Probing postsaddle dissipation with light-particle multiplicity of hot heavy nuclear systems

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Nuclear fission is hindered by dissipation. Using the stochastic Langevin model, we study postsaddle emitted neutrons, protons, and α particles of heavy ^{240}Am nuclei as a function of postsaddle dissipation strength (β) at different excitation energies and angular momenta. It is shown that the sensitivity of these particles to β is significantly enhanced at a high energy and a large angular momentum. Furthermore, we calculate the evolution of postsaddle particles with β under two contrasting initial conditions for the produced heavy nuclei ^{240}Am: (i) high excitation energy but low angular momentum (available in intermediate-energy heavy-ion collisions) and (ii) low excitation energy but high angular momentum (available via fusion reactions). We find that the former type of conditions not only significantly enhances the influence of dissipation on particle evaporation but also substantially increases the sensitivity of light charged particles to β. Our findings suggest that on the experimental side, to accurately probe postsaddle dissipation strength by measuring particle emission, in particular light charged particle multiplicity, it is optimal to choose the intermediate-energy heavy-ion collision approach as a way to populate excited heavy nuclear systems.

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I. INTRODUCTION

Nuclear dissipation affects a variety of phenomena including deep-inelastic scattering [1–3] and fusion [4,5]. Its crucial role in understanding decay mechanisms of excited nuclei [6,7], in particular, on fission properties of hot nuclei, has recently attracted much attention. Dissipation effects in fission processes have been demonstrated to be responsible for the marked deviation of the measured prescission particle multiplicity [8–12] and evaporation residue cross sections [13–15] at a high energy from predictions by standard statistical models. A systematic investigation based on stochastic approaches to fission [16] has shown that by assuming a weak friction inside saddle and a strong postsaddle friction, i.e., a rising function of friction with deformation, the Langevin model can provide a satisfactory description of different types of fission data, but the reduced one-body dissipation strength (a decreasing function of deformation) was also used to reproduce fission data [17].

While the two types of deformation-dependent friction give a similar presaddle friction strength, they predict a quite different strength for postsaddle friction. The shape dependence of nuclear dissipation [18] is identified as a key ingredient in the application of the Langevin model to describe the fission process of a hot nucleus. Currently, the presaddle friction is severely constrained by analyzing various observables that are proposed to be sensitive to presaddle dissipation effects only [13,15,19–24]. Therefore, getting the precise information on the strength of postsaddle friction becomes very ungent and necessary for probing the deformation dependence of friction in nuclear fission. However, to date, less effort has been made on this issue.

Unlike fission probabilities and evaporation residue cross sections, light particles are also affected by postsaddle friction, because they can be emitted prior to saddle and in the saddle-to-scission region. Also, postsaddle emission rises with increasing size of the fissioning nucleus, so light particles of heavy fissioning nuclei have been frequently used to probe postsaddle friction [9,10,16].

Presently, investigations on dissipation properties in the fission process of excited nuclei have been mainly performed via heavy-ion fusion reactions. However, when yielding a heavy composite system ($A \sim 240$) by this way, both fusion-fission and quasifission channels appear [25–27]. Because the features of fragments produced in the two reaction channels have some overlaps, they have contributions to the measured fission fragments. This causes a large uncertainty of determining nuclear friction in fusion-fission processes with multiplicity data of heavy systems, as clearly shown in Refs. [28–30]. Moreover, a higher incident energy will result in a stronger competition between the quasifission channel and the fusion-fission channel [25,28]. This further restricts the reliable use of particle emission data from heavy systems produced in the fusion reaction approach in exploring friction parameters related to fusion-fission processes to a domain of low excitation energy.

On the experimental side, besides the fusion approach, intermediate-energy heavy-ion collisions [31–35] and spallation reactions induced by energetic protons [36–38] have been applied to yield hot nuclei, which can respectively have a high excitation energy E^* up to ~500 MeV [31] and ~1 GeV [36–38], in contrast with that in the fusion reaction approach where compound nuclei produced have a low E^* (<70 MeV). They thus generate widespread interest in the potential of exploiting fission characteristics of these highly excited nuclear systems.

