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Effect of pre-equilibrium emission on probing postsaddle nuclear dissipation with neutrons*

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Abstract: Using the stochastic Langevin model coupled with a statistical decay model, we study the influence of pre-equilibrium (PE) emission on probing postsaddle friction (β) with neutrons. A postsaddle friction value of (14−16.5) $\times 10^{21}$ s^{-1} and (11−13) $\times 10^{21}$ s^{-1} is obtained from comparing calculated and measured prescission neutron multiplicities of heavy fissioning systems ^{248}Fm and ^{256}Fm in the absence and presence of the deformation factor. Moreover, it is found that a larger β is required to fit multiplicity data after the PE effect is accounted for, and that the effect becomes stronger when more energy is removed by PE particles. Our findings suggest that, to more accurately determine the postsaddle friction strength through the measurement of prescission neutrons, in addition to incorporating the contribution of PE evaporation source into the experimental multi-source analysis for particle energy spectra in coincidence with fission fragments, on the theoretical side, it is very important to make a precise evaluation of the energy that PE emission carries away from excited compound systems produced in heavy-ion fusion reactions.

Keywords: nuclear dissipation, Langevin model, pre-equilibrium emission, neutron

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1 Introduction

The nature and the strength of nuclear dissipation remains one of the major problems as yet unsolved in nuclear physics. It affects a variety of low-energy nucleus-nucleus collision phenomena such as deep-inelastic scattering, the quasifission process and the decay of hot nuclei [1–5]. Dissipation hinders fission, which results in an excess of observed prescission light particles and a large evaporation residue cross section with respect to predictions of standard statistical models [6–9]. Accordingly, information on dissipation is obtained by comparing theoretical calculations with experimental measurements [10–13]. It has been demonstrated [14–24] that stochastic approaches are a suitable framework to address a great number of observables, including particle multiplicities and evaporation residue cross sections for a lot of compound nuclei (CNs) over a broad range of excitation energy, angular momentum and fissility.

Currently intensive efforts have been made on the constraint of presaddle dissipation strength [25–32]. As a result, presaddle friction is severely constrained. But little attention is paid to the accurate determination of postsaddle dissipation strength. Light particles can be evaporated along the whole fission path. They are thus considered to be the main indicator for postsaddle dissipation effects [33–35].

Experimentally, the three-source model [36], i.e., a compound nucleus source and two fission fragment sources, are widely used to extract prescission light particle multiplicity by reproducing particle energy spectra originating from fusion-fission processes. The pre-equilibrium (PE) evaporation source is usually neglected in the fitting procedure, because the contribution arising from it to particle energy spectra is considered to be small. However, with an increase in the bombarding energy, the PE emission becomes evident [37], and has been noted to have an effect on the formation and subsequent decay of hot nuclei [38–40]. In a heavy-ion fusion reaction, while the influence of PE emission on the characteristics of the produced CNs, i.e., mass and spin, is not very prominent, given that excitation energy is a key parameter controlling the de-excitation mode of a CN, the energy removed by PE particles from the decaying CN could affect the decay properties of excited nuclei markedly.

In the decay process of a heavy CN, neutron evaporation competes with fission. Moreover, the distance between the saddle and scission points is a rising function of the system size. For these reasons, neutrons evapo-

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rated from heavy decaying systems have been utilized as a principal tool to pin down postsaddle dissipation. In the present work, we investigate the influence of PE emission on neutrons of the heavy fissioning nuclei ^{248}Fm and ^{256}Fm as a sensitive probe of the strength of postsaddle dissipation.

2 Theoretical model

Stochastic equations like the Langevin equations [15–24] have given a successful description of the fission process of a highly excited CN. The model used here combines the Langevin equation with a statistical decay model (CDSM) [41]. The dynamic part of CDSM is described by the Langevin equation that is expressed by entropy. We employ the following one-dimensional overdamped Langevin equation [33] to perform the trajectory calculations:

$$\frac{\mathrm{d}q}{\mathrm{d}t}=\frac{T}{M\beta}\frac{\mathrm{d}S}{\mathrm{d}q}+\sqrt{\frac{T}{M\beta}}\Gamma(t). \tag{1}$$

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 compound nucleus. M is the inertia parameter [41], and β is the dissipation strength. The temperature in Eq. (1) is denoted by T. $\Gamma(t)$ is a fluctuating force with $<\Gamma(t)> = 0$ and $<\Gamma(t)\Gamma(t')> = 2\delta(t-t')$. The driving force of the Langevin equation is calculated from the entropy:

$$S(q,E^*)=2\sqrt{a(q)[E^*-V(q)]}, \tag{2}$$

where E^* is the excitation energy of the system. Equation (2) is constructed from the Fermi-gas expression with a finite-range liquid-drop potential [42]. The q-dependent surface, Coulomb and rotation energy terms are included in the potential $V(q)$.

