Long-Lifetime Fission Component and Langevin Fluctuation-Dissipation Dynamics of Heavy-Ion Induced Nuclear Fission

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A new probe of dynamical effects in heavy-ion induced fission is proposed. This is the "long-lifetime" tail of the time distribution of fission events, or the so-called long-lifetime fission component (LLFC). The excess of LLFC over its standard statistical-model value is calculated by taking into account dissipation and fluctuations of the collective nuclear motion. The magnitude of this excess is shown to be much larger and its dependence upon the reduced friction parameter to be much stronger than those of the corresponding excess of the pre-scission neutron multiplicity. Measurements of LLFC for heavy systems can provide decisive information about the strength of nuclear friction for compact configurations in fission.

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Nowadays static aspects of nuclear fission are understood satisfactorily, so that the main attention is being paid to dynamical features of the process, foremost to nuclear friction effects [1,2]. The most direct information on the dynamics (in particular, on dissipative properties) of large-scale collective nuclear motion associated with fission is contained in the time distribution of fission events $P(t_f)$. However, in trying to decode this information, one faces serious obstacles. First, it is rather difficult to measure $P(t_f)$ directly. Second, the influence of the dynamics on $P(t_f)$ can be masked by purely statistical effects.

The first difficulty can be bypassed by measuring only an appropriate part of the $P(t_f)$ distribution. For instance, the lifetime measurements [3,4] performed by the crystal-blocking technique [5,6] for heavy-ion induced fission of compound nuclei ranging from Hg to Fr have revealed the existence of the so-called long-lifetime fission component (LLFC). This we characterize by a quantity χ_L which is, by definition, the relative amount of fission events corresponding to lifetimes longer than a particular t_L; usually t_L is taken to be 10^{-16} s (χ_{16}) or 3×10^{-17} s (χ_{317}). The origin of the LLFC for Hg to Fr compound nuclei was explained [3] as being due to fission events occurring at the later stages of the neutron deexcitation cascade. In this region of compound nuclei, the magnitude of χ_{317} (or χ_{16}) as well as its bombarding energy dependence can be successfully described by the standard statistical model (SSM) taking into account shell and pairing corrections [4]. A satisfactory description of the LLFC was achieved also in the framework of a purely macroscopic SSM [7,8]. This is due to the fact that, in the region of Hg to Fr, the compound nuclei are protected against fission by rather high macroscopic barriers, and there seems to be not much space left for incorporating dynamical effects in the description of the corresponding experimental LLFC data.

However, the situation is expected to change radically for the heaviest fissioning systems formed by heavy-ion fusion. For intermediate nuclear systems with $Z^2/A \geq 38$, the retarding role of the fission barrier is expected to decrease strongly, and instead the retarding influence of nuclear friction should come into play and give rise to the LLFC mainly due to dynamical effects. Thus measurements of the LLFC for heavy systems can provide interesting information on the strength and influence of nuclear friction. It is the aim of this Letter to corroborate the above statements on the basis of dynamical calculations of $P(t_f)$ and by comparisons with the predictions of the SSM.

The calculations of $P(t_f)$ are performed by applying the model described in Refs. [9,10], to so-called Langevin fluctuation-dissipation dynamics (LFDD). The initial spin distributions of the compound nuclei are obtained in the framework of the surface-friction approach with fluctuations developed by Fröbrich *et al.* (see, e.g., Ref. [11]). The fission mode, which is suggested to be overdamped, is treated dynamically by using a one-dimensional "reduced" Langevin equation (i.e., that without an inertia term). The drift term in the Langevin equation is calculated as the derivative of the entropy with respect to the fission coordinate times the temperature [12]. The dynamical treatment is applied as long as the duration of the process does not exceed a particular delay time t_d. The actual value of t_d is chosen to be long enough ($t_d = 100\times10^{-21}$ s) in order to reach saturation for all the quantities of interest. For $t > t_d$, the fission mode is treated by a modified statistical description (including friction and information on the scission point) provided the fission barrier height B_f is larger than the temperature of the system T. The modified expression for the fission width [12] is necessary to obtain consistency with the dynamical Langevin description. If $B_f \leq T$, the dynamical treatment is continued until the Langevin trajectory ends in fission or in the formation of an evaporation residue. The competing emission of particles (n,p,d,α) as well as the γ emission is treated statistically, with a Monte Carlo procedure, by applying standard expressions for the decay widths (see, e.g., Ref. [13]). The LFDD was proven to be able to reproduce properly both pre-scission neutron multiplicities $\langle n_{\rm pre}\rangle$ and fission probabilities for a wide range of excitation energies, angular momenta, and fissilities [9,10].

