Entrance-channel dependence of fission transients.

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Fission transients describe the fission rate as it evolves towards the quasistationary value given by Kramers’ formula. The nature of fission transients is dependent on the assumed initial distribution of the compound nuclei along the fission coordinate. Although the standard initial assumption of a near-spherical object leads to a transient suppression of the fission rate (fission delay), a moderate initial fission-like deformation can reduce the magnitude of this suppression. For still larger initial deformations, transient fission enhancements are possible. Examples of this behavior are illustrated via a one-dimensional Langevin simulation. It is argued that the initial conditions are determined by the fusion dynamics and thus are entrance-channel dependent. Transient fission may be considered intermediate between statistical fission and quasifission as the rapid time scale of transient fission may not lead to an equilibrium of the angular and mass-asymmetry coordinates. The relationship between the mean first passage time and the transients are discussed. For temperatures much smaller than the fission barrier, the mean first passage time is independent of the nature of the fission transients if there is no strong competition from evaporation. Thus, fission transients are most important when the evaporation time scale is smaller than, or of the order of, the transient time.

PACS numbers: 25.85.-w, 25.70.Jj, 24.60.Dr
Keywords:

I. INTRODUCTION

Nuclear fission at high excitation energies can be modeled as a diffusion-driven escape over a potential barrier. The quasi-stationary or equilibrium fission rate for a one-dimensional problem was determined by Kramers in 1940. Forty years later, Grangé and Weidenmüller considered the time dependence of the fission rate as it approaches this equilibrium limit. Of course, the nature of this transient rate depends on the assumed initial distribution along the fission coordinate. Grangé and Weidenmüller subsequently almost all other treatments of this problem considered that all systems start out near-spherical or with deformations corresponding to the local minimum in the potential energy surface. As a consequence, it takes time for the population at the higher deformations near the saddle point to build up and therefore the fission rate is initially suppressed compared to the equilibrium value. This has led to the concept of a fission delay.

If the light-particle evaporation time scale is shorter than the transient or delay time \( \tau_{\text{trans}} \), then one would expect an increased multiplicity of evaporated particles before the system is committed to fission. It has been suggested that this contributes to the large number of neutrons and other particles which are emitted prior to scission. However, these prescission particles also have contributions associated with evaporative emissions as the fissioning system descends from the saddle to the scission point. A full understanding of the relative contributions from presaddle and saddle-to-scission emissions has not yet been obtained.

It is the purpose of this work to illustrate the sensitivity of the fission transients to the assumed initial distribution using a schematic one-dimensional model. Most calculations will be performed for the limit of high friction which allows a number of simplifications in the calculations. Also a number of studies have suggested this friction limit is appropriate for fission.

II. LANGEVIN SIMULATIONS

Consider the motion along the fission coordinate \( x \) subjected to a potential energy \( V(x) \), of the form indicated in Fig. 1, with a local minimum or ground-state at \( x=x_{\text{min}} \) and a local maximum or saddle-point at \( x=x_{\text{max}} \). The fission barrier is therefore \( B=V(x_{\text{max}})-V(x_{\text{min}}) \). The one-dimensional Langevin equation for this system is

\[
M \ddot{x} = -dV/dx - \gamma \dot{x} + \xi(t)
\]

where \( M \) is the inertia, \( \gamma \) is the friction, and \( t \) is time. The fluctuating Langevin force \( \xi(t) \) is dependent on the temperature \( T \) of the system and its time dependence has the following properties

\[
\langle \xi(t) \rangle = 0, \quad \langle \xi(t) \xi(t') \rangle = 2\gamma T \delta(t-t').
\]

In the limit of high friction, the inertial term drops out and the reduced Langevin equation is

\[
\dot{x} = -\frac{V'(x)}{\gamma} + \frac{\xi(t)}{\gamma}.
\]

