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Angular Momentum Effect on Probing Nuclear Dissipation with Fission Cross Section

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Abstract: Using the Langevin model, we study the effect of angular momentum on the drop of fission cross sections caused by friction over its standard statistical-model value, σ_f^{drop}, as a function of presaddle friction strength β. It is found that friction effects on σ_f^{drop} are substantially enhanced at low spin. In addition, by investigating the evolution of σ_f^{drop} with β for ^{195}Bi, ^{201}Bi and ^{207}Bi nuclei, we find that friction effects become greater with increasing the neutron-to-proton ratio (N/Z) of Bi nucleus. These results suggest that on the experimental side, to precisely probe presaddle dissipation by measuring fission excitation functions, it is best to yield excited nuclear systems with a small spin and a large N/Z.

Key words: angular momentum; nuclear dissipation; fission cross section; stochastic model

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1 Introduction

The property of nuclear dissipation is a key to understanding a variety of phenomena encountered in intermediate- and low-energy nuclear reactions[1–2]. In particular, nuclear dissipation is suggested to be responsible for the excess of prescission particles and evaporation residue cross sections measured in a great number of experiments over predictions from standard statistical models (SMs)[3]. While prescission particle multiplicity[4–5] is widely employed to probe information of nuclear dissipation, it is composed of the emission before and after saddle points. It means that it is sensitive to both presaddle and saddle-to-scission friction strengths. This causes an uncertainty when extracting presaddle friction strength by analyzing particle multiplicity data.

Different from particle emission, fission cross section is sensitive to presaddle friction (β) only. In addition, although various observables including evaporation residue cross section and its spin distribution[6–7] are proposed to constrain β, the presaddle friction strength is still controversial and, hence, it is the focus of recent intensive efforts[8–11]. Compared to evaporation channels, fission channels are more directly affected by fission hindrance. As a consequence, fission is retarded that affects evaporation. Therefore, fission cross section is considered as the most fundamental probe of presaddle dissipation[1, 12].

Till now, less studies are made to address those favorable experimental conditions through which the sensitivity of fission cross sections to presaddle friction can be enhanced. The present work is devoted to the issue. To that end, we survey the influence of angular momentum on the sensitivity in the framework of Langevin models [13–20], which has been recognized as a powerful tool to explore the nuclear dissipation properties. Moreover, to better instruct experimental explorations we investigate the role of the neutron-to-proton ratio of a compound nucleus in probing the friction strength with fission cross sections.

2 Theoretical model

A brief description of the combination of the dynamical Langevin equations with a statistical decay model (CDSM) is given; for more details, see Ref. [21]. The dynamic part of the CDSM is described by the Langevin equation that is expressed by entropy. We employ the following one-dimensional overdamped Langevin equation[22] to perform the trajectory calculations:

$$\frac{\mathrm{d}q}{\mathrm{d}t} = \frac{T}{M\beta}\frac{\mathrm{d}S}{\mathrm{d}q} + \sqrt{\frac{T}{M\beta}}\Gamma(t)\ . \tag{1}$$

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 with $<\Gamma(t)>=0$ and $<\Gamma(t)\Gamma(t')>=2\delta(t-t')$. The driving force of the Langevin equation is calculated from the entropy:

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

The angular momentum ℓ due to rotation is indicated. E^* is the excitation energy of the system. Eq. (2) is constructed from the Fermi-gas expression with a finite-range liquid-drop potential $V(q)$[23] that includes the q-dependent surface, Coulomb and rotation energy terms.

