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Influence of nuclear dissipation on fission dynamics of the excited nucleus ^{248}Cf within a stochastic approach

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Abstract. A stochastic approach to fission dynamics based on two-dimensional Langevin equations was applied to calculate the anisotropy of the fission fragments angular distribution and average pre-scission neutron multiplicities for the compound nucleus ^{248}Cf formed in the $^{16}O + ^{232}Th$ reactions. Postsaddle nuclear dissipation strength of (12–14) $\times 10^{21}$ s^{-1} was extracted for Cf nucleus by fitting the results of calculations with the experimental data. Furthermore, it was found that the results of calculations for the anisotropy of the fission fragments angular distribution and pre-scission neutron multiplicities are very sensitive to the magnitude of post-saddle nuclear dissipation.

Keywords. Anisotropy of the fission fragments angular distribution; nuclear dissipation.

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1. Introduction

The magnitude of nuclear dissipation is one of the most interesting and challenging problems in nuclear physics, particularly in low and intermediate energy regions of heavy ion physics. At present, there are several models for dissipation but they give dependences which are very different from each other. For example, two-body dissipation [1] predicts a decrease of dissipation with temperature as T^{-2}, whereas the linear response theory [2,3] predicts that dissipation increases with temperature. On the other hand, there are certain indications that the nuclear dissipation is deformation-dependent. Fröebrich *et al* [4] made a detailed study of fission dynamics for several nuclei using Langevin equations and after comparing calculated fission probability and pre-scission neutron multiplicity with the experimental data, suggested a phenomenological shape-dependent nuclear friction. The phenomenological friction turned out to be smaller than the standard wall formula value for nuclear friction up to the saddle point, and it would sharply increase between saddle and scission points. Furthermore, for the analysis of different aspects of nuclear fission many researchers have used wall formula [5], while many others have assumed constant nuclear dissipation in their calculations [6–14]. In the present investigation, we use the value of the pre-saddle friction equal to 3×10^{21} s^{-1}, in accordance with recent theoretical estimates and experimental analyses [15–21], whereas the post-saddle friction strength is determined by fitting calculated data on the anisotropy of the fission fragments angular distribution and average pre-scission neutron multiplicities with the experimental data for ^{248}Cf. In our calculations, we use two-dimensional Langevin equations to simulate the fission process of the compound nucleus ^{248}Cf formed in the $^{16}O + ^{232}Th$ reactions. In our dynamical calculations, half of the distance between the centre of mass of the future fission fragments was used as the first dimension and the projection of the total spin of the compound nucleus onto the symmetry axis, *K*, was considered as the second dimension. It should be mentioned that many researchers, for describing different features of fusion–fission reactions in statistical or dynamical models, assumed that compound nuclei have zero spin about the symmetry axis, whereas this assumption is not consistent with statistical or dynamical models as first pointed out by Lestone [22]. Furthermore, Lestone [22] stressed that a large volume of heavy-ion-induced fission data needs to be reanalysed in the framework of statistical or dynamical models. Therefore, consideration of the K coordinate as an independent collective coordinate in the dynamical calculations is necessary to simulate the fission process of the compound nucleus ^{248}Cf.

The present paper is arranged as follows: In §2, we describe the model and basic equations. The results of calculations are presented in §3. Finally concluding remarks are given in §4.

2. Description of the model and basic equations

In the present investigation, we use a stochastic approach based on Langevin equations to describe the fission dynamics of ^{248}Cf formed in the ^{16}O + ^{232}Th reactions. The Langevin equations in one dimension can be given as [23]

$$\frac{\mathrm{d}r}{\mathrm{d}t} = \frac{p}{m(r)}$$
$$\frac{\mathrm{d}p}{\mathrm{d}t} = -\frac{p^2}{2}\frac{\mathrm{d}}{\mathrm{d}r}\left(\frac{1}{m}\right) - \frac{\partial F}{\partial r} - \eta\dot{r} + R(t), \quad (1)$$