Consider the motion of the system inside the potential well without the fluctuating force, i.e., \( \xi(t)=0 \). In this case for all initial deformations not too far from \( x_{\text{min}} \), the solution of this equation is just an exponential approach of the deformation towards \( x_{\text{min}} \) with a time constant of
passage through the saddle point is chosen. Note, if the real scission point is closer to $x_{\text{max}}$ than our effective saddle point $x_{e,s}$, then the equilibrium rate also needs to be modified. From Fröbrich, Gontchar, and Mavlitov \[11\], when the saddle and scission points are close, the quasistationary decay rate is

$$k_f^\infty \approx k_f^{\infty}(\text{Kramers}) \frac{2}{1 + \text{erf} \left( \frac{V(x_{\text{max}}) - V(x_s)}{\sqrt{T}} \right)}$$

where $k_f^{\infty}(\text{Kramers})$ is Kramers’ formula (Eq. \[4\]). If the saddle and scission points are identical ($x_{\text{max}} = x_s$), then fission rate is a factor of two larger than Kramers’ value. It rapidly approaches $k_f^{\infty}(\text{Kramers})$ when the scission point is further away from the saddle point. Note for our effective scission point ($x_s = x_{e,s}$), this formula gives a fission rate which is only 2.3% larger than $k_f^{\infty}(\text{Kramers})$ and this small enhancement can be ignored.

An alternative to the Langevin simulations is to solve the Fokker-Planck or Smoluchowski equations for the probability distribution function $P(x,t)$. Grangé and Weidenmüller\[2\] define the transient fission rate in their Fokker-Planck calculations as

$$\frac{dN}{dt} = -k_f(t) N, \quad N = \int_{-\infty}^{x_{\text{max}}} P(x,t) \, dx.$$  \(7\)

This definition is used in Ref. \[3\] and more recently in Ref. \[19\]. With this definition, those systems that have crossed the saddle point at $x_{\text{max}}$ are no longer counted as part of the “ground-state” population $N$ and the fission rate is equated to the rate of decay of this population. However as already mentioned, those systems that have just crossed the saddle point are not necessarily committed to fission and have a possibility of rejoining this population. Thus, this definition is not equivalent to that adopted is this work and leads to smaller transient times.

Calculations were performed with the potential energy which was first used in Ref. \[3\], and subsequently in Refs. \[4\], \[5\]. The potential, shown in Fig. 1, was deemed appropriate for a compound nucleus with $A = 248$ and has a fission barrier of $B = 4$ MeV. A friction parameter of $\gamma = 3.4$ zs MeV/fm$^2$ was assumed. The transient fission rate relative to the equilibrium value [Eq. \[4\]] is plotted against $t/\tau$ in Fig. 2 for $T = 1$ MeV and with the standard initial condition of $x_0 = x_{\text{min}}$. The purpose of plotting the results in this particular way is that they are independent of the friction parameter $\gamma$. Weidenmüller and Jing-Shang\[5\] first pointed out the simple scaling of the fission rate with friction in the high-friction limit, i.e.,

$$k_f(t, \gamma_1) = (\gamma_2/\gamma_1) k_f(\gamma_1 t/\gamma_2, \gamma_2).$$

Of course the friction must be large enough that the limit is approached, but otherwise the plotted results are independent of $\gamma$. The results obtained with the definition of the fission time proposed in this work and from the definition of Grangé and Weidenmüller [Eq. \[4\]] are indicated by the filled and open data points, respectively. With both definitions, the fission rate is initially suppressed as expected.

\[\tau = \gamma / \left( \frac{d^2V}{dx^2} \right)_{x=x_{\text{min}}}.\]  This time constant set the time scale for motion inside the well.

