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Fission dynamics with systems of intermediate fissility

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Abstract. A 4π light charged particle spectrometer, called 8πLP, is in operation at the Laboratori Nazionali di Legnaro, Italy, for studying reaction mechanisms in low-energy heavy-ion reactions. Besides about 300 telescopes to detect light charged particles, the spectrometer is also equipped with an anular PPAC system to detect evaporation residues and a two-arm time-of-flight spectrometer to detect fission fragments. The spectrometer has been used in several fission dynamics studies using as a probe light charged particles in the fission and evaporation residues (ER) channels. This paper proposes a journey within some open questions about the fission dynamics and a review of the main results concerning nuclear dissipation and fission time-scale obtained from several of these studies. In particular, the advantages of using systems of intermediate fissility will be discussed.

Keywords. Fission dynamics; intermediate fissility systems; nuclear viscosity.

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1. Introduction

Several studies [1–16] on the fission decay of composite systems with $A \approx 180$–250 have shown that the pre-scission multiplicities of neutrons and charged particles increase monotonically with the bombarding energy in contrast with the calculations of the standard statistical model (SM). This finding is considered as the evidence that fission is a slow process with respect to the lifetime for the emission of light particles. With increasing excitation energy, the particle decay lifetime decreases and becomes smaller than the time necessary for building up the collective motion of the nuclear matter towards the saddle point. Consequently, fission does not compete as effectively as predicted by the SM in the early stages of the decay, and particles and γ-ray emissions can occur more favourably. The overall cause of the establishment of these transient effects is believed to be associated with the nuclear matter viscosity which slows down the collective flow of mass from equilibrium to scission and does not allow the fission decay lifetime to be reduced with increasing excitation energy as in the case of light particles. This is equivalent to the assumption that fission is delayed, namely, that the fission probability is not to its full Bohr–Wheeler value in the initial phase of the decay as assumed by the SM. An energy domain has been further identified [6] above which the SM predictions begin to deviate from the data. A strong dissipation due to nuclear viscosity can indeed trigger a variety of effects of dynamical origin, among which the possibility that a CN committed to fission (already at the saddle-point configuration) can still become an evaporation residue (ER) if enough particles are evaporated and the fissility reduced. This correlation between the enhanced yield of pre-scission particles and the survival of evaporation residues might be an important channel for the feeding of evaporation residues having large deformations in the mass region of $A \approx 150$–160 [9].

Most of the estimates of fission time-scale have been obtained from the neutron pre-scission multiplicities on the basis of the SM [1]. However, several variants of the SM have been proposed in the literature to explicitly consider transient effects, time-scales as well as viscosity [2,5,8,10,12]. Following the initial idea of the 'neutron clock' [2–4], the common trend is to split the path from the equilibrium point to the scission point configuration into two regions, the pre- and the post-saddle. The total fission time is defined as $\tau_{\mathrm{f}} = \tau_{\mathrm{d}} + \tau_{\mathrm{ssc}}$, where τ_{d} is the pre-saddle delay, namely, the characteristic time that the composite system spends inside the barrier and τ_{ssc} is the time necessary to travel the path from saddle-to-scission. The relevant observables are computed using τ_{d} and τ_{ssc} as free parameters, along with the other input parameters relative to the specific ingredients of the model, and fit to the experimental data. However, τ_{d} and τ_{ssc} are also considered dependent on the viscosity parameter γ. Following Kramer's work [17], the inclusion of dissipative effects results in an effective time-dependent fission decay width $\Gamma_{\mathrm{f}}(t)$ which is smaller than the standard Bohr–Wheeler (BW) decay width by a hindrance factor,

$$\Gamma_{\mathrm{f}}(t) = \Gamma_{\mathrm{BW}} \left[\sqrt{1 + \gamma_{\mathrm{pre}}^2} - \gamma_{\mathrm{pre}} \right] \left[1 - \exp\left(-\tau/\tau_{\mathrm{d}} \right) \right]. \tag{1}$$

Here τ_{d} is a delay parameter, Γ_{BW} is the Bohr–Wheeler fission decay width and γ_{pre} is the nuclear viscosity parameter in the pre-saddle that can be denoted as $\gamma_{\mathrm{pre}} = \beta/2\omega_0$. β is the so-called reduced dissipation parameter and ω_0 is the potential curvature at the saddle point.

