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Surveying the role of excitation energy in probing nuclear dissipation*

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Abstract A dynamical Langevin model is employed to calculate the excess of the evaporation residue cross sections of the ^{194}Pb nucleus over that predicted by the standard statistical model as a function of nuclear dissipation strength. It is shown that large excitation energy can increase the effects of nuclear dissipation on the excess of the evaporation residues and the sensitivity of this excess to the dissipation strength, and that more higher excitation energies have little contribution to further raising this sensitivity. These results suggest that on the experimental side, producing those compound systems with moderate excitation energy is sufficient for a good determination of the pre-saddle nuclear dissipation strength by measuring the evaporation residue cross section, and that forming an extremely highly excited system does not considerably improve the sensitivity of evaporation residues to the dissipation strength.

Key words nuclear dissipation, excitation energy, evaporation residue cross section, Langevin equation

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1 Introduction

The determination of the pre-saddle nuclear dissipation strength is the focus of current experimental[1—5] and theoretical[6—12] studies on the fission of highly excited nuclei. Experimentally, heavy-ion induced fusion-fission reactions[4, 5, 13—15] are used to yield the compound nucleus (CN) with moderate excitation energy (generally less than 250 MeV). Also, in a recent extremely important work, compound systems were formed via proton-[16] and antiproton-induced[17, 18] reactions or peripheral relativistic heavy-ion collisions[19]. The compound nuclei produced in these reactions have very large excitation energies, up to 1000 MeV[16]. The reason for choosing the latter experimental approaches is based on the assumption that high excitation energy can significantly increase the transient effects on the fission observables and hence favor the survey of transient effects which arise from the pre-saddle friction. Although many authors have successfully analyzed the data on light particle multiplicities[7, 13], evaporation residue cross sections[7, 14, 15, 20] and its spin distributions[5, 21], fission probabilities[16], and widths of the fission fragment charge distributions[1, 19] with Langevin models or modified statistical models, very little attention has been paid to the role of experimental conditions, e.g. the excitation energy of the system, in revealing the pre-saddle dissipation effects.

To facilitate experimental exploration and to obtain a better theoretical understanding of the role of excitation energy in probing the pre-saddle dissipation strength, in this paper we make a detailed calculation for the evolution of the sensitivity of evaporation residues to the nuclear dissipation strength with excitation energy by the Langevin equation.

2 Theoretical model

A combination of a dynamical Langevin equation and a statistical model (CDSM)[6] is utilized to compute the evaporation residue cross section. Here a brief overview of the model is given. The dynamical part of the CDSM model is described by the Langevin equation which is driven by the free energy F. In the

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Fermi gas model F is related to the level density parameter $a(q)$[22] by

$$F(q,T)=V(q)-a(q)T^2\,, \qquad (1)$$

where $V(q)$ is the fission potential and T is the nuclear temperature.

The one-dimensional overdamped Langevin equation reads

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

where q is the dimensionless fission coordinate and is defined as half the distance between the center of masses 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

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

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

$$\langle\varGamma(t)\rangle=0$$

$$\langle\varGamma(t)\varGamma(t')\rangle=2\delta(t-t')\,. \qquad (4)$$

The potential energy $V(Z,A,L,q)$ is obtained from the finite-range liquid-drop model[23, 24]

$$V(A,Z,L,q)=a_2\left[1-k\left(\frac{N-Z}{A}\right)^2\right]A^{2/3}[B_{\mathrm{s}}(q)-1]+ c_3\frac{Z^2}{A^{1/3}}[B_{\mathrm{c}}(q)-1]+c_{\mathrm{r}}L^2A^{-5/3}B_{\mathrm{r}}(q)\,, \qquad (5)$$

where $B_{\mathrm{s}}(q)$, $B_{\mathrm{c}}(q)$ and $B_{\mathrm{r}}(q)$ 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. In our calculations, we take them according to Ref. [7].

After the fission probability flow over the fission barrier attains its quasi-stationary value, the decay of compound systems is described by a statistical model and it is called the statistical part of the CDSM. In the CDSM, 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 $(\mathrm{n},\mathrm{p},\alpha)$ are given by the parametrization of Blann[25].

3 Results and discussion

In this work, to accumulate sufficient statistics, 10^7 Langevin trajectories are simulated. Additionally, to better investigate the sensitivity of evaporation residues to the friction strength (β) within the saddle point, in the calculations β is chosen here as (3, 5, 7, 10, 15 and 20) $\times10^{21}$ s^{-1} throughout the fission process.