The quasi-stationary or equilibrium decay rate in the limit of high friction \[1\] is given by Kramers' formula:

$$k_f^{\infty} = \frac{1}{2\pi\gamma} \exp \left( -\frac{B}{T} \right) \left( 1 - \lambda T \right)$$  \(4\)

This formula is strictly valid for $T \ll B$. The last term contains the first-order correction in $T$ from Ref. \[18\] where

$$\lambda = \frac{1}{8} \left( \frac{dV}{dx} \right)_{x=x_{\text{max}}}^2 - \frac{1}{8} \left( \frac{dV}{dx} \right)_{x=x_{\text{min}}}^2$$

$$+ \frac{5}{24} \left( \frac{dV}{dx} \right)_{x=x_{\text{max}}}^2.$$  \(5\)

In order to determine the transient fission decay rate, the Langevin equation is solved in a Monte Carlo fashion starting at some initial value $x_0$ of the fission coordinate. Each Langevin trajectory can be followed until it crosses the saddle point at $x_{\text{max}}$. However, the system is not committed to fission at this point, the fluctuating force can drive the system back across the saddle point towards $x_{\text{min}}$. The system only becomes completely committed to fission once the scission point is reached. However in practice once the system has crossed the saddle point and descended to a point $x$ where $V(x_{\text{max}}) - V(x) > 2T$, the possibility of returning to the saddle point is remote. So the Langevin trajectories are followed to an effective scission point $x_{e,s}$, where $V(x_{\text{max}}) - V(x_{e,s}) = 2T$. However in order to define a fission time independent of this or the real scission point, the time of the last passage through the saddle point is chosen.

\[\text{FIG. 1: Variation of the potential energy } V \text{ with the fission coordinate } x \text{ used in the Langevin simulations. The locations of the three initial starting configurations are indicated as } x_{\text{min}}, x_1, \text{ and } x_2.\]
for $x_0 = x_{\text{min}}$ and, as also expected, the transient time is a little shorter with the definition of Weidemüller and Jing-Shang. The dashed curve indicates a form of the transient rate as defined by Eq. (7), while the dashed curve is adopted in this work. The open symbols represent the transient rate as found some use in statistical-model calculations. 

$$k_f(t) = k_f^\infty \left[ 1 - \exp \left( -\frac{2.3t}{\tau_d} \right) \right], \quad \tau_d = \frac{\tau}{2 \ln \left( \frac{10B}{T} \right)}.$$\hspace{1cm}(8)$$

One can clearly see it is not a very good approximation.

Let us now concentrate on the dependence of the transients on the initial deformation. Unlike Ref. [2], in which a dependence on the initial starting value was also considered, let us consider only well-bounded initial deformations $x_0$ which lie well inside the potential well, i.e., $B \geq V(x_{\text{max}}) - V(x_0) \geq T$. In such cases, the fission barrier will still be a substantial obstacle to decay. Figure 3 illustrates the strong dependence of the transients on the initial condition for two temperatures; $T = 0.5$ and 1 MeV. Three initial deformations $x_0 = x_{\text{min}}$, $x_1$, $x_2$ were considered and their location on the potential energy surface is indicated in Fig. 1. Note that $V(x_1) - V(x_{\text{min}}) = B/4$ and $V(x_2) - V(x_{\text{min}}) = B/2$. From Fig. 3, one can see that for any small initial fissionlike deformation, such as $x_1$, the magnitude of the fission delay is greatly reduced. For still larger initial deformations, such as $x_2$, one even obtains a substantial transient fission enhancement. In this case, those systems that fissioned in the transient period typically did not pass through the ground-state configuration $x_{\text{min}}$. The systems which fission first are those for which the fluctuations drive that system almost continually towards the saddle point. Such behavior for large initial deformations was initially suggested in Ref. [17].

These simulations indicate that the very existence of a fission delay depends on the appropriate initial deformation. However, all simulations approach the equilibrium rate over a similar time scale which is associated with attaining the equilibrium distribution in $x$. Note for smaller temperatures, the transient deviations from Kramers’ rate are larger and the extent of the transient period is longer.