In constructing the entropy, the deformation-dependent level density parameter is used:

$$a(q)=a_1A+a_2A^{2/3}B_{\mathrm{s}}(q)\ . \qquad (3)$$

where A is the mass number, and $a_1=0.073$ and $a_2=0.095$ are taken from Ignatyuk *et al.*[24]. B_{s} is the dimensionless surface area (for a sphere $B_{\mathrm{s}}=1$) which can be parametrized by the analytical expression[25]

$$B_{\mathrm{s}}(q)=\begin{cases}1+2.844(q-0.375)^2, & \text{if } q<0.452\ ,\\ 0.983+0.439(q-0.375), & \text{if } q\geqslant 0.452\ .\end{cases} \qquad (4)$$

In the CDSM prescission particle evaporation along Langevin fission trajectories from their ground state to their scission point has been taken into account using a Monte Carlo simulation technique. The light-particle evaporation is coupled to the fission mode by a Monte Carlo procedure allowing for the discrete emission of light particles. Particle emission widths are calculated with the formula given in Ref. [26].

When a dynamic trajectory reaches the scission point, it is counted as a fission event. When fission probability flow over the fission barrier attains its quasistationary value, the decay of compound systems is described by the statistical part of the CDSM, which allows for multiple emissions of light particles and higher-chance fission. Fission probabilities are calculated by counting the number of corresponding fission events.

The Langevin equation is started to model fission dynamics from the position of the ground state of a compound nucleus. The angular momentum ℓ for each Langevin trajectory is sampled from the fusion spin distribution function, whose form reads

$$\frac{\mathrm{d}\sigma(\ell)}{\mathrm{d}\ell}=\frac{2\pi}{k^2}\frac{2\ell+1}{1+\exp[(\ell-\ell_{\mathrm{c}})/\delta\ell]}\ . \qquad (5)$$

The parameters ℓ_{c} and $\delta\ell$ are the critical angular momenta for fusion and diffuseness, respectively. To accumulated sufficient statistics, 10^7 Langevin trajectories are simulated.

3 Results and discussions

Dissipation suppresses fission, which provides more time for evaporating particles. An excess of light particles emitted prior to saddle due to friction affects the competition of fission with evaporation, making the measured fission cross section (σ_{f}) to deviate from SMs prediction. Because the magnitude of the deviation is a function of β, studying the deviation thus provides a sensitive method of determining β. For this aim, similar to the suggestion by Lazarev *et al.* [27], we define the relative drop of σ_{f} calculated by SMs over the value by taking into account the dissipation and fluctuations of collective nuclear motion with the following expression:

$$\sigma_{\mathrm{f}}^{\mathrm{drop}}=\frac{\langle\sigma_{\mathrm{f}}^{\mathrm{SM}}\rangle-\langle\sigma_{\mathrm{f}}^{\mathrm{dyn}}\rangle}{\langle\sigma_{\mathrm{f}}^{\mathrm{SM}}\rangle}\ . \qquad (6)$$

We show in Fig. 1 the influence of angular momentum on the variation of $\sigma_{\mathrm{f}}^{\mathrm{drop}}$ with β for ^{201}Bi system at $E^*=100$ MeV. Two features are observed: (i) Irres-

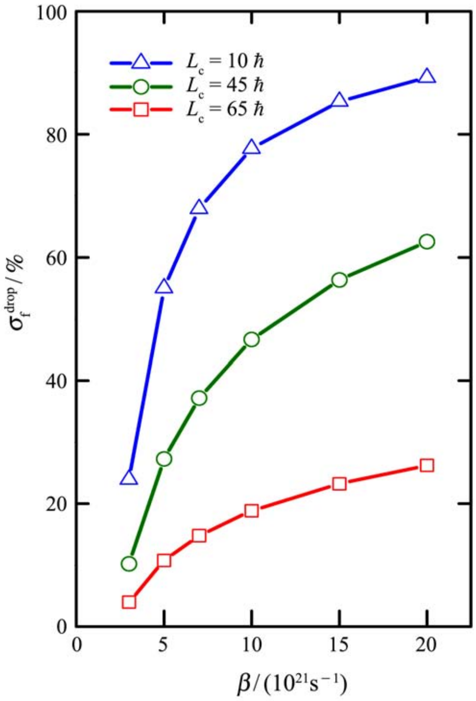

Fig. 1 (color online) Dynamical drop of the fission cross section of ^{201}Bi relative to that predicted by SMs as a function of the presaddle dissipation strength β at excitation energy $E^*=100$ MeV and at critical angular momenta $\ell_{\mathrm{c}}=10$, 45 and 65 $\hbar$.

