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First-chance fission probability and presaddle nuclear dissipation

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Abstract Dissipation retards fission, resulting in a drop in the first-chance fission probability of a fissioning nucleus with respect to its statistical model value. We use the Langevin model to compute the evolution of the drop (due to friction), P_{f0}^{drop}, for the fissioning systems ^{220}Th and ^{240}Cf with the presaddle friction strength (β). The first-chance fission probability is shown to depend sensitively on β, and the sensitivity is apparently greater than that of the total fission probability. We further find that although the total fission probability of heavy ^{240}Cf is insensitive to β, its first-chance fission probability is quite sensitive to β. These results suggest that, to strongly limit the presaddle friction strength, an optimal experimental avenue is to measure the first-chance fission probability of heavy fissioning nuclei.

Keywords First-chance fission probability · Presaddle dissipation effects · Stochastic model

1 Introduction

The nature of nuclear dissipation has been investigated using low-energy nucleus–nucleus collisions [1–5]. The important role of nuclear dissipation in the decay mechanisms of excited nuclei has recently attracted widespread interest [6, 7]. It has been established [8–12] that dissipation effects in fission are responsible for the significant deviation of the measured evaporation residue cross sections [13] and prescission particle multiplicities [14–16] from the predictions of standard statistical models (SMs).

To date, a large number of works have examined the nuclear dissipation properties inside the saddle point. Several new experimental signatures that depend only on presaddle friction have been put forward, such as the evaporation residue spin distributions [17] and the total fission cross section at high energy [18]. Despite these efforts, the presaddle friction strength is still rather uncertain and controversial [19].

Fission and evaporation are the two primary decay channels when an excited compound nucleus (CN) de-excites. Delayed fission is a direct consequence of dissipation effects. Thus, the fission probability is thought to be the most sensitive signal of the presaddle dissipation strength [19–23].

Moreover, particle evaporation competes with fission many times in a fission process. The total fission probability is thus composed of the first-, second-, third-, …chance fission probabilities. Experimental information on the first-chance fission probability can be obtained by measuring the fission excitation functions [24] or prescission particle multiplicities [25] of the two neighboring fissioning isotopes that have matching conditions in their excitation energy and angular momentum population.

In the present study, we will survey the sensitivity of the first-chance fission probability to presaddle friction and identify the experimental conditions under which the sensitivity of the first-chance fission probability to presaddle

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dissipation effects can be enhanced. For this purpose, we calculate the first-chance fission probability within the framework of Langevin models. The stochastic approach [8–12, 16, 26, 27] has been shown to successfully describe many data on the fission cross sections and prescission particle emission for many CNs over wide ranges of the excitation energy, angular momentum, and fissility.

2 Theoretical model

When describing the dynamics of a hot nuclear system, one should use a thermodynamic potential [8, 21]. Thus, the free energy is employed in the following one-dimensional Langevin equation to perform the trajectory calculations:

$$\begin{aligned} \frac{\mathrm{d}q}{\mathrm{d}t} &= \frac{p}{m}, \\ \frac{\mathrm{d}p}{\mathrm{d}t} &= \frac{p^2}{2m^2}\frac{\mathrm{d}m}{\mathrm{d}q} - \frac{\partial F}{\partial q} - \beta p + \sqrt{m\beta T}\Gamma(t). \end{aligned} \tag{1}$$

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 CN, and p is the conjugate momentum. β and T denote the dissipation strength and temperature, respectively. The inertia parameter m is obtained under the Werner–Wheeler approximation of an incompressible irrotational flow [28]. $\Gamma(t)$ is a fluctuating force satisfying the relations $\langle \Gamma(t)\rangle = 0$ and $\langle \Gamma(t)\Gamma(t')\rangle = 2\delta(t-t')$.

The free energy is constructed from the Fermi gas expression [8] of the level density parameter together with a finite-range liquid-drop potential $V(q)$ [29] that contains q-dependent surface, Coulomb, and rotation energy terms; that is,

$$F(q,T) = V(q) - a(q)T^2. \tag{2}$$

In Eq. (2), we use Ignatyuk et al.'s coefficients [30] to calculate the deformation-dependent level density parameter, which reads

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

where B_{s} represents the dimensionless surface area of the nucleus.

When a fissioning system evolves from its ground state to its scission point, prescission particle evaporation along the Langevin fission trajectory is considered via a Monte Carlo simulation technique. Blann's parametrization [31] is applied to evaluate the particle emission width.

When a dynamic trajectory reaches the scission point, it is counted as a fission event. In our calculation, multiple emissions of light particles and higher-chance fission are taken into account. The first-, second-, …, chance fission probabilities are calculated [8] by counting the number of corresponding fission events in which not a single presaddle particle is emitted, only a presaddle particle is emitted, …

In the present work, we assume that the initial conditions for the dynamical Eq. (1) correspond to a spherical CN having an excitation energy E^* and the thermal equilibrium momentum distribution, which are the same as those used in previous studies [8, 9, 27].

