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Fission Dynamics: The Quest of a Temperature Dependent Nuclear Viscosity

E. Vardaci[1*], A. Di Nitto[2], P.N. Nadtochy[3], A. Brondi[1], G. La Rana[1], R. Moro[1], M. Cinausero[4], G. Prete[4], N. Gelli[5], E. M.Kozulin[6], and G.N. Knyazheva[6]

[1]Dipartimento di Fisica, Università degli Studi di Napoli "Federico II", and Istituto Nazionale di Fisica Nucleare, Napoli, 80126, Italy

[2]Johannes Gutenberg- Universität Mainz Institut für Kernchemie, Mainz, Germany

[3]Omsk State University, Mira prospekt 55-A, Omsk 644077, Russia

[4]Laboratori Nazionali di Legnaro dell'Istituto Nazionale di Fisica Nucleare, Legnaro (Padova), 35020, Italy

5Istituto Nazionale di Fisica Nucleare, Sesto Fiorentino (Firenze), 50019, Italy

[6]Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, RU-141980 Dubna, Moscow Region, Russia

[*]*Email: Vardaci@na.infn.it*

Abstract This paper presents a journey within some open questions about the current use of a temperature dependent nuclear viscosity in models of nuclear fission and proposes an alternative experimental approach by using systems of intermediate fissility. This study is particularly relevant because: i) systems of intermediate fissility offer a suitable frame-work since the intervals between the compound nucleus and scission point temperatures with increasing excitation energy are much smaller than in the case of heavier systems, ii) the dependence of viscosity on the temperature may change with the fissility of the composite system; iii) the opportunity to measure also observables in the evaporation residues channel translates into a larger set of effective constraints for the models.

Keywords: fission dynamics; nuclear viscosity; dynamical models; intermediate fissility systems; charged particle multiplicities

1. INTRODUCTION

A large variety of studies [1-19] on the fission decay of composite systems with mass number A≈180-250 has 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 life-time for the emission of light particles. With increasing excitation energy, the particle decay lifetime decreases and becomes smaller than the time necessary for the build up of the collective motion of the nuclear matter toward the saddle point. Consequently, fission does not compete as effectively as predicted by the statistical model in the early stages of the decay, and particles and GDR γ-rays emissions can occur more favorably. 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

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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. In other words, the fission probability is not to its full value already at the beginning of the decay where the compound nucleus is pictured as fully equilibrated, namely, there is a delay in the collective motion toward the fission barrier not accounted for in the statistical picture. An energy domain has further been identified [8] 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 compound nucleus committed to fission (already at the saddle point configuration) can still became an evaporation residue if enough particles are evaporated and the fissility reduced. This correlation between the enhanced yield of prescission 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≈ 150-160 [12].

Most of the estimates of fission time scale have been obtained from the neutron prescission multiplicities on the basis of the statistical model [1]. However, several variants of the statistical model have been proposed in the literature to take explicitly into account transient effects, time scales as well as viscosity [2, 4, 7, 9, 13, 14]. Following the initial idea of the "neutron clock" [2, 4–6], the common trend is to split the path from the equilibrium to the scission point configuration into two regions, the pre- and the post-saddle. The total fission time is defined as $\tau_f = \tau_d + \tau_{ssc}$, where τ_d is the pre-saddle delay, namely, the characteristic time which 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 considered also dependent on another parameter, the viscosity parameter γ, as well. Following Kramer's work [20], the inclusion of dissipative effects results in an effective time-dependent fission decay width $\Gamma_f(t)$ which is smaller than the standard Bohr-Wheeler decay width by a hindrance factor,

$$\Gamma_f(t) = \Gamma_{BW}\left[\sqrt{1+\gamma_d^2} - \gamma_d\right][1 - exp(-\tau/\tau_d)] \tag{1}$$

Here τ_d is a delay parameter, Γ_{BW} is the Bohr-Wheeler fission decay width, and γ_d is the nuclear viscosity parameter in the pre-saddle region which can be written as $\gamma_d = \beta / 2\omega_0$. β is the so-called reduced dissipation parameter and ω_o is the potential curvature at the saddle point.