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In this context, to instruct experimental explorations and to more effectively utilize the opportunity provided by heavy fissioning nuclei produced in the alternative experimental approach in pining down the postsaddle dissipation, the present work is devoted to studying under which conditions the sensitivity of particle emission (in particular, light charged particles) of heavy fissioning systems to postsaddle friction can be enhanced. To this end, we will survey the influences of excitation energy and angular momentum on the sensitivity in the framework of Langevin models. Numerous theoretical investigations have indicated that the stochastic approach [16–18,39–52] is a suitable framework to address the fission process of a hot nucleus, and it has been shown to successfully reproduce a volume of experimental data on fission excitation functions and prescission particle multiplicities for a lot of fissioning systems over a wide range of excitation energy, angular momentum, and fissility.

II. THEORETICAL MODEL

It is known that the driving force of a hot nuclear system is not simply the negative gradient of the conservative force but should also contain a thermodynamic correction [18,53–55]; 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, 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 reduced dissipation coefficient (also called the dissipation strength), $\beta = \gamma/m$, as is usual in the literature (see, e.g., Refs. [6,8,9,13,16,24,38,53,56]), 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 [57]. 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:

$$F(q, T, A, Z, \ell) = V(q, A, Z, \ell) - a(q)T^2. \quad (2)$$

Here A and Z are the mass number and charge number of the fissioning nucleus. The angular momentum ℓ due to rotation is indicated. Equation (2) is constructed from the Fermi-gas expression [55] with a finite-range liquid-drop potential $V(q)$ [58] in the $\{c, h, \alpha\}$ parametrization [59]. The deformation coordinate q is obtained by the relation $q(c, h) = (3c/8)\{1 + \frac{2}{15}[2h + (c - 1)/2]c^3\}$ [16,60], where c and h correspond to the elongation and neck degrees of the freedom of the nucleus, respectively. Since only symmetric fission is considered, the parameter describing the asymmetry of the shape is set to $\alpha = 0$ [41,55]. The q-dependent surface, Coulomb, and rotation energy terms are included in the potential $V(q, A, Z, \ell)$.

In constructing the free energy, we used the coefficients presented by Ignatyuk *et al.* [61] to calculate the deformation-dependent level density parameter, that is,

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

where A is the mass number of the compound nucleus and B_s is the dimensionless surface area of the nucleus (for a sphere $B_s = 1$) [62].

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 $\nu(=n, p, \alpha)$ is given by the parametrization of Blann [63]

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

where s_ν is the spin of the emitted particle ν and m_ν is its reduced mass with respect to the residual nucleus. The intrinsic excitation energy is $E^*_{\rm intr}$ [$=E^* - V(q, A, Z, \ell) - E_{\rm coll} - E_{\rm evap}(t)$[, where E^* denotes the total excitation energy of the fissioning system, $E_{\rm coll}$ is the kinetic energy of the collective degree of freedom, and $E_{\rm evap}(t)$ is the energy carried away by evaporated particles by the time t. B_ν are the liquid-drop binding energies and ε is the kinetic energy of the emitted particle. The level densities of the compound and residual nuclei are denoted by $\rho_c(E^*_{\rm intr})$ and $\rho_R(E^*_{\rm intr} - B_\nu - \varepsilon_\nu)$ and the form for the angular-momentum-dependent level density of the emitting nucleus is taken as [64]

$$\rho(E^*_{\rm intr}, A, I) = (2I + 1)\left[\frac{\hbar^2}{2J_0}\right]^{3/2}\frac{\sqrt{a(q)}}{12}\frac{\exp[2\sqrt{a(q)E^*_{\rm intr}}]}{E^{*2}_{\rm intr}}, \quad (5)$$

where J_0 is the moment of inertia [62] and I is the angular momentum of the rotating fissioning system which minus $1\hbar$ when a neutron is emitted. Note that the quantity $E^*_{\rm intr}$ appearing in the exponential term $\exp[2\sqrt{a(q)E^*_{\rm intr}}]$ in Eq. (5) depends on angular momentum, since its calculation has taken into account rotation energy (which is a function of ℓ) through the potential $V(q, A, Z, \ell)$, as mentioned above. $a(q)$ is deformation-dependent level density parameter defined in Eq. (3). The inverse cross sections are given by [63]

$$\sigma_{\rm inv}(\varepsilon_\nu) = \begin{cases} \pi R_\nu^2(1 - V_\nu/\varepsilon_\nu) & \text{for } \varepsilon_\nu > V_\nu, \\ 0 & \text{for } \varepsilon_\nu < V_\nu. \end{cases} \quad (6)$$