The saddle-to-scission time τ_{ssc} (post-saddle), in this very simplified way of splitting the time-scale of a complex phenomenon, might also be dependent on the nuclear viscosity. One widely used ansatz is the following:

$$\tau_{\mathrm{ssc}} = \tau_{\mathrm{ssc}} \left(\gamma_{\mathrm{post}} = 0 \right) \left[\sqrt{1 + \gamma_{\mathrm{post}}^2} + \gamma_{\mathrm{post}} \right]. \tag{2}$$

In general, the nuclear viscosity parameter might be different inside and outside the saddle point. Furthermore, τ_{d}, τ_{ssc}, γ_{pre} and γ_{post} are dependent on the excitation energy available, the temperature of the nucleus, the fission barrier, the angular momentum, but are kept constant along the decay chain.

In spite of the extensive work, estimates of the fission time-scales are however quite controversial, ranging from ≈ 5 to $\approx 500 \times 10^{-21}$ s, depending on the system and experimental probe. Furthermore, such estimates are weakened by the fact that different sets of input parameters can result in equally good fits within the same model [7,12,13].

Dynamical models [18–26], based on the Euler–Lagrange, Fokker–Planck or Langevin equations, have been proposed to estimate the reduced viscosity parameter β and to gain insight on the nature of dissipation. In this approach, the time evolution of collective variables on a potential energy surface, when a dissipation term is included, describes the fission process.

One of the main issues is whether nuclear dissipation mechanism proceeds primarily by means of individual two-body collisions (two-body friction), as in the case of ordinary fluid, or by means of nucleons colliding with a moving potential wall (one-body friction). The analysis of the fission fragment TKE [18], using the one-body or two-body prescriptions in the dissipation function, indicates that this observable alone is not sufficient to elucidate this point. Two-dimensional Langevin equation has been used to analyse the TKE and the pre-scission neutron multiplicity for the ^{200}Pb nucleus [19]. In this case, one-body dissipation allows reproducing both quantities, while unusually strong two-body viscosity allows reproducing only neutron multiplicity. Similarly, the values of the reduced viscosity parameter $\beta = 15 \times 10^{21}$ and 24×10^{21} s^{-1}, extracted from the pre-scission neutron multiplicities for the composite nucleus ^{188}Pt at $E_x = 99.7$ and 101.4 MeV, are consistent with one-body dissipation. The observed value of $\beta = 6 \times 10^{21}$ s^{-1} for the same CN at $E_x = 66.3$ MeV indicates an increase with temperature. A different result was found for the ^{220}Th system by Rubchenya *et al* [10], on the basis of pre-scission neutron multiplicities: the effective average value decreases with increasing excitation energy, similar to the temperature dependence of the two-body friction. A systematic study was also carried out by Bhattacharya *et al* [20]: the values of viscosity coefficient used to reproduce the observed neutron multiplicities increase with the mass and the excitation energy per nucleon of the composite system and follows a global relation. On the basis of a review of the current studies on the subject, the β values range from ≈ 2 to 30×10^{21} s^{-1}.

In conclusion, the estimates of β from the fits to the particle multiplicities, both from statistical and dynamical models, provides a contradictory picture of the values of β, which range over an order of magnitude, and rather controversial conclusions on the nature of nuclear dissipation and its dependence on the shape and temperature.

2. Dynamical vs. statistical approach

Besides the specialistic details, there are a few characteristic features of the description of the fission process that appear out of these two entirely different approaches that are quite surprising. In the SM approach, the viscosity parameters are treated as constant free parameters to be adjusted on the experimental data. From the fits to the data it turns out that the viscosity is higher in the post-saddle path than in the pre-saddle one, and increases with the temperature or the square of the temperature. Light particles and/or GDR γ-rays are emitted mostly in the post-saddle region where viscosity is higher. Added to this is the fact that the same data can be reproduced equally well if the viscosity is considered to be temperature- or deformation-dependent [11–13].