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

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

In general, the nuclear viscosity parameter might be different inside and outside the saddle point. Furthermore, τ_d , τ_{ssc} , γ_d and γ_{ssc} are dependent on the available excitation energy, the temperature of the nucleus, the fission barrier, the angular momentum.

In spite of the extensive work, estimates of the fission time scales are however quite controversial, ranging from 5 to 500×10^{-21} s, depending on the system and on the 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 [10, 11, 14, 16].

Dynamical models [20-30], based on the Euler-Lagrange, Fokker-Planck or Langevin equations, have been used in order to estimate the reduced viscosity parameter β and to gain insight on the nature of dissipation. A set of collective degrees of freedom is chosen and the internal degrees of freedom constitute the heath bath. Dissipation is the mechanism setup to transfer energy between collective and internal degrees of freedom. The evolution of the collective variables on a potential energy surface 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 Total Kinetic Energy (TKE) [22], using the one-body or two-body prescriptions in the dissipation function, indicates that this observable is not suffcient alone to elucidate this point. A two-dimension Langevin approach has been used to analyze the TKE and the prescission neutron multiplicity for the nucleus ^{200}Pb [23]. 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 $\beta = 15\times10^{21}$ s^{-1} and 24×10^{21}s^{-1}, extracted from the prescission neutron multiplicities for the composite nucleus ^{188}Pt at Ex = 99.7 and 101.4 MeV [33], are consistent with one body dissipation. The observed value of $\beta = 6\times10^{21}$ s^{-1} for the same compound nucleus at Ex = 66.3 MeV indicates an increase with temperature.

A different result was found for the system ^{220}Th by Rubchenya et al. [13] by applying a revised statistical model: the effective average value of β decreases with increasing excitation energy, similarly to the temperature dependence expected for the two-body friction. This result is in striking contrast with the result of Hofman et al. [10] where their set of data is equally well reproduced by a friction coeffcient γ which increases with either T_{saddle} or T^2_{saddle} (T_{saddle} is the temperature at the saddle point), and, in any case, increases with the projectile energy. A systematic study was also carried out by Bhattacharya et al. [24]: the values of a viscosity coeffcient used to reproduce the observed neutron multiplicities increase with the mass and the excitation energy per nucleon of the composite system and follows an empirical relation.

In conclusion, the estimates of β, both from statistical and dynamical models, provide a contradictory picture on the values of β, which range from $\approx$ 2 to 30×10^{21}s^{-1}, and result in rather controversial conclusions on the nature of nuclear dissipation and its dependence on the shape and temperature. More dramatic is the situation from the pure theoretical point of view, where the predicted values of β, on the basis of microscopic models, are spread over three orders of magnitude [33].

2. DYNAMICAL VS. STATISTICAL APPROACH

Besides the specialist details, there are few characteristics of the description of the fission process that come out of these two deeply different approaches that are quite surprising. In the approach based on the statistical model, the viscosity parameters are treated as free parameters to be adjusted on the experimental data. In particular, their values are kept constant during the cool down of the composite nucleus both inside and outside the barrier. 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 $\gamma - rays$ 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 parameters are considered to be temperature or deformation dependent [14–16].

On the opposite side there is the dynamical approach. The compound nucleus can pass the saddle point several times before eventually undergoing fission and no free parameter is possible in the dissipation model (one- or two-body) except for a strength parameter [30, 31]. In the one-body model, the dissipation is shape-dependent but not temperature-dependent. Contrarily 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. In both one-body or two-body dissipation no dependence on the temperature is available.

