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Constraining presaddle dissipation with fission cross sections of light nuclear systems

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Nuclear fission is hindered by dissipation. Based on the stochastic Langevin model, we calculate the drop of fission cross section caused by friction with respect to its standard statistical-model value, σ_f^{drop}, as a function of the presaddle friction strength (β) for fissioning nuclei ^{205}Bi, ^{215}Fr, ^{225}Pa, and ^{230}Np at different angular momenta and excitation energies. It is found that with increasing the size of fissioning systems, the sensitivity of σ_f^{drop} to β is reduced substantially, and it disappears for the ^{230}Np system. Our findings suggest that on the experimental side, to more stringently constrain the presaddle dissipation strength by measuring fission excitation functions, it is optimal to yield those fissioning systems with a small size.

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Introduction. Intensive experimental and theoretical investigations on the nature and magnitude of nuclear dissipation have been performed in the field of low-energy nucleus-nucleus collisions, because dissipation plays important roles in fusion [1,2], the synthesis of superheavy elements [3,4], and decay of excited nuclei [5,6]. In particular, the focus that has recently attracted much attention is the crucial influence of nuclear dissipation on fission processes. It has been demonstrated [7–19] that the key reason resulting in the distinct discrepancy between prescission particle multiplicity [20–24] and evaporation residue cross sections [25] measured at high energy and predictions by standard statistical models (SMs) is the negligence of dissipation effects in the model calculation.

Prescission particles are emitted along the entire fission path, they are thus a less-direct signature of presaddle dissipation due to an interference from postsaddle emission. Fission cross section is dictated by presaddle friction and thus provides a desirable separation between presaddle and postsaddle dissipation effects.

To date, more efforts have been invested to constrain the strength of presaddle dissipation (β) [25–29]. New observables including excitation energy at saddle [30] and the width of fission-fragment charge distributions [31] that are identified to solely depend on β have also been proposed. However, the presaddle friction strength is still quite uncertain and currently under vigorous debate [32]. So, how to accurately determine the strength becomes very urgent and necessary.

Fission and evaporation are two primary de-excitation modes of a compound nucleus. As an immediate consequence of nuclear dissipation, fission is retarded that decreases fission probabilities (or fission cross sections). Thus the measurement of fission cross section is considered to be the most fundamental and sensitive method of pinpointing dissipation effects inside the fission barrier [32–37] and, thereby, it could place a more reliable and a tighter constraint on presaddle friction.

Experimentally, to explore nuclear dissipation effects with fission cross section, the typical mass number of compound systems that have been populated via heavy-ion fusions spans a broad domain of $190 < A_{\text{CN}} < 260$ (see, e.g., [6,15,20,34–36]). Also, the possible influence of the system size on fission observables, e.g., particle emission [38], and the mass distribution of the fission fragments [39] has been discussed.

In this context, to guide the experimental exploration of nuclear dissipation, the present work is devoted to studying under which experimental conditions the sensitivity of the fission cross section to presaddle dissipation effects can be enhanced. Toward that goal, we investigate the role of a system size in probing presaddle friction with fission cross section within the framework of Langevin models. The stochastic approach [7–10,14,40–46] has been shown to successfully describe a large volume of fusion-fission data including prescission particle multiplicities and fission cross sections for a lot of compound nuclei over a wide range of excitation energy, angular momentum, and fissility.

Theoretical model. For a hot nuclear system, as pointed out in Refs. [15,19,40,47], its driving force is not simply the negative gradient of the conservative force, but should also contain a thermodynamic correction; therefore, the dynamics is described by the Langevin equation that is expressed by free energy. We employ the following one-dimensional Langevin equation to perform the trajectory calculations:

$$\frac{dq}{dt} = \frac{p}{m},$$
$$\frac{dp}{dt} = \frac{p^2}{2m^2}\frac{dm}{dq} - \frac{\partial F}{\partial q} - \beta p + \sqrt{m\beta T}\,\Gamma(t). \qquad (1)$$

Here, q is the dimensionless fission coordinate and is defined as half the distance between the center of mass of the future fission fragments divided by the radius of the compound nucleus, and p is its conjugate momentum. The dissipation strength $\beta = \gamma/m$ [6,7,15,17,20,25,26,28–32,36] represents the ratio of the friction coefficient γ to the inertia parameter m obtained in the Werner-Wheeler approximation for the irrotational flow of an incompressible liquid [48]. The temperature in Eq. (1) is denoted by T and $\Gamma(t)$ is a fluctuating force with $\langle\Gamma(t)\rangle = 0$ and $\langle\Gamma(t)\Gamma(t')\rangle = 2\delta(t - t')$.

