Role of the "window" component of the friction tensor in the formation of superheavy nuclei

Yu-Jie Liang,[1,*] Min Zhu,[1] Zu-Hua Liu,[2] and Wen-Zhong Wang[1]
[1]*School of Science, Minzu University of China, Beijing 100081, People's Republic of China*
[2]*China Institute of Atomic Energy, Beijing 102413, People's Republic of China*
(Received 3 December 2013; revised manuscript received 3 February 2014; published 31 March 2014)

Formation of superheavy nuclei is greatly hindered by the inner barrier and strong dissipation on the way from the contact point of two colliding nuclei to the compound nucleus configuration. One of the dissipation mechanisms is related to the exchange of particles across the window between two nuclei in relative motion, which is the "window" term in the "wall-plus-window" formula. By means of the dynamic analysis for the symmetric systems $^{132}Xe + {}^{132}Xe$ and $^{136}Xe + {}^{136}Xe$, we have shown that the window component of friction tensor retards the elongation of the fusing composite nucleus, decreases the height of the inner barrier, and hence increases the fusion probability. Therefore, the friction associated with "window" term enhances the formation cross sections of superheavy nuclei. Besides, we have shown the mass difference (in units of the temperature) of the fission and neutron emission saddle points as a function of mass number of the hassium isotopes, which may provide a useful reference for synthesis and study of the nuclei adjacent to the doubly magic nucleus ^{270}Hs.

DOI: 10.1103/PhysRevC.89.034627 PACS number(s): 24.10.−i, 25.70.Jj

I. INTRODUCTION

Collisions of heavy symmetric nuclei are a possible alternative way for production of neutron-rich superheavy (SH) elements. Within the model based on multidimensional Langevin equations, Zagrebaev and Greiner [1] studied the dynamics of heavy symmetric and asymmetric fusion reactions leading to formation of SH nuclei. Adamian *et al.* [2] investigated fusion of heavy symmetric nuclei within the two-center shell model and found that in order to describe the experimental data, a hindrance for the fast growth of the neck and for the motion to smaller elongations of the system should be incorporated in the calculations. Actually, the physics of the whole process of the interaction between two heavy nuclei is very complicated. One of the primary factors is the severe hindrance of fusion, resulting in the dramatic decrease of the formation of cross sections of SH nuclei. Unfortunately, the fusion hindrance factor is far from clear yet. Therefore, it is necessary to estimate this factor using test reactions with known nuclei. One of the symmetric reactions $^{136}Xe(^{136}Xe, xn)^{272-xn}Hs$ seems to be suitable for this purpose. Experiments on the synthesis of hassium in the $^{136}Xe + {}^{136}Xe$ fusion reaction were performed in Dubna. However, no event was detected at the level of about $4\,pb$ [3]. Siwek-Wilczyńska *et al.* [4] have analyzed the $^{136}Xe + {}^{136}Xe$ fusion reaction with the fusion-by-diffusion (FBD) model [5–7]. The maximum evaporation residue (ER) cross section for production of ^{270}Hs isotope in $2n$ channel calculated with this model is on an order of 10 pb, which exceeds the experimental data by orders of magnitude [3,4]. Liu and Bao [8] have evaluated the $^{136}Xe(^{136}Xe, xn)^{272-xn}Hs$ reaction with a modified FBD model. In the model, early dynamics of neck growth has been taken into account in terms of the multidimensional Langevin equations. However, in their calculations, the schematic liquid-drop model and the corresponding expressions of one-body dissipations including the "window" term [9,10] were used. Since the fusion hindrance factors for such reactions are still very uncertain, further evaluation of the hindrance in the fusion of two heavy nuclei, more or less equal in mass, is required.

In a collision involving heavy nuclei, after contact, a fast growth of neck between target and projectile brings the system from dinuclear regime to mononuclear one. Meanwhile, a transition from fusion valley into an asymmetric fission valley (symmetric fission valley for the symmetric systems), which is located outside the saddle point (inner barrier), takes place. Recently, it is realized that for very heavy systems the injection-point configuration in the asymmetric (or symmetric) fission valley has critical influence on the fusion process [11]. In fact, the fusion process is very sensitive to the treatment of the evolution of the neck between the two colliding nuclei at contact. As shown by Boilley *et al.* [12], the rapid evolution of the neck changes the initial value of the other collective variables through a dynamic coupling. They have demonstrated that for the radial degree of freedom, the shift towards larger distance is not negligible and hence may greatly enlarge the hindrance of the fusion.

The collective variables are coupled dynamically through the inertia and friction tensors. In the stochastic equations, terms with different inertia and friction tensors usually have different, even opposite, influence in the final outcome. In this connection, it is meaningful to make a detailed inspection of their role in the dynamic evolution process. In this work, we pay special attention to the influence of the "window" component of friction tensor, which is related to the energy dissipation associated with the exchange of particles across the window between two colliding nuclei [13], in the fusion probability. Our results show that the friction associated with the "window" component retards the elongation of the fusing system and therefore should be favorable to the formation of superheavy nuclei.