The question is: who is right and how can we disentangle this apparent contradiction. Somehow the answer could be simple because the statistical approach can only mimic a dissipation model by introducing adhoc parameters. However, it must be pointed out that only neutron multiplicities and GDR γ – rays have been measured in most of the studies and mostly for heavy systems ($A \geq 200$), and the lack of a suffcient number of constraints to the models could, in several cases, be the source of misinterpretations. In order to withdraw a more consistent picture of nuclear dissipation, and its connection with the shape and the temperature, it seems crucial to start by taking into account a larger number of observables which can be expected to be sensitive to the nuclear dissipation and to try to reproduce the 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 [34]. They are characterized by an evaporation residue (ER) cross-section comparable or larger than the fission cross-section, and by a shorter path in the deformation space from the saddle-to-scission point [35]. Consequently: 1) the input parameters of the models can be further constrained by the energy spectra and multiplicities of the light particles in the ER channel; 2) the effect of the fission delay over the 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 evaporation residue as consequence of both a reduction of the fissility and the 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 means 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 of the viscosity parameter, and contribute to a better comprehension of the nuclear viscosity. To put this criterion into practice, the 8πLP collaboration has started a research program at the Laboratori Nazionali di Legnaro (Padova, Italy) aimed at studying the fission dynamics in systems of intermediate fissility.

In the system ^{32}S + ^{100}Mo at 200 MeV of bombarding energy we have measured at LNL several quantities which are expected to be affected by nuclear dissipation, namely, TKE-Mass distribution of the fission fragments, the fission and evaporation residues cross sections, protons and alpha particle multiplicities in both the evaporation residues and fission channels. In a first step, this whole set of data was analyzed in the frame of the standard statistical model [31-35]. The main result of this study is that although the standard statistical model is able to reproduce the observables related to the fission channel alone without delay, it overestimates the multiplicities of the protons and alpha particles in the evaporation residues channel. The only way found to reproduce the whole set of data is through the use of a dynamical model in which the fission process, along with the evaporation of light particles in the fission and evaporation residues paths, is treated with a 3D-Langevin approach coupled to the statistical model [39]. In particular, only the full one-body dissipation mechanism, with viscosity dependent on the shape of the fissioning nucleus and not on the temperature, is able to reproduce satisfactorily the whole set of data.

In figure 1 we show how the reduced friction coeffcient varies with the deformation of the nucleus en route toward fission in the one-body dissipation model. The case that is able to give the best agreement with the full set of data is represented by Ks = 1, namely, full one-body dissipation ("wall" and "wall-plus-window") [39]. The two-body dissipation case is represented by the full thick line. It is clear that one-body dissipation shows a stronger dependence on the deformation. Furthermore, the viscosity

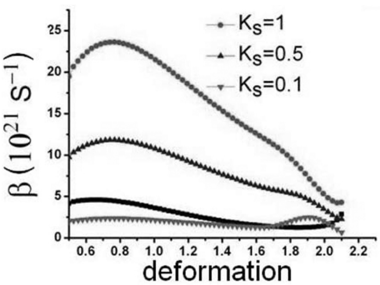

Figure 1: Dependence of the reduced viscosity paramter on the deformation of the compound nucleus. K_s is the strength of the one-body dissipation. Full strength is for $K_s = 1$.

grows at the beginning of the deformation until a maximum is reached; afterwards, it decreases monotonically for increasing deformation. This means that viscosity shows the maximum strength only at the beginning of the collective motion and when the shape is still fairly compact. No dependence on the 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 2. The distribution has a maximum at 30zs but it extends up to 4000zs. This makes the average time for fission to be 1250zs. This figure is hence quite informative because it shows that fission can take place in quite a large interval of time. What is normally used in the statistical approach does not correspond to any of the characteristic times of the distribution above and this confirms the inadequacy of the statistical model approach to describe nuclear dissipation. The shape of this distribution indeed changes when it is gated on specific evaporated particles and also with the decay step before fission (1st chance or 2nd chance particle evaporation). The various shapes of the time distribution as well as its extension may also explain why different time scales are extracted with the statistical model approach when different probes are used. The conclusions of this study are that our extensive set of data, even though for one reaction, is consistent with a deformation dependent nuclear viscosity and that after a time of 5×10^{-21}s, fission occurs in a fairly large interval of time.

