第 31 卷 第 3 期 原 子 核 物 理 评 论 Vol. 31, No. 3
2014 年 9 月 Nuclear Physics Review Sep., 2014

Article ID: 1007-4627(2014) 03-0344-06

Nuclear Friction Determined with He-ion Induced Fission Excitation Functions

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Abstract: The stochastic approach to fission is employed to analyze measured fission excitation functions in the reactions ^{3}He+^{197}Au, ^{3}He+^{208}Pb and ^{3}He+^{186}W. A pre-saddle friction strength of about 4×10^{21} s^{-1} is extracted by comparing theoretical calculations with experimental data. The important role of level-density parameters in accurately determining the strength of nuclear friction is revealed. It is further shown that high-energy conditions can enhance the sensitivity of fission cross sections to nuclear dissipation.

Key words: fission excitation function; nuclear friction; Langevin model; level density parameter

CLC number: O571.6, O571.43 **Document code:** A **DOI:** 10.11804/NuclPhysRev.31.03.344

1 Introduction

The precise determination of the magnitude of nuclear dissipation is the focus of current theoretical and experimental studies in the field of low-energy nuclear physics. Nuclear dissipation affects a variety of phenomena, ranging from low-energy deep-inelastic scattering[1] and decay modes of highly excited nuclei[2] to the evolution of matter at extremely high densities and temperatures created in heavy-ion collisions at ultrarelativistic energies [3]. Dissipation hinders fission that considerably reduces fission probability and increases particle emission. Compared to particle multiplicity which is emitted along the entire fission path, fission probability is sensitive to pre-saddle friction only. Fission excitation functions are thus considered as the most direct and sensitive method of probing the nuclear friction strength inside the fission barrier[4−5].

Systematic measurements of fission excitation functions have been carried out by means of heavy-ion fusion-fission reactions, and a number of model calculations and analyses[6–8] have been made. In contrast, few studies have been performed for light-ion induced fusion-fission reactions, which populate compound nuclei (CNs) with a low spin. This is markedly different from that produced in heavy-ion collisions. The angular momentum plays an important role in the competition between fission and evaporation. In addition, it can modify the magnitude of level density parameter, which is a crucial parameter in decay-type model calculations. Thus, surveying light-ion induced fission reactions not only reveals new information of nuclear dissipation, but also sheds new light on the widely used stochastic model[6−14]. The present work is devoted to the study of nuclear dissipation through fission cross sections as a function of excitation energy measured in ^{3}He+^{197}Au, ^{3}He+^{208}Pb and ^{3}He+^{186}W systems[15−16].

2 Theoretical model

The stochastic model[17] to fission dynamics of a hot CN is adopted here. The model has been successfully applied to reproduce a great number of experimental data on dissipative fission over a wide range of excitation energy and fissility. The dynamic part

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Received date: 15 Sep. 2013; **Revised date:** 27 Sep. 2013

Foundation item: National Natural Science Foundation of China (11075034)

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of the model is expressed by entropy. We employ the following one-dimensional overdamped Langevin equation to perform the trajectory calculations:

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

Here q is the dimensionless fission coordinate and is defined as half the distance between the center of mass of the future fission fragments divided by the radius of the CN, 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:

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

where E^* is the total internal energy of the system. Eq. (2) is constructed from the Fermi-gas expression with a potential $V(q)$ in the $\{c,h,\alpha\}$ parametrization[18]. Here c and h correspond to the elongation and neck degrees of the freedom of the nucleus, respectively. Since only symmetrical fission is considered, the parameter describing the asymmetry of the shape is set to $\alpha=0$. The q-dependent surface, Coulomb, and rotation energy terms are included in the potential $V(q)$.

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_1 and a_2 are constants and their values are taken from Ref. [18]. B_s is the dimensionless surface area (for a sphere $B_\mathrm{s}=1$) which can be parameterized by the analytical expression[20]

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

In the model, light-particle evaporation is coupled to the fission mode by a Monte Carlo procedure. The emission widths of neutrons, protons and alpha particles are calculated with Blan's formula [21].