II. DYNAMICAL APPROACH OF FUSION PROCESS

After contact of two colliding nuclei, the evolution from dinuclear to mononuclear configurations is described using

*Corresponding author: lyj85@126.com

the coupled Langevin equations. The shape of the system is specified in terms of two spheres with radii R_1 and R_2 smoothly connected by a hyperboloidal neck. Three collective variables may be defined: s, n, and η. Here s is the surface separation between two spheres, n is the radius of neck, and η denotes the mass asymmetry degree of freedom. In present work, the symmetric reactions ^{132}Xe + ^{132}Xe and ^{136}Xe + ^{136}Xe are analyzed. Therefore, the mass asymmetry degree of freedom is not taken into account in the calculations. The coupled Langevin equations of motion in two-dimensional collective space have the form

$$\frac{dq_i}{dt} = \mu_{ij} p_j, \qquad \frac{dp_i}{dt} = -\frac{1}{2} p_j p_k \frac{\partial \mu_{jk}}{\partial q_i} - \frac{\partial V(q)}{\partial q_i} - \gamma_{ij}\mu_{jk} p_k + \theta_{ij}\xi_j(t), \tag{1}$$

where $q_i \equiv s,n$ stands for the collective coordinates, p_i are its conjugate momenta, $V(q)$ is the nuclear deformation potential energy, μ_{ij} denotes the inverse matrix elements of the inertia tensor m_{ij}, and γ_{ij} represents the friction tensor. The normalized random variables ξ_j are assumed to be independent white noises. The strength θ_{ij} of the random force is given by $\theta_{ik}\theta_{kj} = T\gamma_{ij}$ with T being the temperature of the heat bath.

The nuclear deformation potential energy $V(q)$ is obtained from the finite-range liquid drop model [14,15]. We make the Werner-Wheeler approximation [16,17] for incompressible and irrotational flow to calculate the inertia tensor m_{ij} and its inverse μ_{ij} in Eq. (1). For the friction tensor, we use the one-body model for nuclear dissipation in our calculations. In the framework of the one-body dissipation model [18–21], the friction tensor is calculated using the "wall-plus-window" formula for strongly necked-in shapes, while only the "wall" formula is used for compact mononuclear shapes. In the intermediate case for the shapes that are neither compact nor strongly necked-in, a smooth interpolation between the wall and wall-plus-window formula is applied with a weighting factor $f(n)$. The corresponding formula reads [9,18–22]

$$\gamma_{ij} = \rho_m \bar{v}\pi \bar{n}^2 f(n)\delta_{sj} + 2\pi\rho_m \bar{v} k \int_{l_1-R_1}^{l_2+R_2} \frac{\rho_s}{\sqrt{1+\rho_s'^2}} [(A_i\rho_s' + A_i'\rho_s/2) \times (A_j\rho_s' + A_j'\rho_s/2)]dz, \tag{2}$$

with the reduction factor $k = 0.25$ [23] and the subscript (i,j) standing for the collective variables (s,n). In the above equation, the primes denote differentiation with respect to z, ρ_m is the nuclear mass density, $\bar{v}$ is the average nucleon speed, $\bar{n}$ is the average neck radius, ρ_s stands for the radius of nuclear surface in a cylindrical coordinate, $l_{1,2}$ are the center positions of two outside spheres, and the quantities A_i and A_j are defined in Ref. [17] as functions of z and q. The first and second terms in Eq. (2) are the window ($\gamma_{ij}^{\text{window}}$) and wall ($\gamma_{ij}^{\text{wall}}$) terms, respectively. The wall term includes the radial ($\gamma_{ss}^{\text{wall}}$), neck ($\gamma_{nn}^{\text{wall}}$) and coupling ($\gamma_{sn}^{\text{wall}}$) components. For the window term, only the radial element $\gamma_{ss}^{\text{window}}$ is important [9]; the others are negligible in magnitude. We refer to $\gamma_{ss}^{\text{window}}$ as the window component of friction tensor. We introduce the weighting function $f(n)$ in the window term with an expression similar to the one used in Refs. [9,10],

