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Dynamical study of fission process at low excitation energies in the framework of the four-dimensional Langevin equations

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ABSTRACT

A stochastic approach based on four-dimensional Langevin equations has been used to estimate the fission probability, the mean kinetic energy of fission fragments, the mean prompt neutron multiplicity, the average pre-scission neutron multiplicity and the mass distribution of fission fragments for the compound nucleus ^{238}Np produced in neutron induced reaction at low excitation energy. Three collective shape coordinates plus the projection of total spin of the compound nucleus to the symmetry axis, K, were considered in the four-dimensional dynamical model. In the dynamical calculations, dissipation was generated through the chaos weighted wall and window friction formula and dissipation coefficient of K, γ_K, considered as a non-constant parameter. Comparison of the theoretical results with the above mentioned experimental data showed that different features of fission of the excited compound uncles ^{238}Np at low excitation energy can be satisfactorily reproduced by the four dimensional Langevin equations.

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1. Introduction

Although the phenomenon of nuclear fission has been discovered since about eighty years back, [1], the study of fission is still of general interest. Fission may take place in any of the heavy nuclei after capture of a neutron. However, thermal neutrons are able to cause fission only in some isotopes of transuranic elements whose nuclei contain odd numbers of neutrons, for example ^{233}U, ^{235}U and ^{239}Pu. For nuclei containing an even number of neutrons, fission can only occur if the incident neutrons have energy above about one million electron volts. Statistical and dynamical descriptions of the fission process are often used to explain different fission characteristics (see for example [2–23]). Many authors for description of different features of fission process in statistical or dynamical models assumed that compound nuclei have zero spin about the symmetry axis, where this assumption is not correct as first pointed out by Lestone in Ref. [24]. The authors in Ref. [25] also stressed that a large volume of heavy-ion-induced fission data needs to be reanalyzed with considering the effect of the orientation degree of freedom. Recently, a three dimensional (3D) dynamical model based on Langevin equations has been used to calculate mass distributions of fission fragments for some isotopes of U and Pu at low excitation energies [26]. In the present investigation, we use the four dimensional (4D) dynamical model based on Langevin equations to simulate the dynamics of nuclear fission of the excited compound nucleus ^{238}Np produced in neutron induced reaction at low excitation energy. In the 4D dynamical model, we use three collective shape coordinates $\{c, h, \alpha\}$ plus the projection of total spin of the compound nucleus to the symmetry axis, K, to reproduce the experimental data on the fission probability, the mean kinetic energy of fission fragments, the mean prompt neutron multiplicity, the average pre-scission neutron multiplicity and the mass distribution of fission fragments for the compound nucleus ^{238}Np. It should be mentioned that recently Randrup, Moller and Sierk published a paper [27] and investigated fission-fragment mass distributions for strongly damped shape evolution. These authors in their calculations for description of fission process of nuclei used parameters elongation, asymmetry, neck and quadrupole deformation of each fragment. Although, they do not account the orientation degree of freedom of the K coordinate in their calculations. Furthermore, Scamps and Simenel in Ref. [28] go one step further by predicting that the octupole deformation of the fragments plays a major role. These authors in Ref. [28] by considering parameters elongation, asymmetry, neck and quadrupole deformation of each fragment and by using the time-dependent Hartree–Fock microscopic calculations with dynamical pairing correlations computed expectation values of proton and neutron numbers in the

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fission fragments, their total kinetic energy, and their octupole and quadrupole deformations for a series of actinides.

