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Abstract

Fission times, pre-scission neutron multiplicities and GDR pre-scission γ -ray multiplicities measured for uranium or thorium nuclei formed with temperatures $T \sim 1.8$ MeV have been compared with calculations performed with CDSM2, a two-dimensional dynamical model combined with a statistical one. Among the three experimental approaches considered, fission times give access to the most precise pieces of information on nuclear dissipation at high excitation energy. For the temperature range under consideration, an agreement between the model and data is achieved if one-body dissipation is used with a strength factor $k_{red} \sim 0.45 \pm 0.10$ applied to the wall term for the mononuclear configuration.

As predicted by Kramers in a very early work [1], nuclear dissipation plays an essential role in the fission process. A first clear evidence has been found in the pioneering work of Gavron et al. [2] that inferred from data pre-scission neutron yields much larger than expected from Bohr and Wheeler's model [3] for fission at high excitation energy. Grangé et al., describing the fission process in terms of a Fokker-Plank equation [4], have then shown that nuclear dissipation strongly suppresses fission with respect to particle evaporation during a transient time and that, for longer times, the Bohr and Wheeler statistical fission widths are reduced, in agreement with Kramers prediction. Nowadays, such dynamical effects have to be taken into account by any model aiming to describe the deexcitation of heavy and medium-weight nuclei. Accurate determinations of the dissipation parameters involved are thus essential since, depending on the assumed values, the fission probabilities of medium-weight nuclei, with high fission barriers, can be modified by orders of magnitude.

Many experimental efforts have been devoted since these first evidences to fission dynamics investigations, measuring pre- and post-scission particle multiplicities [5–12], GDR γ -ray multiplicities [13–17], fission time scales [18–21] or fission probabilities [22–24]. More and more refined dynamical models [25–30] have been used in order to analyse these data, either adjusting in a phenomenological way friction parameters or using theoretical nuclear dissipation parameters [31–38]. Nevertheless, due to the complexity of the fission process, these parameters and their possible evolution with temperature are still quite uncertain. In the present letter, we shall take advantage of "the retarding influence of nuclear friction for highly fissile nuclei that gives rise to long lifetime components in the fission time distributions" (as predicted in reference [39]) to investigate nuclear dissipation from recently published data on fission times of uranium-like nuclei [21]. Results of the two-dimensional combined dynamical and statistical model CDSM2 [30] will be compared with data on the average scission times (fission times), pre-scission neutron multiplicities and pre-scission γ -ray multiplicities measured in various experiments for similar nuclei (uranium or thorium) in the same temperature range ($T \sim 1.8$ MeV). It will be shown that the fission times give access to the most accurate determination of nuclear dissipation involved at high excitation

energy.

CDSM2 [30] is a three step Monte Carlo model. In a first step, a numerical simulation of the classical Langevin equations is performed, following the dynamical evolution of the nucleus in the two dimensional space defined in the $[c, h, \alpha]$ shape parameterization [40] by c , the elongation parameter, and by α , the asymmetry parameter. If fission did not occur after an arbitrarily fixed time (50×10^{-21} s), checked to be long enough for the fission rate to reach its quasi-stationary value, the model switches to statistical calculations. This second step [28] is essential because unrealistic computer times would be needed to follow dynamically all the trajectories up to the very long times that can be involved [41]. Finally, the descent from saddle to scission is followed dynamically, provided fission is decided in one of the two previous steps. Particle and γ -ray emission is taken into account by statistical calculations during the three steps. The present calculations have been performed using finite range model potentials [42,43], with coefficients from [44], and shape-dependent level density parameters, following Ignatuk's prescription [45]. Only one-body dissipation calculated with the wall and window formula [31,33] has been used but a possible reduction [34–36,29] has been considered applying a strength factor k_{red} to the wall term for mononuclear shapes. Typically, 3×10^4 trajectories have been followed and the resulting statistical uncertainties will be presented as error bars on the calculated quantities.

The very strong sensitivity of uranium fission times on the assumed dissipation can be seen in Fig. 1 where the CDSM2 results are presented as a function of k_{red} for ^{237}U and ^{235}U nuclei with initial excitation energy $E^* = 80$ MeV ($T \sim 1.8$ MeV) and with no spin. The fission times increase by more than one order of magnitude when k_{red} increases from 0.10 up to 1.00. This behaviour results from the increasing weight of long lifetime components in the scission time distributions when dissipation increases [39]. The long lifetime components arise from high chance fissions (at low residual excitation energies, associated with long lifetimes) that occur with large probabilities due to the high fissilities of the nuclei after emission of several neutrons (Z^2/A then increases). For the considered uranium nuclei, the probability to reach low excitation energies before undergoing fission sharply increases when

k_{red} increases, leading thus to the strong evolution observed in Fig. 1. However, it must be stressed that, due to the very low excitation energies involved for nuclei undergoing fission at very long times, shell effects, not considered in CDSM2, might alter to some extent the calculated fission times.