4. HOW TO PROBE A TEMPERATURE-DEPENDENT VISCOSITY

In the analysis above on the system ^{32}S + ^{100}Mo the reduced viscosity parameter β has been taken independent from the temperature. The nuclear mechanism of dissipation may indeed depend on the temperature. We propose here a possible scenario to study in more detail the possible dependence of the viscosity on the temperature.

In many experimental studies on heavy systems it is commonly found that if the temperature of the compound nucleus TCN is raised, the temperature at scission point TSC remains almost constant [1, 19, 41]. This supports the picture in which fission occurs after that the composite nucleus has cooled down until has reached an excitation energy

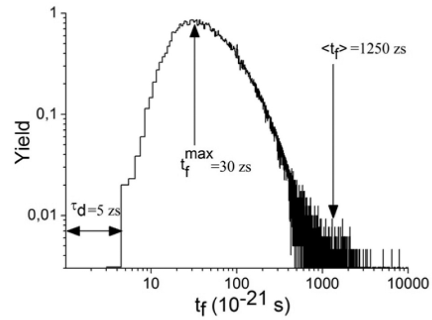

Figure 2: Calculated distribution of the fission times in the system $^{32}S+^{100}Mo$ at 200 MeV.

of roughly 50-60 MeV, independently on the excitation energy of the initial compound nucleus. This is shown in figure 3 for one of the systems found in the literature [19]. The trends of the two temperatures are predicted by 3D dynamical model in [27, 30].

If a study on the dependence of nuclear viscosity on the temperature is performed with this picture in mind (for instance by measuring the excitation function of some observables of the kind above), inevitably the measurable effects on the observables, which are deduced from the deviations from the model used, are averaged over an interval of temperatures $\Delta T = T_{CN} - T_{SC}$ which grows with the bombarding energy. In other words, as the interval of temperatures $T_{CN} - T_{SC}$ increases, the observable effects are integrated over a larger and larger interval of temperatures, and a possible dependence on the temperature is hidden. Consequently, heavy systems are not the ideal frame for the study of the dependence of the viscosity parameter from the temperature.

Systems of intermediate fissility have instead a completely different behavior. With the model in [30, 31, 39] we calculated T_{SC} for several systems. In figure 4 we show the dependence of T_{CN} and T_{SC} from the initial excitation energy of the compound nucleus for the case of the system $^{19}F + ^{106}Cd$. The interesting feature of these systems is that T_{SC} also grows with the excitation energy of the initial compound nucleus, a behavior at variance with that found for heavier systems. This is due to the delicate balance between the time scale of the fission process and the binding energy of the pre-scission particles: the neutron prescission emission, which is mainly responsible for the cooling in the pre-saddle region, is suppressed by the higher binding energy and stronger competition with charged particles. As a result, the two fission fragments retain most of the initial excitation energy.

This peculiarity of the systems of intermediate fissility is a characteristic feature which makes this kind of systems more suitable for a study of the temperature dependence of the viscosity because narrower regions of temperature are accessed. In the choice of the proper system some limitations, typical of this mass region, must be taken in consideration. Fusion-fission is limited to a narrow window of angular momentum

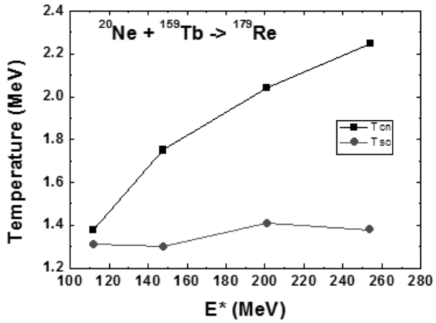

Figure 3: Pre- and post-scission temperatures vs. initial excitation energy of the compound nucleus [19].

and fast fission sets in sharply with the increase of the excitation energy and angular momentum. In consideration of this, to avoid the overlap of the fusion-fission with the fast-fission, the entrance channel mass asymmetry must be chosen in such a way that the critical angular momentum for fusion l_{crit} is lower than the angular momentum at which the fission barriers goes to zero l_{Bf}. This condition sets a limiting angular momentum above which fast-fission sharply raises. As a consequence of this limiting factor, the range of convenient excitation energies is of about ΔEx = 40, 60 MeV. More asymmetric systems are consequently preferable. This will also guarantee a value of the grazing angle smaller than the half of the fission folding angle.