In constructing the entropy, the deformation-dependent level density parameter is used:

$$a(q)=a_1A+a_2A^{2/3}B_{\mathrm{s}}(q), \tag{3}$$

where A is the mass number, and $a_1 = 0.073\ \mathrm{MeV}^{-1}$ and $a_2 = 0.095\ \mathrm{MeV}^{-1}$ are taken from Ignatyuk et al. [43]. B_{s} is the dimensionless surface area (for a sphere $B_{\mathrm{s}} = 1$) which can be parametrized by the analytical expression [44]

$$B_{\mathrm{s}}(q)=\begin{cases}1+2.844(q-0.375)^2, & \text{if } q<0.452\\ 0.983+0.439(q-0.375), & \text{if } q\geqslant 0.452.\end{cases} \tag{4}$$

In the CDSM, prescission particle evaporation along Langevin fission trajectories from their ground state to their scission point is taken into account. The emission width of a particle of kind ν $(=\mathrm{n},\mathrm{p},\alpha)$ is given by [45]

$$\Gamma_\nu=(2s_\nu+1)\frac{m_\nu}{\pi^2\hbar^2\rho_{\mathrm{c}}(E^*)}\times\int_0^{E^*-B_\nu}\mathrm{d}\varepsilon_\nu\rho_R(E^*-B_\nu-\varepsilon_\nu)\varepsilon_\nu\sigma_{\mathrm{inv}}(\varepsilon_\nu), \tag{5}$$

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 $\rho_{\mathrm{c}}(E^*)$ 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 $\sigma_{\mathrm{inv}}(\varepsilon_\nu)$ the inverse cross sections [45].

Light-particle evaporation is coupled to the fission mode by a Monte Carlo way. The present simulation allows for the discrete emission of light particles. The procedure is as follows. We calculate the decay widths for light particles at each Langevin time step τ. Then the emission of particles is allowed by asking along the trajectory at each time step τ whether a random number ζ is less than the ratio of the Langevin time step τ to the decay time $\tau_{\mathrm{dec}}=\hbar/\Gamma_{\mathrm{tot}}$: $\zeta<\tau/\tau_{\mathrm{dec}}$ $(0\leqslant\zeta\leqslant1)$, where Γ_{tot} is 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 $(\nu=\mathrm{n},\mathrm{p},\alpha)$ by a Monte Carlo selection with the weights $\Gamma_\nu/\Gamma_{\mathrm{tot}}$. This procedure simulates the law of radioactive decay for the different particles.

After each emission of a particle of kind ν the energy of the emitted particle is calculated by a hit-and-miss Monte Carlo procedure, using the integrand of the formula for the corresponding decay width as weight function. Then the intrinsic energy, the entropy and the temperature in the Langevin equation are recalculated and the dynamics is continued.

The CDSM describes the fission process as follows: At early times, the decay of the system is modelled by means of the Langevin equation. After the fission probability flow over the fission barrier attains its quasistationary value, the decay of the CN is described by a statistical branch. In the statistical branch we calculate the decay widths for particle emission and the fission width and use a standard Monte Carlo cascade procedure with the weights $\Gamma_{\mathrm{i}}/\Gamma_{\mathrm{tot}}$ $(\mathrm{i}=\mathrm{fission},\mathrm{n},\mathrm{p},\alpha)$ and $\Gamma_{\mathrm{tot}}=\sum_{\mathrm{i}}\Gamma_{\mathrm{i}}$. This procedure allows for multiple emissions of light particles and higher chance fission. In case fission is decided there, one switches again to the Langevin equation for computing the evolution from saddle to scission. Prescission particle multiplicities are calculated by counting the number of corresponding evaporated particle events registered in the dynamic and statistical branch of the CDSM. To accumulate sufficient statistics, 10^7 Langevin trajectories are simulated.