Data on fission times of uranium-like nuclei with initial excitation energy E^* up to 250 MeV have been recently published [21]. In this experiment, excited uranium-like nuclei were formed in peripheral collisions of ^{238}U accelerated at 24 MeV/u on ^{28}Si nuclei. The time evolution with excitation energy gives a clear evidence for significant long lifetime components (between 10^{-19} and 10^{-16}s) in the scission time distributions. The shadowed area in Fig. 1 indicates the fission time range, including the statistical uncertainty and the uncertainties related to the limited sensitivity range [21], measured at $E^* = 80$ MeV. In the experiment, an identification of the projectile-like nucleus (PLN) atomic number has been achieved but the masses were not measured. The mechanisms actually involved in the very peripheral reactions leading to such excited PLNs are not yet known. Therefore, the uncertainty on the PLN mass has been calculated assuming two scenarios. First, an upper mass estimation has been inferred from the nucleon exchange model [46] that has been developed for reactions induced at lower incident kinetic energies (~ 10 MeV/u). For $E^* = 80$ MeV, this model predicts a quite narrow mass distribution centered at $A = 237$ and associated with no net charge transfer, in agreement with the measured Z distribution. A lower mass estimation has been obtained considering either a massive transfer hypothesis or models [47,48] that reproduce in a rather satisfactory way data on peripheral reactions induced at slightly higher incident energies [48,49]. With this high energy hypothesis, about 3 nucleons have to be transferred from the target to the projectile in order to reach $E^* \sim 80$ MeV, but a net charge transfer should take place. Therefore, a maximum uncertainty is obtained comparing the data with calculations performed for ^{237}U and ^{235}U and a strength factor $k_{red} = 0.45 \pm 0.10$ can be inferred from Fig. 1. The PLN spins were not either measured but no sensitive effects on fission times are expected from CDSM2 for spins lower than $30\hbar$ and, for $E^* \sim 80$ MeV, an upper limit $J_{max} = 20\hbar$ can be estimated from the

nucleon exchange model [46]. It must be stressed that most of the uncertainty on k_{red} arises at this excitation energy from the unknown PLN mass and that a better PLN mass definition would allow a very accurate determination of k_{red} . The k_{red} value obtained is slightly higher than the strength factor $k_s = 0.27$ inferred from giant resonance widths [34], but k_{red} is an average over the large excitation energy range of the survival nuclei that undergo fission.

Data for fission times are also available from reference [21] at higher excitation energies, up to 250 MeV. For these energies, comparisons with CDSM2 lead to k_{red} ranges in agreement with the one inferred at $E^* = 80$ MeV. However, very large uncertainties result from possible PLN spins (that might become of the order or even larger than $30\hbar$) and from increasing probabilities of charged particle emission. The latter leads to fissile nuclei with rather small excitation energies and fission barriers much higher than the one that would have uranium nuclei with the same mass. Therefore, the scission times associated with these nuclei are very long and contribute to the average times with high weights. The fission times at high initial temperatures become thus quite dependent on the assumed initial PLN mass and spin that govern the charged particle emission probability.

Fission times are often inferred from experiments measuring pre- and post-scission neutrons or γ -rays. Nevertheless, the times inferred with these probes are usually found much shorter (sometimes by a few orders of magnitude) than those from reference [21], even for very similar nuclei in terms of mass, charge, fission barrier and temperature. These discrepancies can be explained considering the calculated distributions of scission times, of pre-scission neutron emission times and of pre-scission γ -ray emission times presented in Fig. 2 for $k_{red} = 0.45$. The left column corresponds to fissions of ^{235}U nuclei with $E^* = 80$ MeV and with no spin (like in [21]), whereas the right column corresponds to fissions of ^{224}Th compound nuclei formed at a similar temperature in $(140 \text{ MeV}) \text{ } ^{16}\text{O} + ^{208}\text{Pb}$ reactions (like in reference [16]). In the latter case, the full spin distribution corresponding to compound nucleus formation has been taken into account. As expected, the maximum of the scission time distribution in the right column is shifted towards shorter times due to the high spins involved for a large part of the cross-section. However, long lifetime components are still

present with weights comparable to the right column. Therefore, the average times (fission times), indicated by arrows, are of the same order, although slightly shorter in the right column. The middle panels of Fig. 2 clearly show that pre-scission neutrons have no chance to probe the long lifetime components that make the fission times quite sensitive to the assumed dissipation. Therefore, the fission times inferred from pre-scission neutrons have to be shorter than the actual ones. In contrast, the dashed distributions in the lower panels of Fig. 2 show that γ -ray emission takes place with sizeable probabilities during the entire scission time range. However, the experimental discrimination of pre-scission GDR γ -quanta requires a gate on the γ -ray kinetic energies [13]. Such a typical gate has been applied in the calculations and the resulting time distributions are presented as shadowed areas in the lower panels. With such an unavoidable gate, the γ -rays time distributions cannot probe anymore the entire scission time distributions and thus the fission times inferred from γ -ray emission have also to be shorter than the actual ones.

