Simulation of the fission dynamics of the excited compound nuclei ^{206}Po and ^{168}Yb produced in the reactions ^{12}C+^{194}Pt and ^{18}O+^{150}Sm

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Abstract: A two-dimensional dynamical model based on the Langevin equation was used to study the fission dynamics of the compound nuclei ^{206}Po and ^{168}Yb produced in the reactions ^{12}C+^{194}Pt and ^{18}O+^{150}Sm, respectively. The fission cross section and average pre-scission neutron multiplicity were calculated for the compound nuclei^{206}Po and ^{168}Yb, and results of the calculations compared with the experimental data. The elongation coordinate was used as the first dimension and the projection of the total spin of the compound nucleus onto the symmetry axis, K, considered as the second dimension in the Langevin dynamical calculations. In the two-dimensional calculations, a constant dissipation coefficient of K and a non-constant dissipation coefficient have been used to reproduce the above-mentioned experimental data. It is shown that the two-dimensional Langevin equation can satisfactorily reproduce the fission cross section and average pre-scission neutron multiplicity for the compound nuclei ^{206}Po and ^{168}Yb by using constant values of the dissipation coefficient of K equal to $\gamma_K = 0.18(\text{MeV zs})^{-1/2}$ and $\gamma_K = 0.20(\text{MeV zs})^{-1/2}$ for the compound nuclei ^{206}Po and ^{168}Yb, respectively.

Keywords: dissipation coefficient, Langevin model, fission cross section

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1 Introduction

Study of the fission of highly excited nuclei produced in fusion reactions remains a topic of great interest. In the last three decades, much theoretical attention has been directed towards understanding the dynamics of fission (see for example Refs. [1–22]). Many researchers, in their calculations for the description of different features of fusion-fission reactions, have assumed that compound nuclei have zero spin about the symmetry axis. This assumption is not consistent with a dynamical treatment of the orientation degree of freedom (K coordinate), as first pointed out by Lestone in Ref. [23]. The authors in Ref. [10] also stressed that a large volume of heavy-ion-induced fission data needs to be reanalyzed using a dynamical treatment of the orientation degree of freedom. Consequently, in the present investigation we use a two-dimensional dynamical model based on the Langevin equation to study the fission dynamics of the compound nuclei ^{206}Po and ^{168}Yb produced in the reactions $^{12}\text{C}+{}^{194}\text{Pt}$ and $^{18}\text{O}+{}^{150}\text{Sm}$, respectively. In the two-dimensional dynamical model we consider the dynamical evolution of the orientation degree of freedom$K$. Furthermore, in the two-dimensional dynamical calculations we use a constant dissipation coefficient of K, and a non-constant dissipation coefficient to reproduce the fission cross section and average pre-scission neutron multiplicity for the compound nuclei ^{206}Po and ^{168}Yb.

This paper has been arranged as follows. In Section 2 we describe the model and basic equations. The results of the calculations are presented in Section 3. Concluding remarks are given in Section 4.

2 Description of the model

A stochastic approach based on the two-dimensional Langevin equation is used to describe the fission dynamics of the excited compound nuclei ^{206}Po and ^{168}Yb produced in the reactions $^{12}\text{C}+{}^{194}\text{Pt}$ and $^{18}\text{O}+{}^{150}\text{Sm}$, respectively. In the stochastic approach the shape parameters c, h and α as suggested by Brack et al. [24] are taken as the collective coordinates for the fission degree of freedom. However, for simplicity we use only the elongation parameter c, while the parameters h and α are assumed to be zero. Consequently, the one-dimensional over-damped Langevin equation take the form [25]

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

where T is the nuclear temperature, S is the entropy of the system and M is the inertia parameter [26]. $\beta = n/M$

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is the reduced friction coefficient and n is the friction coefficient. The driving force of the Langevin equation is calculated from the entropy:

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

where E^* is the excitation energy of the system and $V(c)$ is the potential energy. The coordinate dependent level density parameter can be considered as

$$a(c)=a_{\rm v}A+a_{\rm s}A^{2/3}B_{\rm s}(c), \tag{3}$$

where A is the mass number of the compound nucleus, and $B_{\rm s}$ is the dimensionless functional of the surface energy in the liquid drop model. The values of the parameters $a_{\rm v}$=0.073 MeV^{-1} and $a_{\rm s}$=0.095 MeV^{-1} in Eq. (3) are taken from the work of Ignatyuk et al. [27].