Although Kramers decay rate is valid only for $T \ll B$, the Langevin simulations produce qualitatively similar behavior for $T \gtrsim B$. For example, Fig. 4 shows the normalized fission rate for $T = 2B$. In this figure $k_f^\infty$ is not determined from Eq. 4 but is just the asymptotic value of $k_f(t)$ in the simulations. The transient time scale is much shorter than those in Fig. 3 and during this period, the deviations from $k_f^\infty$ are much smaller. This does not imply transient effects are less important at higher temperatures. One should remember that the absolute values of $k_f(t)$ are much larger for the higher temperatures and so the probability of fissioning during the transient period is much greater for these hotter systems (ignoring competition for evaporation processes). Let us define the transient time $t_{\text{trans}}$ as the time for $k_f(t)$ to attain 90% of $k_f^\infty$ for $x_0 = x_{\text{min}}$. The temperature dependence of the transient time $t_{\text{trans}}$ and the mean statistical time $t_f = 1/k_f^\infty$ are plotted in Fig. 5 as the data points. It is important to note that for all
the deformation passes through a particular value of time (FPT) in the Langevin simulations is the first time important. Let us examine this closely. The mean first (solid curves) and last (dashed curves) passage times obtained in the same simulation. Thick and thin curves correspond to the two indicated initial deformations.

temperatures, \( t_{\text{trans}} < t_f \). Now for \( T \ll B \), Fig. 6 shows that \( t_{\text{trans}} \ll t_f \) and thus the number of events that fission during the transient period approaches zero. Therefore most fission events in these simulations occur during the period when \( k_f(t) \sim k_f^{\infty} \).

The dashed curves in Fig. 5 give the Kramers’ formula (without the first order correction) and \( \tau_f \) from Eq. 8. Although Kramers formula is not valid for \( T \gtrsim B \), it still predicts the statistical rate to within an order of magnitude. The quantity \( \tau_d \) may be used for a similar estimate of the transient time.

III. MEAN FIRST AND LAST PASSAGE TIMES

Hofmann and Ivanyuk \( ^{23} \) have recently championed the concept of the mean first passage time \( \tau_{\text{MFPT}} \) in fission and have suggested that fission transients are not important. Let us examine this closely. The first passage time (FPT) in the Langevin simulations is the first time the deformation passes through a particular value of \( x \). Following Ref. \( ^{24} \), the mean last passage time \( \tau_{\text{MLPT}} \) can also be considered. The last passage time (LPT) is the last time the deformation passes through a particular value. Note, the fission rate evaluated in this work is based on the LPT at the saddle point as in Ref. \( ^{24} \). Both the \( \tau_{\text{MFPT}} \) (solid curves) and \( \tau_{\text{MLPT}} \) (dashed curves) determined for \( T=1 \) MeV are displayed in Fig. 6 as a function of \( x \). The two times are normalized relative to the mean statistical time \( t_f \). Results are also shown for two initial deformations, \( x_{\text{min}} \) (thin curves) and \( x_{\text{max}} \) (thick curves). As pointed out by Hofmann and Ivanyuk \( ^{23} \), the value of \( \tau_{\text{MFPT}} \) is not very sensitive to the initial deformation. The same is also true for the \( \tau_{\text{MLPT}} \). For deformations well beyond the saddle point \( (x=0) \), \( \tau_{\text{MFPT}} \sim t_f \) and for all deformations \( \tau_{\text{MLPT}} \sim t_f \). These results are true in general as long as \( T/B \) is small.