For starting a Langevin trajectory an orbit angular momentum value is sampled from the fusion spin distribution, which reads

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

The parameters ℓ_c and $\delta\ell$ are the critical angular momenta for fusion and diffuseness, respectively. For different systems, they are found to follow a scaling, which is in accordance with the surface friction model[22] that describes the fusion cross sections very well. Namely,

$$\ell_\mathrm{c}=\sqrt{20.4(E_\mathrm{c.m.}-V_\mathrm{c})-\frac{1.7E_\mathrm{c.m.}}{(\lambda/4\pi)^2}}\ , \qquad (6)$$

where $E_\mathrm{c.m.}=E_\mathrm{lab}A_\mathrm{T}/(A_\mathrm{T}+A_\mathrm{P})$, $\lambda=2\pi\hbar(A_\mathrm{T}+A_\mathrm{P})/(A_\mathrm{T}\sqrt{2A_\mathrm{P}m_\mathrm{nuc}E_\mathrm{lab}})$. E_lab denotes the laboratory energy of the projectile, m_nuc is the nucleon mass. A_T and A_P represent the mass number of target and projectile, respectively. For the barrier $V_\mathrm{c}=19.51$ MeV [6]. The diffuseness δl scales as

$$\delta l=\begin{cases}\left[(A_\mathrm{P}A_\mathrm{T})^{3/2}\times10^{-5}\right][1.5+0.02(E_\mathrm{c.m.}-V_\mathrm{c}-10)] & \text{for } E_\mathrm{c.m.}>V_\mathrm{c}+10\ ,\\ \left[(A_\mathrm{P}A_\mathrm{T})^{3/2}\times10^{-5}\right][1.5-0.04(E_\mathrm{c.m.}-V_\mathrm{c}-10)] & \text{for } E_\mathrm{c.m.}<V_\mathrm{c}+10\ .\end{cases} \qquad (7)$$

These scaling values have widely been tested by successfully fitting particle emission[7, 14], evaporation-residue cross sections[8] and its spin distributions[23], *etc.* Finally they are constrained from the experimental fusion cross sections.

3 Results

For a hot nuclear system, the driving force is not the negative gradient of the conservative potential but contains a thermodynamical correction[17, 24]. Thus, entropy $S(q,E^*,\ell)$ is used in our dynamical calculation, which is a function of angular momentum ℓ. As a result, other physical quantities such as level density parameter and its ratio at saddle (a_f) to that at ground state (a_n), $a_\mathrm{f}/a_\mathrm{n}$, vary with ℓ.

At high ℓ, the saddle point gets closer to the ground-state configuration. This reduces the magnitude of $a_\mathrm{f}/a_\mathrm{n}$, and correspondingly, affects the competition of fission with evaporation. In our model, we calculate the ratio a_f/a_n by the following procedure. We first determine the locations of saddle and ground state, which are defined by the stationary points of entropy[17, 24], by comparing the magnitude of $S(q)$ at different q[20]. Then the magnitudes of level density parameter at saddle (a_f) and at equilibrium shape (a_n) are obtained by means of Eq. (3).

Fission probability is a sensitive function of a_f/a_n[8]. Compared to heavy-ion collisions that yield CNs with a high spin, the CN populated by light-ion induced fusions has a low spin that leads to a larger a_f/a_n. This considerably enhances the role of a_f/a_n in the fission process of hot nuclei.

Apart from friction, level-density parameters also affect the decay process of a nucleus. Disentangling the two effects favors a better understanding of the role of level-density parameters in deciding fission cross sections. To this end, standard statistical model (SM) calculations are first performed.

Model calculations and a comparison with measured fission excitation functions of the ^{3}He+^{197}Au reaction are shown in Fig. 1. The calculations are divided into three types: (i) SM calculation and $a_f/a_n = 1$, $a_n = A/8$ MeV; (ii) SM calculation and Ignatyuk *et al.*'s level-density parameter and (iii) Langevin calculation at three friction strengths $\beta = 3$ zs^{-1}, 4 zs^{-1} and 6 zs^{-1}.

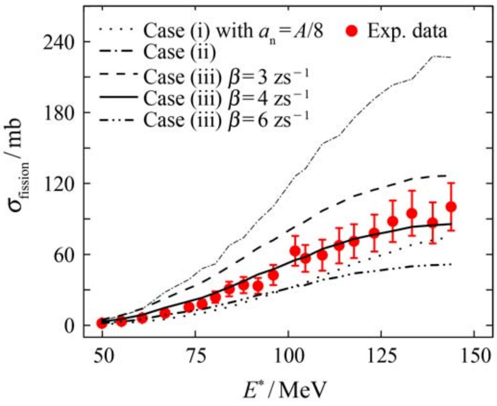

Fig. 1 (color online) Fits to measured excitation function data of fission cross sections (denoted by circles with error bars) in the ^{3}He+^{197}Au system[15]. Curves represent various theoretical calculations: case (i) SM without friction but with $a_f/a_n = 1$ and $a_n = A/8$ (dotted line); case (ii) SM without friction but with $a_f/a_n \neq 1$ (dashed dotted line) and case (iii) Langevin model with $a_f/a_n \neq 1$ at friction strengths $\beta = 3$ zs^{-1} (dashed line), 4 zs^{-1} (solid line) and 6 zs^{-1} (dashed-double dot line). The unit of β is zs^{-1}; 1 zs = 10^{-21} s. The figure is taken from Ref. [24].