In Eq. (1), $\Gamma(t)$ is a fluctuating force whose average and correlation function are

$$\begin{aligned}&<\Gamma(t)>=0,\\&<\Gamma(t)\Gamma(t')>=2\delta(t-t')\ .\end{aligned} \tag{4}$$

The potential energy can be calculated on the basis of the liquid drop model with a finite range of nuclear forces [28] using the parameters from Ref. [29]

$$\begin{aligned}V(c,I,K)=&(B_s(c)-1)E_{\rm s}^0(Z,A)\\&+(B_{\rm c}(c)-1)E_{\rm c}^0(Z,A)+E_{\rm rot}(c,I,K),\end{aligned} \tag{5}$$

where I is the spin of a compound nucleus, K is the projection of I onto the symmetry axis of the nucleus, and $B_{\rm s}(c)$, $B_{\rm c}(c)$ are surface and Coulomb energy terms, respectively. $E_{\rm s}^0$ and $E_{\rm c}^0$ are the surface and Coulomb energies of the corresponding spherical system as determined by Ref. [30, 31] and $E_{\rm rot}$ is the rotational energy of the nucleus. Figure 1 shows the potential energy surface calculated for the compound nucleus ^{206}Po as a function of the coordinate c and for different combinations of I and K.

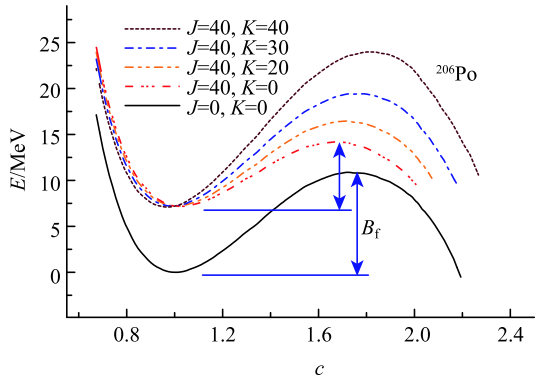

Fig. 1. (color online) Potential energy surface for the compound nucleus ^{206}Po as a function of the coordinate c, for different combinations of I and K.

In the dynamical calculations, dissipation is generated through the chaos weighted wall and window friction formula [32, 33]

$$n(c)=\begin{cases}\mu(c)n_{\rm wall}(c) & c<c_{\rm win}\\ \mu(c)n_{\rm wall}(c)+n_{\rm win}(c) & c\geqslant c_{\rm win},\end{cases} \tag{6}$$

where $\mu(c)$ is chaoticity and $c_{\rm win}$ is the elongation coordinate at which the nucleus has a binary shape. The wall and window friction formula can be considered as follows:

$$\begin{aligned}n_{\rm wall}(c<c_{\rm win})=&\frac{1}{2}\pi\rho_{\rm m}\bar{v}\Bigg\{\int_{z_{\rm min}}^{z_{\rm max}}\left(\frac{\partial\rho^2}{\partial c}\right)^2\\&\times\left(\rho^2+\left(\frac{1}{2}\frac{\partial\rho^2}{\partial z}\right)^2\right)^{-1/2}{\rm d}z\Bigg\},\\n_{\rm wall}(c>c_{\rm win})=&\frac{1}{2}\pi\rho_{\rm m}\bar{v}\Bigg\{\int_{z_{\rm min}}^{z_{\rm N}}\left(\frac{\partial\rho^2}{\partial c}+\frac{\partial\rho^2}{\partial z}\frac{\partial D_1}{\partial c}\right)^2\\&\times\left(\rho^2+\left(\frac{1}{2}\frac{\partial\rho^2}{\partial z}\right)^2\right)^{-1/2}{\rm d}z\\&+\int_{z_{\rm N}}^{z_{\rm max}}\left(\frac{\partial\rho^2}{\partial c}+\frac{\partial\rho^2}{\partial z}\frac{\partial D_2}{\partial c}\right)^2\\&\times\left(\rho^2+\left(\frac{1}{2}\frac{\partial\rho^2}{\partial z}\right)^2\right)^{-1/2}{\rm d}z\Bigg\},\end{aligned} \tag{7}$$

