One-Body Dissipation in Agreement with Prescission Neutrons and Fragment Kinetic Energies

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Fission dynamics of hot nuclei have been investigated using the two-dimensional Langevin equation. Including particle evaporation in the continuous limit, prescission multiplicities of neutrons, protons, and α particles have been calculated. Both the calculated number of prescission neutrons and the average total kinetic energy of fission fragments are consistent with experimental values when one-body dissipation is assumed. Unusually strong hydrodynamical two-body viscosity also reproduces the experimental neutron multiplicity, but it significantly underestimates the average kinetic energy.

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Collective motions of highly excited nuclei have been one of the interesting topics in nuclear physics in the last several years. Fissioning motion is a typical one and provides a good field to study nuclear collective dynamics in high excitation, i.e., fluctuation, dissipation, etc. One viewpoint is to consider collective degrees of freedom as Brownian particles and nucleonic ones as the heat bath. Thus, a primary interest is how strong friction is exerted on collective motions. Experimental evidence of fission as a slow and highly dissipative process has come from prescission multiplicities of neutrons [1], charged particles [2], and γ rays [3]. In particular, neutrons are expected to work as a clock to measure fission time scale, because of their short life. Hinde, Hilscher, and Rossner [1] observed a prescission neutron multiplicity much larger than the value obtained with a simple statistical model. To analyze the prescission neutron data, they had to introduce a long delay time ($\approx 5\times 10^{-20}$ s) during which fission cannot occur. From the observation of prescission γ rays, Thoennessen *et al.* [3] also found a hindrance of fission consistent with neutron data. The delay time has been interpreted as a transient time during which the fissioning degree of freedom attains "thermal equilibrium" inside the potential pocket, more precisely, quasistationary distribution in the phase space [4]. It depends on the strength of the friction force which is interpreted as the average effect of the interaction of the slow collective motion with already thermalized nucleons. Therefore, the friction constant of nuclear matter can be deduced by analyzing the fission time scale using the Fokker-Planck or Langevin equation.

The kinetic energy distribution of fission fragments is another important observable related to fission dynamics; it is related to the descent from saddle to scission. Recently, realistic calculations were made for these two physical quantities using the two-dimensional Langevin equation with both one-body friction and hydrodynamical two-body viscosity [5]. The transient time obtained using the usual hydrodynamical viscosity [6] was 10 times shorter than that extracted from experiment. A stronger viscosity leads to a longer transient time but to a too small average kinetic energy of fission fragments when compared with Viola systematics [7]. On the other hand, the one-body friction gave an average kinetic energy consistent with the systematics and much longer transient time. Thus it appears that the one-body friction might be the right dissipation mechanism of nuclear collective motions. However, the transient time is not a measured quantity but is extracted from the prescission neutron multiplicity with some assumptions. The aim of this Letter, therefore, is to study fission dynamics consistently from the ground state to scission under continuous cooling due to evaporation of particles and to calculate the neutron multiplicity and the kinetic energy distribution at the same time. Insight into the dissipation mechanism of nuclear collective motion at high excitation energy will thus be obtained.

The two-dimensional Langevin equation has the form

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

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

with summation from 1 to 2 over repeated indices; $V(q)$ is the potential energy and $m_{ij}(q)$ and $\gamma_{ij}(q)$ are the shape-dependent collective inertia and dissipation tensors, respectively. The normalized random force, $R_i(t)$, is assumed to be a white noise. The strength of the random force g_{ij} is given by $\sum_k g_{ik}g_{jk} = T\gamma_{ij}$, where T is the temperature of the compound nucleus. It is calculated from