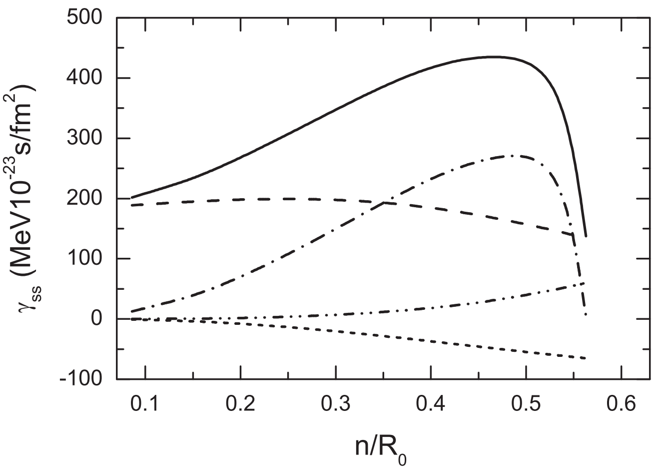

FIG. 1. Different components of friction tensor in the wall-plus-window formula as a function of n/R_0 for the system ^{132}Xe + ^{132}Xe at contact. They are the window ($\gamma_{ss}^{\text{window}}$, dash-dotted line), radial ($\gamma_{ss}^{\text{wall}}$, dashed line), neck ($\gamma_{nn}^{\text{wall}}$, dash-dot-dotted line), and coupling term between radial and neck ($\gamma_{sn}^{\text{wall}}$, short dashed line) degrees of freedom in the wall formula. The solid line represents the sum of $\gamma_{ss}^{\text{wall}} + \gamma_{ss}^{\text{window}}$.

$$f(n) = \cos^2\left(\frac{1}{2}\pi\left[\frac{n}{\sqrt{0.5}R_i}\right]^2\right), \tag{3}$$

where $\sqrt{0.5}R_i$ with $R_i = \min(R_1,R_2)$ was defined to be the boundary between the dinuclear and mononuclear regimes [24]. The components of window ($\gamma_{ss}^{\text{window}}$) and wall ($\gamma_{ss}^{\text{wall}}$, $\gamma_{nn}^{\text{wall}}$, $\gamma_{sn}^{\text{wall}}$) as well as the wall-plus-window ($\gamma_{ss}^{\text{wall}} + \gamma_{ss}^{\text{window}}$) of the radial degree of freedom are displayed in Fig. 1 as a function of n/R_0 with R_0 the radius of the compound nucleus. It is seen from the figure that the window term is an important component of the macroscopic energy dissipation.

The initial conditions for the radial and neck motions, except the initial radial momentum $p_s(0)$, are defined in Refs. [8,22]. The initial radial momentum $p_s(0)$ influences the probability distribution of radial degree of freedom at the injection point s_{inj}, which is the distance between surfaces of two approaching nuclei where injection into asymmetric (or symmetric) fission valley takes place. For sake of simplicity, we set $p_s(0) = 0$ in the present work.

In order to investigate the role of the friction associated with the window term on the fusion probability, we have performed the Monte Carlo simulations using Eq. (1) in the two cases of friction tensor, i.e., with and without the window term in Eq. (2). As an example, the resultant distributions $f(s_{\text{inj}})$ of the injection point s_{inj} are plotted in Fig. 2(a) for the system ^{132}Xe + ^{132}Xe at the center-of-mass energy $E_{\text{c.m.}} = 311$ MeV. The solid and open circles in the figure represent the results calculated with and without the window component of friction tensor. It is seen from the figure that the s_{inj} distribution in the case of the dynamic calculation without the window

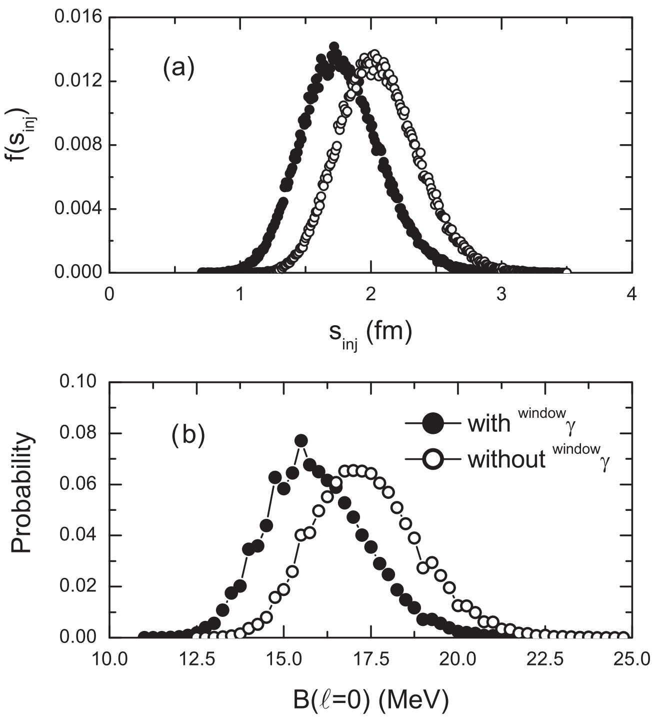

FIG. 2. Probability distributions of s_{inj} (a) and the inner barrier height distributions (b) for the system ^{132}Xe + ^{132}Xe at $E_{\mathrm{c.m.}} =$ 311 MeV. The solid and open circles in panels (a) and (b) represent the results calculated with and without the window term in the friction tensor, respectively.