In the present research, we assume that the scission condition corresponds to the shapes of the fissioning nucleus with a finite neck radius with $0.3R_0$ on the average [29] (R_0 is the radius of the spherical nucleus). It should be mentioned that different scission criteria widely used in simulation of fission of the excited compound nuclei. Some of these are zero-neck-radius $R_N = 0$ [30], finite-neck-radius $R_N = 0.3R_0$ [29] and a probabilistic scission criterion [31]. All of these scission criteria result in a good description of experimental data of the first, second, third and fourth moments of the energy distribution [32]. It should be stressed that zero-neck-radius scission, $R_N = 0$ widely used in theoretical calculations of the fission process of the excited compound nuclei. Although this scission condition is consistent only with the liquid drop model (LDM) with a sharp nuclear surface. It is unsatisfactory [33] because the description of a nucleus in the LDM loses meaning when the radius of the neck becomes comparable with the distance between the nucleons [33]. Nevertheless, this scission criterion was used in many papers and provided a quite good description of the parameters of the mass energy distribution of fission fragments. Another acceptable and physically reasonable scission criterion is based on the equality of the Coulomb repulsion and nuclear attraction forces between future fragments. It was shown in Ref. [34] that this scission criterion leads to scission configurations that have a finite neck radius $R_N \cong 0.2R_0$ for nuclei with $z^2/A^{1/3} \cong 500$ and a neck radius $R_N \cong 0.3R_0$ for nuclei with $z^2/A^{1/3} \cong 2000$. Furthermore, in a random neck rupture model Brosa with co-workers [35,36] have used the criterion of hydrodynamic instability of the neck against rupture. It leads to scission configurations with a finite neck radius $R_N \cong 0.3 - 0.4R_0$.

The present paper has been arranged as follows. In Sec. 2, we describe the models and basic equations. The results of calculations are presented in Sec. 3. Finally, the concluding remarks are given in Sec. 4.

2. Details of the model and basic equations

In the dynamical calculations, we use the "funny hills" $\{c, h, \alpha\}$ parametrization [33]. In the "funny hills" parameterization c denotes the elongation parameter, parameter h describes the variation in the thickness of the neck for a given elongation of the nucleus and the parameter of the mass asymmetry α determines the ratio of the volumes of the future fission fragments. It should be mentioned that the large variety of shapes that a nucleus may take along its path to fission can be described by this parametrization. Another choices of coordinates were also applied in other multi-dimensional Langevin models [5,21,26]. In cylindrical coordinates the surface of the nucleus can be calculated by:

$$\rho_s^2(z) = \begin{cases} (c^2 - z^2)(A_s + Bz^2/c^2 + \alpha z/c), & B \geq 0, \\ (c^2 - z^2)(A_s + \alpha z/c)exp(Bcz^2), & B < 0, \end{cases} \tag{1}$$

where ρ_s is the radial coordinate of the nuclear surface and z is the coordinate along the symmetry axis. In Eq. (1) the quantities A_s and B can be calculated by:

$$B = 2h + \frac{c-1}{2}, \tag{2}$$

$$A_s = \begin{cases} c^{-3} - \frac{B}{5}, & B \geq 0 \\ -\frac{4}{3}\frac{B}{exp(Bc^3) + (1 + \frac{1}{2Bc^3})\sqrt{-\pi Bc^3}erf(\sqrt{-Bc^3})}, & B < 0, \end{cases} \tag{3}$$

where $erf(x)$ is the error function.

The dynamics associated with the fission degree of freedom usually can be considered to be similar to that of a Brownian particle floating in a viscous heat bath. The heat bath in this picture represents all the other nuclear degrees of freedom, which are assumed to be in thermal equilibrium. In our calculations, we use the coupled Langevin equations for description of the dynamics of the collective coordinates

$$\begin{aligned} q_i^{(n+1)} &= q_i^{(n)} + \frac{1}{2}\mu_{ij}^{(n)}(\boldsymbol{q})\left(p_j^{(n)} + p_j^{(n+1)}\right)\tau \\ p_i^{(n+1)} &= p_i^{(n)} - \tau\left[\frac{1}{2}p_j^{(n)}p_k^{(n)}\left(\frac{\partial \mu_{jk}(\boldsymbol{q})}{\partial q_i}\right)^{(n)} - Q_i^{(n)}(\boldsymbol{q}) \right. \\ &\quad \left. - \gamma_{ij}^{(n)}(\boldsymbol{q})\mu_{ik}^{(n)}(\boldsymbol{q})p_k^{(n)}\right] + \theta_{ij}^{(n)}\xi_j^{(n)}\sqrt{\tau}, \end{aligned} \tag{4}$$

