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Influence of angular momentum on evaporation residue cross section as a probe of nuclear dissipation*

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Abstract By calculating the excess of the evaporation residue cross sections of the ^{200}Pb nucleus over that predicted by the standard statistical model as a function of nuclear viscosity coefficient using a Langevin equation combined with a statistical decay model, it is found that high angular momentum not only amplifies the dissipation effects on the excess of the evaporation residue cross sections, but also considerably increases the sensitivity of this excess to the nuclear viscosity coefficient. These results suggest that on the experimental side, to accurately obtain the information of nuclear dissipation inside the saddle point by measuring the evaporation residue cross section, it had better populate those compound systems with high spins.

Key words nuclear dissipation, evaporation residue cross section, angular momentum, Langevin equation

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1 Introduction

Nuclear dissipation is an interesting subject in experimental and theoretical investigations on the decay of hot nuclei[1—21]. Measurement of light particle multiplicity in the fission process shows that dissipation enhances pre-scission particle multiplicity relative to expectations based on the statistical model description[1, 7—9]. Fröbrich et al. have employed Langevin equations[14] to reproduce successfully a lot of experimental data on pre-scission particle multiplicity and evaporation evaporation cross sections for a wide range of excitation energies, angular momenta and fissilities. Compared with the numerous measurements of particle emission, only very few measurements on evaporation residue cross sections have been carried out to understand the fission hindrance phenomenon[2, 22, 23]. Since pre-scission particles stem from the pre-saddle and saddle-to-scission emission, it is difficult to determine dissipation strength inside the saddle point merely using the particle multiplicity. It was found by Fröbrich et al.[24] that evaporation residues are a more sensitive probe of nuclear dissipation than light particles. Moreover, some recent experiments used proton-[3] and antiproton-induced[5, 6] reactions or peripheral relativistic heavy-ion collisions[4] to yield those compound systems with rather small spin because it was assumed that a small nuclear spin can reduce the effects arising from the angular momentum and this possibly is favorable for the study of dissipation effects.

To better instruct experimental exploration and obtain a completely theoretical understanding for the roles of angular momentum in probing pre-saddle nuclear dissipation strength, in the present work we make a detailed calculation for the evolution of the sensitivity of evaporation residues to nuclear dissipation strength with angular momentum by the Langevin equation.

2 Theoretical model

A combined dynamical Langevin equation and a statistical model (CDSM)[14] are employed to study the evaporation residues. Here a brief introduction to 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 Fermi gas model F is related to the level density parameter $a(q)$[25] by

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

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

The one-dimensional overdamped Langevin equation reads

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

where q is the dimensionless fission coordinate and is defined as the 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 viscosity coefficient. 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 Gaussian distribution. Its average and correlation function are written as

$$\begin{gathered}\langle\Gamma(t)\rangle=0,\\ \langle\Gamma(t)\Gamma(t')\rangle=2\delta(t-t')\ .\end{gathered} \tag{4}$$

The potential energy $V(Z,A,L,q)$ is obtained from the finite-range liquid-drop model[26, 27]

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

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. [14].

After 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 statistical part of CDSM. In the CDSM model, 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) are given by the parametrization of Blann[28].

3 Results and discussions

In this work, to accumulate sufficient statistics 10^7 Langevin trajectories are simulated. In addition, to better study the sensitivity of evaporation residues to the viscosity coefficient (β) within the saddle, in the calculations β is respectively chosen as 3, 5, 7, 10, 15 and 20×10^{21} s^{-1} throughout the fission process.

As nuclear dissipation causes the excess of the evaporation residue cross section over that predicted by the standard statistical model and this excess is a function of dissipation strength, thus this excess is extremely sensitive to the dissipation strength. Preset work surveys angular momentum effects on this sensitivity. For this aim, we adopt a definition similar to that suggested by Lazarev, Gontchar and Mavlitov[29]. We define the relative excess of evaporation residues calculated by taking into account dissipation and fluctuations of collective nuclear motion over its standard statistical-model value,

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

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

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

For the heavy nucleus ^{200}Pb, the emission of charged particles is much smaller than the neutrons[14], so in the following our emphasis is placed on neutrons.

Figure 1 shows the excess of evaporation residues ($\sigma_{\mathrm{gs}}^{\mathrm{excess}}$) as a function of viscosity coefficient (β) at excitation energy $E^*=100$ MeV and three critical angular momenta $\ell_{\mathrm{c}}=30\hbar$, $50\hbar$ and $70\hbar$. Two essential features are observed. The first one is that with increasing the angular momentum, the magnitude of the excess increases, i.e., dissipation effects on this excess become stronger at a high angular momentum. A physical understanding for the angular momentum dependence arises from the dependence of pre-saddle neutron emission and fission barrier on the angular momentum. The compound nucleus undergoing fission or surviving as an evaporation residue is decided mainly within the saddle point. Pre-saddle emitted neutrons have an important effect on this decision. The main factors affecting the pre-saddle neutron emission include the excitation energy, the fission barrier and the dissipation strength. Thus to make the role of nuclear dissipation in the particle emission becomes prominent, lowering the effects of formal two factors is desirable. Excitation energy affects the emission time of particles. The higher the excitation energy, the more the neutrons are emitted. As for the fission barrier, its roles in influencing the pre-saddle particles are dual. A high fission barrier not only decreases the fission decay width, but also renders the compound system to stay a longer time inside the saddle point. The former increases the probability of particle evaporation, and the latter means that more time can be available for particle emission. Obviously, both aspects lead to an increase of the survival probability of evaporation residues. This means that a high excitation energy and fission barrier will mask the role of nuclear dissipation in enhancing the pre-saddle particle evaporation more strongly as compared to the case of a low excitation energy and fission barrier and, correspondingly, in the increase of evaporation residues. Note that the shell effects are washed out at the present excitation energy of 100 MeV. Fig. 2 displays the excess of pre-saddle neutrons ($n_{\rm gs}^{\rm excess}$) at three different angular momenta as a function of dissipation strength. As is seen, $n_{\rm gs}^{\rm excess}$ increases with increasing spin, i.e., the higher the nuclear spin, the larger effect the nuclear dissipation has on the pre-saddle neutrons. It is because a high spin carries away a larger energy from the excitation energy with the form of rotational energy (this part of excitation energy is not used for the particle emission) and lowers the fission barrier, which greatly weakens the influences of excitation energy and fission barrier on the pre-saddle particles as mentioned above, and thereby results in an evident role of nuclear dissipation in the pre-saddle particle emission. This implies that at low nuclear spin the reduction of the fission widths due to dissipation makes less noticeable change in $n_{\rm gs}^{\rm excess}$ in comparison with the case of high spin. 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 a high spin. Therefore, Fig. 1 indicates that when using evaporation residue cross sections as a tool to survey pre-saddle nuclear dissipation effects, it is best to populate the compound system with a high spin.

