Langevin study of neutron emission in the reactions $^{16}O+^{181}Ta$ and $^{19}F+^{178}Hf$*

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Abstract The pre-scission neutrons measured in the reactions $^{16}O+^{181}Ta$ and $^{19}F+^{178}Hf$ are studied via a Langevin equation coupled with a statistical decay model. We find that because of the mass asymmetry of different entrance channels, the spin distributions of compound nuclei would be different, consequently, the measured neutrons in these two reactions would also different. This means that the entrance channel will affect the particle emission in the fission process of hot nuclei.

Key words pre-scission neutron multiplicity, entrance channel mass asymmetry, compound nucleus spin distribution, Langevin equation

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1 Introduction

Nuclear dissipation and its influences on the decay of hot nuclei are an interesting subject of current nuclear physics[1—10]. The fact that the enhanced number of the light particles[11] and giant dipole resonance γ rays[12, 13] prior to fission, as well as a large cross section for the evaporation residue[14, 15], exceed the estimation by the statistical model is usually imputed to the effects of nuclear dissipation. With this viewpoint, a great deal of experimental data, such as the particle multiplicity, the evaporation residue cross section, and etc., for many compound nucleus systems over a wide range of excitation energy and fissility have been understood within the framework of diffuse models[16—20]. Comparing with the numerous studies about the role of nuclear dissipation in explaining the enhancement of the emitted particles before fission, very little attention is paid to the entrance channel effect that possibly plays a role in understanding the phenomenon of the enhanced particle emission.

The Langevin model considers the time evolution of the fission decay width and contains a number of dynamical features in the decay of the hot compound nuclei, e.g. the angular momentum dependence of pre-saddle and saddle-to-scission time. These advantages have not been taken into account in the simple statistical model analysis. Thus, to extract a precise value of pre-saddle dissipation strength by comparing theoretical predictions with the experiment ones, using the Langevin model is certainly preferable than employing the statistical model which is modified to include dissipation effects. In this paper, we employ the Langevin model to analyze the newly measured data for neutron multiplicity[21], and consequently investigate the possible entrance channel effect on the pre-scission enhanced neutron emission.

2 The Langevin model

In this section, we briefly introduce the combined dynamical Langevin equation and the statistical decay model (CDSM). For more details, see Ref. [16]. The dynamical part of the CDSM model is described by the Langevin equation which 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 fission potential and T is the nuclear temperature. The level density parameter $a(q)$ is taken from the work of Ignatyuk et al[22].

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The one-dimensional overdamped Langevin equation reads as

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

where q is the dimensionless fission coordinate which is defined as half the distance between the center of mass 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

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

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

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

Here we have dropped terms that do not depend on the deformation coordinate. $B_{\mathrm{s}}(q)$, $B_{\mathrm{c}}(q)$ and $B_{\mathrm{r}}(q)$ are the surface, Coulomb, and rotational energy terms, respectively. a_2, c_3, k, and c_{r} are the parameters not related to q[16].

After the fission probability flow passing 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, 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 GDR γ decay are given by the parametrization of Blann[25] and Lynn[26], respectively.

3 Results and discussions

It has been found[16] that a special form of deformation-dependent friction is needed to simultaneously reproduce pre-scission particle multiplicity and survival probability for many fissioning systems. This form is given by

$$\beta(q)=\begin{cases}\beta_{0\mathrm{q}} & \text{if } q\leqslant q_{\mathrm{neck}},\\ \beta_{0\mathrm{q}}+\dfrac{\beta_{\mathrm{sc}}-\beta_{0\mathrm{q}}}{q_{\mathrm{sc}}-q_{\mathrm{neck}}}(q-q_{\mathrm{neck}}) & \text{if } q_{\mathrm{neck}}<q\leqslant q_{\mathrm{sc}}.\end{cases} \quad (6)$$

This kind of friction is weak for compact shapes. After the necking in is starting (at $q_{\mathrm{neck}}=0.6$), the friction is assumed to increases linearly up to the value of $\beta_{0\mathrm{q}}=30\ \mathrm{zs}^{-1}$ at scission (at $q_{\mathrm{sc}}=1.2$), with $1\ \mathrm{zs}=10^{-21}$ s. Such a kind of deformation-dependent friction is employed in the present calculation.

Note that in this model the pre-saddle friction strength $\beta_{0\mathrm{q}}$ is the only adjustable parameter. Although one believes that the pre-saddle friction strength is not strong in comparison with the one-body dissipation prediction, its specific value is controversial[2, 5, 13, 16, 27]. In this work the pre-saddle friction strength is determined by fitting the experimental data.

In Fig. 1, we shows the newly measured neutron multiplicity of ^{197}Tl which is produced in two mass asymmetric entrance channel reactions, i.e. $^{19}F+^{178}Hf$ and $^{16}O+^{181}Ta$[21]. As can be seen, the measured number of pre-scission neutrons in the former reaction is larger than that in the latter one, and the difference of the measured neutron multiplicities in the two reactions enhances with the increasing excitation energy of the compound nucleus (CN). In this figure, we also plot the result obtained by using the statistical model (i.e. without including nuclear dissipation effects). Clearly the calculations underestimate the data, indicating the necessity of introducing nuclear dissipation[11, 13, 16].