pective of the friction strength, at low angular momentum the amplitude of the drop in fission cross section, $\sigma_{\rm f}^{\rm drop}$, becomes larger, meaning a stronger dissipation effect on fission cross sections. (ii) The slope of curve $\sigma_{\rm f}^{\rm drop}$ vs β reflects the sensitivity of fission cross sections to friction. The lower the angular momentum is, the steeper the slope of the curve is. We note that as β varies from $3 \times 10^{21}{\rm s}^{-1}$ to $20 \times 10^{21}{\rm s}^{-1}$, the change of $\sigma_{\rm f}^{\rm drop}$ at $\ell_{\rm c} = 10\ \hbar$ is approximately three times that at $\ell_{\rm c} = 65\ \hbar$, illustrating a higher sensitivity of fission cross sections to friction at low spin. The reason is that fission barriers decrease with angular momentum [Fig. 2(a)], which favors fission. So, although friction effects modify fission cross sections, the fission cross section predicted by SMs, $\sigma_{\rm f}^{\rm SM}$, becomes greater with increasing nuclear spin. As a result, a high spin causes a low $\sigma_{\rm f}^{\rm drop}$ [see Eq. (6)].

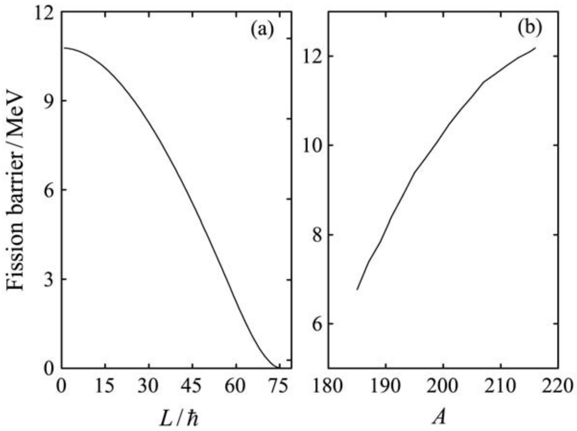

Fig. 2 (a) Fission barrier of nuclei ^{201}Bi as a function of angular momentum. (b) Fission barrier as a function of mass number of element Bi at angular momentum of 10 $\hbar$.

In earlier works on β [12, 16, 18, 21] with fission excitation functions, heavy-ion fusion, which produces compound systems with high spin (up to ~75 $\hbar$), was used. However, one can clearly see from Fig. 1 that the sensitivity of fission cross section to friction is substantially increased at low spin. The result shows that in experiments, populating compound nuclei with low spin is favorable for precisely probing β with fission cross sections. Furthermore, light-ion-induced reactions produce compound nuclei with a smaller spin as compared to that by heavy-ion collisions. This suggests that analyzing fission excitation function data induced by light ions such as protons can place stringent constraints on β and, correspondingly, provide a more reliable value of the friction parameter.

Aside from fusion approach, peripheral relativistic heavy-ion collisions[28–29] and relativistic antiproton-induced[30] reactions can also generate hot nuclei with a rather low angular momentum. The two new experimental avenues thus could be used to accurately probe nuclear friction[31].

The neutron-to-proton ratio (N/Z) of a decaying system has recently been found to have a significant effect on particle emission as a probe of nuclear dissipation[32]. In this context, on the basis of previous investigations on the angular momentum effects, we survey the influence of N/Z on the fission cross section as an observable of presaddle friction. Towards that goal, three Bi systems, which have a marked difference in their N/Z, *i.e.*, ^{195}Bi, ^{201}Bi and ^{207}Bi are considered.

