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Isospin effects on light charged particles as probes of nuclear dissipation

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The multiplicities of postsaddle protons and α particles of the heavy systems ^{234}Cf, ^{240}Cf, ^{246}Cf, and ^{240}U as functions of the postsaddle dissipation strength are calculated in the framework of a dynamical Langevin model coupled with a statistical decay model. It is found that with increasing isospin of the Cf system, the sensitivity of the postsaddle proton and α-particle multiplicity to the dissipation strength decreases substantially, and it disappears for the ^{240}U system. We suggest that on the experimental side, to accurately probe the postsaddle dissipation strength by measuring the prescission proton and α-particle multiplicity, it is best to populate heavy compound systems with low isospin.

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The nature and magnitude of nuclear dissipation has been investigated extensively, both experimentally and theoretically, in recent years [1–10]. Because of dissipation, fission is delayed. This enhances prescission light particle emission and a large evaporation residue cross section with respect to the predictions of standard statistical models. To explain the experimental data associated with the dissipative fission, diffuse models have been utilized [11–19]. An essential conclusion deduced from a comprehensive investigation for this phenomenon is that nuclear dissipation is deformation dependent; namely, the presaddle friction is weak and the postsaddle friction is strong [20]. In particular, Fröbrich and Gontchar found that by adopting a phenomenologically deformation-dependent friction, the Langevin model can successfully reproduce the evaporation residue cross section and light particle multiplicity over a wide range of excitation energies and angular momenta for a great many compound nucleus systems [11,20,21]. On this basis, many recent works have reported on how to make a good determination of the presaddle dissipation strength by analyzing new experimental observables and performing model simulations [6,9,22–24]. However, very little attention has been paid to how to accurately determine the postsaddle dissipation strength. During the fission process, the particle emission occurs mainly before or after the traversal of the saddle points as the system proceeds toward scission. Also, the postsaddle contribution to the enhanced prescission particle emission rises rapidly with increasing size of the system owing to an increment of the saddle-to-scission path [25]. Therefore, surveying the dynamical particle emission in heavy fissioning systems can provide a sensitive method for determining the postsaddle friction strength [20]. In addition, the prescission proton and α-particle multiplicity can be extracted by a multicomponent, moving-source fit to measured particle energy spectra [26,27]. So, experimentally apart from neutrons [28,29], light charged particles (see, e.g., Refs. [30–32]) are also considered to be a main probe of the postsaddle dissipation effects, and they are thus widely employed by experimentalists to gain information regarding the nuclear dissipation.

In this Rapid Communication, we report a study on the favorable experimental condition through which the postsaddle dissipation effects can be better revealed with the light charged-particle multiplicity. To this end, a Langevin model is used to evaluate the particle multiplicity. Recently it has been noted that isospin has a significant effect on the fission observables that have been experimentally identified to be sensitive to the presaddle nuclear dissipation [23,24]. In this context, to better instruct experimental exploration, we investigate the isospin effects on light charged particles as probes of the postsaddle nuclear dissipation strength.

Here we give a brief description of a combined Langevin dynamical equation and a statistical decay model (CDSM) [20,33]. For a review of the model, we refer the reader to Ref. [20]. As pointed out by Fröbrich [34] and McCalla and Lestone [35], the driving force of a hot system is not simply the negative gradient of the conservative potential, but should also contain a thermodynamical correction; therefore, the dynamical part of the CDSM model is described by the Langevin equation that is expressed by the free energy F. In the Fermi gas model, F is related to the level density parameter $a(q)$ by

$$F(q,T) = V(q) - a(q)T^2, \tag{1}$$

where $V(q)$ is the potential energy and T is the nuclear temperature. The level density parameter $a(q)$ is taken from the work of Ignatyuk *et al.* [36]. In Eq. (1), both $F(q,T)$ and T have the dimension of energy, and the unit is MeV.

The one-dimensional overdamped Langevin equation reads

$$\frac{dq}{dt} = -\frac{1}{M\beta(q)}\frac{\partial F(q,T)_T}{\partial q} + \sqrt{D(q)}\,\Gamma(t), \tag{2}$$

where q is the dimensionless fission coordinate and is defined as half of the distance between the center of mass of the future fission fragments divided by the radius of the compound nucleus. $\beta(q)$ is the dissipation strength, its dimension is s^{-1}. The fluctuation strength coefficient $D(q)$ can be expressed according to the fluctuation-dissipation theorem as

$$D(q) = \frac{T}{M\beta(q)}, \tag{3}$$

where M is the inertia parameter that drops out of the overdamped equation. Note that since the fission coordinate q is dimensionless as mentioned before, the dimension of the inertia parameter M in CDSM is MeV s^2. For more details, see Ref. [20] and references therein.