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the excitation energy E^* as $E^*=aT^2$, where a is the level density parameter of Töke and Swiatecki [8] with the assumption of a spherical shape. In the present case of ^{200}Pb, a is equal to 23.2. The potential was calculated [9] as the sum of a generalized surface energy, Coulomb energy for diffused surface, and a centrifugal potential. The moment of inertia of the rigid body was used to calculate the centrifugal potential. The barrier heights obtained are, for example, 12.0, 9.3, and 2.3 MeV for $J=0$, 30, and $60\hbar$, respectively, which are essentially the same as those used in the phenomenological analyses. The temperature dependence of the nuclear surface energy was included in the form $E_s(q,T)=E_s(q,T=0)(1-\xi T^2)$. The parameter ξ is calculated with the extended Thomas-Fermi model [10], but is yet rather ambiguous. We thus took two values within the ambiguity. With ξ equal to 0.014 MeV^{-2}, the above barriers are reduced to 8.6, 6.2, and 0.6 MeV, respectively, at $T=1.5$ MeV. Hydrodynamical inertia tensor was adopted with the Werner-Wheeler approximation for the velocity field. Two kinds of dissipation mechanisms were used; one is the wall-and-window one-body dissipation and the other is the hydrodynamical two-body dissipation [9].

Particle emissions [neutron, proton, α particle, and giant-dipole-resonance (GDR) γ ray] were included in the continuous limit. Accordingly, the excitation energy and the angular momentum of the compound nucleus change continuously with time. The validity of this treatment was studied in Ref. [11]. The effect of particle evaporation on the Langevin equation is to continuously decrease the temperature. The evaporation widths of neutrons, protons, and α particles were calculated according to Ref. [11]. The GDR γ-emission width was calculated with the resonance energy and width equal to 15 and 8 MeV, respectively [12].

Nuclear shapes were described by the Legendre-polynomial parametrization [9]. The numerical method to solve the equation is given in Ref. [13]. Time development is obtained by iterations with a small time step, which was taken as $0.01\hbar$/MeV in the present work. In order to obtain good accuracy, we expanded the equation to the second order in the time step [13]. We prepared a large number of trajectories, of the order of 10^5 for each spin value. The Langevin calculation was performed up to $200\hbar$/MeV, after which the quasistationary fission width was used. This value is long enough to reach the quasistationary regime when the fission barrier exists. It is also long enough for all trajectories to cross the scission line when the fission barrier vanishes.

Calculations have been made for the symmetric fission of the ^{200}Pb nucleus since the following reactions have been studied experimentally: ^{19}F+^{181}Ta ($E^*=80.7$ MeV) [14] and ^{16}O+^{184}W ($E^*=195.8$ MeV) [15]. Figure 1 shows the number of emitted particles from the compound nucleus as functions of time for the initial excitation energy $E^*=80.7$ MeV. The stepwise behavior

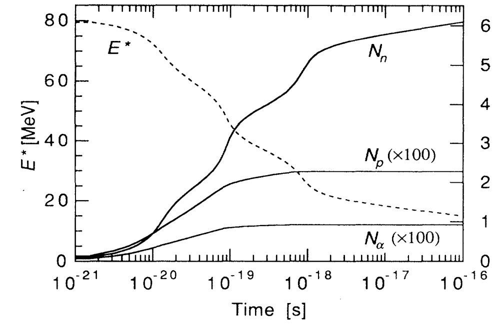

FIG. 1. Numbers of emitted neutrons (N_n), protons (N_p), and α particles (N_α) as a function of time for ^{200}Pb with the initial excitation energy $E^*=80.7$ MeV. Time dependence of the excitation energy (E^*) is also shown (dashed line).

clearly seen in N_n is due to changes of neutron separation energy caused by the shell and pairing corrections. The excitation energy of the compound nucleus (denoted by the dashed line in Fig. 1) decreases with time as a result of the emission of the light particles and γ rays. Figure 2 shows the fission widths as a function of time for the same initial excitation energy with the one-body friction and with $\xi=0.014$ MeV^{-2}. The fission width Γ_f is calculated as $\Gamma_f(t)=-[1/N(t)][dN(t)/dt]$, where $N(t)$ is the number of trajectories which did not escape beyond scission (saddle) at time t. One sees that the fission widths (dotted lines at saddle and solid lines at scission) approach the quasistationary value (dashed lines) after a certain time. The transient time ($t_{\rm tr}$) is the time up to which the dotted lines reach the dashed lines and the saddle-to-scission time ($t_{\rm ssc}$) is the interval between the dotted and the solid lines. From Fig. 2, both $t_{\rm tr}$ and $t_{\rm ssc}$ are about 2×10^{-20} s for $J\leq50\hbar$, where the fission barrier exists. This calculated transient time turns out to be shorter than required by the phenomenological analysis [1].