where r is the dimensionless fission coordinate and is defined as the ratio of half of the distance between the centre of mass of the future fission fragments and the radius of the compound nucleus, p is the conjugate momentum, m is the inertia parameter, η is the friction coefficient, $R(t)$ is a random force with the properties $\langle R(t)\rangle = 0$ and $\langle R(t)R(t')\rangle = 2\eta T\delta(t-t')$ and F is the free energy of the system. The free energy is defined as $F(r,T) = V(r) - a(r)T^2$, where $V(r)$ is the potential energy, $a(r)$ is the coordinate-dependent level density parameter and T is the temperature of the system. The Fermi gas model is used to determine the temperature of the system according to the equation $T = \sqrt{E_{\mathrm{int}}/a(r)}$, where E_{int} is the intrinsic excitation energy. The coordinate-dependent level density parameter is of the form $a(r) = a_{\mathrm{v}}A + a_{\mathrm{s}}A^{2/3}B_{\mathrm{s}}(r)$, where A is the mass number of the compound nucleus and B_{s} is the dimensionless functional of the surface energy in the liquid drop model. Values of the parameters $a_{\mathrm{v}} = 0.073$ MeV^{-1} and $a_{\mathrm{s}} = 0.095$ MeV^{-1} are taken from ref. [24]. In cylindrical coordinates, the surface of a nucleus of mass number A with elongation parameter c can be defined as

$$\rho^2(z) = \left(1 - \frac{z^2}{c_0^2}\right)\left(A_0 c_0^2 + B_0 z^2\right), \quad (2)$$

where z is the coordinate along the symmetry axis and ρ is the radial coordinate of the nuclear surface. In eq. (2), $c_0 = cR$ and $R = 1.16A^{1/3}$. The parameters A_0 and B_0 are given as

$$A_0 = \frac{1}{c^3} - \frac{B_0}{5}$$
$$B_0 = \frac{c-1}{2}. \quad (3)$$

Relation between the dimensionless fission coordinate r and elongation parameter c can be expressed by [18]

$$r(c) = (3c/8)\left(1 + \frac{1}{15}c^3(c-1)\right). \quad (4)$$

The description of the fission process including particle emission starts from an initial state corresponding to the ground state of the compound nucleus whose shape is characterized by the collective coordinate r_0, the corresponding conjugate initial momentum p_0, the intrinsic excitation energy E_{int} with the corresponding temperature $T_0 = \sqrt{E_{\mathrm{int}}/a(r_0)}$ and the initial spin J_0 for each trajectory by the Neumann method with the generating function

$$\Phi(r_0, p_0, J_0, t=0) \propto \exp\left[-\frac{V(r_0) + E_{\mathrm{coll}}(r_0, p_0)}{T}\right] \times\delta\left(r_0 - r_{\mathrm{gs}}\right)\frac{\mathrm{d}\sigma(J)}{\mathrm{d}J}. \quad (5)$$

The initial state is assumed to be characterized by the spin distribution of compound nuclei $\mathrm{d}\sigma(J)/\mathrm{d}J$ according to the scaled prescription [18]

$$\frac{\mathrm{d}\sigma(J)}{\mathrm{d}J} = \frac{2\pi}{k^2}\frac{2J+1}{1+\exp((J-J_{\mathrm{c}})/\delta J)}. \quad (6)$$

Here J_{c} is the critical spin and δJ is the diffuseness. The parameters J_{c} and δJ can be obtained by the following relations [18]:

$$J_{\mathrm{c}} = \sqrt{A_{\mathrm{P}}A_{\mathrm{T}}/A_{\mathrm{CN}}}\left(A_{\mathrm{P}}^{1/3} + A_{\mathrm{T}}^{1/3}\right) \times\left(0.33 + 0.205\sqrt{E_{\mathrm{c.m.}} - V_{\mathrm{c}}}\right) \quad (7)$$

and

$$\delta J = \begin{cases} (A_{\mathrm{P}}A_{\mathrm{T}})^{3/2}\times 10^{-5}\,[1.5 + 0.02(E_{\mathrm{c.m.}} - V_{\mathrm{c}} - 10)] \\ \quad \text{for } E_{\mathrm{c.m.}} > V_{\mathrm{c}} + 10, \\ (A_{\mathrm{P}}A_{\mathrm{T}})^{3/2}\times 10^{-5}\,[1.5 - 0.04(E_{\mathrm{c.m.}} - V_{\mathrm{c}} - 10)] \\ \quad \text{for } E_{\mathrm{c.m.}} < V_{\mathrm{c}} + 10, \end{cases} \quad (8)$$

when $0 < E_{\mathrm{c.m.}} - V_{\mathrm{c}} < 120$ MeV; and when $E_{\mathrm{c.m.}} - V_{\mathrm{c}} > 120$ MeV, the term in the last brackets is put equal to 2.5.