The driving force of the Langevin equation is calculated from the free energy

$$F(q,T) = V(q) - a(q)T^2. \qquad (2)$$

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Equation (2) is constructed from the Fermi-gas expression [47] with a finite-range liquid-drop potential $V(q)$ [49] in the $\{c,h,\alpha\}$ parametrization [50]. The deformation coordinate q is obtained by the relation $q(c,h) = (3c/8)\{1 + \frac{2}{15}[2h + (c-1)/2]c^3\}$ [7,51], where c and h correspond to the elongation and neck degrees of the freedom of the nucleus, respectively. The q-dependent surface, Coulomb, and rotation energy terms are included in the potential $V(q)$.

In constructing the free energy, we used the coefficients presented by Ignatyuk *et al.* [52] to calculate the deformation-dependent level density parameter, that is,

$$a(q) = 0.073A + 0.095A^{2/3}B_s(q), \tag{3}$$

where A is the mass number of the compound nucleus and B_s is the dimensionless surface area of the nucleus (for a sphere $B_s = 1$) [53].

In our calculation, prescission particle evaporation along Langevin fission trajectories from their ground state to their scission point has been taken into account using a Monte Carlo simulation technique. The emission width of a particle of kind ν (=n,p,α) is given by [54]

$$\Gamma_\nu = (2s_\nu + 1)\frac{m_\nu}{\pi^2\hbar^2\rho_c(E^*)} \times \int_0^{E^*-B_\nu} d\varepsilon_\nu \rho_R(E^* - B_\nu - \varepsilon_\nu)\varepsilon_\nu\sigma_{\rm inv}(\varepsilon_\nu), \tag{4}$$

where s_ν is the spin of the emitted particle ν, and m_ν its reduced mass with respect to the residual nucleus. The level densities of the compound and residual nuclei are denoted by $\rho_c(E^*)$ and $\rho_R(E^* - B_\nu - \varepsilon_\nu)$. B_ν are the liquid-drop binding energies. ε is the kinetic energy of the emitted particle and $\sigma_{\rm inv}(\varepsilon_\nu)$ is the inverse cross sections [54].

In addition to a modification to the A and Z of the decaying nucleus, particle emission carries away energy (which is the sum of separation energy and its kinetic energy for neutron case and as well as the inclusion of an additional term accounting for the Coulomb emission barrier for the case of light charged particles, see Ref. [7] for more details). The loss of angular momentum is taken into account by assuming that a neutron carries away $1\hbar$, a proton $1\hbar$, and α particle $2\hbar$. After the emission act of a particle, the free energy, a basic dynamical variable controlling fission dynamics, and the temperature in the Langevin equation are changed. After these quantities are recalculated, the dynamics is continued. So, particle emission affects fission dynamics and hence $\sigma_f^{\rm drop}$ defined in Eq. (6). Since particle emission prior to saddle can determine the destine of a decaying nucleus, i.e., it fissions or survives as an evaporation residue as well as a great contribution of higher (i.e., second, three, ...) chance fission to the total fission probability, the main conclusion obtained here is crucially dependent on the particle emission.

When a dynamic trajectory reaches the scission point, it is counted as a fission event. The present calculation allows for multiple emissions of light particles and higher-chance fission. Fission probabilities and particle multiplicities are calculated by counting the number of corresponding fission and evaporated particle events. The first, second, ... chance fission probability can be separately and directly calculated [7] by counting the number of corresponding fission events in which not a single presaddle particle is emitted, only a presaddle particle is emitted, ...

Similar to earlier Langevin calculations [7,9,10,46], in our study the initial conditions for dynamical Eqs. (1) are assumed to correspond to a spherical compound nucleus with an excitation energy E^* and the thermal equilibrium momentum distribution. For starting a Langevin trajectory an orbital angular momentum value is sampled from the fusion spin distribution, which reads

$$\frac{d\sigma(\ell)}{d\ell} = \frac{2\pi}{k^2}\frac{2\ell + 1}{1 + \exp[(\ell - \ell_c)/\delta\ell]}. \tag{5}$$

The parameters ℓ_c and $\delta\ell$ are the critical angular momentum for fusion and diffuseness, respectively.

Results and discussion. It was noted [55] that the neutron-to-proton ratio (N/Z) of a compound nucleus could have an effect on its decay. Therefore, to better exploit the role of a system size in probing presaddle dissipation, four fissioning nuclei, i.e., ^{205}Bi, ^{215}Fr, ^{225}Pa, and ^{230}Np that have the similar N/Z ratio ($\sim$1.47), are taken as representatives here. A larger size of nucleus usually means a larger fissility Z^2/A. Moreover, to survey the variation of fission cross section with the presaddle friction strength (β), various values of β are set in the calculations throughout the whole presaddle process.