Here the barrier is zero for neutron whereas for the charged particles the barrier is $V_\nu = \frac{(Z-Z_\nu)Z_\nu K_\nu}{R_\nu+1.6}$ with $K_\nu = 1.32$ for α particle and 1.15 for protons. $R_\nu = 1.21[(A - A_\nu)^{1/3} + A_\nu^{1/3}] + (3.4/\varepsilon_\nu^{1/2})\delta_{\nu,n}$, where A_ν and ε_ν are the mass number and the kinetic energy of the emitted particle $\nu = n, p, \alpha$.

The discrete emission of light particles is taken into account [16,17,40,41,47]. The procedure is to calculate the decay widths for light particles at each Langevin time step τ. Then the emission of particle is allowed by asking along the trajectory at each time step τ if a random number ζ ($0 \leqslant \zeta \leqslant 1$) is less than τ/τ_{dec}, where $\tau_{\mathrm{dec}} = \hbar/\Gamma_{\mathrm{part}}$ with Γ_{part} being the sum of light particle decay widths. If this is the case, a particle is emitted and we ask for the kind of particle ν by a Monte Carlo selection with the weights $\Gamma_\nu/\Gamma_{\mathrm{part}}$. The loss of angular momentum is taken into account by assuming that a neutron carries away $1\hbar$, a proton $1\hbar$, and an α particle $2\hbar$ [16,17,41,54]. After each emission act of a particle, the intrinsic energy E^*_{intr}, the angular-momentum-dependent potential energy $V(q, A, Z, \ell)$, the free energy, and the temperature in the Langevin equation are recalculated and the dynamics is continued.

The present calculation allows for multiple emissions of light particles and higher chance fission. When the dynamic trajectory reaches the scission point, it is counted as a fission event. Prescission particle multiplicities are calculated by counting the number of corresponding evaporated particle events. Also, in the calculation, by recording the elongation coordinate q at which a particle is emitted, one can count neutron and light charged particle which are emitted after the system passed through the saddle point by requiring that the q value corresponding to particle emission is over that of saddle point.

Like previous Langevin calculations reported in the literature (see, e.g., Refs. [16,40,47,52]), in the present study theoretical simulations are carried out starting from a spherical nucleus up to its scission point. To accumulate sufficient statistics, 10^7 Langevin trajectories are simulated.

III. RESULTS AND DISCUSSION

In this work, heavy fissioning nuclei ^{240}Am are chosen as a representative for investigating postsaddle dissipation properties with light particle multiplicity. To better reveal postsaddle dissipation effects, the presaddle dissipation strength is set as $4\times10^{21}\ \mathrm{s}^{-1}$, in accordance with recent theoretical estimates and experimental analyses [17,24,55,65–68], and dynamical calculations of postsaddle emission are performed considering different values of the postsaddle dissipation strength (β).

We present in Fig. 1 various postsaddle light particle multiplicities of ^{240}Am as a function of β at angular momentum $\ell = 40\hbar$ and at three excitation energies $E^* = 60$, 120, and 250 MeV. One can notice that particle multiplicities change with friction strength β. The reason is that nuclear dissipation retards fission. As the nuclear dissipation gets stronger, that is, as β gets larger, fission is delayed longer and the fission time increases. A longer fission time at a stronger friction can provide more time for particle emission, resulting in a rise of particle emission with increasing β.

Moreover, two typical features are observed from the figure. First, the calculated postsaddle particle multiplicities at $E^* = 60$ MeV are below those at $E^* = 120$ MeV, and the latter are smaller than those at $E^* = 250$ MeV. The reason that the number of emitted particles in fission is an increasing function of excitation energy is as follows. At low energy, a long time is required to evaporate a particle. However, particle evaporation time is shortened at high energy and a stronger friction yields a longer fission delay, which favors particle emission at large E^*. The two factors contribute to a rise

