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Statistical and dynamical modeling of heavy-ion fusion–fission reactions

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ABSTRACT

A modified statistical model and a four dimensional dynamical model based on Langevin equations have been used to simulate the fission process of the excited compound nuclei ^{207}At and ^{216}Ra produced in the fusion ^{19}F + ^{188}Os and ^{19}F + ^{197}Au reactions. The evaporation residue cross section, the fission cross section, the pre-scission neutron, proton and alpha multiplicities and the anisotropy of fission fragments angular distribution have been calculated for the excited compound nuclei ^{207}At and ^{216}Ra. In the modified statistical model the effects of spin K about the symmetry axis and temperature have been considered in calculations of the fission widths and the potential energy surfaces. It was shown that the modified statistical model can be reproduced the above mentioned experimental data by using appropriate values of the temperature coefficient of the effective potential equal to $\lambda = 0.0180 \pm 0.0055$, 0.0080 ± 0.0030 MeV^{-2} and the scaling factor of the fission barrier height equal to $r_s = 1.0015 \pm 0.0025$, 1.0040 ± 0.0020 for the compound nuclei ^{207}At and ^{216}Ra, respectively. Three collective shape coordinates plus the projection of total spin of the compound nucleus on 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. Comparison of the theoretical results with the experimental data showed that two models make it possible to reproduce satisfactorily the above mentioned experimental data for the excited compound nuclei ^{207}At and ^{216}Ra.

1. Introduction

During the past decades different statistical and dynamical models have been extensively and rather successfully applied to elucidate many problems of the fission process of the excited nuclei produced in fusion reactions. In dynamical models the Langevin and Fokker–Plank equations have been extensively and rather successfully used to simulate the fission process of the excited nuclei [1–16]. It should be mentioned that many authors for description of different features of fusion–fission reactions in statistical or dynamical models assumed that the compound nuclei have zero spin about the symmetry axis, where this assumption is not consistent with statistical model and with dynamical treatment of the orientation degree of freedom as first pointed out by Lestone in Ref. [17]. The authors in Ref. [18] also stressed that a large volume of heavy-ion-induced fission data needs to be reanalyzed with dynamical treatment of the orientation degree of freedom. In many statistical model codes [19–23], the authors have used the ratio of the level density parameters at saddle and equilibrium deformation and a scaling of the fission barrier heights which can be adjusted to reproduce experimental data. But the fission process cannot be accurately modeled as a function of the excitation energy by using a fixed value of the ratio of the level density parameters at saddle and equilibrium deformation and the spin dependence of the $T = 0$ fission barriers [18] (T is temperature). In the present investigation, we want to consider other parameters as free parameters in the modified statistical model [18] which perform similar roles as the ratio of the level density parameters at saddle and equilibrium deformation and a scaling of the fission barrier heights. We consider the temperature coefficient in the effective potential formula, λ, and a scaling of the modified liquid drop model radii from their default values and use the values to calculate the surface and Coulomb energies with the parameter r_s. The surface energy is proportional to the square of r_s, while the Coulomb energy is inversely proportional to r_s. Raising r_s above one decrease the Coulomb energy and increases the surface energy. This cases the fission barriers to increase. A value $r_s = 1$ is the standard modified liquid drop model with fission-barrier heights in agreement with the finite range liquid drop model. It should

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be stressed that the advantage of using r_s instead of a scaling of the fission barrier height is that the curvature at the ground states and the fission transition points, the barrier locations and heights are all being determined in a self-consistent manner as a function of spin, projection of total spin and temperature. In this investigation, we use the four dimensional (4D) dynamical model and the modified statistical model similar to Ref. [18], to reproduce experimental data on the evaporation residue cross section, the fission cross section, the pre-scission neutron, proton and alpha multiplicities and the anisotropy of the fission fragments angular distribution for the excited compound nuclei ^{207}At and ^{216}Ra produced in the fusion ^{19}F + ^{188}Os and ^{19}F + ^{197}Au reactions. The main purpose of this research is comparison of the results of different featured of fission process of the excited nuclei calculated in the framework of the 4D dynamical model and the modified statistical model. The present paper has been arranged as follows. In Section 2, we describe the models and basic equations. The results of calculations are presented in Section 3. Finally, the concluding remarks are given in Section 4.

2. Models

2.1. Dynamical model

In the present investigation, we use a dynamical model based on the 4D Langevin equations to simulate the fission process of the excited nuclei ^{207}At and ^{216}Ra produced in the fusion ^{19}F + ^{188}Os and ^{19}F + ^{197}Au reactions. In our 4D dynamical calculations, we use the three dimensional (3D) Langevin dynamical model was that developed in Refs. [24–26] by adding the orientation degree of freedom (K coordinate) to three collective coordinates. The fourth collective coordinate, K, is the projection of the total spin I on the symmetry axis of the nucleus. In the dynamical calculations, we use the well-known $\{c, h, \alpha\}$ parameterization [27]. In this parameterization c denotes the elongation parameter, the 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. The evolution of a nucleus undergoing fission can be computed by the coupled Langevin equations of motion

$$\dot{q}_i = \mu_{ij} p_j,$$
$$\dot{p}_i = -\frac{1}{2} p_j p_k \frac{\partial \mu_{jk}}{\partial q_i} - \frac{\partial F}{\partial q_i} - \gamma_{ij}\mu_{jk} p_k + \theta_{ij}\xi_j, \quad (1)$$