$\Gamma(t)$ is a time-dependent stochastic variable with a Gaussian distribution. Its average and correlation function are written as

$$\langle\Gamma(t)\rangle = 0,$$
$$\langle\Gamma(t)\Gamma(t')\rangle = 2\delta(t-t'). \quad (4)$$

The potential energy $V(Z, A, L, q)$ can be expressed in the form [37,38]

$$V(A,Z,L,q) = a_2\left[1-k\left(\frac{N-Z}{A}\right)^2\right]A^{2/3}[B_s(q)-1] + c_3\frac{Z^2}{A^{1/3}}[B_c(q)-1] + c_r L^2 A^{-5/3}B_r(q), \quad (5)$$

where $B_s(q)$, $B_c(q)$, and $B_r(q)$ are the surface, Coulomb, and rotational energy terms, respectively, which depend on the deformation coordinate q. Parameters a_2, c_3, k, and c_r are not related to q [20].

After the fission probability flow over the fission barrier attains its quasistationary value, the decay of the compound system is described by a statistical model, which is called the statistical part of the CDSM. In the CDSM, the light-particle evaporation is coupled to the fission mode by a Monte Carlo procedure allowing for the discrete emission of light particles. The widths for light particles (n, p, α) and giant dipole resonance γ decay are given by the parametrization of Blann [39] and Lynn [40], respectively.

In this work, four heavy fissioning nuclei, ^{234}Cf, ^{240}Cf, ^{246}Cf, and ^{240}U, are considered. Their isospin values (defined as the neutron-to-proton ratio N/Z of the system) are 1.39, 1.45, 1.51, and 1.61, respectively. To better survey the evolution of the postsaddle charged particles with the postsaddle friction strength β, in the calculations the postsaddle friction is chosen here as (3, 5, 7, 10, 15, and 20) $\times 10^{21}$ s^{-1} whereas the presaddle friction strength is set as 3×10^{21} s^{-1}, a value that is consistent with experimental analyses and theoretical estimates [6,9,16,18,20,24]. To accumulate sufficient statistics, 10^7 Langevin trajectories are simulated. For each trajectory simulating the fission motion, an angular momentum $L=\hbar\ell$ is sampled from the spin distribution of the compound nucleus [20]

$$\frac{d\sigma(\ell)}{d\ell} = \frac{2\pi}{k^2}\frac{2\ell+1}{1+\exp[(\ell-\ell_c)/\delta\ell]} \quad (6)$$

describing the fusion process. The parameters ℓ_c and $\delta\ell$ are the critical angular momenta for fusion and diffuseness, respectively. The final results are weighted over all relevant waves; namely, the spin distribution is used as the angular momentum weight function.

Figure 1 shows postsaddle proton (M_p) and α-particle (M_α) multiplicities of ^{234}Cf, ^{240}Cf, and ^{246}Cf as functions of the postsaddle dissipation strength β at excitation energy $E^* = 80$ MeV and three critical angular momenta $\ell_c = 5$, 20, and 35$\hbar$. Two typical features are noticed from this figure. First, low isospins can amplify the effects of the postsaddle nuclear dissipation on the particle evaporation. The physical mechanism for this feature is the following. With increasing isospin of the fissioning systems, neutron separation energies are lowered. This favors the neutron emission. Our calculations show that under present conditions, ^{246}Cf evaporates the most presaddle neutrons, whereas those for ^{234}Cf are the least.