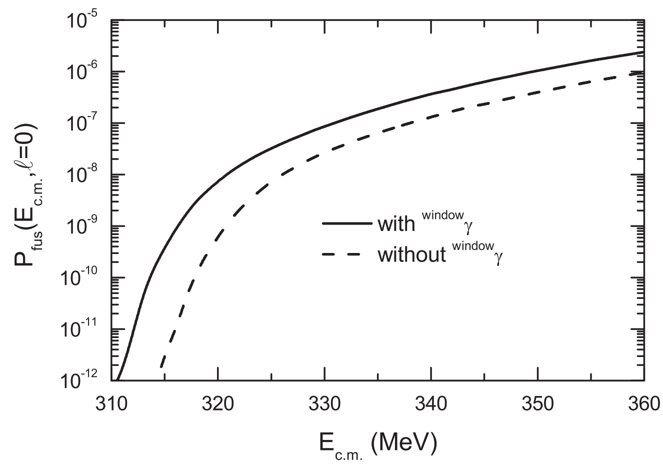

FIG. 3. Fusion probabilities for the system ^{132}Xe + ^{132}Xe at $E_{\mathrm{c.m.}} = 311$ MeV. Only the component with the angular momentum $l = 0$ is shown. The solid and dashed lines represent the results calculated with and without the window term in the friction tensor.

component shifts to a larger distance as compared to the one calculated with the window component of friction tensor. This means that the friction associated with the window term retards to a certain extent the elongation of the fusing system during the evolution process of neck.

From the s_{inj} distribution, one can get the inner barrier height distribution. Displayed in Fig. 2(b) are the barrier distributions for the two cases mentioned above. The barrier height, $B(s_{\mathrm{inj}},l)$ is measured from the injection point, which consists of the macroscopic deformation energy $\Delta E(s_{\mathrm{inj}},l = 0)$ and rotational energy $\Delta E^{\mathrm{rot}}(s_{\mathrm{inj}},l)$ in the l-dependent FBD model [11]. The macroscopic deformation energy along the symmetric fission valley is calculated using the refined algebraic expressions [11]. The corresponding values of the rotational energy at the injection point and at the symmetric saddle point are calculated with moments of inertial specified in Ref. [11]. Only the macroscopic deformation energy $\Delta E(s_{\mathrm{inj}},l = 0)$ is plotted in Fig. 2(b).

After injection into the symmetric fission valley, thermal shape fluctuations in the valley can occasionally bring the system over the saddle point with a probability [5,7,11]

$$P_{\mathrm{fus}}(E_{\mathrm{c.m.}},l) = \frac{1}{2}\int \mathrm{erfc}(\sqrt{B(s_{\mathrm{inj}},l)/T})f(s_{\mathrm{inj}})ds_{\mathrm{inj}}, \quad (4)$$

where T is the temperature of the fusing system, which we take as the mean value of the initial temperature at injection point T_{inj} and the temperature at the top of the saddle point T_{saddle}. Figure 3 shows the fusion probabilities of the angular momentum $l = 0$ for the system ^{132}Xe + ^{132}Xe at $E_{\mathrm{c.m.}} =$ 311 MeV. It is seen from the Figs. 2(b) and 3 that the friction associated with the window term lowers the fusion threshold and obviously increases the fusion probability.

III. RESULTS AND DISCUSSION

The cross section of a superheavy nucleus produced in a heavy-ion fusion-evaporation reaction is calculated as follows [25–27]:

$$\sigma_{\mathrm{ER}}(E_{\mathrm{c.m.}}) = \pi\lambda^2 \sum_{l=0}^{\infty}(2l+1)P_{\mathrm{capt}}(E_{\mathrm{c.m.}},l)P_{\mathrm{fus}} \times (E_{\mathrm{c.m.}},l)P_{xn}(E_{\mathrm{c.m.}},l). \quad (5)$$

Here P_{capt} is the capture probability of the colliding nuclei after overcoming the Coulomb barrier and moving up to the contact point. We calculate P_{capt} by means of a semiphenomenological barrier distribution function method proposed by Zagrebaev *et al.* [28,29]. The last factor, P_{xn}, represents the survival probability of the excited compound nucleus after evaporation of x neutrons in the cooling process. We calculate the survival probability P_{xn} in more or less convenient method; for details, see Refs. [30–32].

In order to compare with the experimental data, we first calculate the ER cross sections for the ^{136}Xe + ^{136}Xe reaction leading to formation of $^{268-271}$Hs isotopes in two approaches, i.e., with and without the window term in the wall-plus-window formula in the dynamic calculations using Eq. (1). Displayed in Fig. 4 is this comparison with the Dubna data. Our calculated maximum ER cross sections in $2n$ and $3n$ channels with the former approach are about 0.4 *pb*, which are one order of magnitude smaller than the the present experimental limit for registration the evaporation residual nuclei. For this reaction, the cross sections calculated with the window term are about two times larger than those evaluated without the window term in Eq. (2).