Figure 1 shows partial cross-sections as a function of spin for ^{248}Cf, for example, for projectile energy

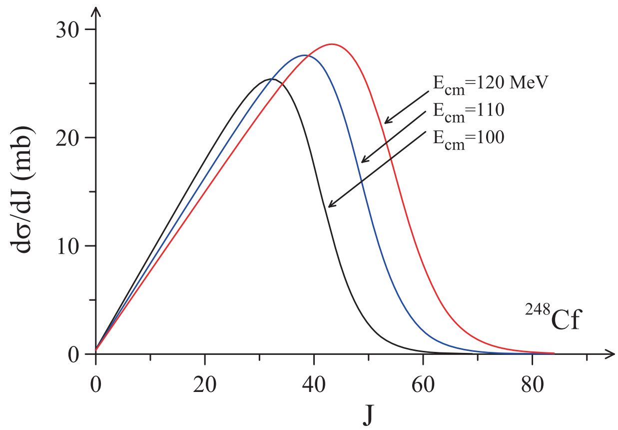

Figure 1. The partial cross-sections as a function of spin for $^{16}O + ^{232}Th$.

$E_{c.m.} = 100, 110$ and 120 MeV. It can be seen from figure 1 that as centre-of-mass energy of the projectile increases, the value of spin of the compound nucleus formed increases.

The collective inertia m, is calculated in the frame of the Werner–Wheeler approach and the intrinsic excitation energy is defined as

$$E_{\rm int} = E^* - p^2/(2m) - V(r) - E_{\rm rot} - E_{\rm evap}(t), \quad (9)$$

where $E_{\rm evap}$ and $E_{\rm rot}$ are the nucleus excitation energy that light particles have carried away by the instant t and the rotational energy, respectively. E^* is the total excitation energy of the nucleus. The potential energy V can be determined from [22,25]

$$V(r, A, Z, J, K) = B_s(r)E_s^0(Z, A) + B_c(r)E_c^0(Z, A) + \frac{(J(J+1) - K^2)\hbar^2}{I_{\perp}^{(\rm sharp)}(r)\frac{4}{5}M_0R_0^2 + 8M_0a^2} + \frac{K^2\hbar^2}{I_{\parallel}^{(\rm sharp)}(r)\frac{4}{5}M_0R_0^2 + 8M_0a^2}, \quad (10)$$

where $B_s(r)$, $B_c(r)$ are the surface and the Coulomb energy terms, respectively. E_s^0 and E_c^0 are the surface and the Coulomb energies of the corresponding spherical system as determined by [26,27], M_0 is the mass of the compound nucleus, $I_{\perp(\parallel)}^{(\rm sharp)}$ are the moments of inertia for a sharp-edged nuclear density distribution with respect to the axes perpendicular and parallel to the symmetry axis of the fissioning nucleus, R_0 is the radius of the spherical system and $a = 0.6$ fm. The decay widths for n, p, α, γ emission are calculated at each Langevin time step Δt. The emission of a particle is allowed by asking at each time step along the trajectory, whether the ratio of the Langevin time step Δt to the particle decay time $\tau_{\rm part}$ is larger than a random number $\xi\,(0 \leq \xi \leq 1)$, where $\tau_{\rm part} = \hbar/\Gamma_{\rm tot}$ and $\Gamma_{\rm tot} = \sum_v \Gamma_v$. The probabilities of decay via different channels can be calculated by using a standard Monte Carlo cascade procedure, where the kind of decay selected with the weights $\Gamma_v/\Gamma_{\rm tot}$ with $v = n, p, \alpha, \gamma$. After the emission of particle of type v, the kinetic energy ε_v of the emitted particle is also generated via a Monte Carlo procedure. Then the intrinsic excitation energy of the residual mass and spin of the compound nucleus are recalculated and the dynamics is continued. The loss of angular momentum is taken into account by assuming that each neutron, proton, or a γ quantum carries away $1\hbar$, while the α-particle carries away $2\hbar$. The particle emission width of a particle of type v can be calculated by [28]

