Spallation reaction and the probe of nuclear dissipation with excitation energy at scission

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Abstract We study in the framework of the Langevin model the influence of initial excitation energy (E^*) of Hg compound nuclei (CNs) on the sensitivity of the excitation energy at scission (E^*_{sc}) to the nuclear friction strength (β). It is shown that the sensitivity is enhanced substantially with increasing E^*. Moreover, we find that the significant sensitivity of E^*_{sc} to β at high E^* is little affected by a marked difference in the neutron-to-proton ratio of a CN and in its size and fissility. Our findings suggest that, on the experimental side, a measurement of E^*_{sc} in energetic proton-induced spallation reactions can provide not only a sensitive but also a robust probe of nuclear dissipation in fission of highly excited nuclei. Further development of a suitable approach to spallation reaction is discussed.

Key words Spallation reaction, Nuclear dissipation, Excitation energy at scission

1 Introduction

In the past two decades[1-6], fusion fission reactions have been widely employed as a common approach to probing nuclear dissipation properties in fission. Despite the intensive efforts in both experimental analyses and theoretical calculations, the precise magnitude of nuclear friction in fission is still controversial and hotly debated[7-11]. This could come from a number of factors that affect the sensitivity of observables (such as particle multiplicity and evaporation residue cross section) to nuclear dissipation. Consequently, a large uncertainty in the extracted friction strength β is found. To stringently constrain the friction strength, it is urgent to develop new experimental methods and to select a suitable observable.

Different from heavy-ion fusions in which the formed compound nuclei (CNs) have a low excitation energy (<200 MeV) but a high angular momentum (up to 70$\hbar$). In contrast, CNs produced in spallation reactions induced by energetic protons[12,13] have high excitation energy (up to 1 GeV) and low angular momentum. When an excited CN evolves toward scission, light particles are evaporated, yielding a lower excitation energy at scission E^*_{sc}. A strong particle emission in the presence of nuclear friction leads to a much smaller E^*_{sc}. The quantity thus carries essential information of nuclear dissipation. In this work, we use E^*_{sc} to probe the nuclear dissipation.

Theoretically, we adopt the Langevin model to perform calculation of E^*_{sc} at various energies. The stochastic approach has been widely used to describe fission data at high energy[14], and it achieves an impressive success in reproducing various types of fission data[15-17].

2 Brief description of theoretical model

The model used here combines both the Langevin equation with a statistical decay model (CDSM). We refer the reader to Ref.[15] for more details. The dynamic part of CDSM is described by entropy. The one-dimensional overdamped Langevin equation is employed to perform the trajectory calculations:

$$\frac{dq}{dt}=\frac{T}{M\beta}\frac{dS}{dq}+\sqrt{\frac{T}{M\beta}}\Gamma(t). \tag{1}$$

Here q is the dimensionless fission coordinate and is defined as half the distance between the center of mass

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of the future fission fragments divided by the radius of the compound nucleus, M is the inertia parameter, and β is the dissipation strength. The temperature in Eq.(1) is denoted by T and $\Gamma(t)$ is a fluctuating force whose average and correlation function are $<\Gamma(t)>=0$ and $<\Gamma(t)\Gamma(t')>=2\delta(t-t')$, respectively. The driving force of the Langevin equation is calculated from the entropy:

$$S(q,E^*)=2\sqrt{a(q)[E^*-V(q)]}, \qquad (2)$$

where E^* is the total internal energy of the system, and $a(q)$ is deformation-dependent level density parameter, taken from the description by Ignatyuk *et al.*[18] and calculated using the formula given in Refs.[18,19]. Eq.(2) is constructed from the Fermi-gas expression with a finite-range liquid-drop potential $V(q)$ in the $\{c, h, \alpha\}$ parametrization[20,21]. The q-dependent surface, Coulomb, and rotation energy terms are included in the potential $V(q)$.

In the CDSM, light-particle evaporation is coupled to the fission mode by a Monte Carlo procedure. Particle emission width is given by Blan's formula[22].

The excitation energy at scission $E^*_{\rm sc}$ is determined by using energy conservation law

$$E^*=E^*_{\rm sc}+E_{\rm coll}+V(q)+E_{\rm evap}(t_{\rm sc}), \qquad (3)$$

where $E_{\rm coll}$ is the kinetic energy of the collective degrees of freedom, and $E_{\rm evap}(t_{\rm sc})$ is the energy carried away by all evaporated particles by the scission time $t_{\rm sc}$. The Eq.(3) has been demonstrated[23] to describe excellently the experimental $E^*_{\rm sc}$ for a great number of fissioning systems which cover a wide range of fissilities and CN mass regions.

The CDSM describes the fission process as follows. At early times, the decay of the system is modelled by means of the Langevin equation. After the fission probability flow over the fission barrier attains its quasistationary value, the decay of the compound system is described by a statistical branch. Prescission particle multiplicities are calculated by counting the number of corresponding evaporated particle events registered in the dynamic and statistical branch of the CDSM. To accumulate sufficient statistics, 10^7 Langevin trajectories are simulated.

