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Isospin effect on probing nuclear dissipation with fission cross sections

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Nuclear dissipation retards fission. Using the stochastic Langevin model, we calculate the drop of fission cross section caused by friction over its standard statistical-model value, $\sigma_f^{\rm drop}$, as a function of the presaddle friction strength for fissioning nuclei ^{195}Bi, ^{202}Bi, and ^{209}Bi as well as for different angular momenta. We find that friction effects on $\sigma_f^{\rm drop}$ are substantially enhanced with increasing isospin of the Bi system and become greater with decreasing angular momentum. Our findings suggest that in experiments, to better constrain the strength of presaddle dissipation through the measurement of fission excitation functions, it is optimal to yield those compound systems with a high isospin and a low spin. Furthermore, we analyze the data of fission excitation functions of ^{210}Po and ^{209}Bi systems, which are populated in $p + {}^{209}$Bi and $p + {}^{208}$Pb reactions and which have a high isospin and a low spin, and find that Langevin calculations with a presaddle friction strength of (3–5) $\times 10^{-21}$ s^{-1} describe these experimental fission data very well.

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Introduction. In the field of low-energy nucleus-nucleus collisions, dissipation effects on entrance channel dynamics in deep-inelastic collisions [1] and fusion mechanisms [2,3] as well as on the deexcitation mode of hot nuclei [4,5] have attracted wide attention, because they have a crucial influence on these phenomena. In particular, one focus that is currently extensively explored in experimental and theoretical research is the influence of dissipation on the fission properties of a decaying system measured at high energy. Numerous measurements of prescission particle multiplicity [6,7] and evaporation residue cross sections [8] as a function of excitation energy have been found to deviate from that given by standard statistical models (SMs). This discrepancy has been demonstrated [9–18] to be due to dissipation effects that are not accounted for in model calculations.

Prescission light particles can be evaporated along the entire fission path as the decaying system proceeds toward scission, and they are thus a less direct signature of presaddle dissipation because of the interference of postsaddle emission. Therefore, it is rather inaccurate to constrain the presaddle friction strength with particle multiplicity. Fission cross section is sensitive only to the dissipation strength inside the fission barrier and hence provides a desirable separation between presaddle and postsaddle dissipation effects.

A great number of studies have been carried out to determine the magnitude of presaddle dissipation (β) [8,19–21]. Various new observables sensitive to β have also been proposed, such as evaporation residue spin distributions [22], the widths of fission-fragment charge distributions [23], etc. However, the presaddle friction strength is still quite uncertain and hotly debated [24].

Fission and evaporation are two competitive decaying channels when an excited nucleus deexcites. As a result of dissipation effects, fission is delayed; that is, fission cross section is decreased. Therefore, fission cross sections are considered to be the most sensitive and fundamental probes of presaddle friction [24–28].

The present work is devoted to the study of the favorable experimental condition through which presaddle dissipation effects can be better revealed with fission cross section. Toward that goal, Langevin models will be employed here to calculate the fission cross section. The stochastic approach [9–12,14,29–31] has been successfully applied to reproduce a large amount of fusion-fission data for many compound nuclei over a broad domain of excitation energy, angular momentum, and fissility. Additionally, it has been recently found that isospin has a significant effect on the emission of light particles [32] and giant dipole resonance gamma rays [33] that have been experimentally identified as sensitive observables of nuclear dissipation. In this context, to better instruct experimental exploration, we will survey the isospin effect on fission cross section as a probe of the presaddle nuclear dissipation strength.

On the basis of investigations on the isospin effect at low spins, proton-induced fission excitation function data of the nuclei ^{210}Po and ^{209}Bi available in the EXFOR database [34] are utilized to place more stringent constraints on the presaddle friction strength. To our knowledge, few researchers have used this type of fission data to pin down presaddle dissipation properties.