$$\Gamma_v = (2s_v + 1)\frac{m_v}{\pi^2\hbar^2\rho_c(E_{\rm int})}\int_0^{E_{\rm int}-B_v} d\varepsilon_v\sigma_{\rm inv}(\varepsilon_v) \times \rho_R(E_{\rm int} - \varepsilon_v)\varepsilon_v\sigma_{\rm inv}(\varepsilon_v), \quad (11)$$

where s_v is the spin of the emitted particle v and m_v is its reduced mass with respect to the residual nucleus. $\sigma_{\rm inv}$ is the inverse cross-section [28]. $\rho_R(E_{\rm int} - B_v - \varepsilon_v)$ and $\rho_c(E_{\rm int})$ are the level densities of the residual and compound nuclei. B_v and ε_v are the separation energy and kinetic energy of the evaporated particle v, respectively. The width of the gamma emission is calculated as in ref. [29].

Figure 2 shows some Langevin trajectories calculated by the Langevin equations as functions of time.

In the simulation of the evolution of a fissile nucleus, a Langevin trajectory either reaches the scission point and counts as a fission event or if the intrinsic excitation energy becomes smaller than the height of the fission barrier or the binding energy of a neutron, it counts as an evaporation residue event.

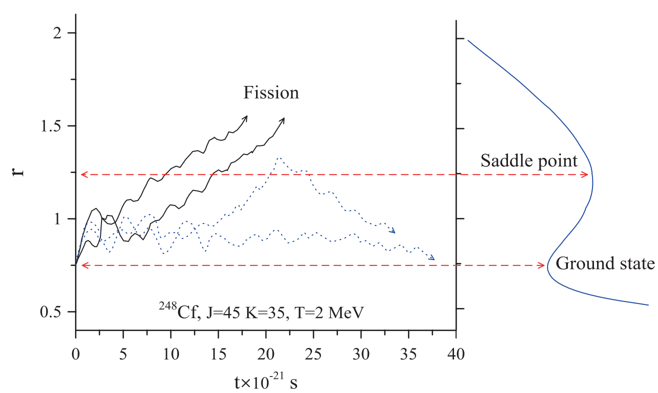

Figure 2. Some Langevin trajectories with initial conditions $J = 45\hbar$, $K = 35\hbar$ and $T = 2$ MeV reach the scission point (solid curves) and terminates in the potential well (dotted curves).

The fission fragment angular distributions can be calculated by the standard transition state model. In the framework of this model, the angular distribution of the fission fragments for a fissile system can be determined by considering a certain transition configuration. There are two assumptions on the position of the transition state and consequently, we can consider two variants of the transition state model. These models are the saddle point transition model (SPTS) [30–32] and the scission point transition model (SCTS) [33–35]. In the SPTS model, it is assumed that the mean time of stay of a nucleus in the saddle point region is sufficiently larger than a characteristic time of equilibration of K mode. In other words, the time τ_{gs} of the motion of the system from the ground state to the saddle point is much longer than the relaxation time of the K degree of freedom, τ_K. Furthermore, it is assumed that the mean time of descent of a nucleus from the saddle to scission point, τ_{ss}, is shorter in comparison with τ_K, and also that the K distribution at the saddle point is determined by the Boltzmann factor $\exp(-E_{rot}/T)$. On the contrary, if τ_K is much shorter than the descent time from saddle to scission point, the SCTS model can be used to determine the anisotropy of the fission fragment angular distribution. It should be mentioned that neither the SPTS nor the SCTS models can be reproduced simultaneously well with the angular distributions for the reactions with both heavy and light ions [36]. Consequently, it was assumed that the transition state is located somewhere between the saddle point and the scission point. Perhaps, this is due to the fact that the K value may be altered during the saddle–scission evolution. In the standard theoretical approach, the angular distribution of fission fragments can be determined as follows:

$$W(\theta, J, K) = (J + 1/2)\left|D^J_{M,K}(\theta)\right|^2, \tag{12}$$

where J is the spin of a compound nucleus, M is the projection of J on the axis of the projectile ion beam, K is the projection of J on the symmetry axis of the nucleus, θ is the angle between the beam axis and the nuclear symmetry axis and function $D^J_{M,K}(\theta)$ is the symmetric-top wave function [30]. In case of the fusion of spinless ions, the value of M is zero and the angular distribution of fission fragments can be determined by averaging expression (12) over an ensemble of Langevin trajectories.