In the dynamical approach, the CN can pass the saddle point several times before eventually undergoing fission and there is no free parameter in the dissipation model (one- or two-body) except for a strength parameter [24,25]. In the one-body model, the dissipation is shape-dependent but not temperature-dependent. Contrary to what occurs in the statistical approach, viscosity is higher in the pre-saddle and, hence, light particles and/or GDR γ-rays are emitted mostly in the pre-saddle region. This behaviour does not change if the one-dimensional (1D) version of the dynamical approach [24,25] is used. In both one- or two-body dissipation there is no explicit dependence on the temperature.

The question is, "who is right and how can we disentangle this apparent contradiction"? Somehow the answer could be simple because the statistical approach, for instance, can only mimic a dissipation model by introducing *ad-hoc* parameters and average shapes in the deformation space. To draw a more consistent description of nuclear dissipation, and its connection with the shape and temperature, it seems reasonable and crucial to start by taking into account a (possibly large) number of observables which can be expected to be sensitive to nuclear dissipation and to try to reproduce this variety of observables with a unique set of input parameters.

3. Dissipation in systems of intermediate fissility

The systems of intermediate fissility ($\chi = 0.5$–0.6) are very little studied, although they offer quite a unique environment where nuclear viscosity can be studied. They are characterized by an ER cross-section comparable to or larger than the fission cross-section, and by a shorter path in the deformation space from the saddle-to-scission point [27]. Consequently, (1) the input parameters of the models can be further constrained by the energy spectra and multiplicities of light particles in the ER channel; (2) the effect of the fission delay over fission and ER cross-section is much more pronounced with respect to heavier systems because the emission of a charged particle in the pre-saddle region strongly enhances the probability of producing an ER as a consequence of both reduction of the fissility and large value of the angular momentum necessary to ignite fission.

The fact that the potential energy surface is characterized by a shorter path from the saddle-to-scission implies that the role of the pre-saddle dynamics relative to the saddle-to-scission dynamics is enhanced and, therefore, some of the ambiguities on the not-well identified separation and interplay between pre- and post-saddle might be reduced in the interpretation of the data.

We expect that the measurements of neutron and charged particle multiplicities and energy spectra in the two channels as well as the measurements of the cross-sections of the channels themselves will allow more severe constraints onto the models. This should provide more reliable values of fission delay and viscosity parameter, and contribute to a better comprehension of nuclear viscosity. To put this criterion into practice, the 8πLP Collaboration has started a research programme at the Laboratori Nazionali di Legnaro (LNL), Italy, aimed at studying the fission dynamics in systems of intermediate fissility.

4. The 8πLP apparatus

The 8πLP apparatus [28] (figure 1) is a light charged particle detector assembly consisting of two detector subsystems, each made of two-stage telescopes: the WALL and the BALL. The WALL contains 116 telescopes and is placed at 60 cm from the target. Each of the WALL telescopes consists of a 300 μm Si detector backed by a 15 mm Csi(Tl) crystal and has an active area of 25 cm^2 corresponding to an angular opening of about 4°. The WALL covers the angular range from 2° to 24°. The BALL has a diameter of 30 cm and consists of seven rings placed coaxially around the beam axis. Each ring contains 18 telescopes and covers an angular opening of about 17°. The telescopes of the BALL are made of a 300 μm Si detector mounted in the flipped configuration (particle entering from the Ohmic side) backed by a 5 mm CsI(Tl) crystal. The BALL has a total of 126 telescopes and covers the angular range from 34° to 177°. The rings are labelled from A to G from backward to forward angles.

Particle identification is carried out by the ΔE–E method for the ions that do not stop in the ΔE stage. The particles stopping in the ΔE stage are identified by the TOF method in the case of WALL telescopes, and by the pulse shape discrimination (PSD) technique in the case of BALL telescopes. In this configuration it is possible to measure energies up to 64 AMeV in the WALL and 34 AMeV in the BALL with energy thresholds of 0.5 and 2 MeV for protons and α-particles, respectively.