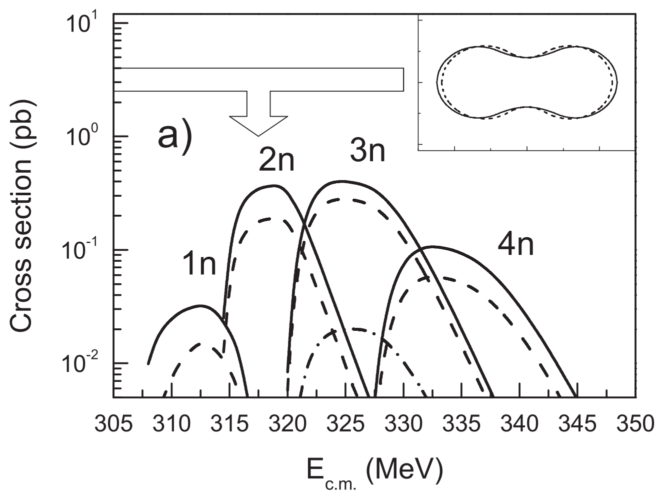

FIG. 4. The evaporation residue cross sections for the ^{136}Xe + ^{136}Xe reaction calculated in two conditions, i.e., with (solid line) and without (dashed line) the window term in the wall-plus-window formula. The dash-dotted line shows the cross sections calculated using the friction of the wall term in Eq. (2) only, but with reduction factor $k = 1.0$. The insert illustrates the nuclear shape in the symmetric valley, in which the thin and thick solid lines are obtained with reduction factors $k = 0.25$ and $k = 1.0$, respectively. The hollow bar in panel (a) shows the upper limit of the experimental ER cross sections in this reaction [3].

Figure 5 displays the predicted ER cross sections for the ^{132}Xe + ^{132}Xe reaction leading to formation of $^{260-263}$Hs isotopes. The results shown in the figure clearly demonstrate that the friction associated with the window term plays an important role in the formation of superheavy nuclei. The ^{132}Xe(^{132}Xe,1n)^{263}Hs fusion-evaporation reaction provides the most obvious example. For this reaction, the peak position of the ER excitation function should be located at $E_{\text{c.m.}} =$ 214 MeV, which is below the threshold of fusion in the case where the window term in Eq. (2) is not taken into account in the dynamic calculations. As a result, the peak of the ER excitation function is pushed to an energy 6 MeV higher than

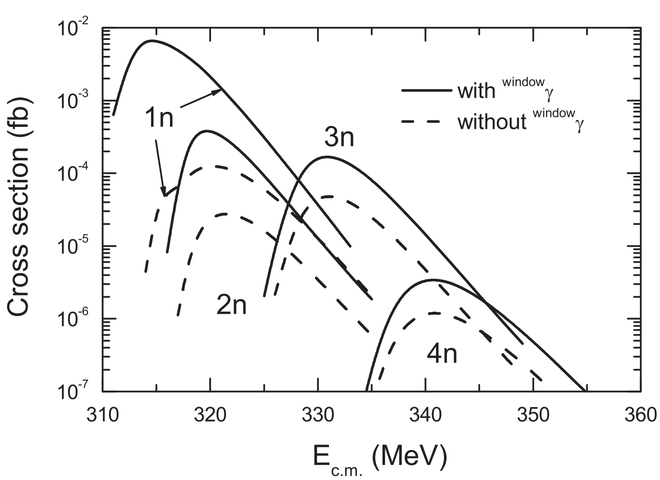

FIG. 5. Same as Fig. 4, but for the ^{132}Xe + ^{132}Xe reaction.

the most favorable value in the 1n evaporation channel and the corresponding ER cross sections are reduced by orders of magnitude as compared to the cross sections in which the s_{inj} distributions are calculated with the window term included in the friction tensor. In other words, the friction associated with the window term greatly increases the ER cross sections of the 1n channel. The ^{132}Xe(^{132}Xe,2n)^{262}Hs reaction takes place in the energy region near the threshold of fusion. The friction associated with the window term brings about the ER cross sections in the 2n evaporation channel increased by more than one order of magnitude. As for the 3n and 4n evaporation channels of the ^{132}Xe + ^{132}Xe reaction, although the effect of the friction of the window term is not as obvious as that observed in the 1n and 2n channels, the cross sections calculated with the window term in the friction tensor are still several times as large as those evaluated without the window term.