$$W(\theta) = \frac{1}{N_f}\sum_{i=1}^{N_i}(J_i + 1/2)\left|D^{J_i}_{M=0,K_i}(\theta)\right|^2, \tag{13}$$

where N_f is the number of Langevin samples that have fissioned and J_i is the spin of the ith Langevin sample. The anisotropy of the fission fragment angular distribution is given by

$$A = \frac{\langle W(0°)\rangle}{\langle W(90°)\rangle}. \tag{14}$$

It can be shown that the anisotropy of the fission fragment angular distribution can be given by the approximate relation

$$\frac{\langle W(0°)\rangle}{\langle W(90°)\rangle} \approx 1 + \frac{\langle J^2\rangle}{4K_0^2}, \tag{15}$$

where the variance of the equilibrium K distribution K_0 is

$$K_0^2 = \frac{T}{\hbar^2}I_{eff}, \qquad I_{eff} = \frac{I_\parallel I_\perp}{I_\perp - I_\parallel}, \tag{16}$$

where $I_\parallel$, $I_\perp$ are the parallel and perpendicular moments of inertia which are calculated at the transition state and T is the nuclear temperature.

In the present investigation, we do not use any approximation for the value of relaxation time for the K coordinate and obtain the value of this parameter as in ref. [37]. Lestone and McCalla [37] proposed the description of evolution of the K collective coordinate using the Langevin equation for overdamped motion and showed that the evolution of the K collective coordinate can be determined by the equation

$$dK = -\frac{\gamma_K^2 J^2}{2}\frac{\partial V}{\partial K}dt + \gamma_K J\xi(t)\sqrt{T\,dt}, \tag{17}$$

where the dissipation coefficient of K, γ_K, is a parameter controlling the coupling between the orientation degree of freedom K and the heat bath and $\xi(t)$ is a random variable that possesses the following statistical properties:

$$\langle\xi(t)\rangle = 0$$

$$\langle\xi(t)\xi(t')\rangle = 2\delta(t - t'). \tag{18}$$

It should be mentioned that Lestone *et al* [38] obtained 0.077 $(\text{MeV zs})^{-1/2}$ as the value for the dissipation coefficient of K. The Langevin equation for the K coordinate, eq. (17), and the Langevin equations, eq. (1), are connected through the potential energy. The rotational part of the potential energy is calculated by

$$E_{rot}(r, J, K) = \frac{(J(J+1) - K^2)\hbar^2}{I_\perp^{(sharp)}(r)\,(4/5)\,M_0R_0^2 + 8M_0a^2} + \frac{K^2\hbar^2}{I_\parallel^{(sharp)}(r)\,(4/5)\,M_0R_0^2 + 8M_0a^2}, \tag{19}$$

In the dynamical calculations eqs (1) and (17) are integrated simultaneously with the same time step until the scission or evaporation residue condition occurs. By averaging eq. (17), it can be shown that

$$\frac{\mathrm{d}\langle K\rangle}{\mathrm{d}t} = -\frac{\gamma_K^2 J^2}{2}\left\langle\frac{\partial V}{\partial K}\right\rangle. \tag{20}$$

From the expression for the rotational energy, it follows that

$$\frac{\mathrm{d}\langle K\rangle}{\mathrm{d}t} = -\frac{\gamma_K^2 J^2\hbar^2}{2J_{\mathrm{eff}}}\langle K\rangle\,. \tag{21}$$

It can be shown that by assuming a constant γ_K, the solution of this equation has the form

$$\langle K(t)\rangle_{K_0} = K_0\exp\left[-\frac{\gamma_K^2 J^2\hbar^2}{2J_{\mathrm{eff}}}(t-t_0)\right], \tag{22}$$

which gives the following expression for the relaxation time:

$$\tau_K = \frac{2J_{\mathrm{eff}}}{\gamma_K^2 J^2\hbar^2}. \tag{23}$$

It can be seen that the relaxation time depends on the effective moment of inertia and consequently, on the shape of the fissioning nucleus.