where $m_{ij}(\|\mu_{ij}\| = \|m_{ij}\|^{-1})$ is the tensor of inertia, γ_{ij} is the friction tensor, $\boldsymbol{q} = (c, h, \alpha)$ are the collective coordinates, $\boldsymbol{p} = (p_c, p_h, p_\alpha)$ are the momenta conjugate to them, $\theta_{ij}\xi_j$ is a random force, θ_{ij} is its amplitude and $\xi_j(t)$ is a random variable that possesses the following statistical properties $\langle \xi_i \rangle = 0$ and $\langle \xi_i(t_1)\xi_j(t_2) \rangle = 2\delta_{ij}\delta(t_1 - t_2)$. $F(\boldsymbol{q}, K) = V(\boldsymbol{q}, K) - a(\boldsymbol{q})T^2$ is the Helmholtz free energy and $V(\boldsymbol{q}, K)$ is the potential energy. The deformation dependence of the level density parameter can be determined as $a(\boldsymbol{q}) = 0.073A + 0.095A^{2/3}B_s(\boldsymbol{q})$, where A is the mass of the fissile nucleus and B_s is the dimensionless functional of the surface-energy in the liquid-drop model. In the dynamical calculations, dissipation is generated through the chaos weighted wall and window friction formula, which described in our previous paper [28]. For small elongation before neck formation, the chaos weighted wall formula is used to calculate the friction tensor and after neck formation used the chaos weighted wall and window friction formula. The inertia tensor is calculated by means of the Werner–Wheeler approximation for the incompressible and irrotational flow [29]. During a random walk along the Langevin trajectory in the collective coordinates space, the conservation of energy law is used in the form $E^* = E_{int}(t) + E_{coll}(\boldsymbol{q}, \boldsymbol{p}) + V(\boldsymbol{q}, K) + E_{evap}(t)$. Here E_{int} is the intrinsic (or internal) excitation energy of the nucleus, E^* is the total excitation energy, $E_{coll} = 0.5\mu_{ij}(\boldsymbol{q})p_i p_j$ is the kinetic energy of the collective motion, $V(\boldsymbol{q}, K)$ is the potential energy of the compound nucleus and $E_{evap}(t)$ is the energy carried away by evaporated particles by time t. The potential energy is calculated on the basis of the liquid drop model with a finite range of nuclear forces [30] using the parameters from Ref. [31]

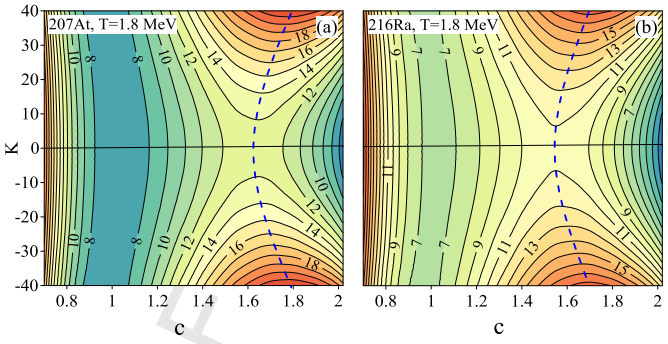

Fig. 1. (Color online) Helmholtz free energy as a function of the collective coordinates c and K calculated for the compound nuclei ^{207}At (a) and ^{216}Ra (b) at $T = 1.8$ MeV and $I = 40\hbar$. The dashed line curves show the dependence of saddle point deformations on K. The numbers at the contour lines indicate the free energy values in MeV.

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

where E_c^0 and E_s^0 are the Coulomb and surface energies of a spherical nucleus, respectively. $B_c(\boldsymbol{q})$ and $B_s(\boldsymbol{q})$ are the Coulomb and surface energy terms, respectively. $B_s(\boldsymbol{q})$ and $B_c(\boldsymbol{q})$ can be calculated as Ref. [30]. M_0 is the compound nucleus mass and $a = 0.704$ fm is the diffuseness parameter of the nuclear surface. $J_{\perp(\parallel)}^{(sharp)}$ are the moments of inertia about and perpendicular to the symmetry axis for a sharp-edged nuclear density distribution. The moments of inertia for a sharp-edged nuclear density distribution can be calculated as Ref. [32]. Figs. 1(a) and 1(b) show the Helmholtz free energy calculated for the compound nuclei ^{207}At and ^{216}Ra as a function of the collective coordinate c and K and for example at initial temperature $T = 1.8$ MeV and $I = 40\hbar$. It can be seen from Figs. 1(a) and 1(b) that for a given value of spin the Helmholtz free energy of the compound nucleus increases with increasing the value of K.

In the simulation of the evolution of a fissile nucleus the decay widths for emission n, p, α and γ are calculated at each Langevin time step τ as in Refs. [33,34]. The emission of a particle is allowed by asking at each time step along the trajectory whether the ratio of the Langevin time step τ to the particle decay time τ_{part} is larger than a random number ξ, where $\tau_{part} = \hbar/\Gamma_{tot}$ and $\Gamma_{tot} = \sum_\nu \Gamma_\nu$. 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 Γ_ν/Γ_{tot} with $(\nu = n, p, \alpha, \gamma)$. After emission act of particle of kind ν the kinetic energy ε_ν of the emitted particle is calculated. Then the intrinsic excitation energy of the residual mass and spin of the compound

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