$$n_{\rm win}(c)=\frac{1}{2}\rho_{\rm m}\bar{v}\left\{\left(\frac{\partial R}{\partial c}\right)^2\Delta\sigma\right\}, \tag{8}$$

where $\rho_{\rm m}$ is the mass density of the nucleus, $\bar{v}$ is the average nucleon speed inside the nucleus, $\Delta\sigma$ is the area of the window between the two parts of the system, R is the distance between the centers of masses of the future fission fragments, ρ^2 is the surface of the nucleus, $z_{\rm min}$ and $z_{\rm max}$ are the two extreme ends of the nuclear shape along the z axis, $z_{\rm N}$ is the position of the neck plane and D_1, D_2 are the positions of the centers of mass of the two parts of the fissioning system relative to the center of mass of the whole system. The chaoticity μ is a measure of chaos in the single particle motion and depends on the shape of the nucleus. It can be given as the average fraction of the nucleon trajectories which are chaotic and it can be evaluated by sampling over a large number of classical trajectories for a given shape of the nucleus. Each such trajectory is identified either as a regular or a chaotic one by considering the magnitude of its Lyapunov exponent and the nature of its variation with time [34]. The magnitude of chaoticity μ changes from 0 to 1 as the nucleus evolves from a spherical to a deformed

shape. Figures 2 and 3 show the calculated values of the chaoticity and reduced friction coefficient as a function of elongation coordinate for the compound nucleus ^{206}Po.

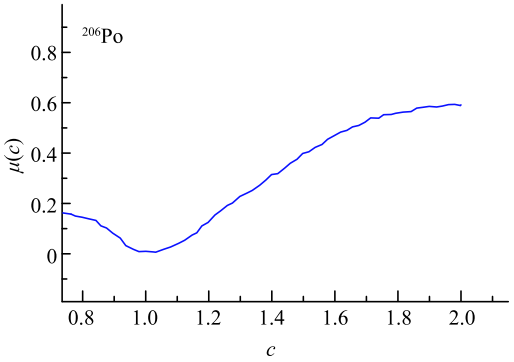

Fig. 2. (color online) The magnitude of chaoticity as a function of elongation coordinate for the compound nucleus ^{206}Po.

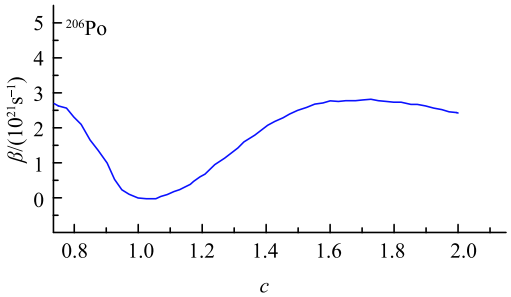

Fig. 3. (color online) The reduced friction coefficient as a function of elongation coordinate for the compound nucleus ^{206}Po.

For starting a trajectory, a spin value is sampled from the fusion spin distribution [35]

$$\sigma(I)=\frac{2\pi}{k^2}\frac{2I+1}{1+\exp\left(\dfrac{I-I_{\rm c}}{\delta I}\right)}, \tag{9}$$

where δI is the diffuseness and $I_{\rm c}$ is the critical spin. The parameters δI and $I_{\rm c}$ can be approximated by the relations presented in Ref. [35].