As an improvement over the LFDD formulation made in Refs. [9,10], we take into account here temperature-dependent shell effects in the entropy controlling the fission dynamics. The temperature dependence of the shell corrections is included in the calculations in a way similar to the prescription of Ignatyuk *et al.* [14] for the level density parameter. The revival of the shell corrections in the fission barrier heights, which takes place because of cooling of the system by particle emission, should play a decisive role in the formation of evaporation residues and it should control the duration of the whole fission process for actinide nuclei.

In Fig. 1 we display excitation functions of χ_{317} calculated within the LFDD for the reaction ^{181}Ta+^{19}F by applying different prescriptions for both the reduced friction parameter β and the level density parameter a. In

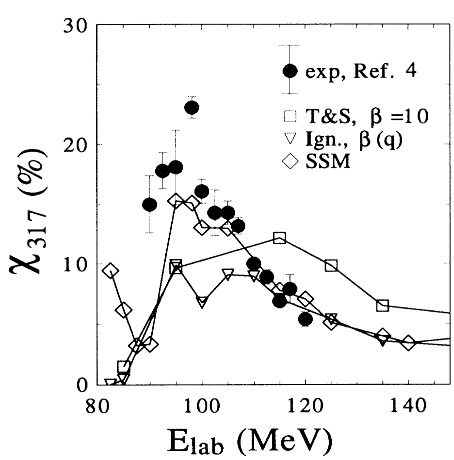

FIG. 1. Measured and calculated excitation functions of the long-lifetime fission component χ_{317} for the ^{181}Ta+^{19}F reaction. Experimental data (closed circles) have been read from Fig. 16 of Ref. [4]. The results of the calculations (open symbols) connected by thin lines correspond to the different prescriptions for the level density parameter (Ign., Ignatyuk *et al.* [14]; T&S, Tõke and Swiatecki [18]) and for the reduced friction parameter β; $\beta(q)$ denotes the coordinate-dependent friction of Ref. [10]. The SSM calculations were performed with $A/a_n = 10$ MeV, $a_f/a_n = 1.00$ and with fission barriers of Sierk [19]. Note that β is measured in units of 10^{21} s^{-1}. See also the text.

particular, the calculations were performed with the coordinate-dependent parameter $\beta(q)$ [10] (being equal, in units of 10^{21} s^{-1}, to 2 for compact shapes but increasing linearly for necked-in shapes, up to a value of 30 at the scission point) and with the coordinate-dependent level density parameter of Ignatyuk *et al.* [14]. With this set of the parameters, the LFDD was shown [10] to be able to reproduce successfully numerous experimental data on fission probabilities and pre-scission neutron multiplicities. At the same time, considering the reduced friction parameter β to be independent of deformation, other authors [15-17] have deduced from neutron multiplicity and γ-ray data β values ranging from 5 to 20. Therefore we also present in Fig. 1 the LFDD calculations for the constant value $\beta=10$. In this case, the prescription of Tõke and Swiatecki [18] for the level density parameter was used, which is known to give larger absolution values and a stronger coordinate dependence for the level density parameter as compared to the prescription of Ignatyuk *et al.* [14]. The excitation functions of χ_{317} calculated dynamically are compared in Fig. 1 with the experimental χ_{317} data [4] as well as with the results of our SSM calculations. It is seen that the existence of the LLFC is clearly predicted by both dynamical and standard statistical calculations. However, it is difficult to decide which description is better, especially when taking into account some contradictions between experimental χ_L data obtained by different groups (cf., e.g., Refs. [3,4,20]). Thus, the differences between the results of the dynamical and statistical calculations in Fig. 1 are not substantial enough to make any definite conclusions regarding the fission dynamics on the basis of LLFC measurements for compound nuclei around ^{200}Pb.

