Dynamical Timescales in Hot Rotating Nuclei

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The effects of dissipation in fission of hot nuclei as well as in heavy-ion reactions are still not well understood and quite controversial. The deformation and/or temperature dependence of the dissipation coefficient as well as the influence of the curvatures of the potential energy surface will be discussed. Evidence for particle/\(\gamma\)-ray decay during compound nucleus formation in certain heavy-ion reactions will be compared to other reactions where no effects were observed.

1. INTRODUCTION

The influence of dissipation on the formation and decay of compound nuclei has been known for a long time. Initially only the dissipation from the saddle-to-scission motion in the fission process \cite{1} and the hindrance of fusion in heavy-ion collisions \cite{2} have been considered.

The observation of an enhanced emission of pre-fission neutrons\(+\)protons\(1\) and \(\gamma\)-rays in the fission of hot nuclei opened up the opportunity to study the detailed influence of dissipation on the total fission process \cite{3}. The hindrance of fusion due to energy dissipation into internal degrees of freedom leads to long compound nucleus formation times which might be comparable to the decay times and thus might be an important influence on the formation and subsequent decay of the compound nucleus.

The giant dipole resonance (GDR) built on highly excited states is an important tool in studying these dynamical effects because the \(\gamma\)-rays from the decay occur predominantly early in the decay cascade and the spectral shape is sensitive to the size and the deformation of the emitting system \cite{4-6}.

Since the first observation of the pre-fission GDR \cite{7} in \(^{234}\text{Th}\) many systems have been studied \cite{8-12} where in most cases angular distributions\(1\) which are particularly important for the shape sensitivity\(1\) were measured in addition to the \(\gamma\)-ray spectra. Recently\(1\) these measurements have been extended to much heavier systems \cite{13-17}. In Chapter 2\(1\) some of the open questions related to the description of dissipative fission which are especially relevant for the GDR studies will be described.

Evidence for dynamical effects in fusion reactions has been observed in the GDR decay following the reaction \(^{64}\text{Ni} + ^{100}\text{Mo}\) forming the compound nucleus \(^{164}\text{Yb}\) \cite{18}. In addition to controversial results from experiments with other probes several other systems have been studied using the \(\gamma\)-ray decay of the GDR where no effect was observed \cite{19-22}. These seemingly contradictory observations will be discussed in the context of the
dissipative dynamical model in Chapter 3.

2. FISSION

Fission as a decay mode of heavy compound nuclei was first described with the transition state model [23] where the fission decay width $\Gamma_{trans}$ is given by:

$$\Gamma_{trans} = \frac{1}{2\pi \rho(E)} \int_0^{E-B} \rho^*(E-E_B-e) \, de$$

(1)

where $E_B$ is the fission barrier $E$ the excitation energy and $\rho$ the compound nuclear level density. $\rho^*$ is the “... density of all levels which arise from excitation of all degrees of freedom other than fission itself.” [23]. With the explicit distinction between $\rho$ and $\rho^*$ equation 1 can be approximated by

$$\Gamma_{trans} = \frac{\hbar \omega_{eq}}{2\pi} e^T (-E_B/T)$$

(2)

where $\omega_{eq}$ is the curvature at the equilibrium deformation (barrier assault frequency).

Kramers introduced fission as a dynamical process and calculated the fission decay width $\Gamma_{Kr}$ as a function of dissipation [24] which can be written as:

$$\Gamma_{Kr} = \frac{\hbar \omega_{sp}}{2\pi} (\sqrt{1+\gamma^2} - \gamma) \, e^T (-E_B/T)$$

(3)

with the temperature $T$ and the nuclear friction coefficient $\gamma$. Kramers derived this equation in terms of the viscosity parameter $\eta$ which is directly related to $\gamma$ via: $\eta = 4\pi \omega_{sp} \gamma$ and the curvature of the saddle point is taken to be $\omega_{sp} = 1 \cdot 10^{21} \text{s}^{-1}$. Thus the Kramers fission width corresponds to the transition state width $\Gamma$ modified by the factor $\sqrt{1+\gamma^2} - \gamma$. For $\gamma >> 1$ the two models converge. However for very small values of $\gamma$ equation 3 is not valid and Kramers derived the fission decay width as

$$\Gamma_{Kr} = 2\hbar \omega_{sp} \gamma^T (-E_B/T)$$

(4)