In the following, we examine whether similar results can be obtained with larger friction coefficients but without the window term. For this purpose, we have calculated the cross sections of the ^{136}Xe(^{136}Xe,3n)^{269}Hs reaction using the wall formula with the reduction factor $k = 1.0$ [Eq. (2) without the window term]. The resultant ER excitation function is shown in Fig. 4 as dash-dotted line. It is noteworthy that its cross sections are more than one order of magnitude smaller than the results calculated with the reduction factor $k = 0.25$. The time scale of the transition from dinuclear to mononuclear configurations is of the order of γ_{nn}/f_n [12], where γ_{nn} and f_n are the friction coefficient of neck motion and slope of the potential $V(q)$ with respective to the neck degree of freedom. The larger value of γ_{nn} results in a longer transition time. Under the Smoluchowski approximation and neglecting the driving force of the radial degree of freedom, $-\partial V(q)/\partial s$, Boilley *et al.* [12] got an approximate relation between the radial distance and neck size in the neck evolution process,

$$\Delta\langle s\rangle \simeq -\frac{\gamma_{sn}}{\gamma_{ss}}\Delta\langle n\rangle. \quad (6)$$

Therefore, the radial motion is basically not influenced by the increase of the friction strength in the transition from the dinuclear regime to the mononuclear one because both γ_{ss} and γ_{sn} are increased with the same ratio. As a consequence of longer transition time needed, the radial driving force pushes the system into a configuration of the mononucleus with a more elongated shape when the injection into the symmetric valley (beyond the inner barrier) takes place. The insert of Fig. 4 illustrates the nuclear shape in the symmetric valley for the two cases, i.e., with the reduction factors $k = 1.0$ (thick solid line) and $k = 0.25$ (thin solid line). Consequently, the fusion probability and hence the cross sections are obviously reduced. On the other hand, if including the window friction term, then the denominator of Eq. (6) becomes $\gamma_{ss} = \gamma_{ss}^{\text{window}} + \gamma_{ss}^{\text{wall}}$, and hence the ratio $-\gamma_{sn}/\gamma_{ss}$ decreases as compared to the case without the window friction term. It turns out that the nuclear system enters the symmetric fission valley with a compact shape. This is why the window friction tensor retards the elongation of the fusing composite nucleus and therefore increases the fusion probability. In this context, we have shown that the window and wall components of friction tensor play a quite different role in the dynamic evolution process of the heavy nuclear systems.

The functional fluctuation-dissipation relation provides us the simplified expression $\gamma_{ij} = \gamma m_{ij}$. Therefore, the value of the inertia tensor should be changed with shutting on and off the window term in the friction tensor. However, because it is based on a somehow different mechanism, there is no inertia counterpart associated with the window term in the friction tensor in the the Werner-Wheeler approximation [16,17]. As an alternative way, one may check the role of the inertia tensor in the nuclear dynamic evolution process. If the terms with the inertia tensor in the Langevin equations do not have important influence on the final results, then it should not be a serious problem to ignore the change of the inertia tensor due to shutting on or off the window component of friction tensor. By means of a detailed study of the one-body dissipation, Blocki *et al.* [18] came to the conclusion that the dynamics would appear to be characterized by superviscidity, i.e., a pronounced dominance of the motions by dissipative effects. In other words, the effects of the inertia tensor should be much less important. In fact, in the Smoluchowski approximation, the inertia terms in the dynamic equations are neglected (see Eq. (9) of Ref. [7] and Eq. (7) of Ref. [12]). We have checked the possible effect of the change of inertia tensor on the ER cross sections by using the relation $\gamma_{ij} = \gamma m_{ij}$. For the sake of simplicity, we take the value of γ as $\gamma = \gamma_{ss}^{\text{wall}}/m_{ss}$, and hence the increase of the inertia tensor in the radial motion may be approximately expressed as $\Delta m_{ss} = (m_{ss}/\gamma_{ss}^{\text{wall}})\gamma_{ss}^{\text{window}}$ due to introducing the window component of friction tensor. Note that Δm_{ss} is collectively coordinate dependent. Adding Δm_{ss} to m_{ss}, we have calculated the ER excitation function for the ^{136}Xe(^{136}Xe,3n)^{269}Hs reaction. As compared with the case without the increased term Δm_{ss}, the calculated cross sections decrease by about 20%, which are one order of magnitude smaller than the variation caused by the window component of friction tensor. Therefore, the above approach clearly demonstrates that the dynamic evolution process does not sensitively depend on the inertia tensor, and in some circumstances, the terms with the inertia tensor even can be neglected, as treated in the Smoluchowski approximation.