In the present investigation, the projection of the total spin of the compound nucleus onto the symmetry axis, K, is considered as the second dimension in the Langevin dynamical calculations. The evolution of the K collective coordinate can be determined by the following formula [10]

$$\mathrm{d}K=-\frac{\gamma_K^2 I^2}{2}\frac{\partial V}{\partial K}\mathrm{d}t+\gamma_K I\Gamma(t)\sqrt{T\mathrm{d}t}, \tag{10}$$

where $\Gamma(t)$ has the same meaning as in Eq. (1) and γ_K is a parameter controlling the coupling between the orientation degree of freedom K and the heat bath. The authors of Refs. [10, 36], based on the works of Døssing and Randrup [37, 38], have shown that in the case of a dinucleus, the deformation dependence of γ_K can be determined as

$$\gamma_K=\frac{1}{R_{\rm N}R\sqrt{2\pi^3 n_0}}\sqrt{\frac{J_R\,|J_{\rm eff}|\,J_{||}}{J_\perp^3}}, \tag{11}$$

where $R_{\rm N}$ is the neck radius, R is the distance between the mass centers of the nascent fragments, $n_0=0.0263$ MeV zs fm^{-4} is the bulk flux in the standard nuclear matter [37] and $J_R=M_0R^2/4$ for a reflection symmetric shape. $J_{||}$, $J_\perp$ are the parallel and perpendicular moments of inertia to the symmetry axis and $J_{\rm eff}$ is the effective moment of inertia. The inverse of the effective moment of inertia is $J_{\rm eff}^{-1}=J_{||}^{-1}-J_\perp^{-1}$. The rigid body moments of inertia, about and perpendicular to the symmetry axis can be determined as Ref. [39]. In the calculations to perform numerical integration of the Langevin equation for the K coordinate, it is necessary to determine the value of $\gamma_{\rm K}$ for all possible nuclear deformations. In the case of a dinucleus, $\gamma_{\rm K}$ can be determined from Eq. (11) and for mononuclear shapes without a neck, we can extrapolate the results of Eq. (11). Figure 4 shows the results of the calculations for the dissipation coefficient of K as a function of elongation parameter c for the compound nucleus ^{206}Po.

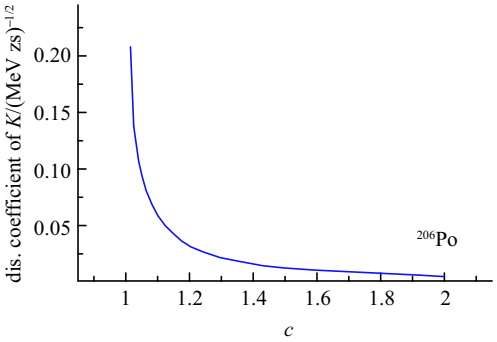

Fig. 4. (color online) The dissipation coefficient of K as a function of elongation parameter c for the compound nucleus ^{206}Po.

It should be noted that the Langevin equation for the K coordinate, Eq. (10), and the Langevin equation, Eq. (1), are connected through the potential energy. The rotational part of the potential energy is calculated by

$$E_{\rm rot}(c,I,K)=\frac{\hbar^2K^2}{2J_{||}(c)}+\frac{\hbar^2[I(I+1)-K^2]}{2J_\perp(c)}. \tag{12}$$

By averaging Eq. (10), it can be shown that

$$\frac{\mathrm{d}\langle K\rangle}{\mathrm{d}t}=-\frac{\gamma_K^2 I^2}{2}\left\langle\frac{\partial V}{\partial K}\right\rangle. \tag{13}$$

From the expression for the rotational energy, Eq. (12), it follows that

$$\frac{\mathrm{d}\langle K\rangle}{\mathrm{d}t}=-\frac{\gamma_K^2 I^2\hbar^2}{2J_{\rm eff}}\langle K\rangle. \quad (14)$$

By assuming a constant γ_K, the solution of this equation is

$$\langle K(t)\rangle_{K_0}=K_0\exp\left[-\frac{\gamma_K^2 I^2\hbar^2}{2J_{\rm eff}}(t-t_0)\right]. \quad (15)$$