One can see that the results of the first-type calculation are below data points for large E^*. In case (i) we assume that the value of level-density parameters at saddle is the same as that at equilibrium shape. But it has been shown in a number of studies[19, 26–28] that a_f should be larger than a_n due to the increased area of nuclear shape at saddle; that is, the ratio a_f/a_n exceeds unity.

In order to explore the role of level-density parameters in decay modes of an excited nucleus, we further carry out SM calculation but adopt the description of Ignatyuk *et al.*'s deformation-dependent level-density parameter. For this case, as a consequence of a larger a_f/a_n which increases fission probability, the calculated fission cross sections (denoted by dashed dotted line) are far higher than measured values (Fig. 1). The result clearly reveals the significant influence of the magnitude of a_f/a_n on fission.

In case (ii), the value of a_f/a_n is evaluated with Eq. (3), in contrast with case (i) where a_f/a_n is set as unity. Case (ii) predicts an evident deviation from experimental data, implying the necessity of explicitly accounting for friction effects in fission[2, 6–8, 12, 14]. Dissipation retards fission, causing a lower fission rate that counterbalances the role of a larger a_f/a_n in modifying the fission rate.

Now we turn to Langevin simulations. Compared to SM, the Langevin model takes into account a great many dynamical features[17, 29] when a CN fissions. In our Langevin calculation a number of β values are chosen. One can see from Fig. 1 that the σ_{fiss} estimated at $\beta = 3$ zs^{-1} are smaller than those in case (ii) but still higher than experimental values. This suggests that while fission is hindered due to an introduction of friction that partially offsets effects arising from a large a_f/a_n, the role of the parameter a_f/a_n is still predominant in determining the amplitude of fission probability. As β is increased up to 6 zs^{-1}, the theoretical σ_{fiss} are lower than the measured ones, indicating that friction has a stronger influence on the fission probability than a_f/a_n.

Langevin calculations at $\beta = 3$ zs^{-1} and 6 zs^{-1} display an opposite deviation from experimental data, in particular at higher energies. This implies that a proper friction strength is required in order to provide a satisfactory description of the measured fission cross sections. We notice that calculation with $\beta = 4$ zs^{-1}, as shown by solid line in Fig. 1, reproduces the data quite well.

Further, we note a greater difference of $\sigma_{\rm fiss}$ calculated at $\beta = 3$ zs^{-1} and $\beta = 6$ zs^{-1} when E^* is raised, showing a larger sensitivity of fission cross sections to friction with increasing energy. This stems from an increasing difference of the number of emitted pre-saddle particles at high energy. At high E^*, $a_{\rm f}/a_{\rm n}$ drops due to a shorter distance between saddle and equilibrium configurations, which enhances friction effects on neutron multiplicity. Another factor is that a longer time is required to emit particles at a lower energy, which decreases the influence of friction on particle evaporation. In contrast, only a short particle evaporation time is needed under the condition of high energy. As a result, a large friction delays fission more strongly. This increases particle emission at large β. The two factors contribute to a greater particle multiplicity at high energy. The particle number emitted inside the barrier determines whether a decaying system fissions or not, namely, it determines the fission probability.

Shown in Fig. 2 are model calculations along with a comparison with data measured in ^{3}He+^{208}Pb. A picture like Fig. 1 is seen for the reaction.

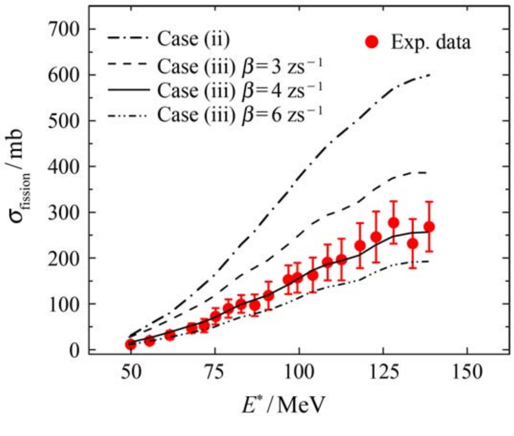

Fig. 2 (color online) Same as Fig. 1, but for the ^{3}He+^{208}Pb system[15].
The figure is taken from Ref. [24].