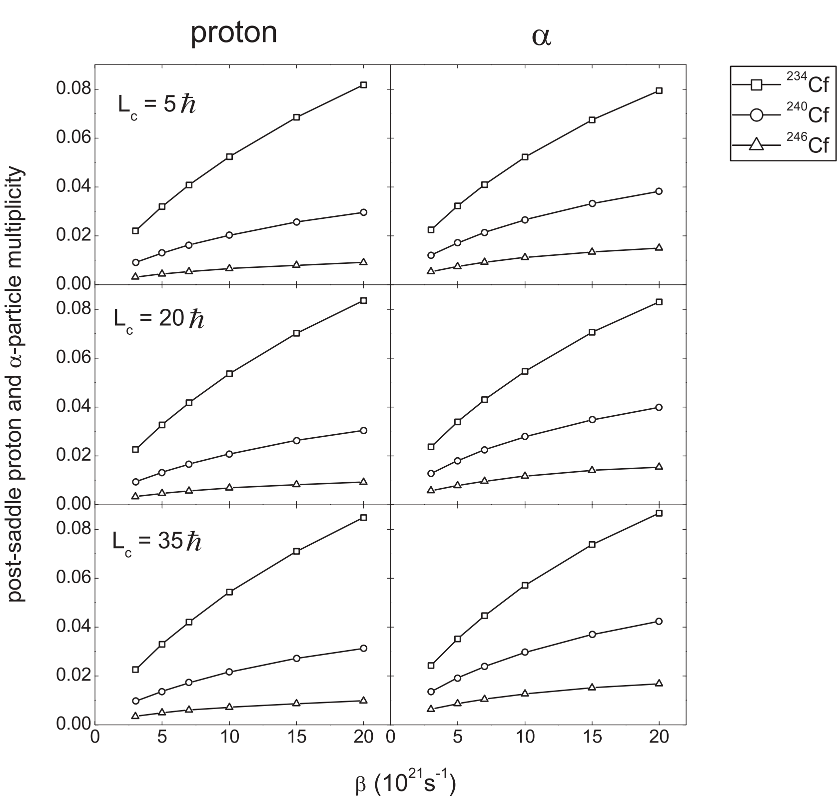

FIG. 1. Multiplicity of postsaddle protons and α particles of the fissioning systems ^{234}Cf, ^{240}Cf, and ^{246}Cf as a function of the postsaddle dissipation strength β at excitation energy $E^* = 80$ MeV and three critical angular momenta $\ell_c = 5$, 20, and 35$\hbar$.

TABLE I. Comparison of the calculated postsaddle neutron multiplicity for three Cf isotopes with different isospins, ^{234}Cf, ^{240}Cf, and ^{246}Cf, at an excitation energy of 80 MeV and critical angular momenta of 5, 20, and 35$\hbar$ for different postsaddle friction strengths β.

β (10^{21} s^{-1})	^{234}Cf			^{240}Cf			^{246}Cf		
	5$\hbar$	20$\hbar$	35$\hbar$	5$\hbar$	20$\hbar$	35$\hbar$	5$\hbar$	20$\hbar$	35$\hbar$
3	0.377	0.387	0.388	0.540	0.564	0.583	0.677	0.713	0.759
5	0.542	0.557	0.561	0.762	0.794	0.822	0.944	0.990	1.052
7	0.683	0.713	0.720	0.959	0.998	1.034	1.175	1.228	1.303
10	0.897	0.923	0.935	1.216	1.263	1.310	1.471	1.531	1.622
15	1.188	1.221	1.241	1.571	1.626	1.687	1.868	1.938	2.050
20	1.430	1.468	1.495	1.860	1.921	1.993	2.187	2.264	2.394

Furthermore, one can see from Table I, which compares the postsaddle neutron emission for the three Cf isotopes, that more postsaddle neutrons are emitted for the ^{246}Cf system than for the ^{240}Cf and ^{234}Cf systems. Since a competition exists between neutron and charged-particle decay during the descent of the fissioning system from saddle to scission point, a strong neutron decay will suppress other decay channels. As a result, the number of postsaddle charged particles is greater for ^{234}Cf than for ^{240}Cf and ^{246}Cf. Another feature is that the variation of proton and α-particle multiplicities with β has a marked difference for the three Cf systems, and these differences become smaller as the isospin of the system is increased. Taking the results at $\ell_c = 20\hbar$ as an illustration, the difference in the postsaddle proton (α-particle) multiplicity for ^{234}Cf at $\beta = 20 \times 10^{21}$ s^{-1} to that at $\beta = 3 \times 10^{21}$ s^{-1} is 0.061 (0.059). Considering that the value of M_p (M_α) at a friction strength of 3×10^{21} s^{-1} is only 0.023 (0.024), the difference caused by the change in the postsaddle friction strength is significant. Obviously, the difference for ^{234}Cf is larger than that for ^{240}Cf for which the corresponding difference is 0.021 (0.027), and it further drops down to 5.9 (9.7) $\times 10^{-3}$ for ^{246}Cf. This different behavior of M_p and M_α with the change of β observed for the three fissioning Cf systems indicates that the sensitivity of light charged-particle multiplicities to the strength of the postsaddle friction decreases substantially at high isospins. A physical understanding of this phenomenon is that for a high-isospin system, a small charged-particle multiplicity lowers its sensitivity to the variation of the friction strength. Consequently, M_p and M_α are clearly manifested as an appreciable enhancement with increasing β for a low-isospin system.