The situation becomes completely different in the region of heavy fissioning nuclei. In Fig. 2 results of fission lifetime calculations are shown for the reaction ^{232}Th + ^{19}F which leads to a much heavier composite system, ^{251}Es. One can see now that the histograms obtained within the LFDD approach differ appreciably from those calculated within the SSM, especially for large values of β. Both the LFDD and SSM lifetime distributions are very wide and highly asymmetric (note that a logarithmic scale is used for the fission lifetime in Fig. 2). These distributions are completely different from Gaussian distributions. Therefore the average lifetime of fission events $\langle t_f\rangle$ (which is also shown in Fig. 2) does not reflect the lifetime of the majority of fission events, i.e., it is not equal to the most probable lifetime; sometimes they do not agree even in the order of magnitude. The $\langle t_f\rangle$ value reflects rather the behavior of the long-lifetime tail of the $P_f(t)$ distribution. For $\beta \geq 7$, some percent of fission events occurs after 10^{-18} s. Such times can be measured by means of the crystal-blocking technique [5,6]. In the ^{232}Th+^{19}F reaction, the origin of the LLFC is again the multichance fission yet here the factor suppressing fission at the earlier stages of the neutron deexcitation cascade is nuclear friction, whereas in the case of ^{181}Ta+^{19}F a

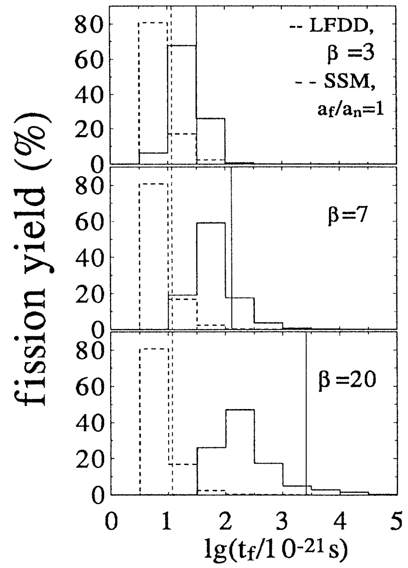

FIG. 2. Calculated fission lifetime distributions (normalized to 100%) for the ^{232}Th+^{19}F(98 MeV) reaction (solid lines, LFDD; dashed lines, SSM). The values of the reduced friction constant β are shown in the panels. The thin vertical lines correspond to the average fission lifetimes $\langle t_f^{\rm LFDD}\rangle$ (solid lines) and $\langle t_f^{\rm SSM}\rangle$ (dashed lines). The calculations were performed using the prescription of Ref. [18] for the level density parameter.

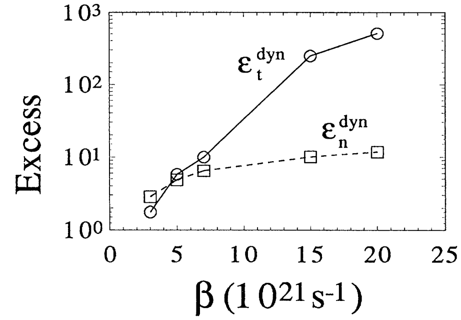

FIG. 3. Excesses of the average fission lifetime and of the pre-scission neutron multiplicity calculated for the reaction ^{232}Th+^{19}F(98 MeV) as functions of the reduced friction parameter β. For definitions of $\varepsilon_t^{\rm dyn}$ and $\varepsilon_n^{\rm dyn}$, see Eqs. (1) and (2).

strong statistical evaporation-to-fission competition was shown to occur when the condition $B_f(l_c)\approx B_n$ holds [3] [here $B_f(l)$ is the angular-momentum-dependent fission barrier height, B_n the neutron binding energy, and l_c the critical angular momentum for fusion]. We should stress also that the LLFC contains information on nuclear friction for rather compact configurations because it probes the early stage of the process, in contradistinction to the pre-scission neutron multiplicity. Because it is now a customary probe of the dynamics of heavy-ion induced fission [1,2], the pre-scission neutron multiplicity is affected by all the stages of the fusion-fission process and thus it bears rather "averaged" information on nuclear friction.

In Fig. 3 we show the relative excess of the calculated average LFDD fission lifetimes over the SSM lifetime predictions,

$$\varepsilon_t^{\rm dyn}=\frac{\langle t_f^{\rm dyn}\rangle-\langle t^{\rm SSM}\rangle}{\langle t_f^{\rm SSM}\rangle}\,, \tag{1}$$

and a similar excess of the calculated average pre-scission neutron multiplicities,

$$\varepsilon_n^{\rm dyn}=\frac{\langle n_{\rm pre}^{\rm dyn}\rangle-\langle n_{\rm pre}^{\rm SSM}\rangle}{\langle n_{\rm pre}^{\rm SSM}\rangle}\,. \tag{2}$$

At present $\langle n_{\rm pre}\rangle$ is the only measurable quantity for which systematic deviations from the SSM predictions are observed [1,2]. Now we propose measurements of χ_L for heavy systems as an even more sensitive probe of these deviations. First of all, it is seen in Fig. 3 that at large β values of the excess $\varepsilon_t^{\rm dyn}$ is orders of magnitude larger than $\varepsilon_n^{\rm dyn}$. Also, the increase of $\varepsilon_t^{\rm dyn}$ with the damping coefficient is much stronger compared to that of $\varepsilon_n^{\rm dyn}$. Taking into account that the behavior of $\langle t_f\rangle$ is controlled by the tail of the fission lifetime distribution, we conclude that the LLFC is shown to be not only a sensitive probe of dynamical effects in fission but even an "amplifier" of these effects.