3. Results of the calculations and discussion

In the present investigation, we have used dynamical model on the basis of two-dimensional Langevin equations to calculate the average pre-scission neutron multiplicities and anisotropy of the fission fragment angular distribution for ^{248}Cf formed in the ^{16}O + ^{232}Th reactions. In our calculations, we have used the value of pre-saddle friction as 3×10^{21} s^{-1} as in refs [15–21], whereas the post-saddle friction strength was determined by fitting calculated data on the average pre-scission neutron multiplicities and anisotropy of the fission fragments angular distribution with the experimental data. In other words, the magnitude of post-saddle friction was considered as a free parameter. It should be stressed that for calculating the anisotropy of fission fragment angular distribution, an accurate prediction of particle multiplicity is necessary. Consequently, in the present investigation, we have considered the deformation effects as in ref. [39] to calculate the pre-scission particle multiplicities for ^{248}Cf. The mass formula [40] contains the deformation Coulomb and surface energy terms ($B_{\mathrm{c}}(r)$ and $B_{\mathrm{s}}(r)$) and so the particle binding energy $B_i(i = n, p, \alpha)$ is a function of the collective coordinate r, because $B_i(r) = M_p(r) - M_d(r) - M_i$, where $M_i(i = n, p, \alpha)$, $M_p(r)$ and $M_d(r)$ are the mass of the emitted particles, the masses of the mother and daughter nuclei, respectively. Figure 3 shows the results of average pre-fission neutron multiplicities for ^{248}Cf, in terms of different values of the post-saddle friction.

It can be seen from figure 3 that the results of calculations for the average pre-scission neutron multiplicities are in good agreement with the experimental data when the value of post-saddle friction is equal to (12–14) $\times$ 10^{21} s^{-1}. Figure 4 shows the results of anisotropy of the fission fragment angular distribution for ^{248}Cf calculated with different values of post-saddle friction.

It can be seen from figure 4 that the results of calculations of the anisotropy of fission fragment angular

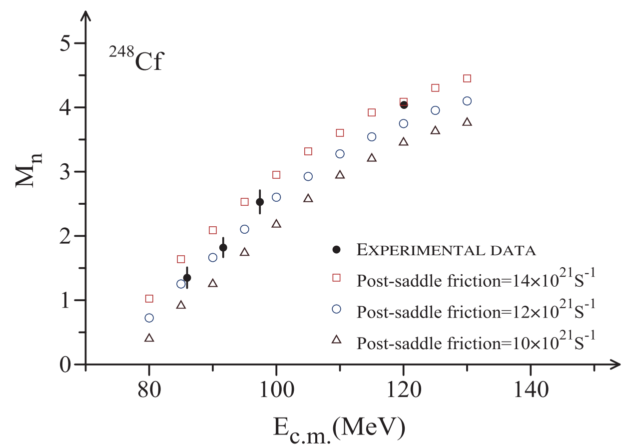

Figure 3. The average pre-scission neutron multiplicity for the compound nucleus ^{248}Cf as a function of energy for different values of post-saddle friction. The experimental data (filled circles) are taken from refs [41,42].

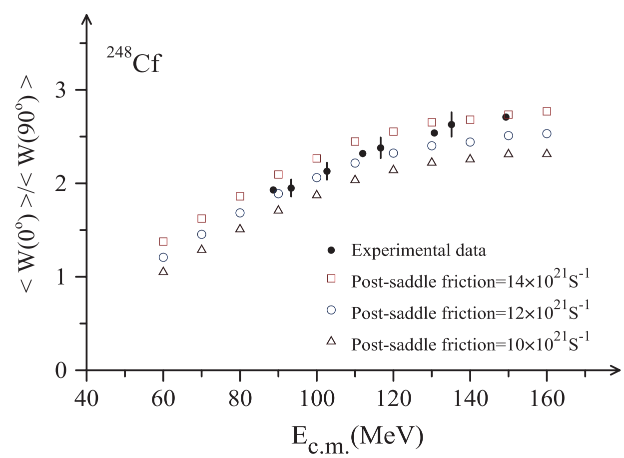

Figure 4. The anisotropy of the fission fragment angular distribution for the compound nucleus ^{248}Cf as a function of energy for different values of post-saddle friction. The experimental data (filled circles) are taken from refs [43,44].