The hindrance to the fission channel due to dissipation suppresses fission, leading to a significant deviation of the measured fission cross section (σ_f) from SMs calculations. The stronger the presaddle friction, the more prominent the amplitude of the deviation. This means that studying the deviation can provide a sensitive method to constrain the presaddle friction. To that end, we adopt a definition similar to that suggested by Lazarev *et al.* [56], and define the relative drop of σ_f calculated by SMs over the value by taking into account the dissipation and fluctuations of collective nuclear motion

$$\sigma_f^{\rm drop} = \frac{\langle\sigma_f^{\rm SM}\rangle - \langle\sigma_f^{\rm dyn}\rangle}{\langle\sigma_f^{\rm SM}\rangle}. \tag{6}$$

We show in Fig. 1(a) the evolution of the drop of fission cross sections relative to SM predictions, $\sigma_f^{\rm drop}$, calculated at excitation energy $E^* = 100$ MeV and angular momentum $\ell_c = 30\hbar$ with the presaddle friction strength for three fissioning nuclei ^{205}Bi, ^{215}Fr, and ^{225}Pa. Two evident features are observed from this figure. First, the lighter the decaying nucleus, the larger the $\sigma_f^{\rm drop}$, indicating that presaddle dissipation effects on fission cross sections are greater for ^{205}Bi and ^{215}Fr than ^{225}Pa. It means that a lighter system can enhance the influence of the nuclear dissipation on the fission cross section. The enhancement can be physically understood as follows: fission barriers are a decreasing function of the system size [Fig. 2(a)], favoring fission.

Besides the fission barrier, the shorter way (i.e., the shorter distance between the location of the barrier and that of the ground state) which a heavier nucleus passes to reach the barrier [see Fig. 2(b)] increases the fission rate as well.

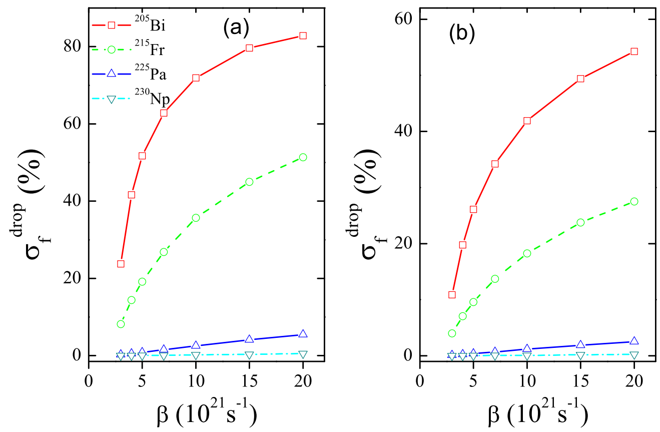

FIG. 1. Comparison of the dynamical drop of fission cross sections [Eq. (6)] of ^{205}Bi, ^{215}Fr, ^{225}Pa, and ^{230}Np systems as a function of the presaddle friction strength β at excitation energy $E^* = 100$ MeV and at angular momentum (a) $\ell_c = 30\hbar$ and (b) $\ell_c = 50\hbar$.

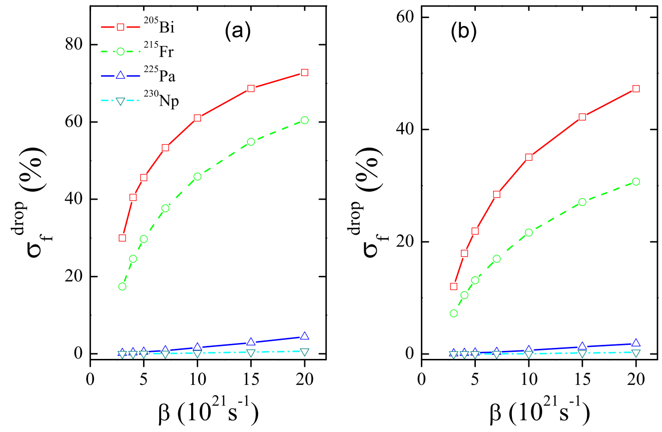

FIG. 3. Same as in Fig. 1 but at $E^* = 50$ MeV.

So, while the dissipation effects modify the magnitude of fission cross sections, the fission cross section estimated by SMs, $\sigma_f^{\rm SM}$, becomes larger with a rise in the system size. As a result, a heavy nucleus yields a low $\sigma_f^{\rm drop}$ [see Eq. (6)].