In Fig. 2, we depict M_p and M_α versus β for an even higher isospin system ^{240}U with the intent of further exploring the isospin effect. It is evident that its M_p and M_α are almost

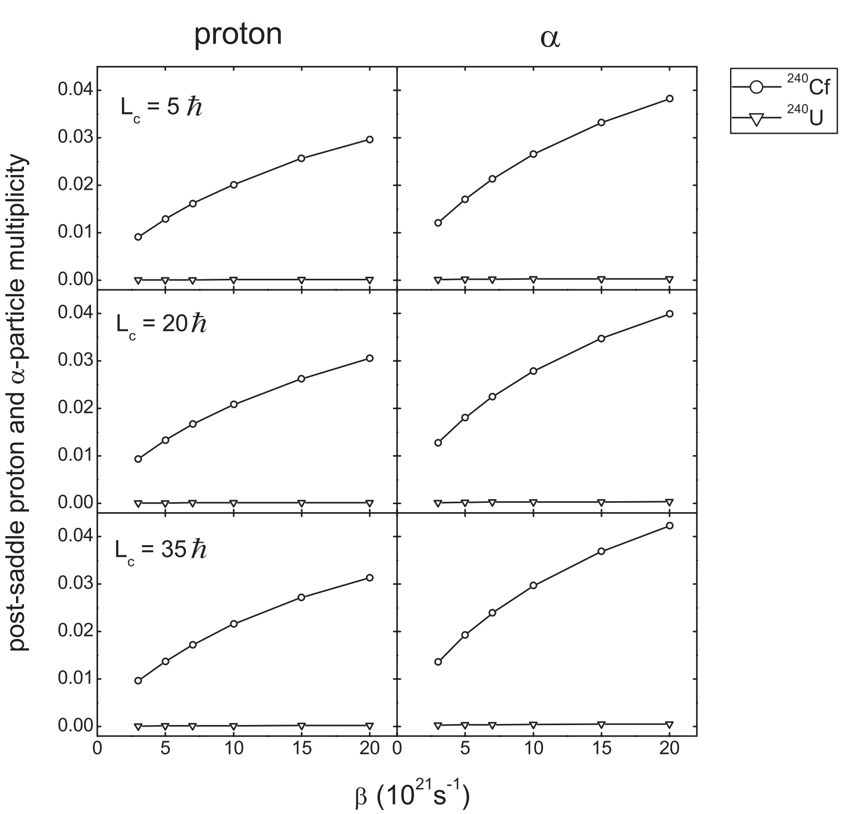

FIG. 2. Same as Fig. 1, but for ^{240}Cf and ^{240}U.

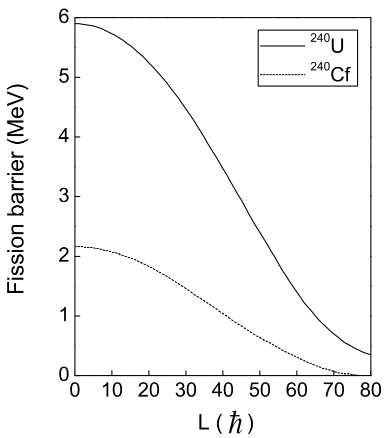

FIG. 3. Fission barriers of the two systems ^{240}Cf and ^{240}U at different angular momenta calculated with the method in Refs. [33,41].

unvarying with β, implying an insensitivity of the emissions of postsaddle protons and α particles to the postsaddle dissipation effect. This is in contrast to the ^{240}Cf case where, for example, at $E^* = 80$ MeV and $\ell_c = 5\ \hbar$, a rise of β from $3\ \times 10^{21}$ to 20×10^{21} s^{-1} makes M_p and M_α increase by 0.021 and 0.026. The increased magnitude in the postsaddle proton and α-particle multiplicity that arises from the postsaddle friction is very prominent, because it is larger by two orders of magnitude than that in the ^{240}U system. The main reason leading to such extremely small changes of M_p and M_α with β for the ^{240}U nucleus is the isospin effect. It is responsible for the fact that ^{240}U has a smaller neutron separation energy and a higher fission barrier than ^{240}Cf (see Fig. 3). A high fission barrier decreases the fission decay width and causes the compound system to stay for a longer time inside the saddle point, which in turn provides more time for particle emission. Calculations show that for ^{240}U at $E^* = 80$ MeV and $\ell_c = 5\,\hbar$, about 5.81 neutrons are emitted prior to the saddle, which is by far greater than for ^{240}Cf which evaporates only 1.01 presaddle neutrons. Note that the emitted presaddle particles are a β-independent constant, because in our calculations, except for β, the presaddle friction strength is fixed and the initial conditions (excitation energy, angular momentum, etc.) that can affect the decay of excited compound nuclei are the same. Because of a rather strong presaddle neutron emission of the ^{240}U nucleus, a considerable part of the excitation energy of the compound nucleus has been carried away before saddle. This largely reduces the energy available for all postsaddle light particle emissions, including protons and α particles. Moreover, as far as the postsaddle particle decay channels of the ^{240}U system are concerned, its high isospin is also favorable to neutron decay rather than to proton and α decay. This also further reduces the postsaddle charged-particle emission. As mentioned before, a weak particle emission decreases the sensitivity to nuclear friction. A similar picture is also observed for the other two angular momenta $\ell_c = 20$ and $35\hbar$. Shown in Fig. 4 are the results evaluated at an excitation energy of 120 MeV. One can see the increment of excitation energy does not alter the sensitivity of protons and α particles to β for the high-isospin ^{240}U nucleus. Therefore, the calculation for ^{240}U demonstrates that for such a system with higher isospin, protons and α particles are not good observables for the postsaddle friction strength. This conclusion indicates that on the experimental side, populating a low-isospin compound system can significantly enhance the

