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Surveying post-saddle nuclear dissipation with protons and α particles as probes*

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Abstract Using a Langevin model, we calculate post-saddle proton and α-particle multiplicities as a function of the post-saddle dissipation strength (β) for the heavy systems ^{234}Cf, ^{240}Cf, ^{246}Cf and ^{240}U. We find that, with increasing isospin of the system, the sensitivity of post-saddle light charged-particle multiplicities to β decreases considerably and, moreover, for ^{240}U the charged-particle multiplicities are no longer sensitive to β. These results suggest that in order to determine the post-saddle friction strength more accurately by measuring the multiplicities of pre-scission protons and α particles, it is best to populate those heavy compound systems with low isospin.

Key words nuclear dissipation, light charged-particle multiplicity, isospin effect

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1 Introduction

Studies on the nature and magnitude of nuclear dissipation have attracted considerable interest in recent years [1–6]. Nuclear dissipation delays the fission process and results in enhanced pre-scission light particle emission and a large evaporation residue cross section relative to that predicted by standard statistical models [7]. Recent works have reported a good determination for the pre-saddle dissipation strength either by analyzing new experimental observables [4, 6, 8, 9] or by model simulations based on the Langevin equation [10]. By contrast, little attention has so far been paid to how to accurately determine the post-saddle friction strength. Light particles can be evaporated during the entire fission process, and the post-saddle contribution to the enhanced pre-scission particle emission rises rapidly with increasing system size owing to an increment of the saddle-to-scission path [11]. Therefore, studying the dynamical particle emission in very heavy fissioning systems can provide a sensitive method to determine the post-saddle friction strength [7]. On the experimental side, light particles are considered to be a main probe for the post-saddle dissipation effects. In addition, the pre-scission proton and α-particle multiplicity can be easily extracted by a procedure of the fit of the three source models, i.e. a compound nucleus source and two fission fragment sources [12]. So, apart from neutrons [13, 14], light charged particles (see, e.g., [15–18]) are also widely employed by experimentalists to gain information regarding nuclear dissipation.

The present work surveys the favorable experimental conditions through which the post-saddle dissipation effects can be better revealed with the multiplicity of protons and α particles. In addition, it was noted recently that isospin has a significant effect on the fission observables sensitive to pre-saddle nuclear dissipation [9]. In this context, to facilitate experimental exploration, we will investigate the isospin effects on light charged particles as probes of the post-saddle nuclear dissipation strength.

2 The Langevin model

Here we briefly describe the combined Langevin equation and a statistical decay model (CDSM). For more details, see Ref. [7]. The dynamical part of the CDSM model is described by the Langevin equation which is expressed by the free energy F. In the Fermi

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gas model F is related to the level density parameter $a(q)$ [19] by

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

where $V(q)$ is the potential energy, T is the nuclear temperature.

The one-dimensional overdamped Langevin equation reads

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

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. 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 which drops out of the overdamped equation. $\Gamma(t)$ is a time-dependent stochastic variable with a Gaussian distribution. Its average and correlation function are written as

$$\langle\Gamma(t)\rangle=0,$$

$$\langle\Gamma(t)\Gamma(t')\rangle=2\delta(t-t'). \tag{4}$$

The potential energy $V(Z,A,L,q)$ is obtained from the finite-range liquid-drop model [20, 21]

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

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. a_2, c_3, k, and c_r are parameters not related to q [7].

After the fission probability flow over the fission barrier attains its quasi-stationary 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 model 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 $(\mathrm{n},\mathrm{p},\alpha)$ and giant dipole resonance γ decay are given by the parametrization of Blann [22] and Lynn [23], respectively.

3 Numerical results and discussion

In this work we select four heavy fissioning nuclei ^{234}Cf, ^{240}Cf, ^{246}Cf, and ^{240}U. Their isospin values (N/Z) are 1.39, 1.45, 1.51, and 1.61, respectively. To accumulate sufficient statistics, 10^7 Langevin trajectories are simulated. In addition, in order to better survey the evolution of the post-saddle charged particles with the post-saddle friction strength (β), in the calculations the post-saddle friction is chosen here as (3, 5, 7, 10, 15 and 20) $\times10^{21}$ s^{-1} whereas the pre-saddle friction strength is fixed at 3 $\times10^{21}$ s^{-1}, a value that is consistent with experimental analyses and theoretical estimates [4, 6, 7, 9].