Figure 1 shows the ratio of the transition state width over the Kramers width as a function of the friction coefficient $\gamma$ for $E_B/T = 10$ and the assumption that $\omega_{sp}$ is equal to $\omega_{eq}$. The validity of this approximation will be discussed in Section 2.3. The shaded area shows the range where the models agree within 10% and differences are not likely to be observable. $\gamma = 1$ corresponds to critical damping of the system whereas for $\gamma > 1$ and $\gamma < 1$ the system is overdamped and underdamped respectively. Thus the transition state model should be valid over a wide range of underdamped motion ($\sim 0.01 < \gamma < 0.1$).

In spite of some early experimental evidence for discrepancies the dynamical description of the fission process has not been applied for over 40 years because the transition state model could reproduce essentially all observables of the fission process. Measurements of fission recoils in 1954 [25] and neutron angular correlation measurements in 1956 [26] indicated that substantially more particles were emitted prior to fission than predicted by the statistical model.
The experiments by Hinde et al. in 1986 [27] where at high excitation energies the statistical model failed to describe the pre-fission neutron multiplicities initiated the analysis of fission data within Kramers’ dynamical model.

Shortly afterwards, the GDR proved to be a sensitive method to further investigate the problem and yield complimentary data to the neutron multiplicity data. Statistical models were modified in order to take the dynamical description into account and extract the dissipation coefficients [9].

One of the main open questions is the origin of the dissipation. Thus it is important to find experimental observables which will be able to distinguish between the different models. In the following two sections the deformation dependence and the temperature dependence of the dissipation will be discussed where the GDR measurements have contributed to understanding the nature of nuclear dissipation.

2.1. Temperature Dependence

The temperature dependence of dissipation is still heavily debated. Whereas one-body dissipation has at most a $\sqrt{T}$ dependence the predictions for the temperature dependence of two-body dissipation varies from stronger than $T^2$ to $1/T^2$ (see Ref. [3R]). Experimentally, the temperature dependence can be explored by excitation function measurements of several different observables. The first excitation function of pre-fission neutron multiplicities showed that the statistical model reproduces the data well only at low energies [27]. However, at higher beam energies the model underpredicted the pre-fission neutron multiplicities indicating a longer fission time scale. Recently, a rather rapid onset of the dissipation was observed as a function of excitation energy in GDR $\gamma$-ray experiments [28, 29].

Although a variety of experiments have been performed measuring long fission times at
higher excitation energies, the transition from low energies to high energies has not been studied in detail. A recent compilation of a large data set found an empirical relation for the onset of the observation for this dynamical effect [30]. The ratio of the temperature above which the statistical model fails to reproduce the data (defined as the threshold temperature $T_{\text{thresh}}$) over the (temperature dependent) fission barrier is 0.26 independent of the system and analysis.

Figure 2 shows this relation for neutron multiplicities following heavy-ion fusion reactions (○) and proton induced fusion (■) charged particle multiplicities (●) GDR γ-ray multiplicities (×) and peripheral reactions (△) [30]. Only two of the GDR measurements do not seem to fit in the systematic. This does not imply a discrepancy between the GDR data and the other experiments because two other GDR data fit very well into the systematics. The two reactions $^{32}\text{S} + ^{184}\text{W}$ and $^{32}\text{S} + ^{208}\text{Pb}$ are the only reactions that have considerable contributions from quasi-fission reactions and it is thus not surprising that these reactions do not follow a systematic trend that depends on the barrier. Several other measurements which were not included in the initial analysis fit this empirical relation nicely [31,32].

A recent analysis of large fragment emission did not need any dynamical effects and could be reproduced with the statistical model in agreement with the present relation [33]. The large barriers for the emission of large fragments yield significantly lower values for $T/E_{\text{bar}}$ (∼0.1) than the expected onset of observation of dissipation.