3 Results and discussion

We choose the fissioning nuclei ^{220}Th and ^{240}Cf to investigate the first-chance fission properties. To better study the change in the first-chance fission probability with the presaddle friction strength (β), we carry out dynamical calculations and consider different values of β.

Dissipation hinders fission. This causes a significant discrepancy between the measured first-chance fission probability and total fission probability and the results of SM calculations, and the magnitude of the discrepancy is a sensitive function of β. Therefore, investigating the deviation can provide a way of determining the presaddle friction. To this end, we adopt a definition analogous to that suggested in Ref. [32] and define the relative drop in the first-chance fission probability P_{f0} evaluated by SMs over the value by addressing dissipation effects in the fission process:

$$P_{f0}^{\mathrm{drop}} = \frac{\left\langle P_{f0}^{\mathrm{SM}}\right\rangle - \left\langle P_{f0}^{\mathrm{dyn}}\right\rangle}{\left\langle P_{f0}^{\mathrm{SM}}\right\rangle}. \tag{4}$$

Similarly, the relative drop in the total fission probability P_f owing to friction is given by

$$P_{f}^{\mathrm{drop}} = \frac{\left\langle P_{f}^{\mathrm{SM}}\right\rangle - \left\langle P_{f}^{\mathrm{dyn}}\right\rangle}{\left\langle P_{f}^{\mathrm{SM}}\right\rangle}. \tag{5}$$

Figure 1 shows the evolution of the drop in the first-chance fission probability P_{f0}^{drop} of ^{220}Th nuclei relative to the value estimated by an SM for various β at two angular momenta. A quick rise in P_{f0}^{drop} with increasing β is found. This indicates that the first-chance fission probability is a very sensitive probe of the presaddle friction strength.

In addition, it is noted that the values of P_{f0}^{drop} at $\ell = 10\hbar$ are greater than those at $\ell = 40\hbar$. This result indicates a weak dissipation effect on the first-chance fission probability at high ℓ. This is a consequence of a larger P_{f0}^{SM} at high ℓ, because a high angular momentum decreases the fission barrier and hence increases the first-chance fission

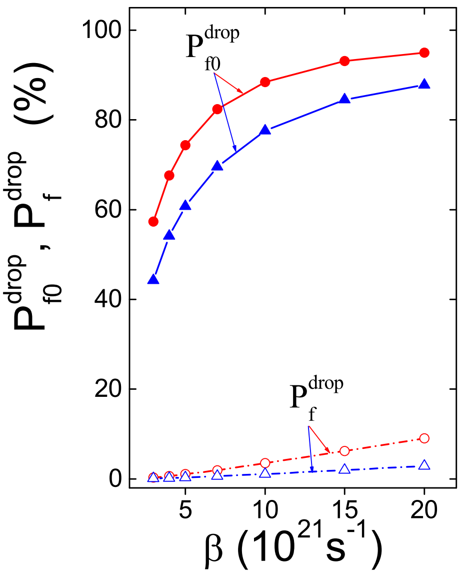

Fig. 1 (Color online) Calculated P_{f0}^{drop} and P_f^{drop} of ^{220}Th nucleus at various β for excitation energy $E^* = 55$MeV and two angular momenta, $\ell = 10\hbar$ (circles) and $40\hbar$ (triangles)

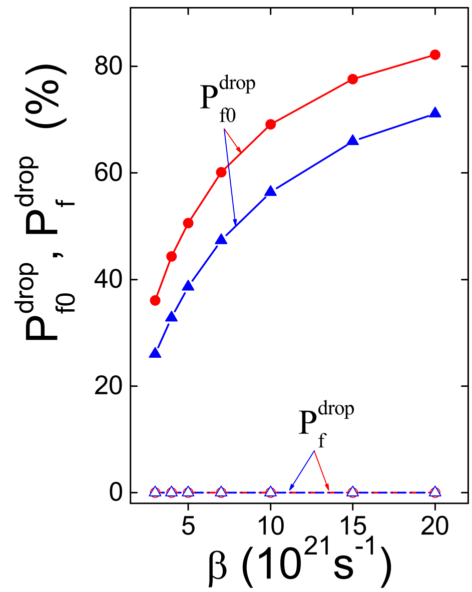

Fig. 2 (Color online) Same as Fig. 1, but for heavier nucleus ^{240}Cf

probability predicted by SMs. Thus, in experiments, obtaining a fissioning system with a small spin could favor exploitation of presaddle dissipation effects on the first-chance fission probability.