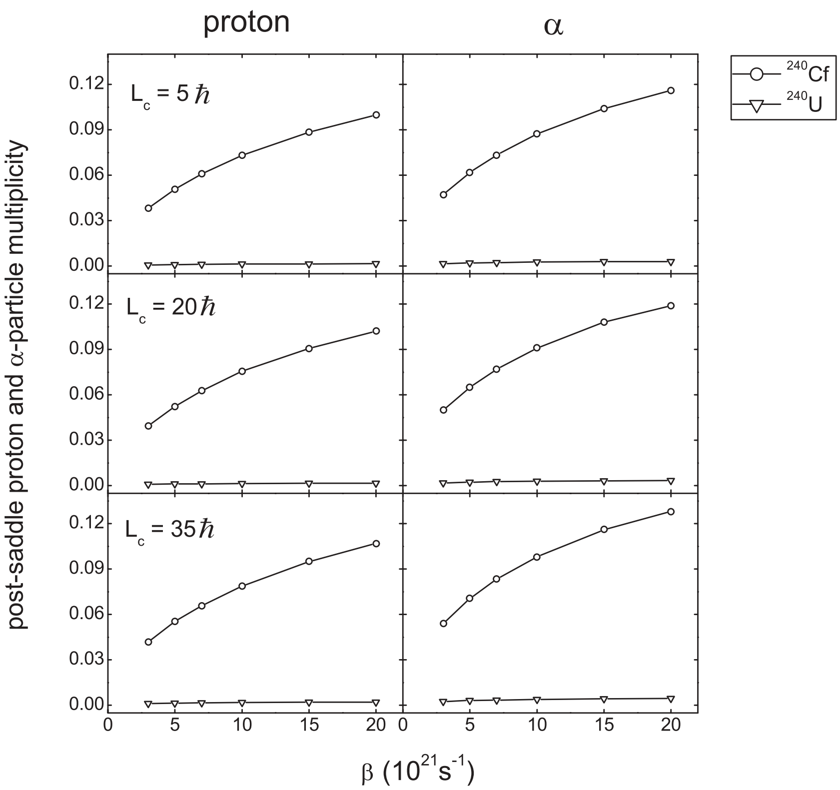

FIG. 4. Same as Fig. 2, but at excitation energy $E^* = 120$ MeV.

sensitivity of the postsaddle proton and α-particle emission to the postsaddle nuclear dissipation.

Finally, it should be mentioned that we also carried out the same calculations at other excitation energies and slightly different presaddle friction strengths. The results were analogous to those discussed above and hence not repeated here. Also, because these compound systems with different isospins can be produced by heavy-ion fusion reactions, current theoretical predictions concerning the isospin effects can therefore be directly compared with data available in future experiments.

In summary, using a Langevin model, we have studied isospin effects on light charged particles as probes of the postsaddle dissipation strength. We have shown that with increasing isospin of the fissioning systems, the sensitivity of the postsaddle proton and α-particle multiplicity to the postsaddle dissipation strength decreases considerably. Furthermore, we find that the emissions of postsaddle light charged particles are no longer sensitive to the postsaddle nuclear dissipation for the high-isospin ^{240}U system. These results suggest that to determine the postsaddle friction strength more accurately by measuring the multiplicities of prescission protons and α particles, it is best to yield heavy compound systems with low isospin.

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