Theoretical model. It is well known [15,18,35] that the driving force of a hot system is not simply the negative gradient of the conservative force, but it 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:

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

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

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p is its conjugate momentum. The reduced dissipation coefficient (also called the dissipation strength) $\beta = \gamma/m$, as is usual in the literature (see, e.g., Refs. [4,6,8,9,15,16,19–24,27]), denotes 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 [36]. 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:

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

Equation (2) is constructed from the Fermi-gas expression [35] with a finite-range liquid-drop potential $V(q)$ [37] in the $\{c,h,\alpha\}$ parametrization [38]. The deformation coordinate q is obtained by the relation $q(c,h) = (3c/8)\{1 + \frac{2}{15}[2h + (c-1)/2]c^3\}$ [9,39], where c and h correspond to the elongation and neck degrees of 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.* [40] 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 $B_s = 1$) [41].

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 $(= n,p,\alpha)$ is given by [42]

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

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 [42]. After each emission act of a particle, the free energy and the temperature in the Langevin equation are recalculated and the dynamics is continued.

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.

Like previous Langevin calculations reported in the literature (see, e.g., Refs. [9,11,12,31]), in the present study the initial conditions for a dynamical Eq. (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 momenta for fusion and diffuseness, respectively. For proton-induced reactions, they are found to follow an approximate scaling, which is in accordance with the surface friction model [43] that describes the fusion cross sections very well. Namely,

$$\ell_c = \sqrt{4.16(E_{\rm c.m.} - 7.21) - 1.7E_{\rm c.m.}/(\pi\lambda^2)}, \tag{6}$$

where $E_{\rm c.m.} = E_{\rm lab}A_T/(A_T + A_P)$, $\lambda = \hbar(A_T + A_P)/A_T/\sqrt{2A_P\, m_{\rm nuc}\, E_{\rm lab}}$. Here $E_{\rm lab}$ denotes the laboratory energy of the projectile proton, and $m_{\rm nuc}$ is the nucleon mass. A_T and A_P represent the mass number of target and projectile, respectively. The diffuseness δl scales as

$$\delta l = \begin{cases} [(A_PA_T)^{3/2} \times 10^{-5}][1.5 + 0.02(E_{\rm c.m.} - 17.21)] \\ \quad \text{for } E_{\rm c.m.} > 17.21, \\ [(A_PA_T)^{3/2} \times 10^{-5}][1.5 - 0.04(E_{\rm c.m.} - 17.21)] \\ \quad \text{for } E_{\rm c.m.} < 17.21. \end{cases} \tag{7}$$

These scaling values have been widely tested by successfully fitting proton-induced fusion cross sections of various reaction systems [43].

Results and discussion. In this work, three Bi fissioning systems having a marked difference in their isospin (defined as the neutron-to-proton ratio N/Z of the system), i.e., ^{195}Bi, ^{202}Bi, and ^{209}Bi are considered. In the decay process of hot nuclei, a strong competition exists between fission and evaporation. Due to dissipation, fission is delayed, which affects the competition among various decaying channels. As a result of the hindrance to fission, particles are more favorably emitted. This causes a deviation of the measured fission cross section (σ_f) from that predicted by SMs, and the amplitude of the deviation is extremely sensitive to the presaddle friction strength (β). An investigation of the deviation thus provides a method of determining presaddle friction. For this purpose, we adopt a definition similar to that suggested by Lazarev *et al.* [44] 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

$$\sigma_f^{\rm drop} = \frac{\langle\sigma_f^{\rm SM}\rangle - \langle\sigma_f^{\rm dyn}\rangle}{\langle\sigma_f^{\rm SM}\rangle}. \tag{8}$$

In Fig. 1, we display the drop of fission cross sections relative to SM estimation, $\sigma_f^{\rm drop}$, calculated at $\beta = 4$ zs^{-1} (1 zs $= 10^{-21}$ s) as a function of excitation energy for three Bi nuclei. Two typical features are observed from this figure. First, the smaller the isospin, the lower the $\sigma_f^{\rm drop}$. It exhibits that friction effects on fission cross sections are greater for ^{209}Bi than for ^{202}Bi and ^{195}Bi. In other words, raising the isospin of a decaying system can enhance the sensitive dependence of fission cross sections on friction. The reason for the enhancement is as follows: fission barriers drop with reduction