In Fig. 1, we also present the drop in the total fission probability, P_f^{drop}, at various β. It is evident that P_f^{drop} is far lower than P_{f0}^{drop}, demonstrating that dissipation has a substantially larger effect on the first-chance fission probability than on the total fission probability. Another prominent feature is the slope of the curve of P_f^{drop} versus β, which reflects the sensitive change in the total fission probability with β. It is less steep than that of the first-chance fission probability, exhibiting a weaker sensitivity to β than the latter. This comparison demonstrates that the first-chance fission probability is a more sensitive probe of presaddle dissipation effects than the total fission probability.

Because measurements of the total fission probability have been reported in the domain of heavy nuclei (up to $A \sim 250$) [33], we make a further calculation for the heavier nucleus ^{240}Cf. Similar to the case of the light nucleus ^{220}Th, nuclear dissipation has a larger effect on the P_{f0}^{drop} value of ^{240}Cf at lower ℓ, as shown in Fig. 2.

In addition, one can observe that for this heavier nucleus, a change in β does not lead to discernible variation in P_f^{drop}. This is because ^{240}Cf is a very fissile system, implying that it always fissions independently of the friction strength. However, P_{f0}^{drop} changes rapidly as β varies; specifically, it depends sensitively on friction. Thus, for a heavier fissioning nucleus, the first-chance fission probability is a more suitable observable for exploiting presaddle dissipation effects than the total fission probability. Moreover, given that the measured total fission probability data of heavy nuclei have been widely employed to constrain the presaddle friction strength (see, e.g., Refs. [8, 34]), it can be anticipated that presaddle dissipation effects could be better probed by confronting model simulations with the first-chance fission probability data. This suggests that on the experimental side, to strongly constrain the presaddle dissipation strength by performing fission measurements of heavy nuclear systems, it is best to measure the first-chance fission probability.

In order to further guide experimental explorations of the use of the first-chance fission probabilities to pinpoint the presaddle dissipation properties, we propose several reactions that use available projectiles and targets in fusion experiments (see Table 1).

Table 1 Incident energy E_{lab} and excitation energy E^* of reactions involving CNs

E_{lab}	Reaction system	CN	E^*	$\bar{L}_{ave}$
67.8	^{4}He + ^{249}Bk	^{253}Es	60.0	14.9
43.4	^{3}He + ^{249}Bk	^{252}Es	50.4	12.1
67.3	^{4}He + ^{248}Cm	^{252}Cf	60.0	14.9
42.9	^{3}He + ^{248}Cm	^{251}Cf	50.6	11.9
67.3	^{4}He + ^{239}Pu	^{243}Cm	60.0	14.9
42.8	^{3}He + ^{239}Pu	^{242}Cm	51.0	11.9

The average angular momentum ($\bar{L}_{ave}$) leading to fission is calculated using the method of Ref. [8]

As mentioned previously, in addition to measurement of the fission excitation functions, the method of measuring the prescission particle multiplicities of two neighboring fissioning isotopes produced in two matching reactions has been successfully used to investigate the first-chance fission characteristics of heavy decaying systems [25], and it is thus adopted here.

In Table 1, the incident energy of a projectile is obtained from the excitation energy of the CN it populates. The excitation energies of ^{252}Es, ^{251}Cf, and ^{242}Cm, which are generated in ^{3}He-induced reactions, are set to those of the residual nuclei, whose excitation energies are calculated by subtracting the energy of a neutron evaporation calculated by Yanez et al.'s method [25] from an excitation energy of 60 MeV for the CNs ^{253}Es, ^{252}Cf, and ^{243}Cm.

In addition, to yield suitable low-spin heavy CNs, the light projectile ^{4}He is chosen to bombard the targets ^{249}Bk, ^{248}Cm, and ^{239}Pu. The main reason is that our calculations have shown that under low angular momentum conditions, the presaddle dissipation effects can be favorably surveyed using the first-chance fission probability.

It is known that a superheavy nucleus fissions regardless of the friction strength. Thus, the total fission probability is not suitable for investigating the fission properties. In contrast, the first-chance fission probability could still be a sensitive probe of the fission characteristics of superheavy nuclei.

In addition, superheavy nuclei populated via a fusion mechanism usually have a low excitation energy, where shell effects are evident. Thus, after accounting for the effect in the model calculation, the use of the first-chance fission probability may be applied to study the dissipation properties in the superheavy region.

4 Summary

Langevin models have been applied to calculate the drop relative to predictions by SMs in the first-chance fission probability, $P_{f0}^{\rm drop}$, of ^{220}Th and ^{240}Cf nuclei (which arises from dissipation effects) as a function of the presaddle friction strength β. It has been found that the first-chance fission probability is sensitive to β and that the sensitivity is significantly larger than that of the total fission probability. Moreover, we have shown that the first-chance fission probability of the heavier nucleus ^{240}Cf is obviously preferable to its total fission probability for determining the nuclear dissipation properties. These results suggest that experimentally, to tightly limit the presaddle friction strength, it is optimal to measure the first-chance fission probability of those heavy fissioning systems with low spin.

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