Typical reaction channels for such an experiment to probe the nuclear viscosity are light charged particles (LCP) in coincidence with fission fragments and evaporation residues (ER), and the TKE-Mass distribution of the fission fragments. Pre and post-scission LCP multiplicities are extracted by such coincident events and compared with the predictions of the dynamical model. An experiment on the system ^{19}F + ^{106}Cd at two different energies was performed at LNL with the 8πLP setup and the data analysis is in progress.

5. CONCLUSIONS AND PERSPECTIVES

Our study on the system ^{32}S + ^{100}Mo highlights the inadequacy of the SM in describing the fission process. This result pours some shade on the application of the SM in studies designed to investigate on the presence of transient effects. These findings also remark the problem of the reliability of the SM in describing the compound nucleus decay and have a relevant impact on the extraction of the fission delay time through the use of the SM. The dynamical approach to fission decay is instead very promising in describing both fission and evaporation residues channel within the same model. Furthermore, a dynamical model allows to penetrate 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 scale found in the literature. At the same time, the model can be more and more refined if more observables are measured for the same system. Of course,

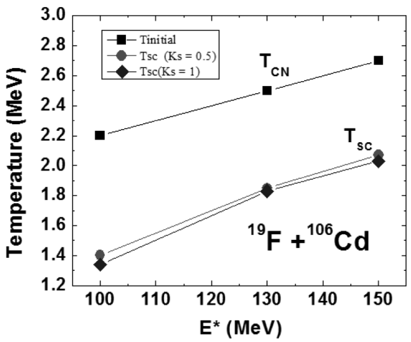

Figure 4: Pre- and post-scission temperatures vs. initial excitation energy of the compound nucleus in the case of an intermediate mass system calculated with a dynamical model [30]. The full one-body dissipation correspond to $K_s = 1$.

the model should be oriented on the calculations of quantities that are directly linked to measured observables. In this respect, we have 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 constraints even more the model parameters and in turn allows to disentangle more characteristic features of the fission process.

One observable which we also consider very informative is the isospin degree of freedom. In [31] it is remarked the importance of selecting the proper probe for testing a dissipation model according to the isospin of the compound nucleus. One part missing in our computational model is the evaporation from the fission fragments. This is an important feature since post-scission light particle multiplicities are 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 more in detail models 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. One of these is the temperature of the nucleus at the scission point. Such an extension of the model should consider the possible dependence of the nuclear viscosity on the temperature. Consequently, experiments should be designed to explore this particular aspect. In this article we have also proposed an alternative scenario where the study of the dependence of the nuclear viscosity from the temperature seems more suitable.

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Emanuele Vardaci is Associate Professor at the Department of Physics of University of Naples “Federico II”. His present research activity concerns with the study of the fission dynamics in systems of intermediate fissility, the production of heavy neutron-rich nuclei via multi-nucleon transfer reactions, the study of the effects of the isospin on the nuclear level density, features of exotic nuclei by means of nuclear reactions at energies around the Coulomb barrier.

Prof. Vardaci is Invited Member of the Joint IUPAC-IUPAP Working Party on the Discovery of Elements of Atomic Number greater than 111 since 2006 and Invited Member of two Programme Advisory Committees (PACs), at the Flerov Laboratory of Nuclear Reactions (JINR, Dubna) since January 2007, and at iThemba Lab (Cape Town, South Africa) since January 2013.