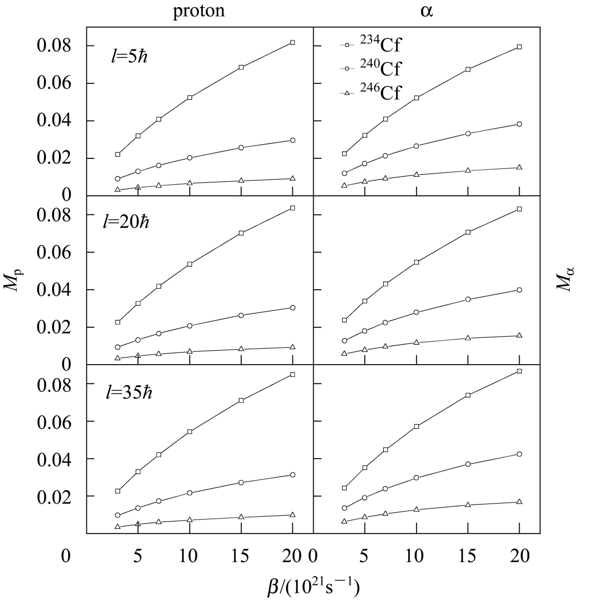

Fig. 1. The multiplicity of post-saddle protons (left column) and α particles (right column) of the fissioning systems ^{234}Cf, ^{240}Cf and ^{246}Cf as a function of the post-saddle dissipation strength (β) at excitation energy $E^*=$ 80 MeV and three angular momenta $\ell=5\hbar$ (top panel), $20\hbar$ (middle panel) and $35\hbar$ (bottom panel).

Figure 1 shows post-saddle proton (M_p) and α-particle (M_α) multiplicities of three Cf isotopes versus β at excitation energy $E^*=80$ MeV for the three angular momenta $\ell=5\hbar$, $20\hbar$ and $35\hbar$. We notice two typical features from this figure. The first feature is that low isospins can amplify the effects of the post-saddle nuclear dissipation on the particle evaporation. The physical mechanism for this feature is the following. With increasing isospin of the fissioning systems the neutron separation energies are lowered. This favors the neutron emission. Our calculations show that ^{246}Cf evaporates the most pre-saddle neutrons whereas those for ^{234}Cf are the least. Furthermore, as far as the three Cf isotopes are concerned, the isospin effects lead to more post-saddle neutron emissions in ^{246}Cf relative to those in ^{240}Cf and ^{234}Cf. Since there exists a competition between neutron and charged particle decay, this means that a strong neutron emission will suppress other decay channels. As a result, the number of post-saddle charged particles is greater for ^{234}Cf than for ^{240}Cf and ^{246}Cf. Another feature is that the variations of M_p and M_α with β have a marked difference for the three Cf systems, and these differences become smaller with increasing isospin of the Cf system. Taking the results at $\ell = 20\hbar$ as an illustration, the difference in M_p (M_α) for ^{234}Cf at $\beta = 20\times10^{21}\mathrm{s}^{-1}$ to that at $\beta = 3\times10^{21}\mathrm{s}^{-1}$ is 0.061 (0.059). Considering that the value of M_p (M_α) at a friction strength of $3\times10^{21}\mathrm{s}^{-1}$ is only 0.023 (0.024), the difference caused by the change in the friction strength is significant. Obviously the difference for ^{234}Cf is larger than that of ^{240}Cf for which the corresponding difference is 0.021 (0.027), and it further drops down to 5.9 (9.7) $\times10^{-3}$ 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 post-saddle friction strength decreases substantially at high isospins.

To further explore the isospin effect, we depict in Fig. 2 the calculations for an even higher isospin system ^{240}U. It is evident that its M_p and M_α show almost no variation with β, implying an insensitivity of the emission of post-saddle light charged particles to the post-saddle dissipation effect. This is in contrast with the ^{240}Cf case where, for example, at $E^* =$ 80 MeV and $\ell = 5\hbar$ a rise of β from 3 $\times10^{21}$ s^{-1} to 20 $\times10^{21}$ s^{-1} effects an increase of 0.021 (0.026) for M_p (M_α). The increases in M_p and M_α of ^{240}Cf which arise from the post-saddle friction are very prominent because they are larger by 2 orders of magnitude than those in the ^{240}U system. The main reason leading to such extremely small post-saddle proton and α-particle multiplicities of the ^{240}U system is due to 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 $\ell = 5\hbar$ about 5.81 neutrons are emitted prior to the saddle, which is far greater than for ^{240}Cf which evaporates only 1.01 pre-saddle neutrons. Note that the emitted pre-saddle particles are a β-independent constant since in our calculations,