Fig. 3 plots the change of $\sigma_{\rm f}^{\rm drop}$ with excitation energy for three Bi nuclei. It is seen that $\sigma_{\rm f}^{\rm drop}$ is lowered with decreasing the N/Z of Bi system, indicating a greater effect of friction on fission cross sections for ^{207}Bi than for ^{201}Bi and ^{195}Bi. That is to say, the sensitive dependence of fission cross sections on friction is increased with raising the N/Z of a decaying system. This is due to a larger fission barrier at high N/Z [Fig. 2(b)]. The low fission barrier of low N/Z ^{195}Bi causes a larger fission probability in comparison with that of high N/Z ^{207}Bi. The case is analogous to that in Fig. 1 where a low fission barrier at high spin is shown to decrease the size of the friction effects on fission cross section. A comparison of the results for three Bi isotopes thus exhibits that dissipation effects could be better revealed with fission cross sections under a high N/Z condition.

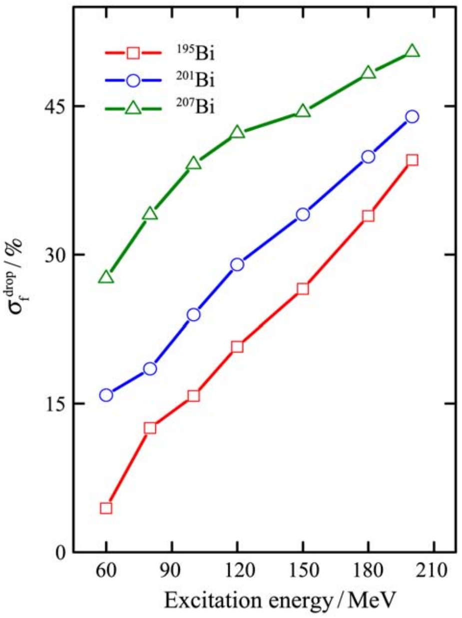

Fig. 3 (color online) Dynamical drop of fission cross sections calculated at $\beta = 3\ {\rm zs}^{-1}$ and $\ell_{\rm c} = 10\ \hbar$ for ^{197}Bi, ^{201}Bi and ^{207}Bi nuclei.

4 Conclusion

In summary, using the dynamical Langevin model we have found that the sensitivity of the drop of fission cross sections ($\sigma_{\rm f}^{\rm drop}$) with respect to SM values due to friction effects to β is significantly enhanced at a small angular momentum. Furthermore, it has been demonstrated that with an increase of N/Z of a decaying system, $\sigma_{\rm f}^{\rm drop}$ shows a greater sensitivity to β. These results suggest that on the experimental side, to severely constrain presaddel friction strength through the measurement of fission excitation functions, it is best to produce a compound system with low spins and high neutron-to-proton ratios.

References:

[1] JACQUET D, MORJEAN M. Prog Part Nucl Phys, 2009, **63**: 155.

[2] FELDMEIER H. Rep Prog Phys, 1987, **50**: 915.

[3] HILSCHER D, ROSSNER H. Ann Phys (Paris), 1992, **17**: 471.

[4] SANDAL R, BEHERA B R, SINGH V, *et al.* Phys Rev C, 2013, **87**: 014604.

[5] HINDE D J, HILSCHER D, ROSSNER H, *et al.* Phys Rev C, 1992, **45**: 1229.

[6] BACK B B, BLUMENTHAL D J, DAVIDS C N, *et al.* Phys Rev C, 1999, **60**: 044602.

[7] SHIDLING P D, MADHAVAN N, RAMAMURTHY V S, *et al.* Phys Rev C, 2006, **74**: 064603.

[8] RAMACHANDRAN K, CHATTERJEE A, NAVIN A, *et al.* Phys Rev C, 2006, **73**: 064609.

[9] LESTONE J P, MCCALLA S G. Phys Rev C, 2009, **79**: 044611.