3 Results and discussion

We show in Fig.1 $E^*_{\rm sc}$ as a function of β at several E^* and at $\ell_c=15\hbar$. One can see a weak dependence of $E^*_{\rm sc}$ on β at E^* = 100 MeV. Raising E^* (=350 MeV) yields a greater sensitivity of $E^*_{\rm sc}$ to β, and the sensitivity is further enhanced when E^* reaches 500 MeV. This finding clearly reveals a substantial increase in the sensitivity of $E^*_{\rm sc}$ to β at high energy.

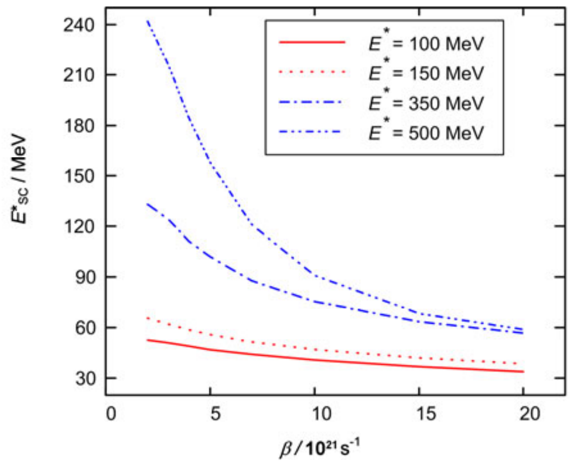

Fig.1 (Color online) $E^*_{\rm sc}$ *vs.* β curves at different initial excitation energies E^* and at critical angular momentum $\ell_c=15\hbar$ for compound systems ^{200}Hg.

It is the significant difference in prescission light particles at low and high energy that causes the difference in $E^*_{\rm sc}$ at different E^*. With increasing excitation energy, the particle evaporation time becomes short. In addition, those closed decay channels like light charged particles (LCPs) are opened at high energy, since more energy can be provided to help them overcome Coulomb emission barriers. The emission of LCPs carries away more energy from the decaying system, leaving a colder nucleus at scission.

Aside from initial excitation energy, the emitted particle number is another important factor that controls the magnitude of $E^*_{\rm sc}$. It has been known from earlier work[24] that the neutron-to-proton ratio (N/Z) of a CN has an appreciable influence on neutrons and LCPs. So, it is necessary to examine the robustness of the significant sensitivity of $E^*_{\rm sc}$ to β found at high energy, as shown in Fig.1, against a variation in N/Z. The calculation results for ^{194}Hg, ^{200}Hg and ^{206}Hg are presented in Fig.2.

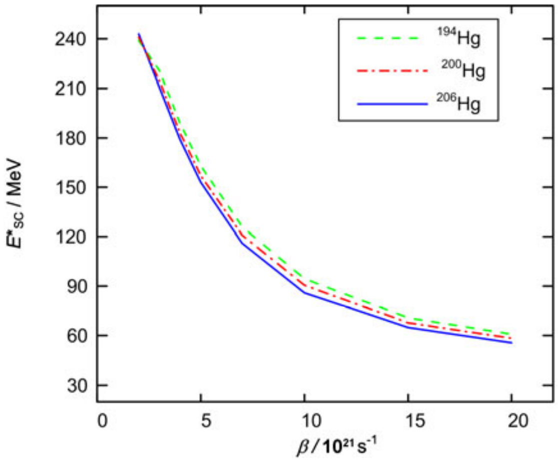

Fig.2 (Color online) Evolution E^*_{sc} with β at E^* = 500 MeV and $\ell_c = 10\hbar$ for three compound systems ^{194}Hg, ^{200}Hg and ^{206}Hg.

As seen from the figure, a similar E^*_{sc} is observed for the three Hg isotopes. A physical understanding for this is that while a larger *N*/*Z* increases neutron emission but it decreases LCPs multiplicity. As a consequence, the excitation energy taken away by both neutrons and LCPs is almost comparable for these Hg systems with different *N*/*Z*.

A heavy nucleus favors particle emission due to a long descent of the decaying system from saddle to scission. Also, the fission lifetime is a function of the fissility, meaning that a change in the fissility parameter can affect the particle multiplicity emitted throughout the fission time scale. Here we survey the influences of the two factors on the sensitivity. Our calculation results are displayed in Fig.3 and Fig.4.

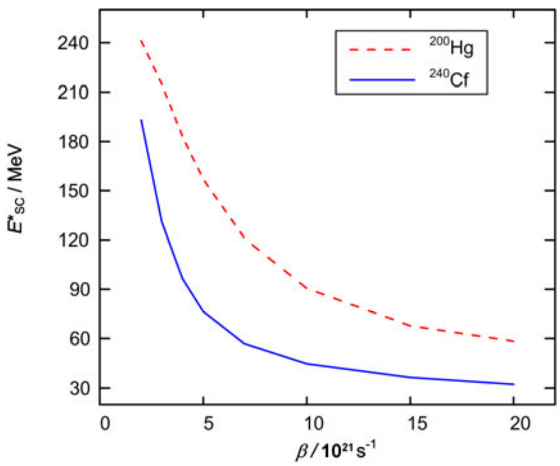

Fig.3 (Color online) E^*_{sc} as a function of β at E^*=500 MeV and $\ell_c = 10\hbar$ for compound systems ^{200}Hg and ^{240}Cf.