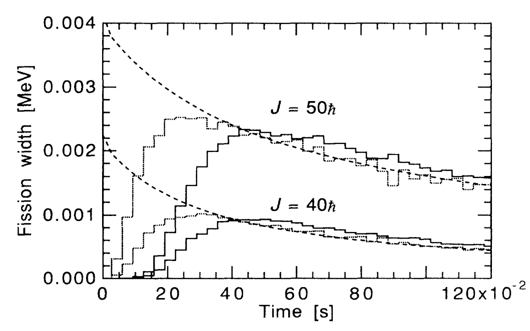

FIG. 2. Time dependence of the fission width for the symmetric fission of ^{200}Pb for two values of angular momentum $J=40\hbar$ and $50\hbar$, and initial excitation energy $E^*=80.7$ MeV. Solid lines are the widths calculated at scission and dotted lines are those at saddle. Dashed lines denote quasistationary fission widths.

TABLE I. Calculated results for the case of one-body friction. The columns contain the excitation energy (E^*), the temperature-dependence parameter (ξ), the fusion cross section (σ_{fus}), the fusion-fission cross section (σ_{fiss}), the fusion-evaporation cross section (σ_{ev}), the prescission multiplicity of neutron (ν_{pre}), proton (π_{pre}), α particle (α_{pre}), the average total kinetic energy of the fission fragments (TKE), and the variance (σ_{TKE}).

E^* (MeV)	ξ (MeV^{-2})	σ_{fus} (mb)	σ_{fiss} (mb)	σ_{ev} (mb)	ν_{pre}	π_{pre}	α_{pre}	TKE (MeV)	σ_{TKE} (MeV)
	0.014	1150	790	360	2.93	0.0092	0.0037	135.1	8.46
80.7	0.009	1150	758	392	3.08	0.0091	0.0036	135.5	8.33
	exp.	1150	767	383	3.2 ± 0.3	···	···	···	···
	0.014	1400	1244	156	7.33	0.363	0.140	137.0	10.2
195.8	0.009	1400	1223	177	7.64	0.385	0.140	137.5	9.82
	exp.	1400	···	···	7.7 ± 0.3	···	···	139	16.5

In order to facilitate a direct comparison with experiment, we calculated multiplicities of neutrons emitted prior to scission and kinetic energy distributions of fission fragments, averaged over the spin distribution of the compound nucleus. The spin distribution is parametrized as follows: $\sigma_{fus} = \pi\lambda^2 \sum_J (2J+1)/[1+\exp((J-J_c)/\Delta_J)]$, where J_c and Δ_J are determined to reproduce the experimental fusion cross section (σ_{fus}). We assign an event as fusion evaporation if the corresponding trajectory did not escape before the fission width becomes smaller than the γ decay width. Calculated results are given in Table I for the one-body dissipation case and for the two values of ξ (0.014 and 0.009 MeV^{-2}), which turned out to give not so much difference in all the results, particle multiplicities, kinetic energies, etc. It is remarkable that the calculated prescission neutron multiplicity (ν_{pre}) coincides with the experimental one within the error bar. The fusion-fission cross section is also quite well reproduced. With the same prescription, we have made calculations starting at $E^* = 195.8$ MeV; the results are also given in Table I. Again the neutron multiplicity is quite well reproduced. As for the kinetic energy distribution, the calculated mean value (TKE) is in good agreement with Viola systematics and in good agreement with the experimental one at $E^* = 195.8$ MeV. The calculated variance (σ_{TKE}), however, is too small to reproduce the experiment at $E^* = 195.8$ MeV. It should be noted that the experimental variance includes all masses, not only symmetric fission products. The small σ_{TKE} indicates that the present two-dimensional description of the nuclear shape is not sufficient to describe all possible scission configurations.