Heavy fragments can be detected in the telescopes of the BALL. The PSD technique allows the separation between heavy fragments and light particles stopping in the same detector. The selection between symmetric and asymmetric mass splittings can nevertheless be achieved on a kinematics ground [31].

In the 8πLP set-up it is also possible to detect ER. The WALL detectors between 2.5° and 7.5° around the beam axis are in fact replaced by four parallel plate avalanche counter (PPAC) modules, each one subtending a solid angle of about 0.3 msr. Each module consists of two coaxial PPACs mounted and operating in the same gas volume at a distance of 15 cm from each other. By adjusting the gas pressure, it is possible to stop the ER between the two PPACs, and let the fission fragments and elastic scattered ions to impinge on the second PPAC. Consequently, ERs are sorted out from the first PPAC signals using the signals from the second PPAC as a VETO signal.

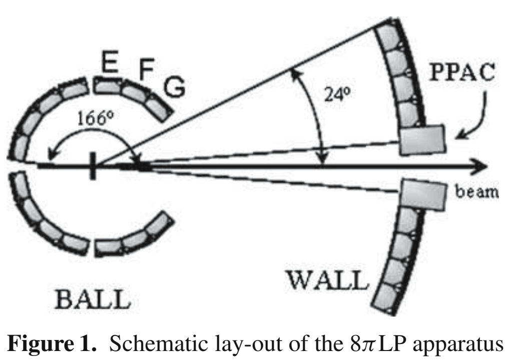

Figure 1. Schematic lay-out of the 8πLP apparatus at LNL.

5. A case study: the system ^{32}S + ^{100}Mo at 200 MeV

The ^{32}S +^{100}Mo reaction at 200 MeV leads to the composite system ^{132}Ce at $E_x = 122$ MeV and fusion angular momentum $L_{\rm fus} = 72\hbar$, derived from the measured fusion cross-section in the sharp cut-off approximation. We shall show the inability of the SM to provide an estimate of the fission time-scale when the ER channel is included as a further constraint in the procedure used to estimate the fission delay time. Afterwards, our study with an advanced realistic dynamical approach based on a 3D-Langevin approach will be discussed.

5.1 *Experimental procedure and data analysis*

The experiment was performed at the XTU Tandem-ALPI Superconducting LINAC accelerator complex of the LNL. A 200 MeV pulsed beam of ^{32}S of about 1 pnA intensity was used to bombard a self-supporting ^{100}Mo target of 300 μg/cm^2 thickness. A beam burst with a frequency of about 1.25 MHz and duration of about 2 ns was used. We used the BALL and the WALL sections of the 8πLP apparatus to detect light charged particles (LCP). The experimental method consists of measuring LCP in coincidence with both fission fragments and ERs.

The fission fragments were detected in the telescopes of the rings F and G of the BALL. The PSD technique allows the separation between heavy fragments and LCP stopping in the same detector. ERs were detected through four parallel plate avalanche counter modules. In a separate experiment at LNL, ER and FF cross-sections were measured, respectively, using electrostatic deflector and the double-arm time-of-flight spectrometer CORSET [29]. To extract the pre- and post-scission integrated multiplicities, particle energy spectra have been analysed by considering three evaporative sources: the composite nucleus prior to scission and the two fully accelerated fission fragments [30,31]. We used a well-established procedure which employs the Monte Carlo statistical code GANES.

The full set of data is shown in table 1 along with the results of the SM calculations performed with the code PACE2_N97 [32] and a 3D Langevin dynamical code [22,24] which implements one- and two-body dissipation models. The dynamical model was coupled with the statistical model Lilita_N97 [33] to simulate the emission of LCP from ER and the composite system before scission (pre-scission emission). The symbols are

Table 1. Proton and α-particle multiplicities in the ER and pre-scission channels together with the FF and ER cross-sections for 200 MeV ^{32}S+^{100}Mo reaction. The SM calculation refers to the case where the parameters are chosen to best reproduce the FF channel data without time delay (see text for details).