One may observe from Figs. 4 and 5 that the ER cross sections for the ^{136}Xe + ^{136}Xe reaction are several order of magnitude larger than the ER cross sections of the ^{132}Xe + ^{132}Xe reaction. The capture and fusion probabilities of these two reactions are similar. The large differences should caused by the survival probability. The ratio between the neutron and fission disintegration widths has a simple relationship [30],

$$\frac{\Gamma_n}{\Gamma_f} \propto \exp[(B_f - B_n)/T]. \tag{7}$$

Equation (7) means that the logarithm of Γ_n/Γ_f and the difference, d, between the fission barrier height and the neutron binding energy $(B_f - B_n)$ have a simple relationship, i.e., a linear function. In the present approach, Γ_n/Γ_f depends on the mass difference (in units of the temperature) of the fission and neutron emission saddle points (see Fig. 9 in Ref. [7]). Correspondingly, the d value for the emission of k neutrons [32,33] is

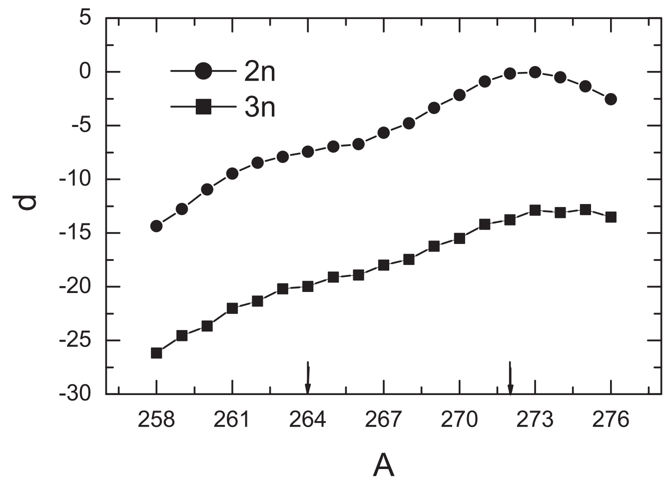

FIG. 6. The difference of the effective fission barrier hight and neutron separation energy in units of the temperature as a function of the mass number for the hassium isotopes. The arrows indicate the mass numbers of the ^{132}Xe + ^{132}Xe and ^{136}Xe + ^{136}Xe systems.

$$d = \sum_{i=1}^{k} \Big(\big[\big(B_{LD} - \Delta_{sh}^{gs} + \Delta_p - B_n\big]_{i-1} - \big\{\Delta_p - \Delta_{sh}^{gs}[1 - \exp(-U/E_D)]\big\}_i \Big) / T_{i-1}. \tag{8}$$

Here Δ_{sh}^{gs}, $\Delta_p(k)$, and B_{LD} denote, respectively, the microscopic shell correction of ground state, the pairing energy, and the barrier height of the macroscopic liquid drop energy. Data of Δ_{sh}^{gs} and $\Delta_p(k)$ are taken from Ref. [34]. $E_D = 18.5$ MeV [31,35] is the damping parameter describing the decrease of the influence of the shell effects on the energy level density with increasing excitation energy. The suffixes in the sum of the first and second terms represent the values taken in the $(i-1)$th and its daughter nuclei, respectively. T_{i-1} is the corresponding nuclear temperature. The initial compound nucleus is indexed as $i = 0$. Figure 6 shows the d values of the 2n and 3n evaporation channel as a function of the mass number of the hassium isotopes. It may be seen from the figure that the d values of ^{272}Hs are several times lager that those of ^{264}Hs. Thus, Fig. 6 clearly demonstrates the origin responsible for the large differences of the ER cross sections between the ^{132}Xe + ^{132}Xe and ^{136}Xe + ^{136}Xe reactions.

IV. SUMMARY

The coupled Langevin equations in two-dimensional collective space are used to study the neck evolution for the mass symmetric systems ^{132}Xe + ^{132}Xe and ^{136}Xe + ^{136}Xe. By solving these Langevin equations the s_{inj} probability distributions are obtained. We have shown that the friction associated with the window term retards the fusing system to drift towards a larger distance of the injection point s_{inj}, and hence decreases the height of the inner barrier. Fusion probability exponentially depends on the barrier height. Therefore, the window component of friction tensor obviously increases the fusion probability. Correspondingly, the ER cross sections are greatly enhanced, especially for those evaporation channels which its peak position locates below or near the fusion threshold. In such a case, the cross sections are increased by orders of magnitude. Therefore, by means of the dynamic analysis for these symmetric systems, we have demonstrated that the friction associated with the window term in the wall-plus-window formula is favorable to the formation of superheavy nuclei.

According to the predictions of microscopic theory, the existence of surperheavy element Hs is fully controlled by the closed deformed shell at $Z = 108$ and $N = 162$. Very recently, the doubly magic nucleus ^{270}Hs has been synthesized using the ^{226}Ra + ^{48}Ca hot fusion reaction [36]. It is very attractive to synthesize and study the nuclei adjacent to ^{270}Hs. The mass difference (in units of the temperature) of the fission and neutron emission saddle points as a function of mass number of the hassium isotopes shown in Fig. 6 may provide a useful reference for these purpose.