In the dynamical calculations, the Langevin trajectories are simulated starting from the ground state of the compound nucleus with the excitation energy E^*. During a random walk along the Langevin trajectory the energy conservation law is used in the form

$$E_{\rm int}=E^*-E_{\rm coll}-V(c,I,K)-E_{\rm evap}(t), \quad (16)$$

where $E_{\rm int}$, E^* and $E_{\rm coll}$ are the intrinsic energy, excitation energy and the kinetic energy of the nucleus, respectively. $E_{\rm evap}$ is the nucleus excitation energy that light particles have carried away by time t. The decay widths for emission n, p, α, γ are calculated at each Langevin time step Δt. The emission of a particle is allowed by asking whether, along the trajectory at each time step Δt, a random number ξ is less than the ratio of the Langevin time step Δt to the decay time $\tau=\hbar/\Gamma_{\rm tot}$: $\xi<\Delta t/\tau(0\leqslant\xi\leqslant 1)$, where $\Gamma_{\rm tot}=\sum_\nu\Gamma_\nu$ with $\nu=\mathrm{n},\mathrm{p},\alpha,\gamma$. After the particle type is randomly chosen, the kinetic energy ε_ν of the emitted particle is also generated via a Monte Carlo procedure. Then the intrinsic energy, entropy, and temperature in the Langevin equation are recalculated and the dynamics is continued. The spin of the compound nucleus is reduced only in an approximate way by assuming that each neutron, proton or gamma quanta carries away $1\hbar$ and each α particle carries away $2\hbar$. A dynamical trajectory will either reach the scission point, in this case it is counted as a fission event, or if the excitation energy for a trajectory which is still inside the saddle reaches the value $E_{\rm int}+E_{\rm coll}<\min(B_\nu,B_{\rm f})$ (B_ν is the binding energy of the particle ν and $B_{\rm f}$ is the fission barrier height), the event is counted as an evaporation residue.

The particle emission width of a particle of kind ν can be calculated by [40]

$$\Gamma_\nu=(2s_\nu+1)\frac{m_\nu}{\pi^2\hbar^2\rho_{\rm c}(E_{\rm int})}\times\int_0^{E_{\rm int}-B_\nu}\mathrm{d}\varepsilon_\nu\rho_R(E_{\rm int}-B_\nu-\varepsilon_\nu)\varepsilon_\nu\sigma_{\rm inv}(\varepsilon_\nu), \quad (17)$$

where s_ν is the spin of the emitted particle ν and m_ν is its reduced mass with respect to the residual nucleus. $E_{\rm int}$ and B_ν are the intrinsic energy and the separation energy of particle ν, respectively. $\rho_{\rm c}(E_{\rm int})$ and $\rho_R(E_{\rm int}-B_\nu-\varepsilon_\nu)$ are the level densities of the compound and residual nuclei. The variable ε_ν is the kinetic energy of the evaporated particle ν. The inverse cross section, $\sigma_{\rm inv}$, can be calculated as Ref. [40]. The width of the gamma emission can be calculated as in Ref. [41].

3 Results and discussion

In this investigation, a stochastic approach based on two-dimensional Langevin equation has been used to calculate the fission cross section and average pre-scission neutron multiplicity for the compound nuclei ^{206}Po and ^{168}Yb produced in the reactions $^{12}\mathrm{C}+{}^{194}\mathrm{Pt}$ and $^{18}\mathrm{O}+{}^{150}\mathrm{Sm}$, respectively. Furthermore, the one-dimensional Langevin equation has been also used to calculate the above mentioned experimental data. The results of one- and two-dimensional calculations have been compared with the experimental data. In the two-dimensional Langevin equation we used a constant dissipation coefficient of K and a non-constant dissipation coefficient based on Eq. (11). In the two-dimensional calculations using a constant dissipation coefficient, the magnitude of dissipation is considered as a free parameter and its magnitude inferred by fitting measured data on the fission cross section and average pre-scission neutron multiplicity for the compound nuclei ^{206}Po and ^{168}Yb. Figures 5(a), 5(b), 6(a) and 6(b) show the results of fission cross section and average pre-scission neutron multiplicity as a function of excitation energy for the compound nuclei ^{206}Po and ^{168}Yb. It can be seen from Figs. 5(a), 5(b), 6(a) and 6(b) that the two-dimensional Langevin equation can satisfactorily reproduce the fission cross section and average pre-scission neutron multiplicity for the compound nuclei ^{206}Po and ^{168}Yb by using constant values of the dissipation coefficient of K equal to $\gamma_K=0.18(\mathrm{MeV\ zs})^{-1/2}$ and $\gamma_K=0.20(\mathrm{MeV\ zs})^{-1/2}$ for the compound nuclei ^{206}Po and ^{168}Yb, respectively.