Results with the hydrodynamical two-body viscosity are given in Table II. One can see that the case with $\mu = 0.06$ TP (1 P=0.1 Pas) gives too small ν_{pre}. The cross sections are poorly reproduced as well. With $\mu = 0.20$ TP, ν_{pre} is closer to experiment but TKE is far smaller than Viola systematics. This tendency does not change when we take $\xi = 0.009$ MeV^{-2}. Therefore, one can conclude that the hydrodynamical two-body viscosity cannot give a consistent explanation of both neutron multiplicities and kinetic energies, while the one-body friction can. The only remaining problem is the too small σ_{TKE}. An improvement of the scission configuration description is now being made by including a mass asymmetry coordinate. As for prescission emission of charged particles, we do not have experimental data for the same system to compare. As is seen in Table I, the calculated multiplicities are very small anyway.

Now we can understand why the calculated ν_{pre} have reproduced the experimental values, as shown in Table I, even though the calculated transient time is shorter than the "delay time" in the phenomenological analysis. The reason is that prescission neutron multiplicities are influenced by fission dynamics in three significant ways. The first, of course, is the transient time. The second is the time for descent from saddle to scission, which becomes longer for stronger dissipation. In addition, the

TABLE II. Calculated results for the case of two-body viscosity and for $\xi = 0.014$ MeV^{-2}.

E^* (MeV)	μ (TP)	σ_{fus} (mb)	σ_{fiss} (mb)	σ_{ev} (mb)	ν_{pre}	π_{pre}	α_{pre}	TKE (MeV)	σ_{TKE} (MeV)
	0.06	1150	928	222	2.06	0.0084	0.0035	124.9	10.2
80.7	0.20	1150	817	333	2.84	0.0108	0.0037	108.6	9.92
	exp.	1150	767	383	3.2 ± 0.3	···	···	···	···
	0.06	1400	1338	62	4.79	0.242	0.106	123.6	13.9
195.8	0.20	1400	1261	139	7.03	0.350	0.137	107.4	11.5
	exp.	1400	···	···	7.7 ± 0.3	···	···	139	16.5

quasistationary fission width is smaller than the Bohr-Wheeler width adopted in usual statistical analyses; this is known as the Kramers' factor [4]. All contribute to additional emitted neutrons as compared with usual statistical calculation. In the present case, the contributions from the transient time and the saddle-to-scission time are found to be fairly small, which are about 10% and 20% of the total calculated neutron multiplicities for 80.7 and 195.8 MeV, respectively. They are obtained from the comparison with the case that stationary values (dashed lines in Fig. 2) of fission widths are used from the beginning. Therefore, reproductions of the experimental data are mainly due to the small stationary widths calculated with the Langevin equation. Actually, a rough comparison of them with Bohr-Wheeler widths gives factors of 1/several, which will be discussed in detail in a forthcoming paper. It should be noted here that in higher excitation energies the contributions increase more and more, because the fission life gets shorter while the transient time remains rather constant. In the phenomenological analysis [1], the fission width is set to zero during the "delay time" and to the Bohr-Wheeler value afterwards. It should also be noted that a large part of the fusion-fission events comes from the large values of J where the fission barrier does not exist any more. In our dynamical calculation, the average of the traveling time from the initial point to the scission line is long due to strong friction and the distribution of this traveling time is broad due to strong random force.

We have investigated the fission dynamics of hot nuclei using the two-dimensional Langevin equation. Including the particle emission in the continuous limit, we have calculated the prescission multiplicities of neutrons, protons, and α particles as well as the kinetic energy distribution of fission fragments. The obtained numbers of prescission neutrons agree well with the experimental ones when we adopt the one-body dissipation. Unusually strong ($\mu = 0.20$ TP or larger) two-body viscosity is necessary to reproduce the observed neutron multiplicity, but this assumption is incompatible with the fission-fragment kinetic energy. We conclude that the fission of hot nuclei is strongly dissipative. A consistent explanation of neutron multiplicities and fragment kinetic energies indeed supports the one-body friction and not the hydrodynamical two-body viscosity. This means that the fission phenomena require a dissipation mechanism which is very strong and makes scission configuration compact. It is, therefore, extremely interesting to derive the one-body friction or its equivalent by microscopic theories. Recent microscopic calculations of diffusion coefficient [16] and friction constant [17], however, appear to give too strong dissipation for nuclear collective motions. Yamaji *et al.* [18], on the other hand, obtained a friction coefficient comparable with the wall formula using the linear response theory.

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