Is this apparent onset evidence for the temperature dependence of dissipation or is it possible to explain the threshold behavior without a temperature dependence [34]? Recently it has been suggested that the dissipation is constant as a function of temperature and the apparent onset is attributed to the fact that at excitation energies below the threshold value the statistical lifetimes become so long that the influence of the dissipation becomes negligible [35,36]. Figure 3 shows the fission times calculated with the transition state model as a function of $T/E_{\text{bar}}$.

The vertical dashed line indicates the empirical threshold value. The experimental fission times are taken from Ref. [37]. VanderPloeg et al. argue in Ref. [35] that the dynamical fission times are temperature independent and cross with the transition state
fission times just at the threshold value of $T_{\text{thresh}}/E_{\text{Bar}}$. However, the statistical model calculation with a constant large ($\gamma = 10$) dissipation which fits the data at high energies overpredicts the data around the threshold value as shown in Figure 3. Thus the dissipation coefficient would have to be reduced at low temperatures in order to reproduce the experimental fission times which is further evidence for a temperature dependence of dissipation. A detailed analysis with a temperature dependent $\gamma$ has recently been performed to fit pre-fission $\gamma$-ray spectra following the reaction $^{16}$O + $^{208}$Pb [29].

The preceding argument is valid if one assumes that the long fission times are due to dissipation inside the saddle point because a constant $\gamma$ in equation 3 does not correspond to constant fission times. The apparent onset could again just be a crossing of the transition state time scale below $T_{\text{thresh}}/E_{\text{Bar}}$ to the dynamical time scale above $T_{\text{thresh}}/E_{\text{Bar}}$ if the dynamical timescale corresponds to long saddle-to-scission times as was indicated in Ref. [35]. However, a recent dynamical analysis of the data of Hinde et al. [38] seems to indicate that the long timescales are coming from inside the saddle [39].

The arguments about the dependence of dissipation inside and/or outside the saddle leads directly to the question if the dissipation parameters depend only for in addition to the temperature on the deformation.

### 2.2. Deformation Dependence

The many different dissipation models which predict conflicting behavior of the deformation dependence of the dissipation will not be discussed in detail in this section. However, as an example the predictions of two different models are shown in Figure 4.
Figure 4. Dependence of the dissipation coefficient $\beta$ as a function of deformation. The left side is adapted from Fröbrich et al. [40] and the right side from the surface-plus-window dissipation model [41B3].

The model of Fröbrich et al. [40] and the surface-plus-window one-body dissipation [41] are presented in the left and right side respectively. In the figure the dissipation is expressed in terms of the reduced dissipation constant $\beta$. The constant $\beta$ is related to the nuclear friction coefficient:

$$\gamma = \beta/2\omega_{sp}.$$  \hfill (5)

With $\omega_{sp} = 1 \times 10^{21} \text{s}^{-1}$ this results in the conversion $\gamma = \beta/2 \cdot 10^{-21} \text{s}$. However this conversion should be taken with care as will be discussed in Section 2.4.

Fröbrich’s approach is guided by two different sets of experimental information: (i) evaporation residue and fission cross section measurements and (ii) pre-fission neutron and GDR $\gamma$-ray multiplicities [40]. In order to reproduce the first set of data the dissipation inside the saddle has to be small because standard statistical models were able to reproduce the cross sections. However the statistical model does not describe the pre-fission particle multiplicities correctly. By introducing large dissipation outside the saddle it is possible to increase the pre-fission particle emission probability without changing the evaporation residue and fission cross sections. The strong increase of dissipation starting at $q = 0.6$ in Figure 4 corresponds to the saddle point where $q$ is a general deformation coordinate along the fission direction. The two dashed lines denote the equilibrium and scission points. Fröbrich et al. were able to reproduce a wide variety of systems over a wide range of excitation energies [40].