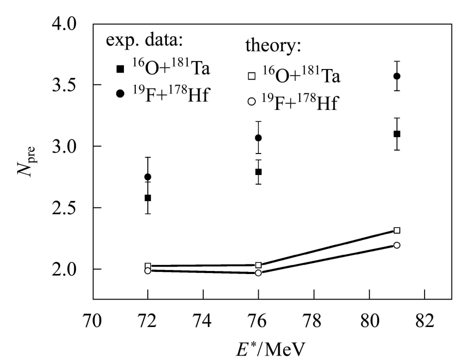

Fig. 1. The measured pre-scission neutrons in the reactions $^{16}O+^{181}Ta$ and $^{19}F+^{178}Hf$ as well as statistical model predictions at three excitation energies.

To better determine the magnitude of pre-saddle friction, we made a detailed calculation by taking a numbers of $\beta_{0\mathrm{q}}$ values. The results and the corresponding data are plotted in Fig. 2. From this figure, one sees that for $^{16}O + ^{181}Ta$, by adopting $\beta_{0\mathrm{q}} = 2\ \mathrm{zs}^{-1}$, a good description for the measured neutrons can be obtained. A slight increase of β_{0q}, for example $\beta_{0q}=2.5\ \mathrm{zs}^{-1}$, leads to an evident deviation from the data at excitation energies E^*=76 MeV and 81 MeV. This indicates that the calculated neutron multiplicity is very sensitive to the value of β_{0q}. However, $\beta_{0q}=2\ \mathrm{zs}^{-1}$ obviously underestimates the number of neutrons emitted in the ^{19}F+^{178}Hf reaction. In order to reproduce the neutron data, the magnitude of β_{0q} is at least larger than 3 zs^{-1}, particularly for the case at $E^*=81$ MeV.

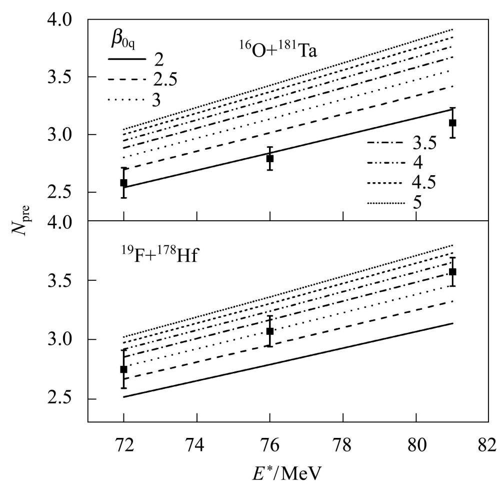

Fig. 2. The theoretical fit to the neutron multiplicity data (solid points with error bars) for two mass asymmetry reactions. Different lines correspond to different pre-saddle dissipation strengths (β_{0q}). The unit of β_{0q} is zs^{-1}. 1 zs $=10^{-21}$ s.

We notice that the two reactions can produce the same compound nuclei ^{197}Tl which have the same excitation energy. Since the decay properties of CN are mainly determined by its mass number, excitation energy and angular momentum, the measured pre-scission neutron yields are actually an averaged number of emitted neutrons for all the fission events weighted by the relevant partial waves. This means that the measured difference of neutron yields is actually related to the difference of the averaged fission angular momentum ($\bar{L}_{\rm fiss}$) contributing to the fission process in two reactions. The larger the $\bar{L}_{\rm fiss}$, the smaller number of the pre-scission neutrons. Although fission cross sections of the two reactions are not measured, the difference of $\bar{L}_{\rm fiss}$ in two reactions can still be obtained by surveying respective CN spin distributions. To be consistent with the real experimental measurement for neutrons, in the theoretical calculations, for each trajectory simulating the fission motion, an angular momentum $L=\hbar\ell$ is sampled from the CN spin distribution[16]

$$\frac{\mathrm{d}\sigma(\ell)}{\mathrm{d}\ell}=\frac{2\pi}{k^2}\frac{2\ell+1}{1+\exp[(\ell-\ell_{\rm c})/\delta\ell]}, \tag{7}$$

with which the fusion process is described. The final results are weighted over all the relevant partial waves; i.e., the spin distribution is used as the angular momentum weight function. The parameters $\ell_{\rm c}$ and $\delta\ell$ are, respectively, the critical angular momentum for the fusion and the diffuseness. It is found that these parameters for different systems follow an approximate scaling[16], namely, when $0<E_{\rm c.m.}-V_{\rm c}<120$ MeV

$$\ell_{\rm c}=\sqrt{A_{\rm P}A_{\rm T}/A_{\rm CN}}(A_{\rm P}^{1/3}+A_{\rm T}^{1/3})\times \left(0.33+0.205\sqrt{E_{\rm c.m.}-V_{\rm c}}\ \right), \tag{8}$$