For starting a Langevin trajectory an orbital angular momentum value is sampled from the fusion spin distribution, which reads

$$\frac{\mathrm{d}\sigma(\ell)}{\mathrm{d}\ell}=\frac{2\pi}{k^2}\frac{2\ell+1}{1+\exp[(\ell-\ell_{\mathrm{c}})/\delta\ell]}. \tag{6}$$

The parameters ℓ_{c} and $\delta\ell$ are the critical angular momenta for fusion and diffuseness, respectively.

3 Results and discussion

Neutrons are a dominant decay channel of heavy CNs. So, for the analysis of neutron yields we have chosen two heavy systems ^{256}Fm and ^{248}Fm, which were formed in the reactions ^{18}O+^{238}U and ^{40}Ar+^{208}Pb, respectively [46].

In the present study, the presaddle friction strength is fixed as 3 zs^{-1} (1 zs = 10^{-21} s), in accordance with recent theoretical estimates and experimental analyses [27–32, 47, 48], whereas the postsaddle friction strength β is determined by fitting measured data.

We show in Fig. 1 the experimental prescission neutron multiplicity of fissioning systems ^{248}Fm and ^{256}Fm and theoretical values which are calculated based on the Langevin model considering various β. At the same postsaddle friction strength, the M_{n} calculated without the PE effect is evidently higher than that calculated with it. The reason is that the PE emission removes some amount of energy from these systems, which decreases the excitation energy available for particle emission, resulting in a reduction in the number of the emitted prescission neutrons. Consequently, a larger β is required to fit neutron multiplicity data. This is confirmed in Fig. 1(a), where the best-fit β value (denoted by ■ in the figure) rises from 11.5 zs^{-1} to 14 zs^{-1} when the PE effect is taken into account. This clearly indicates the importance of the PE emission in the accurate determination of the postsaddle friction strength.

A similar picture is seen for another heavy ^{248}Fm system [Fig. 1(b)], where the PE effect leads to an increase of the best-fit value of β from 13.5 zs^{-1} to 16.5 zs^{-1}.

Moreover, we note in Fig. 1(a) that the gap between solid and blue dashed lines, which reflects the magnitude of the PE effect on the extraction of β, is wider than that between solid and red dashed double-dot lines. This is because in the latter case, the energy removal by PE emission estimated with BME code [46, 50] is $\sim$ 3.1 MeV, which is lower than that in the former case, where the numerical value estimated with Holub's approach [49] is $\sim$ 4.6 MeV. As a consequence of a smaller correction (caused by PE effects) to the excitation energy of the populated ^{256}Fm, while the friction strength (represented by the red dashed double-dot line) required to fit data has a change with respect to that of neglecting the PE effect, its changed amplitude is smaller than that represented by the blue dashed line. This comparison demonstrates that precisely evaluating the energy carried away by the PE emission will play an important role in more stringently constraining the postsaddle friction strength.

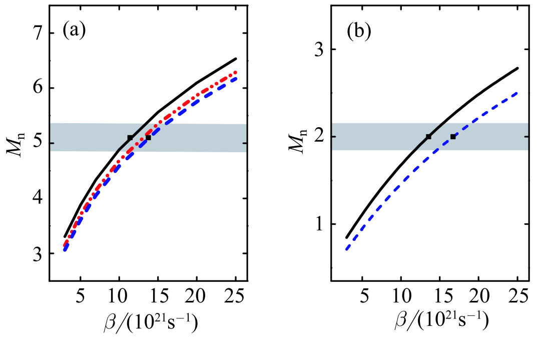

Fig. 1. (color online) Fits to prescission neutron multiplicity measured in (a) ^{18}O (E_{lab} = 159 MeV) + ^{238}U $\longrightarrow$ ^{256}Fm and (b) ^{40}Ar (E_{lab} = 249 MeV) + ^{208}Pb $\longrightarrow$ ^{248}Fm systems. Experimental values [46] are denoted by the shaded band. Solid lines and dashed lines are model calculations without and with the PE effect, respectively. In panel (a), blue dashed and red dashed double-dot lines correspond to energy removed by PE particles as estimated with Holub's systematic method [49] and with Boltzmann master equation computer code BME [50], respectively. In panel (b), since no estimate [46] for the energy removal by PE emission for ^{248}Fm using the BME code was made, the corresponding calculation results are not displayed here.