The results of the one-body surface-plus-window dissipation formula in the right side of Figure 4 is shown as a function of the normalized radius $r/R_0$. $k_s$ is a reduction factor of the strength of the surface dissipation which had been introduced to reproduce various measurements. For example a value of $k_s = 0.5 \pm 0.2$ was extracted for largely
deformed systems from fission fragment kinetic energy measurements [41, 42] whereas for almost spherical systems $k_s = 0.27 \pm 0.06$ was needed to fit isoscalar giant quadrupole data [41, 42]. Two recent analyses of pre-fission charged particle [43] and GDR $\gamma$-ray experiments [44] in terms of dissipation inside as well as outside the saddle seem to agree with the one-body dissipation description. Lemmon derived $\beta = 8.9(2.4) \cdot 10^{21} \text{s}^{-1}$ inside and $\beta = 8.4(3.1) \cdot 10^{21} \text{s}^{-1}$ outside the saddle respectively which corresponds to a reduced value of $k_s$ inside and a larger value of $k_s$ outside the saddle. Hofman et al. analysed GDR $\gamma$-ray spectra following the reaction $^{16}\text{O} + ^{208}\text{Pb}$ in terms of different nuclear friction coefficients for inside and outside the saddle and extracted $\gamma = 5-10 (\beta \sim 10-20 \cdot 10^{21} \text{s}^{-1})$ inside and $\gamma \sim 5 (\beta \sim 10 \cdot 10^{21} \text{s}^{-1})$ respectively [44]. Although this analysis agrees within the uncertainties with the results of Lemmon, they are also consistent with full one-body dissipation independent of deformation.

Clearly this question is not resolved and further detailed measurements are necessary. It is absolutely essential that future experiments include both evaporation residue/fission cross sections and pre-fission particle/\gamma-ray multiplicities measurements simultaneously. Otherwise it is not possible to constrain statistical model parameters and extract the dissipation coefficients. One important additional observable could be high statistics angular distributions of the GDR $\gamma$-rays. Because of the shape dependence of the GDR the analysis of angular distributions could possibly distinguish between the two processes emission inside and outside the saddle point.

### 2.3. Influence of the Equilibrium- and Fission Barrier Curvatures

The incorporation of the dynamical model into a statistical model code like CASCADe involves several approximations which might play an important role in the results of the calculations. Statistical models do not depend on intrinsic quantities like the shape of the barrier and the fission decay width of the statistical model differs from the transition state model decay width as approximated in Equation 2.

In the statistical model the two level densities of Equation 1 are set equal $\rho = \rho^*$ and the fission decay width used in statistical model codes can be expressed as:

$$\Gamma_{\text{stat}} = \frac{T}{2\pi} \exp(-E_B/T)$$  \hspace{1cm} (6)

Thus the transition state value and the statistical model value are not identical and are related via:

$$\Gamma_{\text{trans}} = \frac{\hbar \omega_{eq}}{T} \Gamma_{\text{stat}}$$  \hspace{1cm} (7)

This difference has actually been known for a long time [45] but it is usually not taken into account and the approximation $\hbar \omega_{eq} = T$ is typically made in the analyses.

It is not obvious that this approximation should be valid because the decay of the compound nucleus covers a wide range of temperatures and the curvature at the equilibrium deformation (assault frequency) certainly changes with increasing angular momentum until the barrier vanishes. The left side of Figure 5 shows the assault frequency as a function of compound nuclear spin for different temperatures for $^{208}\text{Pb}$. The calculations were performed based on the finite range liquid drop model and the parameterization of Lestone
Figure 5. Curvature of the potential (left) and the ratio of the curvature over the temperature (right) as a function of spin for $^{200}\text{Pb}$ at temperatures of 0.8 MeV (solid), 1.2 MeV (short-dashed), 1.6 MeV (dot-dashed) and 2.0 MeV (long-dashed).