The calculation shows that the pre-saddle friction strength of 4.5 zs^{-1} gives a best reproduction of the experimental fission cross sections.

Here, we further compare Langevin calculations with fission data of light compound systems provided in the ^{3}He+^{186}W reaction. Results are displayed in Fig. 3. It is seen that a narrow range of β, *i.e.*, (3.5 ～ 4.5) zs^{-1}, describes the experimental data. The friction value is similar to that obtained from Figs. 1 and 2.

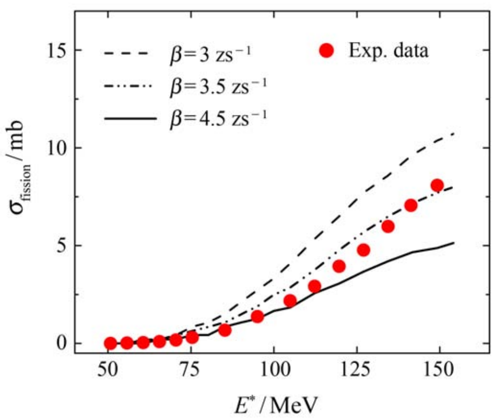

Fig. 3 (color online) Comparison between measured excitation function data (denoted by circles with error bars) in the ^{3}He+^{186}W system[16] with Langevin calculations at friction strengths $\beta = 3$ zs^{-1} (dashed line), 3.5 zs^{-1} (dashed-double dot line) and 4.5 zs^{-1} (solid line).

Various types of observables have been suggested to probe the strength of nuclear friction. Using the measured particle multiplicity the β extracted is (5 ～ 8)[30] and 5[31] (zs^{-1}). An analysis of evaporation-residue cross sections reveals that $\beta \leqslant 10$[32]. Evaporation-residue spin distribution data give a pre-saddle β of 5 zs^{-1}[23]. A pre-saddle β of (2 ～ 5) zs^{-1} describes well the width of fission-fragment charge distributions[33]. These friction strengths including ours are weaker than predicted by one-body dissipation model.

4 Summary and outlook

In summary, we have extracted the pre-saddle friction strength of about 4 zs^{-1} by comparing calculated and experimental fission excitation functions in ^{3}He+^{197}Au (^{208}Pb and ^{186}W). The role of level-density parameter in accurately constraining the friction strength is revealed by comparing three types of model calculations in which the magnitude of $a_\mathrm{f}/a_\mathrm{n}$ is different. This clearly demonstrates the importance of evaluating the parameter value in a realistic and an elaborate manner. Further, it has been shown that $a_\mathrm{f}/a_\mathrm{n}$ contributes a marked difference of fission cross sections as a function of the friction strength at higher energies. The result suggests that raising excitation energy of a populated CN favors a more precise determination of nuclear friction with fission cross sections.

In addition to He-ions induced fusion reactions, fission excitation functions measured in energetic proton- and antiproton-nucleus collisions have recently received a wide attention[34]. For the latter, the produced residual hot nuclear systems have a distribution in its excitation energy, angular momentum, mass number and atomic number, which can be estimated by the intranuclear cascade model (INCL)[35]. A new approach that combines Langevin description of fission of hot nuclei with INCL model has been developed to determine the nuclear friction strength in proton induced spallation reactions[36]. Work along this direction is now underway.

Acknowledgments The author thanks Professors L.W.Chen, Z.G.Xia, Z.Q.Feng and F.S.Zhang for their excellent organization of the conference of Intermediate energy heavy-ion collisions.

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用 He 离子诱导的裂变激发函数探测核摩擦强度

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摘要： 随机模型被用于分析 ^{3}He+^{197}Au，^{3}He+^{208}Pb 和 ^{3}He ^{186}W 反应测量的裂变激发函数。提取的鞍点前摩擦强度约为 4×10^{21} s^{-1}。揭示了能级密度参数的大小在约束核摩擦强度中的作用。计算表明，高激发条件能能显著增强裂变截面对核耗散的敏感性。

关键词： 裂变激发函数；核摩擦；Langevin 模型；能级密度参数

收稿日期： 2013-09-15； **修改日期：** 2013-09-27

基金项目： 国家自然科学基金资助项目(11075034)

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