In the literature (e.g., [49]), the energy removed by PE neutrons is usually calculated as follows: First, the neutron multiplicity emitted in the PE phase and the PE source temperature and its energy per nucleon are extracted by fitting measured particle energy spectra with the PE evaporation source and the other three known evaporation sources mentioned before. Then, the loss of the excitation energy of a decaying CN because of the PE effect is computed with an empirical approach [49] that contains the experimentally extracted information about PE emission pointed out above and neutron binding energy. In this respect, it is clear that a dynamical model that can handle entrance channel collision dynamics, such as Feldmeier's program HICOL [51], which was successfully applied by Siwek-Wilczyńska et al. [52] to simulate the dynamical evolution of the intrinsic excitation of the composite system populated in projectile-target collisions, can be employed to provide a more precise estimate for the energy that PE emission takes away by comparing its predictions with the experimental PE neutron multiplicity. Also, a hybrid Monte Carlo simulation (HMS) model [53] was proposed to treat precompound decay. Therefore, to further explore the PE effect on pinpointing dissipation properties in fission of excited nuclei, it is interesting to develop a new framework based on the HICOL−Langevin model or the HMS−Langevin model.

A nucleus undergoes deformation when it fissions. The amplitude of postsaddle deformation in a fission process is obviously greater than that of presaddle deformation, especially for heavy fissioning nuclei. Since various decay channels compete with each other in a decay process and neutrons and light-charged particles (LCPs) respond differently to deformation effects [54, 55], it is thus important to further examine the influence of PE emission on the determination of β in the presence of deformation effects.

Deformation affects emission barriers for LCPs, which can be evaluated with the formula in [33]. In addition, it also modifies particle binding energies. The reason is that mass formula [56] contains the deformation-dependent surface energy term and Coulomb energy term. Particle binding energy is thus a function of q [54, 55, 57], and it can be written as $B_i(q) = M_\mathrm{p}(q) - M_\mathrm{d}(q) + M_\mathrm{i}$. Here M_i ($\mathrm{i} = \mathrm{n}, \mathrm{p}, \alpha$) is the mass of the emitted particles. $M_\mathrm{p}(q)$ and $M_\mathrm{d}(q)$ are the masses of the mother and daughter nuclei, respectively.

Figure 2 shows that deformation decreases the magnitude of M_p (M_α) as a consequence of the competition between the rapid rise of binding energies of LCPs [Fig. 2(a)] and a drop in their emission barriers [Fig. 2(b)] with increasing deformation. Different from LCPs, deformation lowers the neutron binding energy, which enhances the neutron emission and hence a smaller β is found to reproduce the measured M_n, as seen from a comparison between the solid lines shown in Fig. 1 and those shown in Fig. 3.

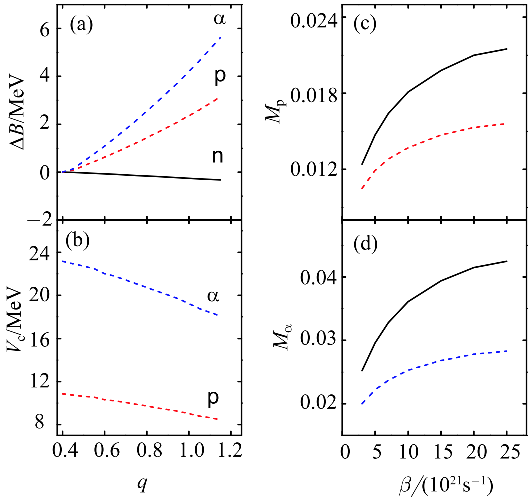

Fig. 2. (color online) (a) Change in neutron, proton and α-particle binding energies ΔB as a function of deformation coordinate q relative to the spherical binding energies for ^{256}Fm. (b) Emission barrier (V_c) of protons and α particles of the ^{256}Fm system as a function of q. Theoretical predictions of prescission multiplicities of protons (c) and α particles (d) as a function of postsaddle friction strength β for the reaction ^{18}O ($E_\mathrm{lab} = 159$ MeV) + $^{238}\mathrm{U} \longrightarrow {}^{256}$Fm. Curves represent calculations without (solid line) and with (dashed line) deformation effects.