Fragmentary experimental information about the existence of χ_{16} or χ_{217} has already been reported for the reactions ^{238}U+^{12}C [21] and ^{238}U+^{22}Ne [22]. The existence of χ_{218} and χ_{918} seems to have been also observed in deep inelastic ^{238}U+^{238}U collisions followed by sequential fission of U-like products [23]. The authors of Refs. [21,22] explain their χ_L data as being due to low-energy fission of targetlike transfer products. It would be of great importance to confirm or to refute this explanation by making more extensive and detailed measurements for these fusion-fission reactions. From that point of view we propose to carry out χ_L measurements by using also reaction systems with nonfissile targets, such as, e.g., ^{208}Pb+^{32}S or ^{209}Bi+^{31}P, etc.

In order to make some predictions, we have performed LFDD and SSM lifetime calculations for the ^{208}Pb+^{32}S (176 MeV) reaction with $\beta=20$, the value proposed in Ref. [17]. The results are presented in Table I. One can see that the existence of χ_{318} is clearly predicted by the LFDD irrespective of the uncertainties of the parameters of the model. On the other hand, no variation of the SSM parameters can make the average fission lifetimes calculated within the SSM similar to those obtained in the framework of the LFDD approach.

To conclude, we have demonstrated in this Letter that the tail of the fission lifetime distribution, or the long-lifetime fission component, represents a new, sensitive probe of dynamical (dissipative) effects in heavy-ion induced fission of heavy composite nuclear systems. The distribution has been calculated in the framework of both

TABLE I. Calculations of LLFC for the reaction $^{208}Pb+^{32}S$ (176 MeV) performed within the LFDD and SSM. Here A is the mass number of the compound nucleus, a_f/a_n is the ratio of the level density parameters for fission and neutron evaporation channels, B_f^{ld} and B_f^{sh} are the liquid-drop part and the shell-correction part of the fission barrier height, respectively, χ_{318} is the long-lifetime fission component for $t_L=3\times10^{-18}$ s calculated in the framework of the LFDD, and $\langle t_f^{LFDD}\rangle$ and $\langle t_f^{SSM}\rangle$ are the average fission lifetimes calculated within the LFDD and SSM, respectively.

A/a_n (MeV)	a_f/a_n	B_f^{ld} (MeV)	B_f^{sh} (MeV)	χ_{318} (%)	$\langle t_f^{LFDD}\rangle$ (10^{-18} s)	$\langle t_f^{SSM}\rangle$ (10^{-18} s)
9.1	1.01	1.8	4.2	4.0	8.3	0.011
9.1	1.01	1.8	5.2	9.8	50.6	0.013
9.1	1.01	1.8	3.2	2.5	1.6	0.009
9.1	1.01	2.8	4.2	13.4	54.1	0.406
9.1	1.01	0.8	4.2	0.4	0.3	0.005
9.1	1.00	1.8	4.2	4.6	8.8	0.024
9.1	0.99	1.8	4.2	5.7	8.4	0.033
8.0	1.01	1.8	4.2	2.7	3.4	0.012
10.0	1.01	1.8	4.2	7.0	4.0	0.011
12.0	1.01	1.8	4.2	8.3	15.6	0.013

the LFDD and SSM. The excess of the LFDD lifetimes over the SSM values is caused by nuclear friction. This excess is orders of magnitude larger and its dependence upon the reduced fission parameter is much stronger than those of the corresponding excess of the pre-scission neutron multiplicity which is presently the main indicator of the dynamical effects in fission of highly excited nuclei. Therefore systematic and detailed experimental studies of the LLFC phenomena for the heaviest reaction systems could open up a way of obtaining decisive conclusions on the strength of nuclear friction for compact nuclear shapes in nuclear fission induced by heavy ions. Such investigations would be very helpful also for resolving the contradictions between the values of the reduced friction parameter β given by different authors.

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