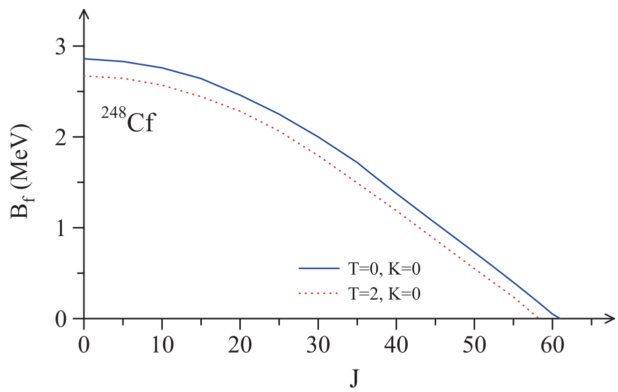

Figure 5. Fission barrier height of ^{248}Cf as a function of total spin J at $T = 0$, $T = 2$ MeV and $K = 0\hbar$.

distribution for ^{248}Cf are in good agreement with the experimental data when the value of post-saddle friction is equal to (12–14) $\times$ 10^{21} s^{-1}. It can also be seen from figures 3 and 4 that the results of calculations for the average pre-fission neutron multiplicities and anisotropy of fission fragment angular distribution for ^{248}Cf are very sensitive to the magnitude of the post-saddle friction. Furthermore, it can be seen from figures 3 and 4 that at lower centre of mass energies, the values of the average pre-fission neutron multiplicities and anisotropy of fission fragment angular distribution calculated with the value of post-saddle friction equal to 12×10^{21} s^{-1} are very close to the experimental data, although, at higher centre of mass energies, the experimental data can be reproduced by considering the value of post-saddle friction equal to 14×10^{21} s^{-1}. It can be explained as follows: at higher centre of mass energies a compound nucleus is formed with a larger value of spin and so the fission barrier height and the fission time will be reduced (see figures 1 and 5). Consequently, for reproducing experimental data, the value of post-saddle friction should be increased.

4. Conclusions

A stochastic approach to fission dynamics based on two-dimensional Langevin equations was applied to calculate the average pre-scission neutron multiplicities and anisotropy of the fission fragment angular distribution for the compound nucleus ^{248}Cf formed in the ^{16}O + ^{232}Th reactions. In the calculations, the magnitude of pre-saddle friction was considered equal to 3×10^{21} s^{-1} as in refs [15,21], whereas the post-saddle friction strength was determined by fitting the calculated data on the average pre-scission neutron multiplicities and anisotropy of the fission fragments angular distribution with the experimental data. In other words, the magnitude of post-saddle friction was considered as a free parameter. It was also shown that the results of calculations of the pre-scission neutron multiplicities and anisotropy of the fission fragment angular distribution for ^{248}Cf are very sensitive to the magnitude of the post-saddle friction. Furthermore, it was shown that the above-mentioned experimental data can be satisfactorily reproduced for ^{248}Cf by considering the magnitude of post-saddle friction as (12–14) $\times$ 10^{21} s^{-1}.