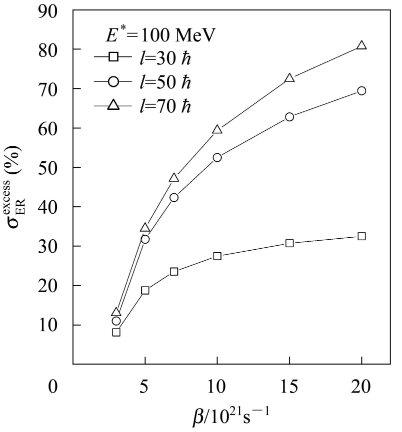

Fig. 1. Excess of evaporation residues of ^{200}Pb as a function of viscosity coefficient at excitation energy $E^* = 100$ MeV and three angular momenta $\ell = 30\hbar$, $50\hbar$ and $70\hbar$.

Another feature seen from Fig. 1 is that the rising speed of $\sigma_{\rm ER}^{\rm excess}$ with increasing β has a rather large difference for three angular momenta, namely angular momentum affects strongly the sensitivity of the excess of evaporation residues to the variation of viscosity coefficient. Specially speaking, at $\ell_{\rm c} = 30\hbar$, $\sigma_{\rm ER}^{\rm excess}$ changes by 24.4% as β varies from $3\times10^{21}{\rm s}^{-1}$ to $20\times10^{21}{\rm s}^{-1}$. The change is 57.4% for $\ell_{\rm c} = 50\hbar$. As $\ell_{\rm c}$ is $70\hbar$, the corresponding change rises up to 67.7%. These numerical values clearly indicate that a larger nuclear spin enhances the sensitivity of the excess of evaporation residues to the variation of dissipation strength. The physical mechanism for this phenomenon is that for a large spin, fission probability increases quickly and particle emission is reduced considerably. Hence, under this circumstance, the magnitude of evaporation residues, to a large extent, depends on the nuclear dissipation effects which lowers the fission decay width and delays the fission process. Both enhance particle emission. Fig. 2 illustrates that at high spin dissipation effects on pre-saddle neutrons become more important relative to that at low spin. One can easily observe that $n_{\rm gs}^{\rm excess}$ differs much at three angular momenta. At $\ell_{\rm c} = 30\hbar$ the excess of pre-saddle neutrons $n_{\rm gs}^{\rm excess}$ increases 46.9% as β changes from 3×10^{21} ${\rm s}^{-1}$ to 20×10^{21} ${\rm s}^{-1}$. For $\ell_{\rm c} = 50\hbar$ this change becomes 68.4%. As $\ell_{\rm c} = 70\hbar$ the changed magnitude attains 97.9%. As a result of particle emission, at a high spin the excess of evaporation residues is more sensitive to the change of the dissipation strength compared with the case of a low spin (see Fig. 1). Therefore, the second feature appearing in Fig. 1 also implies that high-spin condition can provide a more precise determination about the strength of nuclear friction inside the barrier.

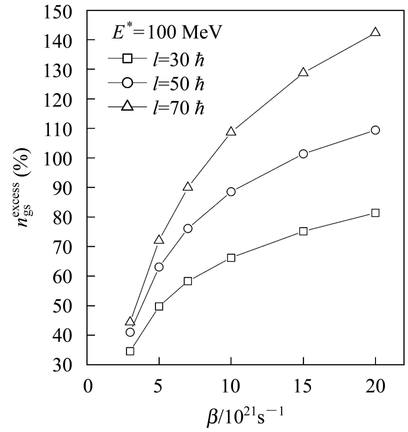

Fig. 2. Excess of pre-saddle neutrons ^{200}Pb as a function of viscosity coefficient at excitation energy $E^* = 100$ MeV and three angular momenta $\ell = 30\hbar$, $50\hbar$ and $70\hbar$.

Finally, it should be mentioned that we also carry out the same calculations at other excitation energies and find that the conclusions are similar and hence not repeated here.

4 Summary

In summary, using the Langevin equation we exploit the roles of nuclear spin in probing pre-saddle nuclear dissipation strength. The calculated results show that a high spin not only amplifies the dissipation effects on the excess of the evaporations residues but also significantly increases the sensitivity of this excess to the dissipation strength. These results suggest that on the experimental side, to accurately determine dissipation strength inside the saddle point through the measurement of evaporation residue cross sections, it had better produce those compound systems with high spin.

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