the tail of the evaporation residue (dissipation, long-dashed) extends to higher angular momenta than the standard calculation (dot-dashed).

This seems to be a small effect, but if one considers processes that are coming from a small range of angular momenta and only from a fraction of the total cross section, like the feeding of superdeformed bands, it might be important.

For example, the population above 60\( \hbar \) (65 \( \hbar \)) leading to evaporation residues is 25% (65%) larger when dissipation is included in the calculation. Assuming
that the superdeformed band population originates from a narrow spin window (16A) bound by the fission limit [32], the dissipation enhancement would imply an approximate increase of 20% in the total superdeformed population. This enhancement is purely due to the additional high-spin population that does not fission.

The present calculations show the importance of dissipation on the decay of compound nuclei. As was shown in the first section dissipative effects can also delay the coalescence of reactants in heavy-ion fusion. Thus one might be able to attribute recent observations of entrance channel dependent feeding of superdeformed bands [33] to indirect effects of dissipative dynamics, however such calculations have not yet been performed.

4. SUMMARY AND CONCLUSIONS

The study of the γ-decay of the giant dipole resonance built on highly excited states is a versatile tool to study dynamical effects in the formation and the decay of compound nuclei. The γ-ray spectra following the fusion of almost symmetric systems showed evidence for long formation times. The giant dipole resonance is also sensitive to the dynamical hindrance of fission. This effect does not only enhance the pre-fission particle and γ-ray emission, and thus makes the study of those system possible, it also effects the spin distribution leading to evaporation residues, which might be important when when very small effect are studied like the population of superdeformed bands.

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6. REFERENCES


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