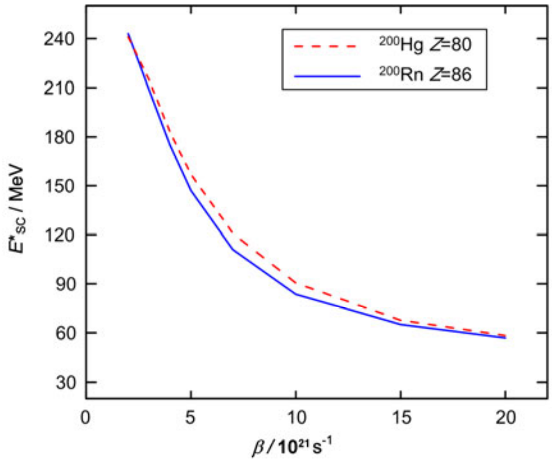

Fig.4 (Color online) E^*_{sc} as a function of β at E^* = 500 MeV and $\ell_c = 10\hbar$ for compound systems ^{200}Hg (Z = 80) and ^{200}Rn (*Z* = 86).

We notice from Fig.3 and Fig.4 that under the condition of high energy, while varying the size of a fissioning system and its fissility value can influence the number of different kinds of particles, overall, the significant sensitivity found at high energy remains unchanged.

The insensitivity of E^*_{sc} to β revealed in Figs.2−4 underlines the essential roles of excitation energy and friction strength in determining the emitted particle number. The feature is favorable to a more reliable and stringent constraint on the β. In other words, proton-nucleus collisions could provide an avenue to probe dissipation in fission of a highly excited CN.

In energetic proton-nucleus reactions, the populated residual nucleus has a distribution in its E^*, *J*, *A* and *Z*. As illustration we use the intranuclear cascade model (INCL) to simulate (1 GeV) p+Hg collisions, the results of which are plotted in Fig.5.

The distribution information should be used as input for subsequent Langevin calculation of the formed hot nuclear systems. Thus, for more accurate results, it is necessary to combine the INCL, which treats the collision stage between protons and nuclei in spallation reactions, with Langevin description of fission of excited nuclei. This new approach may offer a more suitable framework to explore E^*_{sc} deduced in spallation reactions. The work along this direction is in progress.

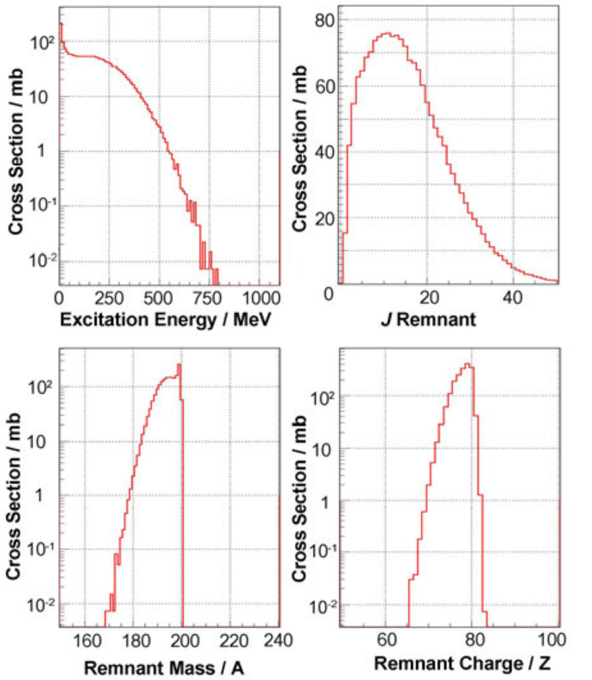

Fig.5 (Color online) The E^*, J, A and Z distributions of residual nuclei populated in (1 GeV) p+^{200}Hg collisions predicted by the INCL model[25].

4 Conclusion

The Langevin model of fission is applied to survey the role of the initial excitation energy E^* of Hg CNs in $E^*_{\rm sc}$ as a tool of β. We find that the sensitivity of $E^*_{\rm sc}$ to β is increased significantly under the condition of high energy. Furthermore, we examine the robustness of the sensitivity to an evident change in the size of a fissioning system, in its N/Z ratio and fissility. It has been shown that these changes have minor effects on the sensitivity. Our findings suggest that, experimentally, when one uses $E^*_{\rm sc}$ to obtain information of nuclear friction, energetic proton induced reactions can be used as a way to populate excited nuclear systems. In addition to that, the $E^*_{\rm sc}$ measured at high energy and provided via the new experimental approach could place a more reliable and tighter constraint on the friction strength in nuclear fission.

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