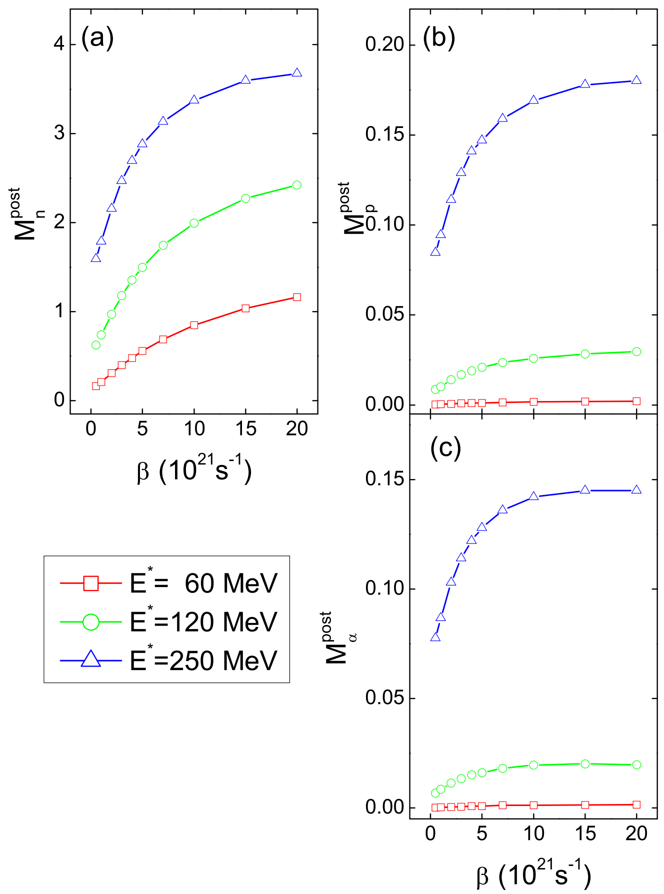

FIG. 1. Postsaddle multiplicities of neutrons (a), protons (b), and α particles (c) of fissioning nuclei ^{240}Am as a function postsaddle dissipation strength (β) at angular momentum $\ell = 40\hbar$ and at three excitation energies $E^* = 60$ MeV (squares connected by red lines), 120 MeV (circles connected by green lines), and 250 MeV (triangles connected by blue lines).

of particle emission with E^*. In addition, at low E^*, particle emission is not very strong. Because of the competition among various decay channels, a larger neutron emission will suppress light charged particles (LCPs) emission, leading to a small LCPs multiplicity, which reduces its sensitive change with β. Thus, a larger particle multiplicity at high energy illustrates an enhanced dissipation effect on particle emission with increasing E^*. It means that a greater particle multiplicity including LCPs at a high energy favors a more stringent constraint on postsaddle friction.

Second, the slope of the curve of the postsaddle particle multiplicity versus β, which reflects the sensitivity of postsaddle emission to the variation of the postsaddle friction strength, differs very much for different excitation energies. Specifically speaking, for neutrons, the slope of $\mathrm{M}_n^{\mathrm{post}}$ versus β at $E^* = 250$ MeV is obviously steeper than that at $E^* = 60$ MeV, showing a greater sensitivity of the neutron emission to β at a high E^*. For LCPs, one can see that at $E^* = 60$ MeV, due to a very weak emission, both $\mathrm{M}_p^{\mathrm{post}}$ and $\mathrm{M}_\alpha^{\mathrm{post}}$ almost do not change with a variation in β; that is, they are insensitive to β. But the slope of the curve of $\mathrm{M}_p^{\mathrm{post}}$ (or $\mathrm{M}_\alpha^{\mathrm{post}}$) versus β

at $E^* = 120$ MeV becomes steeper, indicating a rise in the sensitivity of postsaddle LCPs to β, and the sensitivity is further raised at a higher $E^* = 250$ MeV because of a stronger LCPs emission.

In order to survey postsaddle dissipation, the experimental measurements are usually focused on prescission neutrons of several heavy fissioning nuclei created in the low-energy fusion reaction approach [8,9]. One reason is that neutrons rather than LCPs are a principle decay channel of a heavy nucleus. In addition, due to the appearance of the strong interference from quasifission channels with increasing bombarding energy [25,28], the measurement of particle multiplicity in fusion-fission reactions is usually restricted to low energy. So, LCPs emissions of heavy fissioning nuclei formed in heavy-ion fusion experiments [8,9] are rather weak.