The second feature is that the slope of the curve $\sigma_f^{\rm drop}$ vs β, which reflects the sensitivity of fission cross sections to friction, has a marked difference for the three fissioning nuclei. Specifically speaking, $\sigma_f^{\rm drop}$ of ^{205}Bi displays a fast rise with β. But the rising speed becomes slow for ^{215}Fr, and it is slowest for ^{225}Pa. In other words, the steepness of $\sigma_f^{\rm drop}$ with respect to β becomes more and more gentle as a fissioning nucleus becomes heavier and heavier, exhibiting a reduced sensitivity of fission cross sections to friction for heavy nuclei. An analogous picture is seen at another angular momentum $\ell_c = 50\,\hbar$ [Fig. 1(b)]. Therefore, presaddle dissipation can be better revealed with fission cross sections of light systems.

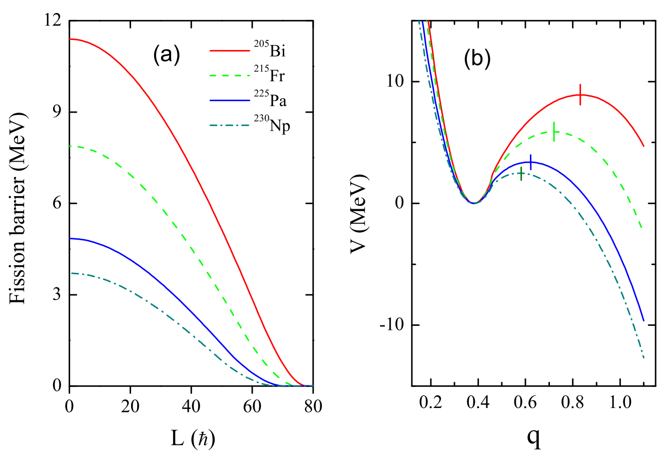

FIG. 2. Left: Fission barriers of nuclei ^{205}Bi, ^{215}Fr, ^{225}Pa, and ^{230}Np at different angular momenta calculated with the method in Refs. [49,53]. Right: The potential V of systems ^{205}Bi, ^{215}Fr, ^{225}Pa, and ^{230}Np at angular momentum of $30\hbar$ as a function of deformation coordinate q. The vertical lines denote the location of the barrier. Note that the upper and lower lines refer to nuclei ^{205}Bi and ^{230}Np, respectively.

The total fission probability is the sum of the first chance and higher (second, three, ...) chance fission probability. Take the results calculated at $E^* = 100$ MeV, $\ell_c = 50\,\hbar$, and $\beta = 5 \times 10^{21}\,{\rm s}^{-1}$ as a demonstration. Our calculations show that the first (higher) chance fission contribution to the total fission probability of systems ^{205}Bi, ^{215}Fr, ^{225}Pa, and ^{230}Np is 3% (97%), 3.6% (96.4%), 6.6% (93.4%), and 4.3% (95.7%), respectively.

To further explore the role of the system size, we depict in Fig. 1 the calculated results for an even heavier system ^{230}Np. We observe that $\sigma_f^{\rm drop}$ of ^{205}Bi changes rapidly as β varies. This is in sharp contrast with the heavier ^{230}Np case, whose $\sigma_f^{\rm drop}$ is almost unvarying with β, implying an insensitivity of the fission cross section on friction. Thus, the calculation results for the ^{230}Np nucleus illustrate that for such a decaying nucleus with larger size, fission cross section is not a suitable tool of the presaddle friction strength. Given that currently, the fission cross section is a critical and dominant source of gaining information on presaddle dissipation properties, the comparison made in Fig. 1 shows that producing a light fissioning nucleus in experiments can apparently raise the precise determination of β and thereby provides a more optimal condition for stringently constraining β.

Displayed in Fig. 3 are calculations carried out at $E^* = 50$ MeV for the four systems. As seen, the picture is like that in Fig. 1 where $E^* = 100$ MeV, that is, heavier nucleus has a smaller sensitivity to friction. Also, we notice that the excitation energy effect on the evolution of $\sigma_f^{\rm drop}$ of heavy ^{230}Np system with β is minor.

Conclusions. Using the dynamical Langevin equations coupled to a statistical decay model, we have investigated the sensitivity of the drop of fission cross section arising from dissipation over its SM values, $\sigma_f^{\rm drop}$, to the presaddle friction strength β for four fissioning systems having different sizes. We have found that the sensitivity is significantly lowered with increasing the size of a fissioning nucleus, and that σ_f^{drop} is no longer sensitive to β for the heavier nucleus ^{230}Np. These results suggest that experimentally, to accurately probe information of presaddle dissipation through the measurement of fission excitation functions, it is best to populate a compound system with a small size or a low fissility.

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