[10] SINGH H, BEHERA B R, SINGH G, *et al.* Phys Rev C, 2009, **80**: 064615.

[11] MANCUSI D, CHARITY R J, CUGNON J. Phys Rev C, 2010, **82**: 044610.

[12] FABRIS D, VIESTI G, FIORETTO E, *et al.* Phys Rev Lett, 1994, **73**: 2676.

[13] FRÖBRICH P. Prog Theor Phys Suppl, 2004, **154**: 279.

[14] WADA T, ABE Y, CARJAN N. Phys Rev Lett, 1993, **70**: 3538.

[15] POMORSKI K, NERLO-POMORSKA B, SUROWIEC A, *et al.* Nucl Phys A, 2000, **679**: 25.

[16] NADTOCHY P N, ADEEV G D, KARPOV A V. Phys Rev C, 2002, **65**: 064615.

[17] YE W, YANG H W, WU F. Phys Rev C, 2008, **77**: 011302(R); YE W. Phys Lett B, 2009, **681**: 413.

[18] SADHUKHAN J, PAL S. Phys Rev C, 2008, **78**: 011603(R).

[19] MIRFATHI S M, PAHLAVANI M R. Phys Rev C, 2008, **78**: 064612.

[20] WANG N, YE W. Phys Rev C, 2013, **78**: 051601(R).

[21] FRÖBRICH P, GONTCHAR I I. Phys Rep, 1998, **292**: 131.

[22] FRÖBRICH P. Nucl Phys A, 2007, **787**: 170c.

[23] SIERK A J. Phys Rev C, 1986, **33**: 2039; MÖLLERP, MYERS W D, SWIATECKI W J, *et al.* At Data & Nucl Data Tables, 1988, **39**: 225.

[24] IGNATYUK A V, ITKIS M G, OKOLOVICH V N, *et al.* Sov J Nucl Phys, 1975, **21**: 612.

[25] GONTCHAR I I, FRÖBRICH P, PISCHASOV N I. Phys Rev C, 1993, **47**: 2228.

[26] BLANN M. Phys Rev C, 1980, **21**: 1770.

[27] LAZAREV YU A, GONTCHAR I I, MAVLITOV N D. Phys Rev Lett, 1993, **70**: 1220.

[28] SCHMITT C, SCHMIDT K H, KELIĆA, *et al.* Phys Rev C, 2010, **81**: 064602.

[29] JURADO B, SCHMITT C, SCHMIDT K H, *et al.* Phys Rev Lett, 2004, **93**: 072501; BENLLIURE J, CASAREJOS E, PEREIRA J, *et al.* Phys Rev C, 2006, **74**: 014609.

[30] LOTT B, GOLDENBAUM F, BOHM A, *et al.* Phys Rev C, 2001, **63**: 034616; JAHNKE U, BOHNE W, EGIDY T, *et al.* Phys Rev Lett, 1999, **83**: 4959.

[31] YE W. Phys Rev C, 2012, **85**: 011601(R).

[32] YE W. Phys Rev C, 2009, **80**: 011601(R).

角动量对基于裂变截面探测核耗散的影响

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摘要： 核耗散降低了裂变截面值($\sigma_{\rm f}^{\rm drop}$)。基于Langevin模型，研究了角动量对$\sigma_{\rm f}^{\rm drop}$作为鞍点前摩擦强度$\beta$函数的影响。发现在低自旋，摩擦对$\sigma_{\rm f}^{\rm drop}$的影响显著增强。通过考察系统^{195}Bi，^{201}Bi和^{207}Bi的$\sigma_{\rm f}^{\rm drop}$随$\beta$的演化，发现摩擦效应随着Bi核中质比($N/Z$)的增加而变大。这些结果建议，为了更好地在实验上用裂变截面探测β，应产生那些具有低自旋、高N/Z的热核系统。

关键词： 角动量；核耗散；裂变截面；随机模型

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