Figure 6. Pre-fission neutron multiplicities (top) and evaporation residue cross sections (bottom) for the reaction $^{19}\text{F} + ^{200}\text{Pb}$ at $E_{\text{Beam}} = 120$ MeV calculated for conditions explained in the text. The experimental values (with uncertainties) are indicated by the shaded areas.
The average value of $\hbar \omega_{eq}$ is around 1 MeV; however, it varies considerably, especially towards larger spins close to the vanishing of the barrier. The right side of Figure 5 shows the ratio of the curvature over the temperature $\hbar \omega_{eq}/T$. The approximation of the statistical model assumes this value to be constant equal to unity. As can be seen, the ratio is certainly not constant and varies in the present range from $\sim 0.5$ to $\sim 1.6$, which could certainly have a significant influence on the calculation of pre-fission particle emission probabilities and particle multiplicities.

The effect of this dependence is illustrated for the case of $^{19}$F + $^{200}$Pb at 120 MeV. Figure 6 shows the experimental evaporation residue cross section (bottom) and the neutron multiplicity (top) as a shaded area. A standard statistical model calculation reproduces the cross section but underpredicts the pre-fission neutron multiplicities. The incorporation of the $\hbar \omega_{eq}/T$ correction changes the results significantly. Neither the cross section nor the multiplicity is reproduced. This discrepancy becomes even larger when the temperature dependence of the potential landscape is included in the calculation of the barrier curvature. Thus, a delay of the fission process which can be incorporated with the Kramers' description is still necessary. However, in contrast to earlier calculations where equation 3 was applied, thus assuming $\Gamma_{stat} = \Gamma_{trans}$, now the curvature of the barrier is explicitly included by combining equations 2 and 7:

$$\Gamma_{Kra} = (\sqrt{1 + \gamma^2 - \gamma}) \frac{\hbar \omega_{eq}}{T} \Gamma_{stat}$$

Such a dynamical calculation with $\gamma = 10\Gamma$ which had been applied in previous calculations for this system [8] reproduces the multiplicity; however, the cross section is overestimated (see Figure 6). This overprediction was also present in the calculation of Ref. [8] however, the data were reproduced by reducing the overall fission barrier. The last column of Figure 6 which reproduces both evaporation and pre-fission neutron multiplicity is a calculation with a temperature dependent dissipation coefficient in a description similar to the one applied in Ref. [29].

The linear dependence of the dissipation coefficient $\gamma$ as a function of the excitation energy (top) and the resulting reduction of the fission decay width compared to the transition state calculation is shown in Figure 7. At high excitation energies the influence of the dissipation is large whereas at low excitation energies the full statistical rate is restored.

The analysis presented in Figure 6 is not meant to extract details of the temperature dependent dissipation coefficient $\gamma$ but rather to demonstrate the importance of the detailed shape of the fission barrier.

Another approximation that was applied in equation 3 was the value of the curvature of the barrier which was taken to be $\omega_{sp} = 1 \cdot 10^{21}$ s$^{-1}$. This influences directly the conversion of the friction parameter $\gamma$ to the reduced dissipation coefficient $\beta$ which are related via equation 5. The assumption of a constant $\omega_{sp} = 1 \cdot 10^{21}$ s$^{-1}$ yields $\gamma = \beta/2 \cdot 10^{-21}$ s$^{-1}$ which is typically used and was applied in Section 2.2. However, Figure 8 shows the curvature as a function of the compound nucleus spin for different temperatures for $^{200}$Pb. Again, these calculations were performed with the finite range liquid drop model using the parameterization of Lestone [46F7]. Although the average value is $\hbar \omega_{sp} \sim 0.75 MeV$ corresponding to $\omega_{sp} \sim 1 \cdot 10^{21}$ s$^{-1}$ there is a rather large spread which is strongly
temperature as well as spin dependent. Thus no direct conversion between $\gamma$ and $\beta$ is possible and the comparison of results with analyses based on the two different dissipation constants should be treated with caution.