Figures 1(b) and 1(c) show that an excitation energy of 60 MeV [which is generally provided in a low-energy fusion reaction for the produced heavy fissioning system] leads to a very small LCPs multiplicity. As a result, LCPs are not a good observable of exploiting postsaddle dissipation.

However, Fig. 1 also exhibits that at a higher E^*, besides neutrons, the magnitudes of $M_p^{\rm post}$ and $M_\alpha^{\rm post}$ are not only substantially increased, but also they are quite sensitive to the variation of β, in contrast with the situation observed at a low energy, $E^* = 60$ MeV. In other words, LCPs of heavy fissioning systems created at a high energy are a sensitive signal of postsaddle friction.

We carry out calculations at different angular momenta and find that the conclusions derived are analogous to those drawn from Fig. 1.

Experimentally, in addition to fusion reactions, intermediate-energy heavy-ion collisions, where the incident energy per nucleon for the projectile ranges from several tens of MeV (Fermi energy) to a few hundreds of MeV, are also applied to yield hot nuclei, including those having a high excitation energy and a small spin generated in near-central collisions and those with excitation energy over 200 MeV and large spin around 50$\hbar$ generated in peripheral collisions [31–33].

Moreover, fission events originating from different collision centralities, i.e., from near-central, semiperipheral, and peripheral collisions, can be identified in experiment by using the folding angle technique that measures the correlation angle of the two fission fragments [31,32]. And experimental information on A, Z, E^*, etc. of the fissioning source can be conveniently obtained with the technique; see, e.g., Refs. [33,35].

In addition, the multisource model method, i.e., the produced residue nucleus evaporation source, two fission fragment sources, and a pre-equilibrium emission source, is employed to disentangle the contribution from different emission sources to the measured particle energy spectra in coincidence with two fission fragments in intermediate energy reactions. This method has been widely used in fusion-fission [8,9] and intermediate-energy [31,32,35] reactions. Unlik pre-equilibrium emission, which is focused on the forward angle (due to kinematic effects), the produced residue nucleus evaporation source dominates the particle energy spectrum measured at large angles (i.e., at backward angles). In Ref. [35],

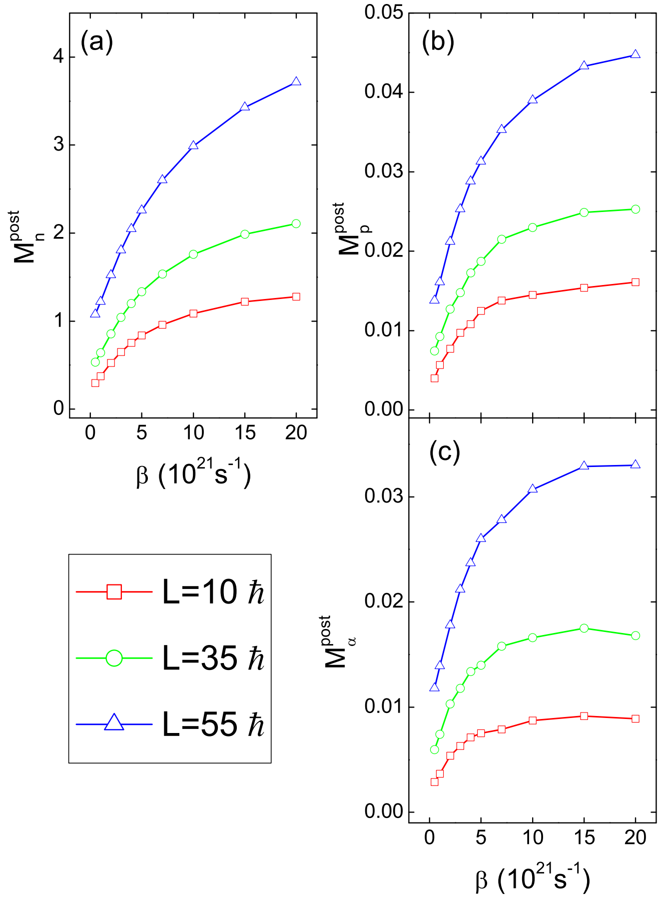

FIG. 2. Postsaddle multiplicities of neutrons (a), protons (b), and α particles (c) of fissioning nuclei ^{240}Am as a function of β at excitation energy $E^* = 120$ MeV and at three angular momenta $\ell = 10\hbar$ (squares connected by red lines), 35$\hbar$ (circles connected by green lines), and 55$\hbar$ (triangles connected by blue lines).

it was shown that by analyzing the energy spectra of LCPs (measured at large angles) in coincidence with two fission fragments, the multiplicity of LCP evaporated from the produced residue nucleus is obtained. Therefore, intermediate-energy nuclear reactions are quite suited for studying postsaddle friction with particle emission of highly excited heavy fissioning nuclei.