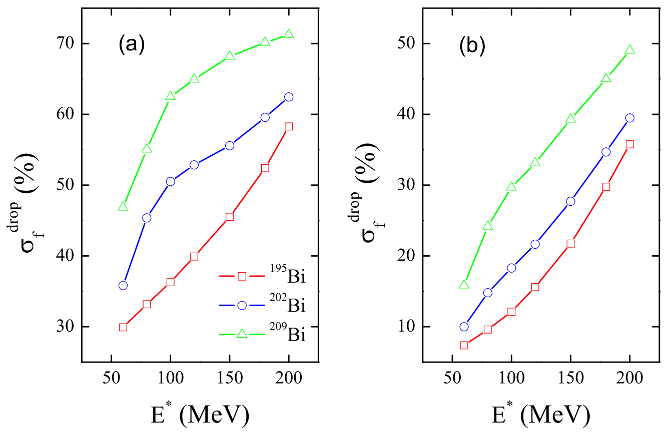

FIG. 1. Comparison of the dynamical drop of fission cross sections [Eq. (8)] of ^{195}Bi, ^{202}Bi, and ^{209}Bi systems at angular momentum (a) $\ell_c = 15\ \hbar$ and (b) $\ell_c = 50\ \hbar$ and at the friction strength $\beta = 4\ \text{zs}^{-1}$ for different excitation energies E^*.

in the isospin of the system [Fig. 2(a)], which favors fission. Thus, while the magnitude of fission cross sections is modified by friction effects, the fission cross section estimated by SMs, σ_f^{SM}, becomes larger with a drop of isospin. Consequently, a low isospin causes a small σ_f^{drop} [see Eq. (8)].

The second feature is that while a picture like Fig. 1(a) is seen at a high spin [Fig. 1(b)], the friction effects on σ_f^{drop} differ very much for the two different spins. In order to see this point clearly, as an illustration we plot in Fig. 3 the change of σ_f^{drop} vs β with angular momentum at $E^* = 80$ MeV. As one can notice, friction effects on fission cross sections rise at a small angular momentum. Another characteristic is that the slope of the curve σ_f^{drop} vs β, which reflects the sensitivity of fission cross sections to friction, becomes steeper with decreasing ℓ_c, demonstrating an enhanced sensitivity of fission cross sections to friction at low spins. The reason is that fission barriers are a decreasing function of angular

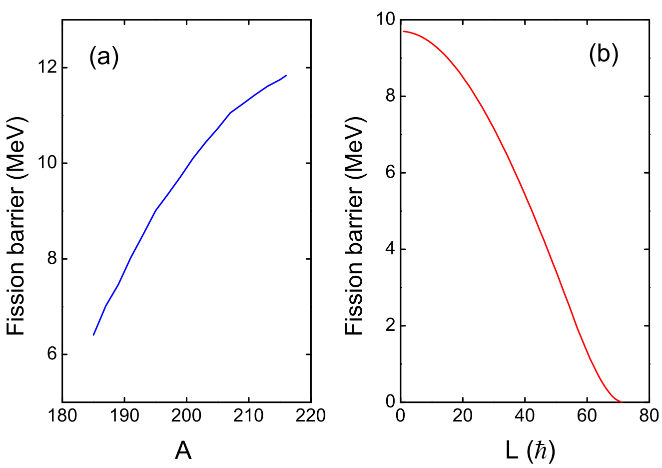

FIG. 2. (a) Fission barrier as a function of mass number of element Bi at angular momentum of 15 $\hbar$. (b) Fission barrier of nuclei ^{195}Bi as a function of angular momentum.