3. DYNAMICAL EFFECTS IN FUSION

Essentially the inverse process to fission is fusion of almost mass-symmetric heavy-ions. The hindrance of fusion due to dissipation of energy has been used to explain the reduction of fusion cross sections compared to predictions of static interaction potentials for certain projectile-target combinations [2]. Whether the resulting slow fusion time affects the decay of the compound system is still an open question. Again neutron multiplicity measurements yielded the first evidence for the so-called “entrance channel” effects [48]. The decay of $^{199}$Er seemed to depend on the mode of formation whereas the almost symmetrical reaction $^{64}$Ni + $^{92}$Zr could not be explained with the standard statistical model. As in fission the decay of the GDR is an ideal probe because any influence of the formation time is expected to occur early on and involves extreme shapes of the system. A first experiment studying the decay of $^{164}$Yb found discrepancies in the high energy $\gamma$-ray spectra between an almost symmetric reaction and when the system was formed with a light projectile and a heavy target [18]. Figure 9 shows the $\gamma$-ray spectra following the fusion of $^{16}$O + $^{148}$Sm and $^{94}$Ni + $^{100}$Mo forming the same compound nucleus of $^{164}$Yb at an excitation energy of $E^* = 53 MeV$. A multiplicity filter selected a similar spin range.
for both systems. Whereas the more asymmetric combination could be described with the statistical model code (a) the more symmetric system could not be reproduced (b).

In order to explain the data a simplified model was developed which incorporated statistical decay during the formation time. Calculations using the dissipative dynamical model code HICOL [49] predicted formation times ($\sim 10^{-20} s$) which were comparable to neutron evaporation times ($1.6 \cdot 10^{-20} s$) for the reaction $^{64}\text{Ni} + ^{100}\text{Mo}$.

Figure 10 shows equilibration times of the excitation energy (top) and the shape degree of freedom (bottom) for the two systems as calculated with HICOL. In this first approach of incorporating the formation times into the statistical model the formation stage was treated not time dependent but average values for the excitation energy and shape were used. Particle and $\gamma$-ray emission was then calculated for a finite time (formation time) which was treated as a free parameter.

The total $\gamma$-ray spectrum is thus a sum of the contribution from the formation stage (dashed) and the compound decay (dot-dashed) as shown in Figure 9(c). The change in the $\gamma$-ray spectra is due to two effects. The smaller one is the emission of $\gamma$-rays during the formation which has a different shape because of the large deformations involved. However, more important is the reduction of excitation energy available to the compound nucleus decay due to the neutron emission during the formation. This lower average excitation energy of the compound nucleus reduces the emission probability of GDR $\gamma$-rays and thus changes the overall shape of the spectrum.

The formation time necessary for the fit of Figure 9(c) was two times longer than calculated by HICOL however the present average approach of the formation stage is oversimplified to extract detailed quantitative values of the formation time. Also rather small level densities were used and the emission of GDR $\gamma$-rays from such largely deformed non-equilibrated systems is not well understood [50].

Another experiment which seems to support long formation times is a measurement of the ratio of deuterons to protons [51]. During this stage predominantly protons and neutrons are emitted and the emission of deuterons is suppressed because of the relatively

Figure 9: Comparison of the $\gamma$-ray spectra from $^{166}\text{Yb}$ following the reaction $^{16}\text{O} + ^{148}\text{Sm}$ (a) and $^{64}\text{Ni} + ^{100}\text{Mo}$ (b) and (c). The solid curves are calculations using the code CASCADE. Part (c) shows the calculation which included contributions from the formation (dashed) and the compound nucleus (dot-dashed) decay (adapted from Ref. [18]).
low excitation energy. Deuterons are then again suppressed during the compound nucleus decay because the effective excitation energy is reduced by the emission of protons and neutrons during the formation. The influence of the formation should thus result in a reduction of deuteron emission. This effect was indeed observed in the reaction $^{64}\text{Ni} + ^{100}\text{Mo}$ forming $^{164}\text{Yb}$ where the deuteron to proton ratio was significantly reduced compared to the reaction $^{16}\text{O} + ^{148}\text{Sm}$ where no contributions from the formation are expected [51].