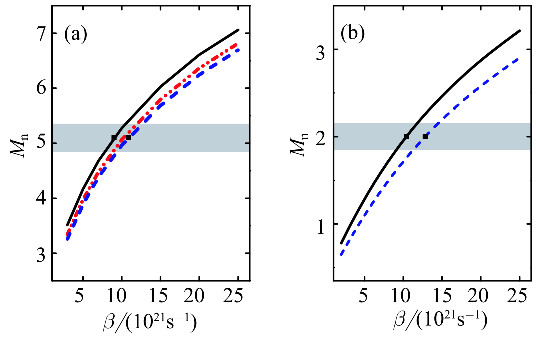

Fig. 3. (color online) Same as Fig. 1 but with deformation effects included in the model calculation.

In the presence of deformation effects, Fig. 3(a) reveals that PE effects make the deduced best-fit β value (denoted by ■) rise from 9 zs^{-1} to 11 zs^{-1} for ^{256}Fm. Displayed in Fig. 3(b) is the result for the ^{248}Fm system, for which the PE effect increases the friction strength (close to 13 zs^{-1}) as well.

Overall, a friction strength of (14−16.5) zs^{-1} is obtained in Fig. 1. While taking account of deformation factors yields a sightly small postsaddle friction of (11−13) zs^{-1} (see Fig. 3), the typical features of the PE effect observed in Fig. 1, where the deformation factor is neglected in calculation, are not altered. That is, accounting for the PE effect requires the introduction of a stronger friction to explain neutron data, and the more energy the PE emission removes, the larger the β is required. This again illustrates that, to more tightly limit the postsaddle friction strength with neutrons, on the experimental side, when applying the multi-source model to analyze particle energy spectra, the PE evaporation source is indispensable.

In the fission process of a hot nucleus, both dissipation effects and excitation energy can affect prescission particles. A change in the excitation energy will affect the contribution from the dissipation effects to particle emission. Thus, an accurate determination of the friction parameter requires a better evaluation of the excitation energy of the decaying system.

While a reduction in the initial excitation energy due to PE emission affects the contributions of pre- and post-saddle dissipative effects to prescission particles, it does not mean that the presaddle dissipation parameter (fixed to 3 zs^{-1} here) should be changed with energy. As pointed out recently by Lestone et al. [58], the possible temperature dependence of nuclear dissipation assumed in the literature arises from the use of an inadequate statistical fission model. So, the presaddle friction parameter used here is treated as a temperature-independent quantity and thereby, not altered due to the reduction of the excitation energy resulting from the PE emission.

In Figs. 1 and 3, the presaddle friction parameter is fixed to 3 zs^{-1}. While the presaddle friction parameter is currently severely constrained, there exists an uncertainty on it. Here we check the possible influence of a slightly different presaddle friction parameter on the present results. As an illustration, we show a comparison between theory and experiment at the presaddle friction strength of 4.5 zs^{-1}; see Fig. 4. The best-fit postsaddle friction strength (denoted by solid squares in the figure) required to fit the prescission neutron multiplicity of ^{248}Fm is 15.5 zs^{-1} [Fig. 4(a)] for the case with PE effect considered and is 12 zs^{-1} [Fig. 4(b)] for the case with both deformation and PE effects included in the calculation. These values are smaller than that obtained using the presaddle friction strength of 3 zs^{-1}. An increasing presaddle friction contributes to more prescission neutrons, which correspondingly decreases the contribution from the postsaddle region. This leads to a decrease of the extracted postsaddle friction parameter. However, the deduced postsaddle friction strength is still stronger than the presaddle one.

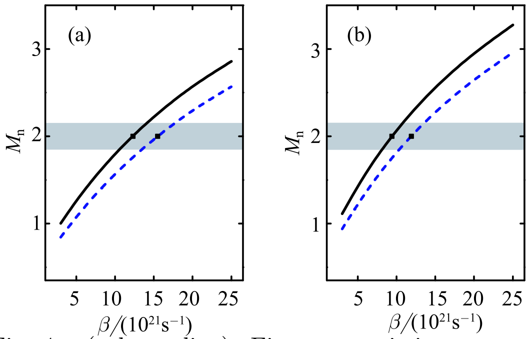

Fig. 4. (color online) Fits to prescission neutron multiplicity measured in the ^{40}Ar (E_{lab} = 249 MeV) + ^{208}Pb $\longrightarrow$ ^{248}Fm system. Here panel (a) and panel (b) are respectively the same as Fig. 1(b) and Fig. 3(b), but the theoretical calculations are performed at the presaddle friction strength of 4.5 zs^{-1}.