ACKNOWLEDGMENTS

This work is supported by the 985 Project (Grant No. 98507-012009) of the Ministry of Education of China and the National Natural Science Foundation of China (NSFC, Grants No. 11074312, No. 11374377, No. 11104360 and No. 11204191).

[1] V. Zagrebaev and W. Greiner, Nucl. Phys. A **787**, 363 (2007).
[2] G. G. Adamian, N. V. Antonenko, S. P. Ivanova, and W. Scheid, Nucl. Phys. A **646**, 29 (1999).
[3] Yu. Ts. Oganessian *et al.*, Phys. Rev. C **79**, 024608 (2009).
[4] K. Siwek-Wilczyńska, I. Skwira-Chalot, and J. Wilczyński, Int. J. Mod. Phys. E **16**, 483 (2007).
[5] W. J. Światecki, K. Siwek-Wilczyńska, and J. Wilczyński, Acta Phys. Pol. B **34**, 2049 (2003).
[6] W. J. Światecki, K. Siwek-Wilczyńska, and J. Wilczyński, Int. J. Mod. Phys. E **13**, 261 (2004).
[7] W. J. Światecki, K. Siwek-Wilczyńska, and J. Wilczyński, Phys. Rev. C **71**, 014602 (2005).
[8] Z. H. Liu and J. D. Bao, Phys. Rev. C **81**, 044606 (2010).
[9] R. Donangelo and L. F. Canto, Nucl. Phys. A **451**, 349 (1986).
[10] C. E. Aguiar, V. C. Barbosa, and R. Donangelo, Nucl. Phys. A **517**, 205 (1990).
[11] T. Cap, K. Siwek-Wilczyńska, and J. Wilczyński, Phys. Rev. C **83**, 054602 (2011).
[12] D. Boilley, H. Lü, C. W. Shen, Y. Abe, and B. G. Giraud, Phys. Rev. C **84**, 054608 (2011).
[13] J. Blocki, H. Feldmeier, and W. J. Światecki, Nucl. Phys. A **459**, 145 (1986).
[14] H. J. Krappe, J. R. Nix, and A. J. Sierk, Phys. Rev. Lett. **42**, 215 (1979); Phys. Rev. C **20**, 992 (1979).
[15] A. J. Sierk, Phys. Rev. C **33**, 2039 (1986).
[16] J. R. Nix, Nucl. Phys. A **130**, 241 (1969).
[17] K. T. R. Davies, A. J. Sierk, and J. R. Nix, Phys. Rev. C **13**, 2385 (1976).
[18] J. Blocki, Y. Bonch, J. R. Nix, J. Randrup, M. Robel, A. J. Sierk, and W. J. Światecki, Ann. Phys. **113**, 330 (1978).
[19] J. Randrup and W. J. Światecki, Ann. Phys. **125**, 193 (1980).
[20] A. K. Dhara, K. Krishan, C. Bhattacharya, and S. Bhattacharya, Phys. Rev. C **57**, 2453 (1998).
[21] S. M. Mirfathi and M. R. Pahlavani, Phys. Rev. C **78**, 064612 (2008).
[22] Z. H. Liu and J. D. Bao, Phys. Rev. C **83**, 044613 (2011).
[23] J. Sadhukhan and S. Pal, Phys. Rev. C **84**, 044610 (2011).
[24] W. J. Swiatecki, Phys. Scr. **24**, 113 (1981).
[25] N. V. Antonenko, E. A. Cherepanov, A. K. Nasirov, V. P. Permjakov, and V. V. Volkov, Phys. Lett. B **319**, 425 (1993).
[26] N. V. Antonenko, E. A. Cherepanov, A. K. Nasirov, V. P. Permjakov, and V. V. Volkov, Phys. Rev. C **51**, 2635 (1995).
[27] G. G. Adamian, N. V. Antonenko, and W. Scheid, Nucl. Phys. A **618**, 176 (1997).
[28] V. I. Zagrebaev, Phys. Rev. C **64**, 034606 (2001).
[29] V. I. Zagrebaev, Y. Aritomo, M. G. Itkis, Yu. Ts. Oganessian, and M. Ohta, Phys. Rev. C **65**, 014607 (2001).
[30] R. Vandenbosch and J. R. Huizenga, in *Nuclear Fission* (Academic Press, New York, 1973), p. 233.
[31] K. Siwek-Wilczyńska, I. Skwira, and J. Wilczyński, Phys. Rev. C **72**, 034605 (2005).
[32] Z. H. Liu and J. D. Bao, Phys. Rev. C **80**, 034601 (2009).
[33] Z. H. Liu and J. D. Bao, Phys. Rev. C **87**, 034616 (2013).
[34] P. Moller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995).
[35] W. Reisdorf, Z. Phys. A **300**, 227 (1981).
[36] Yu. Ts. Oganessian *et al.*, Phys. Rev. C **87**, 034605 (2013).