Our calculated results (Fig. 1) suggest that experimentally, populating heavy fissioning systems via intermediate-energy heavy-ion collisions can provide a more preferable condition of exploring postsaddle nuclear dissipation with particle multiplicity, especially with LCPs as compared to the low-energy fusion reaction approach, since the former can deposit more energy into the decaying nucleus.

Apart from excitation energy, angular momentum is another crucial parameter that has an important influence on de-excitation modes of hot nuclei. So we make a calculation of postsaddle neutrons and LCPs at different angular momenta ℓ. As a demonstration, the results calculated at $E^* = 120$ MeV and $\ell = 10\hbar$, 35$\hbar$, and 55$\hbar$ are displayed in Fig. 2.

The most prominent feature seen from this figure is that the higher the ℓ, the larger the sensitivity of postsaddle

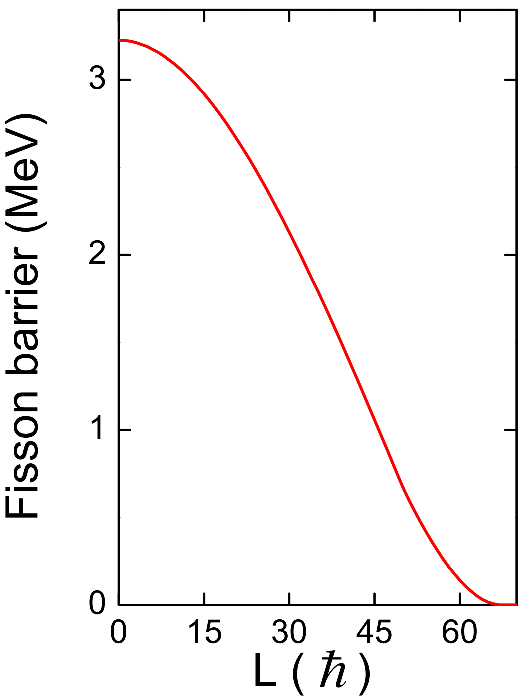

FIG. 3. Fission barriers of the ^{240}Am system as a function of angular momentum calculated with the method in Refs. [58,60,62].