Owing to the nuclear dissipation, fission is delayed by about 10^{-20} s in which light particles could be emitted. This results in a deviation of the measured evaporation residue cross section from that predicted by the standard statistical model. Furthermore, the magnitude of the deviation is extremely sensitive to the strength of the nuclear dissipation. Thus, studying this deviation can provide a method of determining β. The present work surveys the role of excitation energy in probing the dissipation effects prior to fission. To this end, we adopt a definition similar to that suggested by Lazarev, Gontchar and Mavlitov[26], and define the relative excess of evaporation residues calculated by taking into account the dissipation and fluctuations of collective nuclear motion over its standard statistical-model value,

$$\sigma_{\mathrm{ER}}^{\mathrm{excess}}=\frac{\langle\sigma_{\mathrm{ER}}^{\mathrm{dyn}}\rangle-\langle\sigma_{\mathrm{ER}}^{\mathrm{SSM}}\rangle}{\langle\sigma_{\mathrm{ER}}^{\mathrm{SSM}}\rangle}, \qquad (6)$$

and a similar excess of the calculated average pre-saddle neutron multiplicities:

$$n_{\mathrm{gs}}^{\mathrm{excess}}=\frac{\langle n_{\mathrm{gs}}^{\mathrm{dyn}}\rangle-\langle n^{\mathrm{SSM}}\rangle}{\langle n^{\mathrm{SSM}}\rangle}. \qquad (7)$$

For the heavy nucleus ^{194}Pb, the emission of light charged particles is much smaller than the neutron emission[7], so in the following our emphasis is placed on neutrons.

One can see two essential features from Fig. 1, where the excess of evaporation residues ($\sigma_{\mathrm{ER}}^{\mathrm{excess}}$) as a function of friction strength (β) at angular momentum $\ell=70\hbar$ and at initial excitation energies of $E^*=$ 80 MeV, 120 MeV, 180 MeV is shown. The first feature is that the magnitude of the excess increases with increasing excitation energy; that is, the dissipation effects on this excess become stronger at high excitation energy. A physical understanding of the excitation energy dependence comes from the dependence of pre-saddle neutrons on the excitation energy. As is well known, the destiny of a compound nucleus as fission or surviving as an evaporation residue is decided within the barrier. The emitted pre-saddle neutron numbers have an important effect on this decision.

Excitation energies, fission barriers and dissipation strengths are the three main factors that influence the pre-saddle neutrons. For a given CN spin, the fission barrier is the same for different CN initial energies. This means that the difference in $\sigma_{\rm gs}^{\rm excess}(\beta)$ for three E^* is due to the effect of the excitation energy. Large excitation energies shorten the particle evaporation time, leading to an evident role of nuclear dissipation in the pre-saddle particle multiplicity. This can be seen from Fig. 2 where the effects of excitation energy on the dependence of the excess of pre-saddle neutrons ($n_{\rm gs}^{\rm excess}$) on the dissipation strength are presented. Fig. 2 indicates that the larger the excitation energy, the larger effect of the nuclear dissipation on the pre-saddle neutrons. That is to say, compared with low excitation energies, high energies enhance the pre-saddle neutrons, implying that the reduction of the fission widths due to dissipation makes a more noticeable change in $n_{\rm gs}^{\rm excess}$. Consequently, the effect of slowing down of the fission process caused by dissipation is clearly manifested as a large increase of the evaporation residue cross section at high excitation energies. Therefore, Fig. 1 shows that if we use the evaporation residue cross section as an observable to extract information on pre-saddle dissipation effects, then the condition of high excitation energies is favorable for an experimental survey for the nuclear dissipation effects.