	ER channel			FF channel				
	$M_{\rm n}$	$M_{\rm p}$	M_α	$M_{\rm n}$	$M_{\rm p}$	M_α	$\sigma_{\rm ER}$ (mb)	$\sigma_{\rm FF}$ (mb)
Exp.	–	0.90 ± 0.14	0.56 ± 0.09	–	0.055 ± 0.007	0.038 ± 0.005	828 ± 50	130 ± 13
SM	4.26	1.44	1.64	0.42	0.058	0.034	813	143
One-body	5.30	1.198	0.556	0.63	0.064	0.0399	786	150

as follows: the multiplicities of the protons and α-particles are, respectively, M_p and M_α. σ_ER and σ_FF are, respectively, the ER and FF cross-sections.

5.2 *Statistical model analysis*

The measured quantities in table 1 were analysed with the SM implemented in the code PACE2. The original code has indeed been extended by including new options for the level density and the transmission coefficients as well as fission delay according to the prescription given in [1].

If we limit our analysis to the FF channel only, namely, if we try to reproduce only the multiplicities in the FF channel as usually done [1], the data shown in table 1 can be reasonably well reproduced by assuming $a_\nu = A/9$, $a_\mathrm{f}/a_\nu = 1.04$, liquid-drop model (LDM) yrast line and optical model (OM) transmission coefficients, without any delay. The parameter $a_\nu = A/9$ is the Fermi gas level density parameter for particle evaporation and a_f is the level density parameter for fission. From this result one could conclude that no transient effect takes place in this decay, although it has been verified that a different combination of input parameters does not exclude the presence of a relatively small fission delay. On the other hand, with the same input parameters, the model strongly overestimates the ER particle multiplicities even though it reproduces the ER cross-section. This is an evident contradiction: if the model is not able to reproduce the LCP multiplicities in the ER channel, once the ER cross-section is well accounted for, the same model cannot be assumed to be a reliable tool to estimate the fission time-scale through the pre-scission light particle multiplicities.

To explore the possibility to reproduce the data in both channels with a unique set of input parameters we performed an extensive analysis with different prescriptions of the level density parameter and TC. Calculations were carried out by adopting three different and well-known directives for the yrast line: (1) Gilbert–Cameron, (2) LDM and (3) sharp rigid sphere with radius parameter $r_0 = 1.2$ fm. Different prescriptions have also been used for the level density parameter a_ν: (1) a constant value ranging from $A/6$ to $A/12$, (2) inclusion of shell effects with a damping term as a function of the excitation energy and (3) a temperature-dependent prescription. Transmission coefficients derived from OM and fusion systematics were used. Different values of fission delay and a_f/a_ν were adopted to modulate the particle-fission competition. Calculations were constrained by the sum of the measured ER and fission cross-section $\sigma_\mathrm{fus} = \sigma_\mathrm{ER} + \sigma_\mathrm{FF} =$ 958 mb.

In figure 2 we show the multiplicities for protons and α-particles, in the ER and FF channels, as well as the measured channel cross-sections, compared to the calculated values, as a function of the ratio a_f/a_ν. We report in the figure the results corresponding to the prescriptions labelled as (a), (b), (c) and (d), whose peculiarities are reported in table 2. The prescriptions (a), (b), (c) and (d) presented here were chosen among the many combinations for which calculations were performed as they allow to explore the full range of variability of the calculated values of the observables under examination. No fission delay was included in the calculations. From figure 2 we infer that the SM strongly overestimates proton and α-particle multiplicities in the ER channel for this system, irrespective of the input parameters and prescriptions used for the level density and TCs. The same result is confirmed by the calculations performed with the well-known code