Let us define the thermal length scale as \( l_{\text{th}} = \sqrt{2T/\left| \frac{d^2V}{dx^2} \right|_{x=x_{\text{max}}}} \). Now in the limit of high friction and \( T/B \to 0 \), Hänggi et al. \( ^{25} \) showed that \( \tau_{\text{MFPT}} \to t_f \) for all deformations more than the distance \( l_{\text{th}} \) beyond the barrier. This result is independent of initial deformation as long as this deformation is located before the barrier by distance greater than \( l_{\text{th}} \). In the simulations associated with Fig. 6, the thermal length is small, i.e., \( l_{\text{th}} = 1 \) fm. The reason for this insensitivity to the initial deformation should be obvious, the number of events which fission within the transient period is vanishingly small when \( T \ll B \). However for larger temperatures, this is no longer the case. For example, Fig. 6b shows the mean times for \( T = 2B \). Here there is a more significant dependence on the initial deformation.
evaporation time was chosen in a Monte-Carlo fashion from an exponential distribution with partial decay rate $k_{ev}$. Each Langevin simulation was then stopped when it reached this time. The mean times $\tau_{MFPT}$ and $\tau_{MLPT}$ were then determined only from events that reached a given deformation. These are displayed in Fig. 6b for the same $T$ and initial deformations as in Fig. 6a, but with a mean evaporation time approximately equal to the transient time, $t_{ev}=0.93 \times t_{trans}$ ($k_{ev}=77 \times k_f$). Clearly from Fig. 6b, the inclusion of evaporation competition has now produced a large dependence of the mean times on the initial deformation. All mean times are much smaller than those in Fig. 6a and are of the order of the mean evaporation time $t_{ev}$. This latter time is indicated in the figure by the horizontal dashed line. For deformations well beyond the barrier, the times $\tau_{MFPT}$ and $\tau_{MLPT}$ are identical indicating that the fluctuating forces are unimportant as the systems smoothly drop down the barrier. In fact, the relative dependencies of the times in this deformation region are identical for all curves in Figs. 6a–6b. This behavior is dictated by the very sharp drop off in the potential beyond the barrier and is not general for all possible potentials.

The previous simulation where $T \ll B$, $t_{ev} \sim t_{trans}$ and thus $k_f^{\infty} \ll k_{ev}$ is not well represented by studies of precission particle emission as the small fission probability makes coincidence measurements with evaporated light particles difficult. For most measurements with heavy-ion reactions, the fission yield is associated with compound-nucleus spins where $k_f^{\infty} \gtrsim k_{ev}$ and the sensitivity to the fission transients is not large unless $T \gtrsim B$. For example consider the precission multiplicity measurements of Hinde et al. for a number of compound systems with $A=168$ to $A=251$. The authors consider a number of simulations including fission delays and saddle-to-scission evaporations to reproduce the fission and residue cross sections and the precission neutron multiplicities. Take for example the $^{19}$F+$^{183}$Ta reaction producing a compound nucleus with 80 MeV of excitation energy. Most of the fission yield for this reaction occurs for compound-nucleus spins of $J=40$ to $J=63 \ h$ in their simulations. In this range, $k_f^{\infty}/k_{ev}$ (first chance) varies from 0.05 to 1.1. If the compound nucleus survives first chance fission competition, then the surviving daughter nucleus (and its daughters) may also undergo fission. The total fission yield depends on the contribution from all chances, i.e., the sum of the fission yield from all daughters produced in the decay cascade. The total fission probability from all chances varied from $\sim 56\%$ to almost 100% over this spin range, but it is dependent of the form of the transients assumed. However, only for the lowest part of this spin range is $k_f^{\infty} \ll k_{ev}$ (first chance) and thus only here may there be a large sensitivity to the transients. In Ref. [17] it was concluded that if all prescission neutrons are entirely from presad- dle emissions, then this would require a transient fission suppression with $t_{trans}=70 \ zs$. For the $^{19}$F+$^{183}$Ta system discussed above, the first-chance statistical-fission

FIG. 6: (Color online) Mean normalized times plotted as a function of deformation for $T=1 \ MeV$. The solid curves show the mean first passage time $\tau_{MFPT}$ while the dashed curves are for the mean last passage time $\tau_{MLPT}$. Results are shown for two initial deformations indicated by the arrows: $x_0=x_{\min}$ (thin curves) and $x_0=x_2$ (thick curves). a) No evaporation competition. b) Evaporation competition with an evaporation rate of $k_{ev} = 77 \times k_f^{\infty}$.