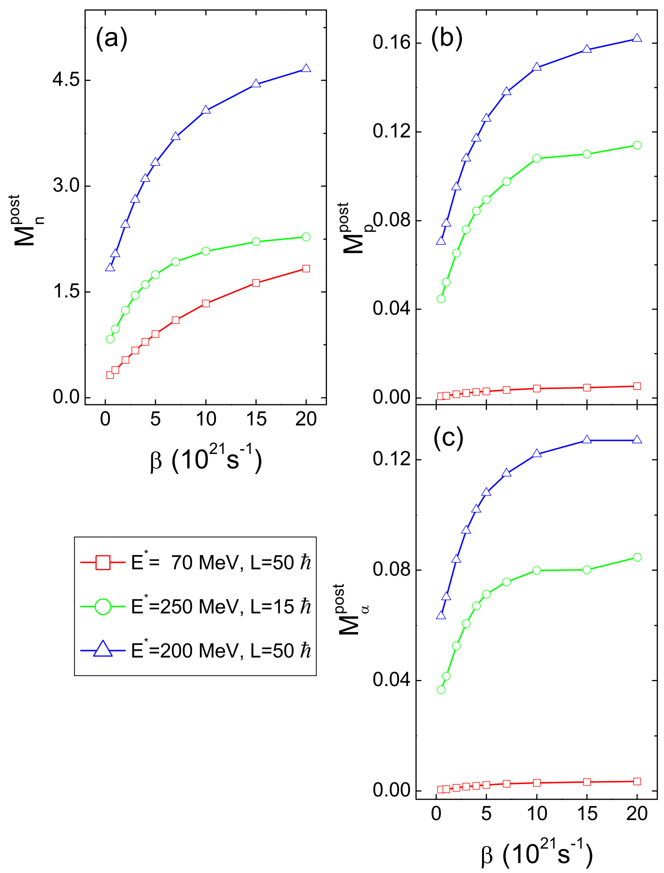

FIG. 4. Comparison of postsaddle multiplicities of neutrons (a), protons (b), and α particles (c) of fissioning nuclei ^{240}Am vs postsaddle dissipation strength β between case (i) $E^* = 250$ MeV and $\ell = 15\hbar$ (circles connected by green lines) and case (ii) $E^* = 70$ MeV and $\ell = 50\hbar$ (squares connected by red lines). Results calculated at $E^* = 200$ MeV and $\ell = 50\hbar$ are shown by triangles connected by blue lines.

particles to β. The enhancement in the sensitivity can be physically understood as follows: Fission barriers are a decreasing function of angular momentum (see Fig. 3), favoring fission. That is to say, at high ℓ, fission probabilities become greater and presaddle evaporation drops. As a consequence, more energy is left for postsaddle emission, leading to a larger postsaddle multiplicity. A larger postsaddle particle multiplicity increases its sensitivity to β.

In intermediate-energy peripheral heavy-ion collisions, the populated excited nuclei have a large angular momentum [31,33,35]. The results shown in Fig. 2 thus indicate that employing this way to yield fissioning systems can provide optimal conditions for examining postsaddle dissipation effects with particle multiplicity and thereby it can place a tighter constraint on β.

As mentioned previously, in the fusion reaction approach, it is quite difficult to obtain the conditions of a high E^* (>200 MeV) and ℓ (around $50\hbar$) for the populated heavy fissioning nuclei due to the evident onset of the quasifission channel at a large incident energy of projectiles. As a result of a low incident energy, the excitation energy deposited into heavy fissioning systems through a fusion mechanism is not very high. In contrast, nuclear systems populated in intermediate-energy heavy-ion collisions can reach a rather high excitation energy.

To further examine the difference of the two different experimental ways in exploiting decay features of hot nuclei, particularly concerning dissipation properties in fission with particle multiplicity, we first compute the evolution of postsaddle particles with β for two cases: (i) $E^* = 250$ MeV, $\ell = 15\hbar$ and (ii) $E^* = 70$ MeV, $\ell = 50\hbar$. The case (i) corresponds to a situation of heavy fissioning systems produced in intermediate-energy heavy-ion collisions, and case (ii) represents the typical conditions of the formed heavy compound nuclei via fusion.

From Fig. 4(a), which depicts neutron emission, we observe a similar slope of the curve in case (i) and case (ii), but that slope for postsaddle LCPs [Figs. 4(b) and 4(c)] differs very much for the two cases. There, one can note that postsaddle protons and α particles in case (ii) have only a minor change with increasing β, revealing that LCPs of heavy fissioning nuclei produced in a fusion reaction are not a good indicator of postsaddle friction. But a much higher sensitivity of M_p^{post} and M_α^{post} to β is seen in case (i) than in case (ii).

Besides near-central collisions that generate the nuclear system with a high energy and a small spin that is considered in case (i), peripheral collisions at intermediate energies can generate those heavy nuclear systems with an excitation energy over 200 MeV and a large spin (around $50\hbar$) [33]. So, we make a further calculation under the conditions of $E^* = 200$ MeV and $\ell = 50\hbar$, which is plotted as triangles connected by blue lines in Fig. 4.

For this case, in addition to LCPs which display an apparently rapid increase with β, $M_n^{\rm post}$ is also observed to exhibit a quicker rise with a change in β than that in case (ii) [see the triangles and the squares connected by the blue line and the red line, respectively, as shown in Fig. 4(a)], demonstrating an enhanced sensitivity to β. It illustrates that large E^* and ℓ are preferable for exploiting β with the particle emission data. Therefore, measuring prescission particles of heavy fissioning nuclei produced in intermediate-energy peripheral heavy-ion collisions constitutes a powerful tool to stringently limit the postsaddle friction strength.