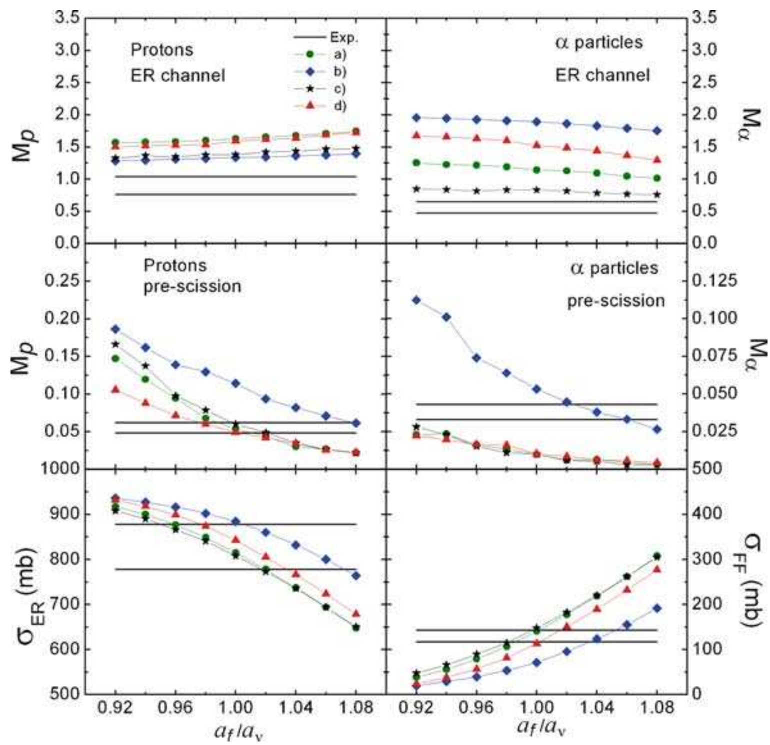

Figure 2. Measured ER and pre-scission LCP multiplicities along with the FF and ER cross-sections (horizontal solid lines indicate measured lower and upper limits due to the experimental errors), compared to the calculations of the SM changing (i) the level density parameter a_ν, (ii) the yrast line and (iii) the transmission coefficients (for details see text).

Lilita_N97 [33]. Furthermore, the inclusion of a time delay to further suppress the fission does not change the overall pattern of the calculated data with respect to the experimental data. At the same time, the influence of nuclear deformation would further enhance the predictions of SM particle multiplicities, resulting in a larger overestimation. On the other hand, the comparison of the measured proton and α-particle energy spectra with the SM does not show any evidence of nuclear deformation.

Table 2. Summary of the SM parameters used in the calculations for the level density parameter a_ν, yrast line (YR) and TC.

Prescription	a_ν	YR	TC
(a)	$A/6$	RS	OM
(b)	$A/12$	LDM	OM
(c)	$A/6$	RS	FM
(d)	$A/6$	LDM	OM

It should be pointed out that the overestimate in the ER channel found for the present compound system was also found in other systems of similar mass. We have, in fact compared the experimental data taken from the literature with the predictions of our code PACE2_N97. Indeed, in the literature there are only few systems for which the ER channel LCP multiplicities were measured. From the calculations performed by us, once again we find that the SM overestimates protons and α-particle multiplicities in the ER channel which makes us to suspect that the SM is behaving surprisingly at variance with what is expected.

5.3 *Dynamical model analysis*

These contradictory results outline the necessity of considering dynamical models. Recently, we have coupled the Lilita_N97 code with a dynamical model [22,24] which describes the fission process by using a 3D Langevin stochastic approach. This coupling was necessary to allow the evaporation of light particles from the composite system during the evolution along trajectories in the phase space. In this study, we have performed several sets of calculations for the $^{32}S + ^{100}Mo$ system at $E_{Lab} = 200$ MeV by assuming different prescriptions of TCs and level densities for particle evaporation, and by modulating the values of the strength of the one- and two-body dissipation schemes. From table 1 we see that the one-body model can reproduce most of the measured quantities, including the ones in the ER channel, by assuming full one-body dissipation. The value $a_\nu = A/6$ is used in the SM decay branch. To obtain a similar agreement with two-body dissipation, an unrealistic value of viscosity parameter has to be used, as already found in [19].

