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Independent fission yields studied based on Langevin equation

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ABSTRACT

Mass distributions of fission fragments of U and Pu isotopes at low excitation energies are studied using a dynamical model based on the fluctuation-dissipation theorem formulated as Langevin equations. Though the Langevin approaches have been applied successfully to the fission process at high excitation energy, it is the first time to obtain the mass distribution of fission fragments for the neutron-induced fission of ^{233,235}U and ^{239}Pu. It was found that the shell effect of the potential energy landscape has the dominant role in determining the mass distribution. The calculation results show the asymmetric fission and the good agreement with the experimental data without any parameter adjustments. Using this approach, we obtain the independent protons and neutrons fission yields of $n + {}^{233}$U. The present approach can serve as a basis for more refined analysis being planned in the future aiming at a realistic description of the whole process of fission, starting from the compound nuclei at various excitation energies reaching to the fission products populated after β-decay.

1. Introduction

The discovery of nuclear fission (Hahn and Straßmann, 1939; Meitner and Frisch, 1939) opened an important chapter not only in the study of nuclear physics but also in the technology of energy supply. Further understanding of the fission process has been required to quantitatively predict the amounts of heavy elements and radioactive fission products and the amount of melted spent nuclear fuel still present in the remains of the power plant. Moreover, such information is also important for improving the safety of planned nuclear power plants world wide. Therefore, further study of the nuclear fission process is necessary.

Just after the discovery of nuclear fission, it was interpreted in analogy with the fission of a charged liquid drop (Bohr and Wheeler, 1939). However, this concept could not explain asymmetric mass splitting, which is the dominant mode of fission in nuclear fuel, namely, U and Pu nuclei. Mass-asymmetric fission, for example, by the thermal-neutron-induced fission of Th, U, and Pu nuclei, might be linked to the microscopic structure of fissioning nuclei or fragments. However, the origin and mechanism of mass-asymmetric fission have not yet been clarified.

To clarify the above contradiction and give a possibly unified picture of the fission process, it is necessary to introduce a dynamical model of fission starting from a nearly spherical shape and finishing at the scission region via the fission saddle point. Such a shape evolution proceeds in competition with pre-scission particle emissions; thus, a dynamical treatment is essential.

As such an approach, the method involving Langevin equations based on the fluctuation-dissipation theorem has been applied by several groups to the nuclear fission process. These past investigations focused on systems having high excitation energy. The calculations resulted in a symmetric mass distribution of fission fragments (MDFF), in good agreement with experimental data at high excitation energies. The MDFF reflects the properties of the potential energy surface in the liquid drop model. In contract, the dynamical calculation using Langevin equations has been seldom applied to the fission process at low excitation energies (Asano et al., 2004), owing to difficulties in obtaining the shell correction energy of configurations in the multi-dimensional space of collective coordinates, as well as the huge computation time. However, the computation time has recently been dramatically reduced with the recent advances in computer technologies and the utilization of parallel computing. Moreover, we can calculate the shell correction energy at each configuration using the two-center shell model.

In this paper, we propose the possibility of dynamically calculating the fission process at a low excitation energy using Langevin equations, taking into account the shell effects, pairing effects, dissipation and fluctuation. Using this model, we calculate the MDFFs

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of n + ^{235}U, n + ^{233}U, and n + ^{239}Pu at a low excitation energy and compare them with experimental data, and obtain the independent fission yield. Using this approach, we can investigate the fission mechanism, including the origin of mass-asymmetric fission.

The paper is organized as follows. In Sec. II, we detail the framework of the model. In Sec. III, we show the results for MDFF for n + ^{235}U, n + ^{233}U, and n + ^{239}Pu at the excitation energy $E^* = 20$ MeV, and the independent fission yields. In Sec. IV, we present a summary of this study and further discussion.

2. Model

We use the fluctuation-dissipation model and employ Langevin equations (Aritomo and Ohta, 2004) to investigate the dynamics of the fission process. The nuclear shape is defined by the two-center parametrization (Maruhn and Greiner, 1972; Sato et al., 1978), which has three deformation parameters, z_0, δ, and α to serve as collective coordinates: z_0 is the distance between two potential centers, while $\alpha = (A_1 - A_2)/(A_1 + A_2)$ is the mass asymmetry of the two fragments, where A_1 and A_2 denote the mass numbers of heavy and light fragments (Aritomo and Ohta, 2004). The symbol δ denotes the deformation of the fragments, and is defined as $\delta = 3(R_\parallel - R_\perp)/(2R_\parallel + R_\perp)$, where $R_\parallel$ and $R_\perp$ are the half length of the axes of an ellipse in the z_0 and ρ directions of the cylindrical coordinate, respectively, as shown in Fig. 1 in Ref. Maruhn and Greiner (1972). We assume in this work that each fragment has the same deformation. This constraint should be relaxed in the future work since the deformations of the heavy and light fragments in the fission of U region are known to be different from each other. In order to reduce the computational time, we employ the coordinate z defined as $z = z_0/(R_{CN}B)$, where R_{CN} denotes the radius of a spherical compound nucleus and B is defined as $B = (3 + \delta)/(3 - 2\delta)$. We use the neck parameter $\varepsilon = 0.35$, which is recommended in Ref. (Sato et al., 1978) for the fission process. The three collective coordinates may be abbreviated as q, $q = \{z, \delta, \alpha\}$.