The Weisskopf formula [69,70] is utilized here to calculate the particle emission width [see Eq. (4)]. However, for a more accurate estimate of the particle emission width, the Hauser-Feshbach formula [71] is needed, since it includes all angular momentum couplings between the initial and final states, which are absent in Weisskopf formula. The Hauser-Feshbach formula has been used in some statistical model calculations of the particle emission width, such as GEMINI [72,73]. Although in the framework of the current Langevin dynamical models, a tremendous computation time will be required if applying the Hauser-Feshbach formula to calculate the particle emission width in a fission process, it is very necessary to make such an effort because theoretically getting a more precise value of the particle multiplicity favors a stronger constraint of nuclear dissipation.

In previous calculations, we fix presaddle dissipation strength and change the postsaddle dissipation strength, which may cause a discontinuity of the dissipation strength at the saddle point. However, both the deformation coordinate q and its conjugate momentum p are continuous at the saddle point, since they are two independent variables. Also, the temperature T and the free energy F are continuous at the saddle point, because they are only functions of continuous variables q and p.

To our knowledge, until now, several proposals [16,17,41] on the dependence of friction on deformation have been suggested. However, the precise form for this dependence is still not known. For instance, for the one-body dissipation strength (i.e., Wall-and-Window friction), a reduced factor $k_s = 0.25$–0.5 for the wall friction strength was found to be needed to account for fission data [17]. In addition, fission competes with particle evaporation many times in the deexcitation process of a fissioning nucleus. As a result, fission observables are sensitive to the average strength of friction along the entire fission trajectory, and they are not sensitive to the specific deformation form that friction depends on. Due to these reasons, a new and complicated form that friction depends on deformation is not assumed in the present work, and one constant friction value before saddle-point deformation and another one beyond the saddle are taken into account in the model calculation. The specific numerical value of the calculated postsaddle particle multiplicities may be affected by using a steplike deformation function form or a continuous deformation function form of the friction, but the conclusion that a greater sensitivity of particle emission (particularly LCPs) to postsaddle friction at high E^* reached here is not altered. This is because the magnitude of the postsaddle particle multiplicity is determined by the average postsaddle friction strength throughout the postsaddle deformation region.

The present work employs a one-dimensional (which considers elongation as a collective coordinate) Langevin equation to study the case of symmetric fission and ignores the collective coordinate that may be used to express deformation of the fragments, which possesses kinetic energy, but which is ignored in the present one-dimensional calculation. This will underestimate the collective energy, leading to overestimation of the intrinsic energy and therefore to overestimation of multiplicities of neutrons and LCPs. So, to make more quantitative conclusions, it is desirable to employ multidimensional Langevin approach to perform calculation.

It is known that that intranuclear cascade (INCL) model [74] and quantum molecular dynamics (QMD) model [75–77] have been widely applied to describe the features of the residue nucleus produced in spallation reactions. Statistical models GEMINI [56,72,73] and ABLA07 [68] then treat the decay process of the produced residue nucleus. Similar to the case in spallation reactions, in intermediate-energy reactions, the QMD model can be used to give information of the related parameters (i.e., A, Z, E^*, etc.) characterizing each generated residue nucleus, which will be used in subsequent decay model calculations. When dealing with the decay process of a hot nucleus, a use of the Langevin model is preferable to the statistical model, because it contains a number of dynamical features of the fission process that are absent in the latter. Moreover, the present work shows that intermediate-energy reactions offer a way to better probe postsaddle dissipation properties with particle multiplicity than heavy-ion fusion, and developing the QMD-Langevin model is thus interesting in the future.

IV. CONCLUSIONS

In the framework of the dynamical Langevin equations coupled to a statistical decay model, we have investigated the influences of the excitation energy and angular momentum on probing postsaddle dissipation strength β with particle observables of heavy fissioning systems. It has been shown that the sensitivity of light particles to β is enhanced significantly at high energy and high spin. Furthermore, we find that LCPs are more sensitive to β under the conditions of high excitation energy and low angular momentum than under the conditions of low excitation energy and high angular momentum, which corresponds to the characteristics of the formed heavy fissioning nuclei provided by intermediate-energy heavy-ion collisions and fusion reactions, respectively. These results suggest that on the experimental side, to accurately determine the strength of postsaddle dissipation through the measurement of light particle multiplicity, especially LCPs multiplicity, intermediate-energy heavy-ion collisions may be an avenue to yield highly excited heavy fissioning nuclei.

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