where q_i and p_i are the collective coordinates and momenta conjugate to them, γ_{ij} is the friction tensor, m_{ij} ($\|\mu_{ij}\| = \|m_{ij}\|^{-1}$) is the tensor of inertia, $\theta_{ij}\xi_j$ is a random force, θ_{ij} is its amplitude and ξ_j is a random variable that possesses the following statistical properties $\langle \xi_i \rangle = 0$ and $\langle \xi_i(t_1)\xi_j(t_2)\rangle = 2\delta_{ij}\delta(t_1 - t_2)$. The superscript n in Eq. (4) shows that the corresponding quantity is calculated at the instant $t_n = n\tau$, where τ is the time step of integration of the Langevin equations. Q_i is a conservative force and can be given by the Helmholtz free energy $Q_i(\boldsymbol{q}, I, K) = -(\partial F/\partial q_i)_T$. The Helmholtz free energy can be determined in terms of potential energy and level density parameter as follows

$$F(\boldsymbol{q}, I, K) = V(\boldsymbol{q}, I, K) - a(\boldsymbol{q})T^2. \tag{5}$$

In the Fermi gas model the conservation force is given by

$$Q_i(\boldsymbol{q}, I, K) = -\partial V(\boldsymbol{q}, I, K)/\partial q_i + T^2 \partial a(\boldsymbol{q})/\partial q_i, \tag{6}$$

where the deformation dependence of the level density parameter [37] can be expressed by $a(\boldsymbol{q}) = 0.073A + 0.095A^{2/3}B_s(\boldsymbol{q})$. During a random walk along the Langevin trajectory, conservation of energy is satisfied by

$$E^* = E_{int}(t) + E_{coll}(\boldsymbol{q}, \boldsymbol{p}) + V(\boldsymbol{q}, I, K) + E_{evap}(t), \tag{7}$$

where E_{int} is the intrinsic excitation energy of the nucleus, $E_{coll} = 0.5\mu_{ij}(\boldsymbol{q})p_i p_j$ is the kinetic energy of the collective motion of the nucleus, $V(\boldsymbol{q}, I, K)$ is the potential energy of the compound nucleus, $E_{evap}(t)$ is the energy carried away by evaporated particles by time t and E^* is the total excitation energy of the compound nucleus. At low excitation energy the potential energy can be calculated on the basis of the liquid drop model with a finite range of nuclear forces [38,39] and by considering shell correction as follows

$$\begin{aligned} V(\boldsymbol{q}, I, K, T) &= V_{SH}(\boldsymbol{q}, T) + V_{LDM}(\boldsymbol{q}) + E_{rot} \\ &= V_{SH}(\boldsymbol{q}, T) + \left(B_s(\boldsymbol{q}) - 1\right)E_s^0(A, Z) \\ &\quad + \left(B_c(\boldsymbol{q}) - 1\right)E_c^0(A, Z) + \frac{\hbar^2 I(I+1)}{2J_\perp(\boldsymbol{q})} + \frac{\hbar^2 K^2}{2J_{eff}(\boldsymbol{q})}, \end{aligned} \tag{8}$$

where $B_s(\boldsymbol{q})$ and $B_c(\boldsymbol{q})$ are surface and Coulomb energy terms, respectively. $B_s(\boldsymbol{q})$ and $B_c(\boldsymbol{q})$ can be calculated as Ref. [38]. E_s^0 and E_c^0 are the surface and Coulomb energies of a spherical nucleus, respectively. E_{rot} is the rotational energy, I is the spin of a compound nucleus and K is the projection of I on the symmetry axis of the nucleus. $J_\parallel$ and $J_\perp$ are the rigid body moments of inertia about and perpendicular to the symmetry axis and J_{eff} is the

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