Another possible indication of formation times are the measurements of GDR $\gamma$-ray difference spectra by Zelazny et al. [14]. In this technique two compound systems differing by one neutron and by 12 MeV excitation energy ($^{162}\text{Yb}$ at $E^*=50.8$ MeV and $^{161}\text{Yb}$ at $E^*=38.8$ MeV) are measured. The difference between these $\gamma$-ray spectra should then correspond to emission during the first stage of the compound nucleus decay. In the reactions with $^{17}\text{O}$ and $^{18}\text{O}$ projectiles on $^{144}\text{Sm}$ the difference spectrum agreed nicely with statistical model predictions. However, the $\gamma$-ray spectra following the reactions $^{48}\text{Ti} + ^{114}\text{Cd}$ and $^{48}\text{Ti} + ^{115}\text{Cd}$ at 225 MeV and 210 MeV respectively were identical. This effect has not yet been explained. One possible explanation would be a stronger influence of long formation times at the higher energy thus reducing the excitation energy and yielding similar $\gamma$-ray spectra as in the lower energy reaction. A quantitative analysis of this hypothesis has not yet been performed.

The most thoroughly investigated system is $^{156}\text{Er}$ where not only the neutron multiplicities but also detailed $\gamma$-ray spectra were measured [19P2288]. In a very recent study neither probe showed evidence for entrance channel effects. The $\gamma$-ray spectra from the reaction $^{64}\text{Ni} + ^{92}\text{Zr}$ and $^{12}\text{C} + ^{144}\text{Sm}$ were identical when gated by isomer transition in the residues and the same compound nucleus angular momentum [22].

In order to understand these apparent contradictions to the $^{164}\text{Yb}$ data of Ref. [18]
one has to calculate the formation times. Figure 11 shows the fusion times for the two reactions as a function of angular momentum. Although the predicted formation time around 25 h for the reaction $^{64}\text{Ni} + ^{92}\text{Zr}$ is smaller than the $^{64}\text{Ni} + ^{100}\text{Mo}$ times this small difference cannot account for the differences in the observations. However, these formation times depend critically on the populated angular momenta. The $^{64}\text{Ni} + ^{100}\text{Mo}$ reaction covered angular momenta between 10 h and 30 h with contributions up to 50 h [18]. The formation times needed to fit the $\gamma$-ray spectra were $200 \cdot 10^{-22}$ s for a factor of two longer than the predicted average time. However the strong increase around 25 h might indicate much longer times. HICOL is a semiclassical code that does not predict fusion to occur above angular momenta of 29 h. However, experimentally, much larger angular momenta lead to fusion [52].

The $\gamma$-ray spectrum following the reaction $^{64}\text{Ni} + ^{92}\text{Zr}$ was gated by lower angular momenta between 14 and 28 h and an average of 25 h [22]. In addition, the strong increase of the fusion times is predicted to occur at larger values $> 35 h$. This difference might explain the fact that the influence of formation times was observed in $^{164}\text{Yb}$ and not in $^{156}\text{Er}$. Another difference that might lead to an enhancement of the influence of formation times is the excitation energy. The first chance neutron evaporation times are a factor of two larger in $^{156}\text{Er}$ at 47 MeV compared to $^{164}\text{Yb}$ at 53 MeV. This difference reduces the contribution of the formation stage relative to the compound nucleus decay in $^{156}\text{Er}$.

4. CONCLUSIONS AND OUTLOOK

The giant dipole experiments are clearly a powerful tool for the study of dynamical effects. They are complimentary to the neutron and charged particle multiplicity measurements. Both of these methods are sensitive to different features of the reactions. Future experiments of the $\gamma$-ray decay of the GDR should include detailed angular distribution measurements because they contain detailed information about the deformation of the system. In addition, for all these measurements it is essential to measure the evaporation residue cross sections simultaneously in order to constrain statistical model parameters.

The formation time studies should be performed in coincidence with evaporation residues in order to rule out any possible contaminations of other reaction mechanisms. Very careful measurements of the spin distributions are also necessary because the effect is predicted to be highly sensitive to this distribution. With the new large arrays more of these measurements should be feasible in the near future.

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