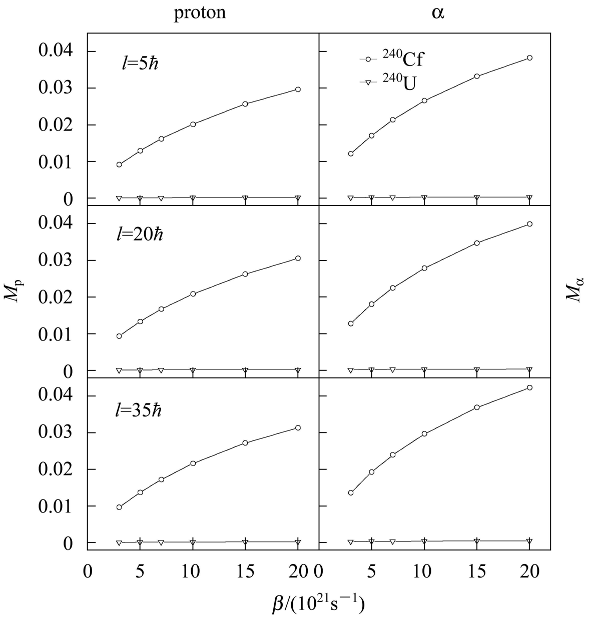

Fig. 2. Comparison of the multiplicity of post-saddle protons (left column) and α particles (right column) between the two fissioning systems ^{240}Cf and ^{240}U as a function of the post-saddle dissipation strength (β) at excitation energy $E^* = 80$ MeV and three angular momenta $\ell = 5\hbar$ (top panel), $20\hbar$ (middle panel) and $35\hbar$ (bottom panel).

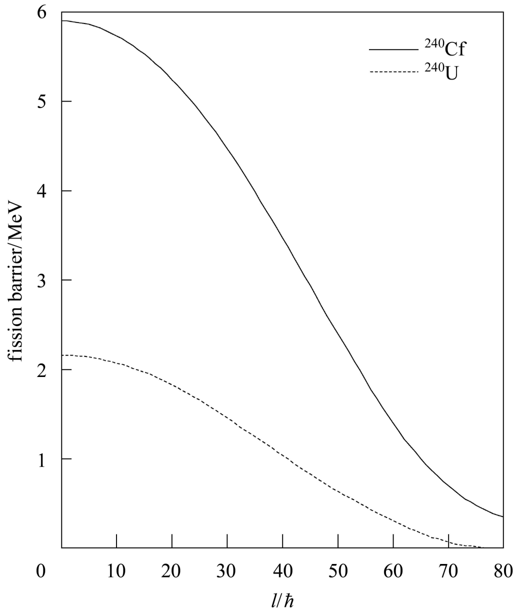

Fig. 3. Fission barriers of the two compound systems ^{240}Cf and ^{240}U at different angular momenta calculated with the method in Refs. [7, 24].

except for β, the pre-saddle friction strength is fixed and the initial conditions (excitation energy, angular momentum, etc.) that can affect the decay properties of an excited compound nucleus are the same. Because of the rather stronger pre-saddle neutron emission of the ^{240}U nucleus, a considerable part of the excitation energy of the compound nucleus is carried away before the saddle. This largely reduces the energy available for all post-saddle light particle emissions including protons and α particles. Moreover, as far as the post-saddle 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 further reduces the post-saddle 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 $\ell = 20\hbar$ and $35\hbar$. 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 post-saddle friction strength. This conclusion indicates that, on the experimental side, populating a low-isospin compound system can significantly enhance the sensitivity of the proton and α-particle emission to the post-saddle nuclear dissipation. As these compound systems with different isospins can be produced by heavy-ion fusion reactions, current theoretical predictions concerning the isospin effects could therefore be directly compared with the data available in future experiments.

Finally, it should be mentioned that we also carried out the same calculations at other excitation energies and slightly different pre-saddle friction strengths. The results were analogous to those discussed above and are hence not repeated here.

4 Conclusions

In conclusion, based on a Langevin equation coupled with a statistical decay model we have studied isospin effects on protons and α particles as probes of the post-saddle dissipation strength. It is shown that with increasing isospin of the fissioning systems, the sensitivity of the post-saddle light charged particles to the post-saddle dissipation decreases considerably. Furthermore, it is found that, for the high-isospin ^{240}U system, the emissions of protons and α particles are no longer sensitive to the strength of the post-saddle dissipation. These results suggest that, on the experimental side, to obtain more accurate information on the post-saddle dissipation strength by measuring the pre-scission proton and α-particle multiplicity of heavy nuclei, it is best to populate compound systems with low isospin.

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