It is clear from Figs. 5(a), 5(b) that at higher excitation energies the fission cross section reaches a stationary value. This is because with increasing excitation energy the pre-scission particle multiplicity increases and each emission of a light particle carries away spin and excitation energy, therefore fission barrier height of the residual nucleus increases and consequently the fission event is less and less probable. It can also be seen from Figs. 5(a), 5(b), 6(a) and 6(b) that the results of calculations with a constant dissipation coefficient for rotational degrees of freedom provide a better description than that with a deformation-dependent dissipation coefficient. This discrepancy can be explained in terms of Eq. (11). This equation was obtained assuming a dinucleus (a system consisting of two nuclei connected by a neck) and is only valid for systems with a well-defined neck. The extrapolation to more compact configurations should be considered with caution, and is only shown to give some guidance on the possible nature of the coupling between the orientation and thermal degrees of freedom.

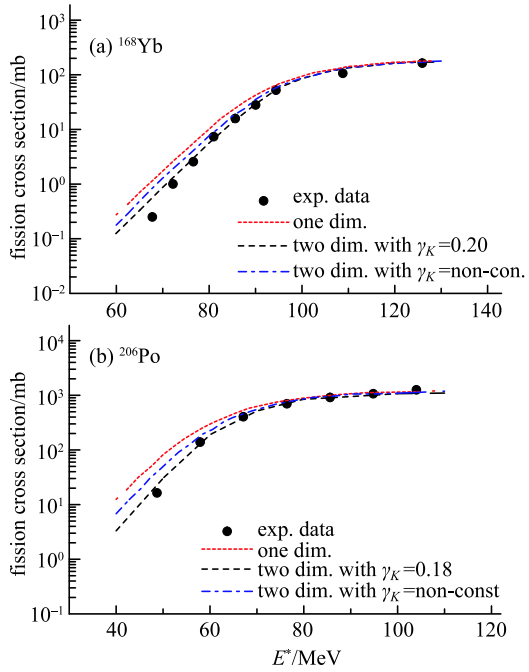

Fig. 5. (color online) Fission cross section calculated with one- and two-dimensional Langevin equation for the compound nuclei ^{206}Po and ^{168}Yb. The experimental data (filled circles) are taken from Ref. [42–44].

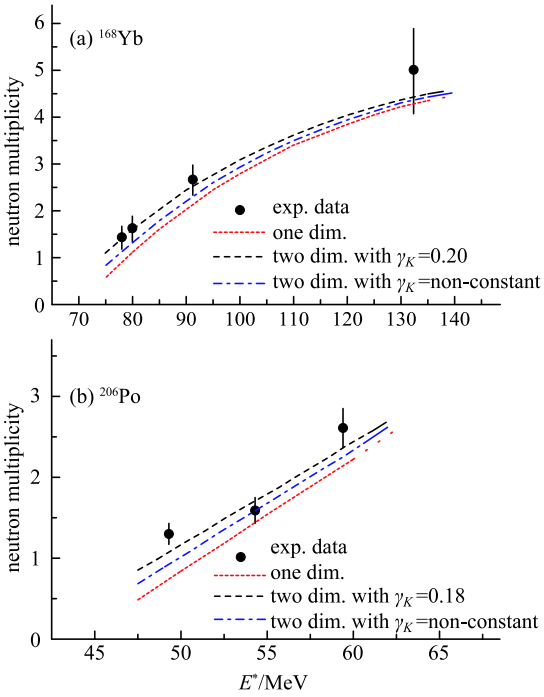

Fig. 6. (color online) Pre-scission neutron multiplicity as a function of excitation energy calculated with one- and two-dimensional Langevin equation for the compound nuclei ^{206}Po and ^{168}Yb. The experimental data (filled circles) are taken from Ref. [45–46].