For a given value of a temperature of a system, T, the potential energy is defined as a sum of the liquid-drop (LD) part, a rotational energy and a microscopic (SH) part;

$$V(q,\ell,T) = V_{\mathrm{LD}}(q) + \frac{\hbar^2 \ell(\ell+1)}{2I(q)} + V_{\mathrm{SH}}(q,T), \tag{1}$$

$$V_{\mathrm{LD}}(q) = E_{\mathrm{S}}(q) + E_{\mathrm{C}}(q), \tag{2}$$

$$V_{\mathrm{SH}}(q,T) = E^0_{\mathrm{shell}}(q)\Phi(T), \tag{3}$$

$$\Phi(T) = \exp\left(-\frac{aT^2}{E_{\mathrm{d}}}\right). \tag{4}$$

Here, V_{LD} is the potential energy calculated with the finite-range liquid drop model, given as a sum of the surface energy E_{S} (Krappe et al., 1979) and the Coulomb energy E_{C}. V_{SH} is the shell correction energy evaluated by Strutinski method from the single-particle levels of the two-center shell model. The shell correction have a temperature dependence expressed by a factor $\Phi(T)$, in which E_{d} is the shell damping energy chosen to be 20 MeV (Ignatyuk et al., 1975) and a is the level density parameter. At the zero temperature ($T = 0$), the shell correction energy reduces to that of the two-center shell model values E^0_{shell}. The second term on the right hand side of Eq. (1) is the rotational energy for an angular momentum ℓ (Aritomo and Ohta, 2004), with a moment of inertia at q, $I(q)$.

The multidimensional Langevin equations (Aritomo and Ohta, 2004) are given as

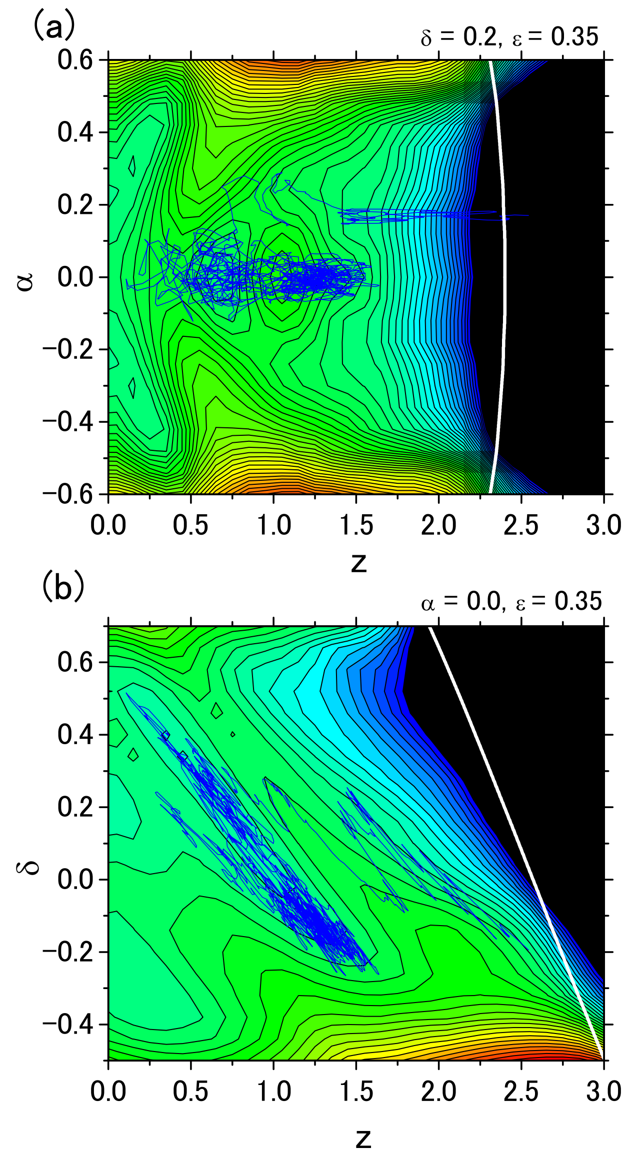

Fig. 1. Sample trajectory of $V_{\mathrm{LD}} + E^0_{\mathrm{shell}}$ for n + ^{235}U projected onto the z–α plane at $\delta = 0.2$ (a) and the z–δ plane at $\alpha = 0.0$ (b). The trajectory starts at $z = 0.65$, $\delta = 0.2$, and $\alpha = 0.0$, at $E^* = 20$ MeV, corresponding to the second minimum of the potential energy surface, to reduce the calculation time.

$$\frac{dq_i}{dt} = \left(m^{-1}\right)_{ij} p_j,$$

$$\frac{dp_i}{dt} = -\frac{\partial V}{\partial q_i} - \frac{1}{2}\frac{\partial}{\partial q_i}\left(m^{-1}\right)_{jk} p_j p_k - \gamma_{ij}\left(m^{-1}\right)_{jk} p_k + g_{ij} R_j(t),$$

where $i = \{z, \delta, \alpha\}$ and $p_i = m_{ij} dq_j/dt$ is a momentum conjugate to coordinate q_i. The summation is performed over repeated indices. In the Langevin equation, m_{ij} and γ_{ij} are the shape-dependent collective inertia and the friction tensors, respectively. The wall-and-window one-body dissipation (Blocki et al., 1978; Nix and Sierk, 1984; Feldmeier, 1987)is adopted for the friction tensor which can describe the pre-scission neutron multiplicities and total kinetic energy of fragments simultaneously (Wada et al., 1993). A hydrodynamical inertia tensor is adopted with the Werner-Wheeler approximation for the velocity field (Davies et al., 1976). The normalized random force $R_i(t)$ is assumed to be that of white