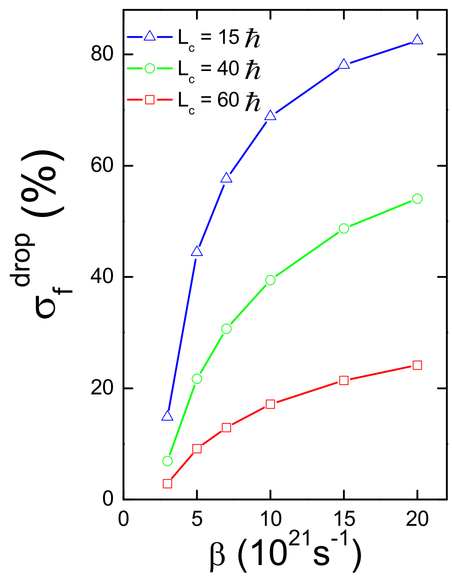

FIG. 3. Dynamical drop of the fission cross section of ^{195}Bi relative to that predicted by SMs as a function of the presaddle dissipation strength β at excitation energy $E^* = 80$ MeV and at three critical angular momenta $\ell_c = 15$, 40, and 60 $\hbar$.

momentum [Fig. 2(b)]. Thus, the case is similar to that in Fig. 1(a) where a low fission barrier at low isospin is shown to reduce the amplitude of friction effects on the fission cross section. The result above is further checked at other excitation energies, and the conclusions drawn are analogous. Therefore, under the condition of a small angular momentum, dissipation effects in fission could be better revealed with fission cross sections.

Fission excitation functions from heavy-ion collisions [6,9,12,15] are generally utilized to gain information on nuclear dissipation. As is well known, the compound systems populated via this kind of experimental approach have a large angular momentum (up to ∼75 $\hbar$ [45]). The results in Fig. 3 show that the decaying system with a small angular momentum favors a precise determination of β, suggesting that choosing light ions as projectiles to produce hot decaying systems can provide a more favorable condition for tightly constraining β with fission cross section.

Moreover, given the prominent role that the isospin of the system plays in probing presaddle nuclear dissipation (see Fig. 1), we make use of fission excitation function data of ^{210}Po systems (formed in $p + {}^{209}$Bi) which have the largest isospin and a low spin from currently available experiments [34], and compare them with Langevin simulations. Light-ion-induced fission data were seldom considered in the stochastic model analysis of dissipation properties in previous works [9,12,18,29]. Thus, confronting these data with Langevin calculations will provide a strict test for the widely adopted stochastic approach to fission and also shed new light on the presaddle dissipation strength.

Figure 4 illustrates that SM calculations appreciably overestimate experimental σ_f, indicating the necessity of accounting for the dissipation effects in calculations. To better constrain the strength of presaddle friction, we made a detailed

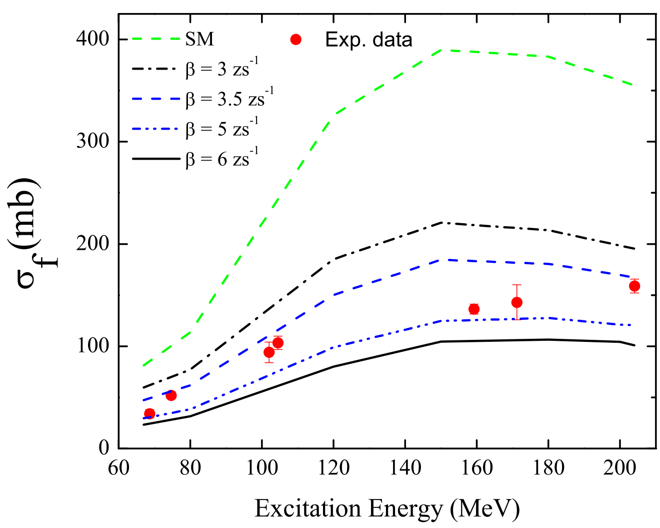

FIG. 4. Fits to measured excitation function data of fission cross sections in the $p + {}^{209}$Bi system [34]. SM predictions are compared to Langevin model calculations carried out at friction strengths $\beta =$ 3, 3.5, 5, and 6 zs^{-1}.