Despite their lack of sensitivity to long scission times, the calculated neutron and γ -ray pre-scission multiplicities (M_n^{pre} and M_γ^{pre}) are sensitive to the assumed dissipation. This sensitivity arises from the partial overlaps, that can be seen for $k_{red} = 0.45$ in Fig. 2, between the time distributions of scissions and of pre-scission emissions. Therefore, calculations have been performed for different strength factors k_{red} for the (128 and 140 MeV) $^{16}\text{O} + ^{208}\text{Pb}$ reactions. These reactions have been chosen because M_n^{pre} has been measured at 128 MeV [8] and M_γ^{pre} at 140 MeV [16] and they both lead to ^{224}Th compound nuclei with $T \sim 1.8$ MeV. Fig. 3 shows in its upper panel the comparison between M_n^{pre} calculated for different k_{red} and the data indicated by a shadowed area. The range of k_{red} selected by the data is very broad but has no overlap with the one inferred from fission time. Nevertheless, as stressed in [10], some of the measured pre-scission neutrons can arise from entrance channel emission. Such neutrons are not taken into account by CDSM2 that considers only evaporation from the supposed formed compound nucleus and subtracting less than 0.3 neutron from the data would lead to an agreement with the k_{red} range inferred from fission time. In the lower panel of Fig. 3 the same γ energy selection as in [16] has been applied to the calculation

results. In order to underline dynamical effects in their data, the authors of reference [16] subtract from M_{γ}^{pre} a multiplicity M_{γ}^{stat} calculated with the Bohr and Wheeler model (no friction). An equivalent quantity has been estimated from CDSM2 calculations with no friction. However, the calculated M_{γ}^{pre} are quite sensitive to the assumed GDR strength that remains quite uncertain [50,51]. Fig. 3 shows that $M_{\gamma}^{pre} - M_{\gamma}^{stat}$ increases by about 50 % when a strength factor S_{GDR} , in terms of the classical E1 sum rule, is increased from 1.0 up to 1.3, the maximum value extracted from [50]. Taking into account this uncertainty, the very broad k_{red} range defined by M_{γ}^{pre} presents a satisfactory overlap with the one inferred from fission time.

To summarize, the nuclear dissipation involved during the fission process of uranium-like nuclei at temperatures $T \sim 1.8$ MeV has been investigated from comparisons between calculations performed with CDSM2, a combined dynamical and statistical model, and three independent sets of data on fission times, on pre-scission neutron multiplicities and on pre-scission γ -ray multiplicities. The fission time measured by the blocking technique in single crystal indicates that one-body dissipation leads to a too long calculated fission time. A strength factor $k_{red} = 0.45 \pm 0.10$ applied for the mononuclear configurations permits a reproduction of the data. Depending on the assumed GDR strength, this value can be in agreement with the one inferred from pre-scission γ -ray multiplicities, but cannot account for the measured pre-scission multiplicity, a hint for entrance channel emission. The disagreement between fission times measured by the blocking technique and the ones inferred from pre-scission emission results from the lack of sensitivity of pre-scission emission to long times. In order to determine the nuclear dissipation evolution at higher temperatures, experimental efforts have to be undertaken in order to form well defined fissioning nuclei (in terms of spin, atomic number, mass and excitation energy) and to measure with good accuracy their fission times.

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FIGURES

FIG. 1. Evolution of calculated fission time with the strength factor k_{red} . The dashed area indicates the measured range of fission time [21].

FIG. 2. Calculated time distributions for ^{235}U nuclei with $E^* = 80$ MeV (left column) and for $^{16}\text{O} + ^{208}\text{Pb}$ reactions at 140 MeV (right column). Upper panels: Scission time distributions; the arrows indicate the average time. Middle panels: Time distributions of pre-scission neutron emission. Lower panels: Time distributions of pre-scission γ -ray emission (dashed areas); the filled areas show these distributions for γ -rays with energies corresponding to the GDR selection.

FIG. 3. Evolution of pre-scission neutron and γ -ray multiplicities with k_{red} . The shadowed areas correspond to data from [8] for pre-scission neutron multiplicity and [16] for pre-scission γ -ray multiplicity.

Fig. 1

Fig. 2

Fig. 3