Prescission neutrons are sensitive to both fractions of the fission path, implying that one cannot disentangle between pre- and post-saddle dissipative effects using the observable only. So, in the present work the presaddle friction parameter adopted is not determined by the neutron multiplicity, but from the result of a number of previous studies. There, by reproducing those observables (e.g., fission excitation function and evaporation residue cross sections) sensitive to presaddle dynamics only, the presaddle friction parameter is tightly constrained, and is around 3 zs^{-1}. For the Fm systems studied here, no experimental fission excitation function is available. So, the strength of presaddle friction mentioned above was used in our calculation. Thus, our conclusion on the deformation dependence should be considered as a result that combines previous studies for presaddle friction with observable fission/evaporation residue excitation function and the current analysis for postsaddle friction with neutron multiplicity of heavy fissioning systems, and not solely determined by the neutron multiplicity.

A strong postsaddle was noted earlier based on different approaches. In the framework of a statistical model that contains dissipation effects, Shaw et al. [59] showed that a strong postsaddle friction along with a weak presaddle friction described giant dipole resonance γ-ray spectra measured for heavy ^{240}Cf nuclei very well. With the nonequilibrium statistical-operator theory, Aleshin [60] has indicated that the friction strength rises with deformation, lending a certain support to a strong postsaddle friction. Our present calculations show that the PE effect not only has an obvious influence on the accurate determination of β, but it reinforces the result; that is, postsaddle friction is greater than presaddle friction. This conclusion is consistent with that reached recently with a different observable, i.e., excitation energy at scission [61].

In the literature, a weak dependence of the friction parameter with deformation predicted by the one-body chaos-weighted wall formula [62] and observed in the investigation of fusion reactions by using the linear response theory [63] was used in calculation. A study based on Langevin models indicated that employing the chaos-weighted friction [64], which predicts a presaddle friction value analogous to that used here, and assuming a small postsaddle friction β, underestimates significantly the measured prescission neutron multiplicity of heavy fissioning systems ($A \sim 250$), showing that a larger β [41] needs to be incorporated into model calculations. In addition, multi-dimensional Langevin calculations were made [65, 66] which even predict a small decrease of the friction parameter with deformation by introducing a reduction factor k_s ($\leqslant 1$) for the wall formula. This type of friction was found to be able to reproduce the fission excitation function, but it also significantly underestimates the measured prescission neutron multiplicity of heavy fissioning systems ($A > 240$); see Table I in Ref. [65]. This may be a signature that hints at introducing a greater postsaddle friction to address the evident discrepancy between theoretical and experimental prescission neutron multiplicity of heavy fissioning systems.

In previous calculations, only neutron emission in the PE phase was considered. While charged particles such as protons can be emitted in the precompound stage, their emission probability is smaller than that of neutrons. In addition, as far as the present reaction systems are concerned, PE emission (even for neutrons) in heavy-ion fusion reactions is not very strong, so the angular momentum carried away by the PE particles is very small. As a result, proton evaporation and the angular momentum brought by the emitted particles are not considered here. However, they can also affect the fission dynamics and hence, the accuracy of the postsaddle friction parameter extracted here. This indicates the necessity of employing advanced models to better treat various types of particle emission in the PE phase, as shown in a recent work [40].

4 Summary and conclusions

In the framework of the Langevin model of fission dynamics, we have surveyed the role of PE emission in extracting postsaddle friction strength with neutrons. It is demonstrated that accounting for the PE effect leads to a requirement of a stronger β to fit the prescission neutron data of fissioning nuclei ^{248,256}Fm. A friction strength of (14−16.5) zs^{-1} and (11−13) zs^{-1} is deduced by comparing model simulations with these measured multiplicity data when deformation effects are absent and present, respectively. Our results suggest that, to more accurately probe postsaddle dissipation with light particles, in experiments, the PE evaporation source should be included in the multi-source model fit to particle energy spectra, in particular for the case of high incident energy. On the theoretical side, it is also very important to make a more careful evaluation of the energy that PE emission takes away from the formed hot fissioning systems.

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