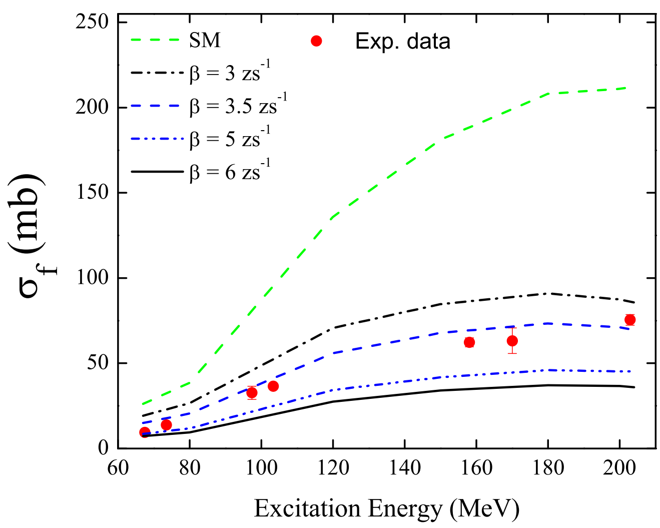

FIG. 5. Same as Fig. 4, but for the $p + {}^{208}$Pb system [34].

calculation by taking a number of β values. As can be seen, the estimated σ_f at $\beta = 3$ zs^{-1} are lower than SM results but still higher than data. It means that although introducing friction effects can retard fission, a stronger hindrance is required to fit data. We find that the experimental data lie between the curves calculated at $\beta = 3.5$ and $\beta = 5$ zs^{-1}. A slight increase of β, for example, $\beta = 6$ zs^{-1}, leads to an evident deviation from all data points. This clearly shows the crucial role that friction plays in satisfactorily interpreting the experimental results.

The fission excitation functions measured in $p + {}^{208}$Pb are also analyzed and a quite narrow range of $\beta =$ (3–5) zs^{-1} is obtained; see Fig. 5.

We note that the magnitude of the presaddle friction strength obtained here is comparable with those of one-body dissipation with a reduction factor $k_s = 0.25$–0.5 for wall friction [12] and of chaos-weighted one-body dissipation [29] that were proposed to describe the data of fission excitation functions from heavy-ion reactions.

Furthermore, we compare the resulting β value with other works, where various presaddle friction strengths were reported. A fit to prescission multiplicity gives different β values, for example, (5−8) [46], (3−10) [47], ∼5 [48], <10 [12] zs^{-1}, etc. The good agreement between theoretical and experimental giant dipole resonance gamma rays and evaporation-residue cross sections proposes the friction strength of (4−6) [49], <8 [50], and ⩽10 [8] zs^{-1}. Explaining the data of evaporation residue spin distributions requires a friction strength of ∼5 zs^{-1} [14]. The measured mass and kinetic-energy distributions of fission fragments suggests a β value of 5.5 zs^{-1} [51]. Recent measurements for fission-fragment charge-distribution widths found that the magnitude of β is (2–5) zs^{-1} [23,27,52].

These diverse deduced β's may have a dependence on the physical quantities that are chosen to survey the friction strength. In addition, the diversity in β is closely related to the different sensitivity of these quantities to friction. Thus, to more tightly constrain the presaddle friction, identifying those most sensitive experimental observables and exploring how their sensitivities to friction evolve with the controllable and typical experimental conditions such as isospin and spin for the produced decaying systems in a reaction becomes very urgent and important, as was done in the present work for the isospin effect on the fission cross section at low angular momentum.

Conclusions. Based on the dynamical Langevin equations coupled to a statistical decay model, we have exploited the sensitivity of the drop in fission cross sections with respect to SM values caused by friction effects, $\sigma_f^{\rm drop}$, to β for three Bi nuclei with different isospins. We have found that the sensitivity is significantly increased for high-isospin systems, and that with decreasing spin of the decaying system, the $\sigma_f^{\rm drop}$ shows a greater sensitivity to β. These results suggest that on the experimental side, to accurately probe information of presaddle dissipation by measuring fission excitation functions, it is best to populate a compound system with high isospin and low spin. In addition, we have shown that Langevin calculations with a presaddle friction value of (3–5) zs^{-1} give a satisfactory description of fission excitation function data from p+^{209}Bi (^{208}Pb) reactions.

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