and when $E_{\rm c.m.}-V_{\rm c}>$120 MeV, the term in the last bracket is taken to be 2.5. In Eq. (8), $A_{\rm T}$ and $A_{\rm P}$ represent the masses of the target and the projectile, respectively, and $A_{\rm CN}$ is the mass of compound nucleus. For the barrier $V_{\rm c}$, an ansatz is used, i.e., $V_{\rm c}=\dfrac{5}{3}c_3\dfrac{A_{\rm P}A_{\rm T}}{A_{\rm P}^{1/3}+A_{\rm T}^{1/3}+1.6}$ with $c_3=0.7053$ MeV. The diffuseness δl scales as

$$\delta l=\begin{cases}\left[(A_{\rm P}A_{\rm T})^{3/2}\times10^{-5}\right][1.5+0.02(E_{\rm c.m.}-V_{\rm c}-10)] \\ \quad\text{for } E_{\rm c.m.}>V_{\rm c}+10, \\ \left[(A_{\rm P}A_{\rm T})^{3/2}\times10^{-5}\right][1.5-0.04(E_{\rm c.m.}-V_{\rm c}-10)] \\ \quad\text{for } E_{\rm c.m.}<V_{\rm c}+10.\end{cases} \tag{9}$$

These scaling values are used in the present work. It should be mentioned that the general validity of Eqs. (7)—(9) has been widely tested by successfully fitting to the fusion cross sections[28, 29] and various fission observables, for instance the particle emission[30], the survival probability[19], and the kinetic energy distribution of fission fragments[31—33]. Thus, these formulae are utilized to evaluate the spin distribution of the compound nucleus ^{197}Tl produced in the reactions ^{19}F+^{181}Hf and ^{16}O+^{181}Ta. The calculated results are displayed in Fig. 3. As is known, in these reactions the fission cross section is just a small part of the fusion reaction cross section and the fission usually happens at the tail part of the spin distribution, because high spin lowers the fission barrier, that is favorable for the occurance of fission. From Fig. 3, one obviously sees that the CN spin distribution produced in ^{19}F+^{178}Hf is extended to a larger angular momentum domain than that produced in ^{16}O+^{181}Ta, and the spin distribution difference between the two reactions in the high-spin region becomes larger with increasing excitation energy. These observations demonstrate that there exists a larger $\bar{L}_{\rm fiss}$ in the ^{19}F+^{181}Hf reaction than in the ^{16}O+^{181}Ta reaction, implying a larger dissipation strength for the former reaction. This is because a phenomenol-

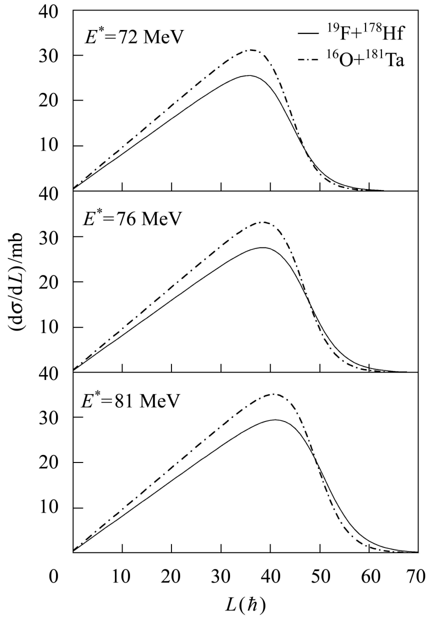

Fig. 3. Comparison of the spin distribution of the compound nucleus ^{197}Tl formed by the reactions $^{16}O+^{181}Ta$ and $^{19}F+^{178}Hf$ at three excitation energies.

ogical analysis[34] has shown that the pre-saddle dissipation strength depends not only on the deformation, but also on the angular momentum, and that a high angular momentum can raise the pre-saddle dissipation strength. In addition, the linear response theory[35, 36] also predicts that the dissipation strength could be much larger at a higher rotational frequency. One can easily find from Fig. 2 that a larger β_{0q} is indeed needed for explaining the data of the reaction $^{19}F+^{181}Hf$ compared to that of the reaction $^{16}O+^{181}Ta$. It is clear that a stronger dissipation delays the fission, provides more time for neutron emission and thus increases neutron multiplicity in the reaction $^{19}F+^{178}Hf$.

Because the difference of the CN spin distribution in the two reactions originates from the difference of entrance channel mass asymmetry, the present calculations actually illustrate that the entrance channel has an effect on the pre-scission neutron emission by affecting the dissipation property through the dependence of the dissipation strength on the angular momentum[34—36].

4 Summary

In conclusion, by comparing the measured neutrons in the fission process of $^{16}O+^{181}Ta$ and $^{19}F+^{178}Hf$ with our results in the framework of the Langevin model, we find that the difference of the measured neutrons originates from the spin distribution difference of the produced compound nucleus ^{197}Tl. This means that the entrance channel plays a role in affecting the pre-scission neutron emission.

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