Another feature is the rising speed of $\sigma_{\rm ER}^{\rm excess}$ with increasing β which reflects the sensitivity of the excess of the evaporation residue to the variation of the friction strength. The excitation energy effects on this sensitivity can be observed from Fig. 1. There, as β varies from 3×10^{21} s^{-1} to 20×10^{21} s^{-1}, $\sigma_{\rm ER}^{\rm excess}$ changes by 112.9% for $E^*=80$ MeV, a value that is smaller than the one calculated at $E^*=120$ MeV where the changed magnitude is 127.2%. However, further raising the excitation energy up to 180 MeV, the corresponding change in $\sigma_{\rm ER}^{\rm excess}$ only arrives at 135.0%. These numerical values clearly illustrate that high E^* can enhance the sensitivity of $\sigma_{\rm ER}^{\rm excess}$ to the variation of β. This is due to a stronger particle emission at high excitation energies. Under these circumstances, the magnitude of evaporation residues mainly depends on the nuclear dissipation effects, which decrease the fission decay width and hinder the fission process, and hence increase the particle emission. Fig. 2 demonstrates that the pre-saddle neutrons are affected more strongly by the dissipation effects at high energies, and this results in a stronger sensitivity of $\sigma_{\rm ER}^{\rm excess}$ to the change of β compared with the case of low energies. Besides, from Fig. 2 it is easily noticed that the gap of $n_{\rm gs}^{\rm excess}$ between 80 MeV and 120 MeV is greater than that between 120 MeV and 180 MeV although the latter has a much higher starting point in excitation energy and a much larger change in the excitation energy of the CN system. In particular, at $E^*=80$ MeV the excess of pre-saddle neutrons $n_{\rm gs}^{\rm excess}$ increases by 107.1% as β increases from 3×10^{21} s^{-1} up to 20×10^{21} s^{-1}. For $E^*=120$ MeV this rise becomes 116.0%. As $E^*=180$ MeV the rising value is only 118.0%. As a result of particle emission, the increasing magnitude of the sensitivity of $\sigma_{\rm ER}^{\rm excess}$ to the change of β decreases as E^* increases from 80 MeV to 120 MeV relative to the situation that E^* increases from 120 MeV to 180 MeV.

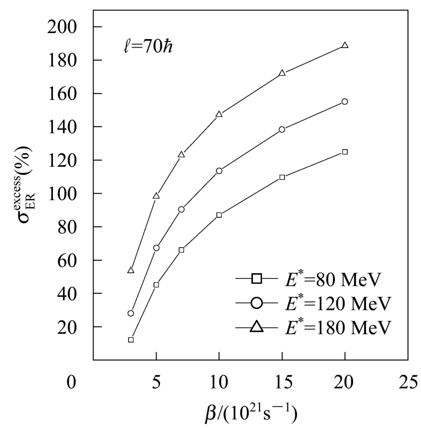

Fig. 1. Dynamical excess of the evaporation residue cross section of the ^{194}Pb system relative to that of the standard statistical model as a function of dissipation strength at angular momentum $\ell=70\hbar$ and three excitation energies $E^*=80$, 120 and 180 MeV.

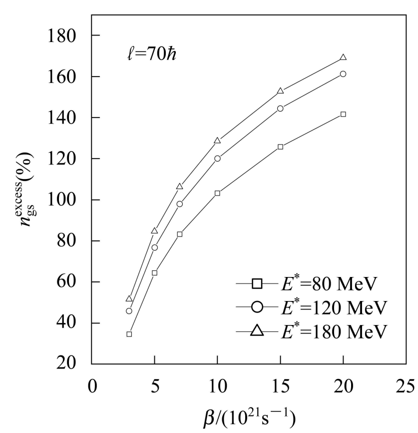

Fig. 2. Dynamical excess of the pre-saddle neutrons of the ^{194}Pb system relative to that of the standard statistical model as a function of dissipation strength at angular momentum $\ell=70\hbar$ and three excitation energies $E^*=80$, 120 and 180 MeV.

An interpretation of this point is that after the excitation energy of the system reaches a relatively large value, the pre-saddle neutrons are little influenced at even larger energies. This implies that although proton- and anti-proton induced GeV reactions or peripheral relativistic heavy-ion collisions can deposit more energy in a CN system than heavy-ion fusion reactions, the extremely high excitation energy possibly does not appreciably increase the sensitivity of evaporation residues to the change of the friction strength.

It is worth mentioning that at other nuclear spins such as $\ell = 50\hbar$, the conclusions derived are analogous and hence they are not repeated here. Also, by means of different combinations of projectiles and targets, heavy compound nuclei with different excitation energies but with the same spin can be produced in experiments. Therefore, our theoretical predictions can be directly compared with data available in the future.

4 Summary

In summary, based on the Langevin model we investigate the role of the excitation energy in probing the pre-saddle nuclear dissipation strength. It is found that a large excitation energy can clearly amplify the dissipation effects on the excess of the evaporation residues and increase its sensitivity to the dissipation strength, and that the increase of this sensitivity to the dissipation strength is reduced at larger excitation energy. These results suggest that on the experimental side, for a good determination for the friction strength inside the saddle point through the measurement of the evaporation residue cross sections, it is enough to use those compound systems with moderate excitation energy that can be provided with a heavy-ion fusion reaction approach, and that those experimental avenues that are employed to yield extremely large excitation energy do not significantly increase the sensitivity of the evaporation residue cross section to the friction strength.

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