Given the insensitivity of $\tau_{MFPT}$ and $\tau_{MLPT}$ to the transients effects for $T \ll B$, one may question their relevance for fission. If all events are allowed to fission as in the previous simulations, then clearly the transient decay rate has little relevance. However, fission is not the only decay mode of a compound nucleus. Competition from light-particle evaporative decays can drastically alter the probability for fission and make the transients important. Consider competing fission and evaporation branches. Let $k_f(t)$ now represent the partial decay rate for fission, i.e., the rate in the absence of evaporation. Let the partial evaporation rate be $k_{ev}$ and its mean time, in the absence of fission, is thus $t_{ev}=1/k_{ev}$. If there are no transients and the partial fission rate is constant, i.e., $k_f(t)=k_f^{\infty}$, then the fission probability is just $k_f^{\infty}/(k_f^{\infty}+k_{ev})$ and the final fission rate is given by the total decay rate $k_f^{\infty}+k_{ev}$. If $k_{ev} > k_f^{\infty}$, then not only is the fission probability small, but those events that do fission occur on the shorter time scale of $t_{ev}$. If $t_{ev}$ is less than, or of the order of, $t_{trans}$, then the transients will be very important. To illustrate this, the effect of a competing evaporative decay mode was included in a simplistic way into the Langevin simulations. For each event, an
time is \( t_f = 70 \text{ zs at } J = 45 \) and drops to \( t_f = 10 \text{ zs at } J = 63 \text{ h} \). Clearly such a transient time does not make sense as \( t_f < t_{\text{trans}} \) for these spin values and this suggests that transients cannot explain all the observed prescission neutrons in this reaction. Thus, this should serve as a warning that one cannot assume arbitrary large fission delays when fitting such data.

IV. WEAK FRICTION

Although we have considered the high friction limit, most of the previous conclusions are also valid for moderate to low friction. In general in this regime, the initial conditions for the simulations must be specified by the initial deformation and its time derivative. However in the limit of weak friction, the system will oscillate within the potential well and the total energy \( E_{\text{tot}} \) (potential plus kinetic) of the system will evolve more slowly. Thus in this limit, the initial condition can be specified by the initial total energy. Results are shown for underdamped simulations in Fig. 7a. Here the inertia was set to 62 nucleon masses and \( \gamma = 0.015 \text{ zs MeV/fm}^2 \). The reduced friction is thus \( \gamma/M = 0.023 \text{ zs}^{-1} \) and is small compared to the oscillation frequency in the ground state minimum \( \omega = \sqrt{(\frac{d^2V}{dx^2})_{x=x_{\text{min}}}/M} = 1.87 \text{ zs}^{-1} \). Curves for initial energies of \( E_{\text{tot}} = 0 \) and \( B/2 \) are indicated for a temperature of \( T = 1 \text{ MeV} \). The most noticeable difference from the high friction results is the oscillations at small times associated with the underdamped motion. Otherwise the general behavior is similar. The calculation with \( E_{\text{tot}} = 0 \), starting further from the barrier energy, shows a suppression during the transient period while the calculation with \( E_{\text{tot}} = B/2 \), starting closer to the barrier energy, displays a fission enhancement.

The mean times \( \tau_{\text{MFPT}} \) and \( \tau_{\text{MLPT}} \) from these simulations are displayed in Fig. 7b. Because of the underdamped motion, after the system crosses the saddle point \((x=0)\) it keeps going and never returns. Thus the mean FPT reaches its asymptotic value at the saddle point. Unlike the mean times in Fig. 7a, calculated for the same temperature, but with high friction, the mean time here shows a more significant dependence on the initial condition. However, this will decrease for smaller temperatures. The greater dependence on the initial condition is a direct consequence of the fact that the fraction of fission events occurring during the transient time \( t_{\text{trans}} \) is larger. In the same vein, the transient times are relatively larger compared to \( t_f \) for these low friction simulations. Fig. 7c shows the evolution of \( t_f \) and \( t_{\text{trans}} \) with temperature. Although qualitatively similar to the high friction results in Fig. 7a the two times become quite similar in magnitude for \( T \gtrsim B \), but still \( t_{\text{trans}} < t_f \).