Acknowledgement

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References

[1] D Hilscher and H Rossner, *Ann. Phys.* **17**, 471 (1992)
[2] S Yamaji, H Hofmann and R Samhammer, *Nucl. Phys. A* **475**, 487 (1988)
[3] S Yamaji, F A Ivanyuk and H Hofmann, *Nucl. Phys. A* **612**, 1 (1997)
[4] P Fröebrich, I I Gontchar and N D Mavlitov, *Nucl. Phys. A* **556**, 281 (1993)
[5] J Blocki, Y Boneh, J R Nix, J Randrup, M Robel, A J Sierk and W J Swiatecki, *Ann. Phys. (N.Y.)* **113**, 330 (1978)
[6] H Eslamizade and M Soltani, *Ann. Nucl. Energy* **80**, 261 (2015)
[7] H Eslamizadeh and H Raanaei, *Ann. Nucl. Energy* **51**, 252 (2013)
[8] W Ye, *Phys. Rev. C* **81**, 011603 (2010)
[9] H Eslamizadeh, *Pramana – J. Phys.* **80**, 621 (2013)
[10] H Eslamizadeh, *Chin. Phys. C* **34**, 1714 (2010)
[11] W Ye, *Phys. Rev. C* **80**, 011601 (2009)
[12] B Bouriquet, Y Abe and D Boilley, *Comp. Phys. Comm.* **159**, 1 (2004)
[13] H Eslamizadeh, *Chin. J. Phys.* **50**, 385 (2012)
[14] H Eslamizadeh, *Pramana – J. Phys.* **81**, 807 (2013)
[15] E G Ryabov *et al*, *Phys. Rev. C* **78**, 044614 (2008)
[16] C Schmitt *et al*, *Phys. Rev. Lett.* **99**, 0642701 (2007)
[17] W Ye *et al*, *Phys. Rev. C* **77**, 011302(R) (2008)
[18] P Fröbrich and I I Gontchar, *Phys. Rep.* **292**, 131 (1998)
[19] G Chaudhuri and S Pal, *Phys. Rev. C* **65**, 054612 (2002)
[20] C Schmitt *et al*, *Phys. Rev. C* **81**, 064602 (2010)
[21] P N Nadtochy *et al*, *Phys. Rev. C* **65**, 064615 (2002)
[22] J P Lestone, *Phys. Rev. C* **59**, 1540 (1999)
[23] T Wada, Y Abe and N Carjan, *Phys. Rev. Lett.* **70**, 3538 (1993)
[24] A V Ignatyuk *et al*, *Yad. Fiz.* **21**, 1185 (1975)
[25] J P Lestone, *Phys. Rev. C* **51**, 580 (1995)
[26] W D Myers and W J Swiatecki, *Nucl. Phys.* **81**, 1 (1966)
[27] W D Myers and W J Swiatecki, *Ark. Fys.* **36**, 343 (1967)
[28] M Blann, *Phys. Rev. C* **21**, 1770 (1980)
[29] J E Lynn, *The theory of neutron resonance reactions* (Clarendon, Oxford, 1968) p. 325

[30] H H Rossner *et al*, *Phys. Rev. Lett.* **53**, 38 (1984)
[31] P D Bond, *Phys. Rev. C* **32**, 471 (1985)
[32] H H Rossner *et al*, *Phys. Rev. C* **33**, 560 (1986)
[33] R Vandenbosch and J R Huizenga, *Nuclear fission* (Academic, New York, 1973)
[34] A Bohr, *Proceedings of the United Nations International Conference on the Peaceful Uses of Atomic Energy* (United Nations, New York, 1956) Vol. 2, p. 151
[35] I Halpern and V M Strutinsky, *Proceedings of the United Nations International Conference on the Peaceful Uses of Atomic Energy* (United Nations, Geneva, 1958) Vol. 15, p. 408
[36] R Feifelder, M Prakash and J M Alexander, *Phys. Rep.* **133**, 315 (1986)
[37] J P Lestone and S G McCalla, *Phys. Rev. C* **79**, 044611 (2009)
[38] J P Lestone, A A Sonzogni, M P Kelly and R Vandenbosch, *J. Phys. G: Nucl. Part. Phys.* **23**, 1349 (1997)
[39] N Wang and W Ye, *Phys. Rev. C* **87**, 051601 (2013)
[40] P Möller, W D Myers, W J Swiatecki and J Treiner, *Data Nucl. Data Tables* **39**, 225 (1988)
[41] M G Itkis *et al*, *Phys. At. Nucl.* **52**, 15 (1990)
[42] A Saxena, *Phys. Rev. C* **49**, 932 (1994)
[43] B B Back *et al*, *Phys. Rev. C* **32**, 195 (1985)
[44] S Kailas *et al*, *Phys. Rev. C* **59**, 2580 (1999)