Role of shape-dependence of dissipation on nuclear fission

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Consider fission of a highly excited heavy nucleus. The multiplicity of neutrons (n_{pre}) evaporated before scission and the evaporation residue (ER) cross-section, taken together, portray a delicate balance between the rates of evaporation and fission. It is now established that the transition-state fission rate given by Bohr and Wheeler [1] underestimates both the n_{pre} and the ER data. The dissipative property of the nuclear bulk is necessary to be incorporated into the fission dynamics and Kramers [2, 3] obtained the fission width

$$\Gamma_K = \frac{\hbar\omega_g}{2\pi} e^{-V_B/T} \left\{ \sqrt{1 + \left(\frac{\eta}{2\omega_s}\right)^2} - \frac{\eta}{2\omega_s} \right\} \tag{1}$$

considering fission as diffusion of a Brownian particle across the fission barrier (V_B) placed in a hot (temperature T) and viscous fluid (of dissipation coefficient η) bath. The frequencies of the harmonic oscillator potentials describing the nuclear potential near the ground state (c_g) and the saddle (c_s) are ω_g and ω_s respectively. It is evident from Eq.(1) that dissipation reduces the fission rate, thus enhances the ER cross-section and also allows a longer time interval for more neutrons to evaporate. The dissipation coefficient η is usually treated as an adjustable parameter to fit the experimental data.

It is however observed [4–6] that it is not possible to fit both the n_{pre} and ER data with the same value of η. While a smaller value of η can account for the ER excitation function, a larger value of η is necessary to describe the n_{pre} data. It is usually argued that pre-saddle dynamics essentially determines the fission (and ER) cross-section while neutron evaporation (contributing to n_{pre}) can continue till the scission configuration is reached. Thus one can consider two different dissipation strengths, a smaller one (η_{in}) operating within the saddle point in order to fit the ER cross-sections and a larger one (η_{out}) effective outside the saddle point in order to enhance the number of saddle-to-scission neutrons. In a statistical model calculation of nuclear fission, one considers Γ_K^{in} (Γ in Eq.(1) with η_{in}) as the relevant fission width till fission occurs. Subsequently, η_{out} is used to calculate the saddle-to-scission transition time during which neutron evaporation continues. In the present work, we shall examine the validity of using a shape-dependent dissipation in Kramers' width which was originally obtained assuming a shape-independent dissipation. To this end, we shall compare Γ_K^{in} with stationary widths from Langevin dynamical model calculations considering the latter to represent the true fission width.

The Langevin equations in one dimension with elongation c as the relevant collective coordinate is solved using the collective potential V and shape-dependent dissipation coefficient η as shown Fig.1 for ^{224}Th. Denoting by c_η the elongation at which the dissipation changes its strength from η_{in} to η_{out} , the Langevin equations are solved for different values of c_η and Fig.2 shows the resulting time-dependent fission widths. The values of the Kramers'fission width Γ_K^{in} and Γ_K^{out} (from Eq.(1) with η_{out}) are also marked in this figure by a and b respectively. It is immediately noted from Fig.2 that for $c_\eta = 1.6$, which corresponds to the elongation at saddle, the stationary

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fission width from Langevin equations (Γ_L) is substantially smaller than Γ_K^{in} (labeled by a). This observation is contrary to the expectation that pre-saddle dynamics solely determines whether a CN undergoes fission or not. We further note in Fig.2 that as c_η is shifted outward beyond the saddle point, Γ_L approaches Γ_K^{in}. When c_η is moved inward, Γ_L approaches Γ_K^{out} (labeled by b).

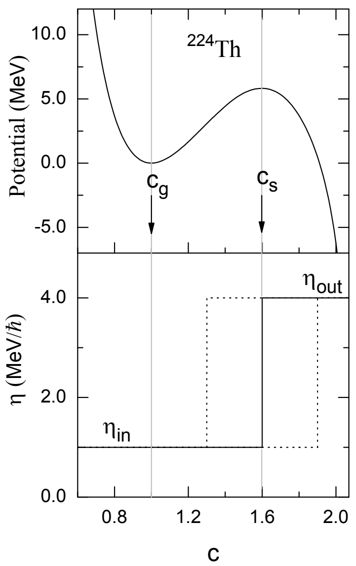

FIG. 1: Collective potential (upper panel) and shape-dependent dissipations (lower panel) for ^{224}Th

To understand the above observations, we recall that the Kramers' width (Γ_K) (Eq.(1)) represents the steady-state diffusion rate of phase-space density ρ of Brownian particles across the fission barrier satisfying the appropriate Liouville equation and the net flux or current across the saddle is

$$j = \int_{-\infty}^{+\infty} \rho(c = c_s, p) \frac{p}{m_s} dp \qquad (2)$$

where both the outward (positive p) and inward (negative p) fluxes are considered in order to obtain the net flux. In terms of Langevin fission trajectories, while the

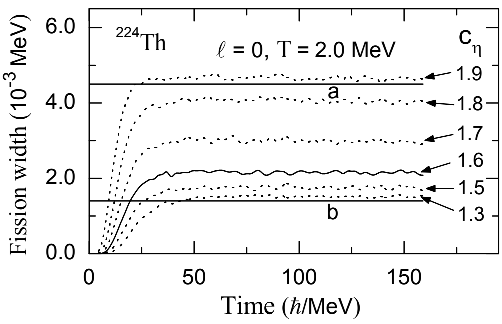

FIG. 2: Time-dependent fission rates from Langevin equations for different c_η (see text).

outward flux is controlled by the dissipation within the saddle, the inward flux (from outside to inside the saddle) or the backstreaming trajectories experience the dissipation outside the saddle. Hence the net flux in Eq.(2) depends upon both the 'inside' and 'outside' dissipation strengths and the fision width is no longer determined by the pre-saddle dynamics alone. The stochastic nature of nuclear fission makes it to depend upon the fission dynamics around the saddle, the extent of which is illustrated in Fig.2.

In conclusion, the present work demonstrates that the probability of a hot compound nucleus undergoing fission depends upon both the pre-saddle and the post-saddle dynamics of collective nuclear motion.

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