V. DISCUSSION

These calculations have emphasized that the nature of the fission transients is very sensitive to the initial deformation of the compound nucleus. Given this sensitivity, it is important to consider what determines these initial conditions and whether they lead to a fission delay? Only a fission delay will result in an increase in the predicted presaddle neutrons. If instead one has a transient fission enhancement, then this will not help explain the large numbers of prescission neutrons measured in experiments. As far as the present calculations are concerned, time zero should correspond to the time when shape fluctuations commence. As these are thermally driven, then the initial deformation should correspond to the configuration at which a significant fraction of the final excitation energy is dissipated. For proton, \( \alpha \)-particle, or other light-ion induced reactions, one might expect the dissipation of the initial kinetic energy to occur without any significant change in the deformation of the target nucleus. The choice of the ground-state or a spherical configuration as the starting value, thus seems reason-
able. On the other hand for fusion reactions between heavy fragments, a more deformed initial configuration may be appropriate. Clearly the transient effects cannot be decoupled from the fusion dynamics.

In the HICOL dynamical model,[26] which uses the full wall friction,[27] the fusion dynamics can be divided into two time regimes. First an initial rapid dissipation of the relative kinetic energy between the projectile and target and then a slower relaxation of the shape degrees of freedom. For example, Ref. [28] discusses a HICOL simulation for the $E/A=5$ MeV $^{64}$Ni$^{+100}$Mo ($J=0$) reaction where the thermal excitation energy is dissipated in 0.5 zs leaving a highly deformed mononuclear configuration whose subsequent evolution can be treated in the limit of high friction. This deformed configuration would represent the initial deformation in the Langevin simulations.

Another example of this is illustrated in Fig. 8. Here the predicted dissipated thermal excitation energy is shown as a function of time for two reactions ($^{64}$Ni$^{+100}$Mo and $^{16}$O$^{+148}$Sm) making the same $^{164}$Yb compound nucleus with excitation energy of 100 MeV and $J=40 \hbar$. Both reactions show a rapid rise in the thermal energy over a period less than 1 zs and subsequently this energy plateaus. The difference between the plateau values in the two reactions reflects the difference in the deformation-plus-rotational energy of the initial configurations. The times indicated by the filled symbols in Fig. 8 are at the end of the periods of rapid dissipation and will be taken as the “initial” configurations after which shape fluctuations need to be considered. The shapes of the compound nucleus at these times are shown in Fig. 9 for the two reactions. It is clear that the initial shape depends of the entrance-channel mass asymmetry. However, it also depends of the bombarding energy and impact parameter. The more symmetric the entrance channel, the larger is the initial deformation. Thus it is possible that the nature of the fission transients may change from a fission suppression for very asymmetric entrance channels to an enhancement for the symmetric entrance channels.

The assumption of high friction is not universal, e.g. Nix and Sierk have used a reduced wall friction (scaled by 27%) to explain the widths of the giant isoscalar quadrupole and octupole resonances.[29] This reduced friction is also consistent with experimental fission-fragment kinetic energies. In this case, the damping of the fission coordinate is closer to critical damping. With this friction, if the fusion dynamics bring in sufficient energy into the motion of the fission coordinate (either potential or kinetic), transient fission enhancement will again be possible.