In figure 3a we show how the reduced friction coefficient varies with the deformation of the nucleus en route towards fission in the one-body dissipation model. The case that can give the best agreement with the full set of data is represented by the red line ($K_s = 1$),

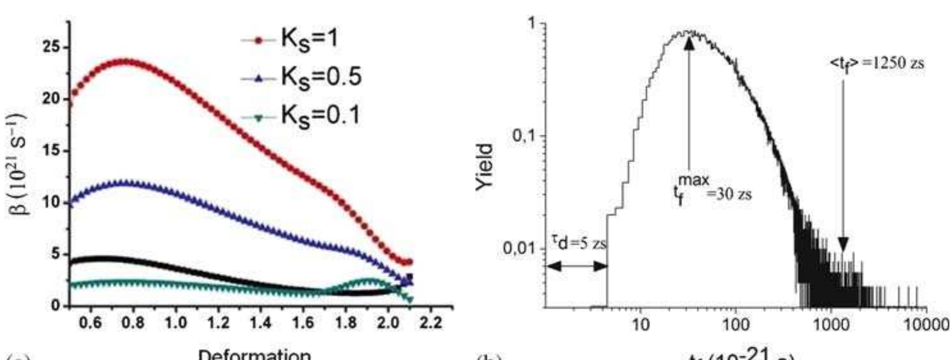

Figure 3. (**a**) Reduced dissipation parameter vs. deformation of the compound nucleus. K_s is the strength of the one-body dissipation. $K_s = 1$ represents full strength. The black solid line is the functional dependency expected in the case of two-body dissipation. (**b**) Time distribution of all fission events for the ^{132}Ce nucleus in one-body dissipation.

namely, full one-body dissipation. The two-body dissipation case is represented by the black line. It is clear that the one-body dissipation shows a stronger dependence on deformation. Furthermore, the viscosity grows at the beginning of the deformation until a maximum is reached; later, it decreases monotonically for increasing deformation. This implies that the viscosity shows the maximum strength only at the beginning of the collective motion and when the shape is still fairly compact. No dependence on temperature is assumed so far.

From the model and the computational method it is also possible to build the time distribution of all fission events. This is shown in figure 3b. The distribution has a maximum at 30 zs but it extends up to 4000 zs. This makes the average time for fission to be 1250 zs. This figure is hence quite informative because it shows that fission can take place in quite a large interval of time. The time delay parameter widely used in the statistical approach does not correspond to any of the above characteristic times of the distribution and this confirms the inadequacy of the SM approach to nuclear dissipation. The extension of time distribution may also explain why different time-scales are extracted with the SM approach when different probes are used.

6. Conclusions and perspectives

The study on the system $^{32}S + ^{100}Mo$ at 200 MeV highlights the inadequacy of the SM in describing the LCP particle multiplicities in the ER channel. The same analysis performed on the data from literature in the region of mass number $A \approx 150$ and excitation energy $E_x A \approx 100$–150 MeV, for the ER channel, provides similar conclusions. These findings repropose the problem of reliability of the SM in describing the CN decay and have a relevant impact on the extraction of the fission delay time through the use of SM.

The dynamical approach to fission decay is indeed very promising in describing both fission and ER channel within the same model. Furthermore, a dynamical model reveals more intimate details of the fission process. For instance, the time distribution of the fission events provides hints to interpret the large variety of fission time-scales found in the literature. The model can be more and more refined. We have indeed enlarged the computational capabilities of our code to include the calculation of energy spectra and angular distribution of the pre-scission particles. This is a novel feature that constrains the model parameters even more. One observable which we also consider important is the isospin degree of freedom. In [27] the importance of selecting the proper probe for testing a dissipation model according to the isospin of the CN is discussed.

A component still missing in our computational model is the evaporation from the fission fragments. This is an important feature because post-scission light particle multiplicities are also measured. The comparison of these observables with the predictions of a model that follows the full decay chain, from equilibrium to fragment decays, would probe the models in more detail for the share of excitation energy and angular momentum, and would provide a more direct link to the features of a nucleus at the scission point. An example for this is the temperature of the nucleus at the scission point. Such an extension of the model should also consider the possible dependence of nuclear viscosity on the temperature. Consequently, experiments should be designed to explore this particular aspect. Both of these developments are currently in progress.

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