By changing some of the assumptions used to obtain Eq. (11), the magnitude of γ_K about the spherical shape can be changed. It is likely that a more detailed and accurate model for the motion in K will have a coupling term γ_K that depends on deformation, the rate of change of the deformation, and the nuclear orientation.

In this investigation, in order to obtain further insight into the dynamics of fission, we have also calculated the percentage yield of the pre-scission neutrons as a function of c for the compound nucleus ^{206}Po. Figure 7 shows the percentage yield of the pre-scission neutrons as a function of elongation parameter c calculated with the one- and two-dimensional Langevin equations by using $\gamma_K = 0.18(\text{MeV zs})^{-1/2}$.

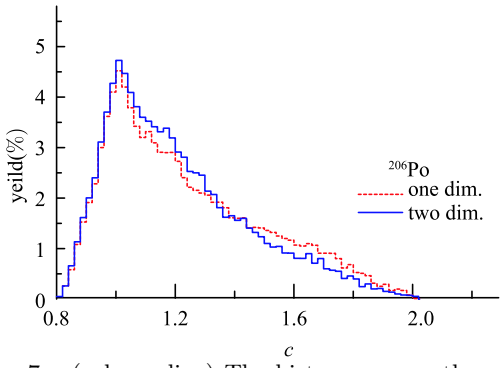

Fig. 7. (color online) The histograms are the percentage yield of the pre-scission neutrons as a function of elongation parameter c calculated with the one-dimensional Langevin equation (dotted histogram) and two-dimensional Langevin equation (solid histogram).

It is clear from Fig. 7 that the pre-saddle contribution of neutron multiplicities in the two-dimensional Langevin calculations ($k \neq 0$) increases relative to one-dimensional Langevin calculations($k = 0$). This can be explained as due to the height of the potential energy surface increasing when $k \neq 0$ (see Fig. 1). Consequently, the number of evaporated pre-scission neutrons increases in the two-dimensional Langevin calculations.

Finally, it should be stressed that a correlation may exist between dissipation coefficients assumed for shape and the rotational degrees of freedom which were used in this investigation. In other words, a different dissipation strength assumed for shape degrees of freedom may affect the numerical value of the dissipation coefficient deduced for rotational degrees of freedom, which is determined by comparing theory and experiment. This issue will be investigated in future studies.

4 Summary and conclusions

A stochastic approach based on the two-dimensional Langevin equation has been used to calculate the fission

cross section and average pre-scission neutron multiplicity for the compound nuclei ^{206}Po and ^{168}Yb and results of the calculations compared with the experimental data. In the Langevin dynamical calculations the elongation coordinate was considered as the first dimension and the projection of the total spin of the compound nucleus onto the symmetry axis considered as the second dimension. In the two-dimensional calculations, a constant dissipation coefficient K and a non-constant dissipation coefficient have been used to describe the fission dynamics of the compound nuclei ^{206}Po and ^{168}Yb. In the two-dimensional calculations with a constant dissipation coefficient, the magnitude of dissipation has been considered as a free parameter and its magnitude inferred by fitting measured data on the fission cross section and average pre-scission neutron multiplicity. Comparison of the theoretical results with the experimental data showed that the results of calculations obtained by the two-dimensional Langevin equation can satisfactorily reproduce the fission cross section and average pre-scission neutron multiplicity for the compound nuclei ^{206}Po and ^{168}Yb by using constant values of the dissipation coefficient of K equal to $\gamma_K = 0.18(\text{MeV zs})^{-1/2}$ and $\gamma_K = 0.20(\text{MeV zs})^{-1/2}$ for the compound nuclei ^{206}Po and ^{168}Yb, respectively.

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