Whatever the nature of the friction, a full understanding of the transients would require consideration of more than just a fission coordinate. Initial deformations for asymmetric entrance channels may have a mass asymmetry or an octupole moment as is the case for the $^{16}$O$^{+148}$Sm reaction in Fig. 8. Thus the transients may affect the mass distribution of the fission fragments. Transient fission may be considered intermediate between statistical fission and quasifission as the rapid time scale of transient fission may not lead to an equilibrium of the angular and mass-asymmetry coordinates. As such, transient fission may contribute to the observed suppression of the residue yield, and the broadening of the fission-fragment mass distribution, for more symmetric entrance channels.[29] These are usually considered a consequence of “fusion inhibition” due to quasifission competition, but transient fission enhancements for the more symmetric entrances channels will lead to similar effects.

Apart from fusion reactions, transient effects may play

![FIG. 8](Image)

**FIG. 8**: (Color online) Predicted evolution with time of the dissipated thermal excitation energy in the $E/A=5$ MeV $^{64}$Ni$^{+100}$Mo and the $E/A=8.5$ MeV $^{16}$O$^{+148}$Sm reactions. Results were obtained with the HICOL code for $J=40\hbar$. The filled symbol indicates the “initial” configurations for which the shapes are shown in Fig. 9.

![FIG. 9](Image)

**FIG. 9**: Predicted “initial” deformations of the $^{164}$Yb compound nuclei ($J=40 \hbar$) predicted by the HICOL code for the two indicated reactions.
a role in the sequential fission of targetlike (TLF) and projectilelike fragments (PLF) following deep inelastic interactions. After the deep inelastic interaction, these fragments may process a strong deformation with the remnant of the neck, which connected the TLF and PLF during their interaction, orientated towards the other fragment. This remnant gives the fragments octupole deformations and hence an emergent mass-asymmetry.

In $^{100}$Mo+$^{100}$Mo and $^{120}$Sn+$^{120}$Sn reactions at $E/A \sim 20$ MeV, Stefanini et al. found the sequential fission axis for asymmetric fission of the PLF is preferentially aligned along the beam axis such that the smaller fission fragment is emitted towards the TLF. They suggest an explanation based on transient fission to explain their observation; due to the neck remnant, the PLF is created with a deformation close to the saddle point for the mass asymmetric fission. Thus there will be a transient enhancement for these mass asymmetries allowing them to compete more favorably against evaporation and symmetric fission. More recently, Hudan et al. have used Langevin simulations to illustrate these general ideas for more asymmetric splits.

VI. CONCLUSION

One-dimensional Langevin simulations were performed to emphasize the strong sensitivity of fission transients to the assumed initial shape distribution of the compound nuclei. Fission delays or transient fission suppressions are found if the assumed initial deformation of the compound nucleus is spherical or near the ground-state value. However with an initial fission-like deformation for strong friction or with sufficient energy in the fission degree of freedom for weak friction, then a transient fission enhancement will result. It is argued that the initial conditions are determined by the fusion dynamics and thus fission transients are dependent on the entrance channel. The nature of the transients may change from a suppression to an enhancement as the entrance-channel changes from asymmetric to symmetric. Calculations which invoke fission delays to explain the large number of prescission neutrons measured in experiments should be reexamined in light of these considerations.

For temperatures smaller than the value of the fission barrier, the probability of fissioning during the transient period is small. Thus if there are no competing decay mode and all systems eventually fission, then the mean first and last passage times for deformations beyond the saddle point will be insensitive to the initial conditions as most fissions occur when the quasistationary rate is attained. Transient fission will only be important when there is strong competition from evaporation where the only systems that fission at all are those that fission early. Calculations including strong competition from evaporative decays show a pronounce dependence of the mean first and last passage times on the initial condition.

Acknowledgments

I wish to acknowledge many informative discussions with Professor L. Sobotka and Dr. A. Sierk. This work was supported by the Director, Office of High Energy and Nuclear Physics, Nuclear Physics Division of the U.S. Department of Energy under contract number DE-FG02-87ER-40316.

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