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Abstract. Systems of intermediate fissility are characterized by an evaporation residues cross section comparable or larger than the fission cross section, and by a relatively higher probability for charged particle emission in the pre-scission channel. In a theoretical framework in which time scale estimates of the fission process rely on statistical model calculations, the analysis of particle emission in the evaporation residues channel is the source of additional constraints on statistical and dynamical models. This contribution will focus on our statistical and dynamical analysis of a more complete set of data from the system $^{12}$S + $^{100}$Mo at $E_{	ext{lab}} = 200$ MeV. Statistical model fails in reproducing the whole set of data and no convincing estimate is possible of the fission time scale. In particular, while pre-scission multiplicities can be reproduced without delay, the model strongly overestimates proton and alpha particle multiplicities in the evaporation residues channel irrespective of the statistical model input parameters and prescriptions used for the level density and the transmission coefficients. The analysis of the same set of data with a dynamical model produces a very good agreement with the full set of data and indicates that one-body dissipation plays a dominant role in the fission process, implying a fission delay of $23-25 \times 10^{-21}$ s.

1. Introduction

A large variety of experimental studies of induced fission in heavy ion reactions [1] have shown that pre-scission multiplicities of light particles (neutrons, protons and alpha particles) increase monotonically with the bombarding energy, in contrast with the calculations of the standard statistical model (SM) which start from the complete thermalization of the compound system. Since the fission process is considered to be affected by nuclear dissipation [1, 2], this result is considered as the evidence that fission is a slow process with respect to the lifetime for the evaporation 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 SM in the early stage of the decay, and light particles, and possibly GDR γ-ray, emissions can occur with higher probability. The overall cause of this transient effect is believed to be associated with the nuclear matter viscosity which slows down the collective flow of mass from the equilibrium to the scission point and does not allow the fission decay lifetime to be downscaled with the excitation energy as in the case of light particles evaporation. This is equivalent to consider that fission is delayed with respect to the picture of the SM in which the fission width has its full Bohr-Wheeler value already at the beginning of the decay. An energy domain has further been identified [3] above which the SM predictions begin to deviate from the data. Several variants of the SM have been proposed in the literature to take explicitly into account time scales as well as nuclear viscosity. In the simplest fashion, known as the “neutron clock” [1], the SM is modified so to include another free parameter, the fission delay \( \tau_d \): at the beginning of the evaporative cascade the fission decay width is kept to zero for a time \( \tau_d \). After \( \tau_d \), the fission width is set to the full Bohr-Wheeler value. The time scale is defined by the light particle life time. This means that at the beginning of the decay cascade fission does not compete with light particle evaporation until a time \( \tau_d \) has passed. Estimates of \( \tau_d \) are obtained by the fit of the experimental multiplicities to the ones predicted by the SM which includes this new parameter. Other refinements of the neutron clock approach have been proposed to distinguish between different time steps during the fission process [4]. The common approach is to split the path from the equilibrium-to-scission into two regions, the pre- and the post-saddle. The total fission delay is defined as the sum of \( \tau_d \) and \( \tau_{sc} \), where \( \tau_{sc} \) is the time necessary to travel the path from saddle to scission. The relevant observables are computed using \( \tau_d \) and \( \tau_{sc} \) as free parameters, along with the other input parameters relative to the specific ingredients of the model, and fit to the experimental data. In spite of the extensive work, estimates of the fission time scales are however quite controversial. The reported values range from 0 [5] to 500 x 10^{-21} s [6], 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 [7, 8]. It must be pointed out that only neutron multiplicities have been measured in most of the studies and mostly for heavy systems (\( A > 200 \)), and the lack of a sufficient number of constraints to the models could, in several cases, be the source of discrepancies. In order to withdraw a more consistent picture of nuclear dissipation it is crucial, in our opinion, to take into account simultaneously a larger number of observables and probes 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.

2. Dissipation in systems of intermediate fissility

Systems of intermediate fissility (\( \chi = 0.5-0.6 \)) are very little studied although they offer several advantages. They are characterized by an evaporation residue (ER) cross section comparable or larger than the fusion-fission (FF) cross section, and by a shorter path in the deformation space from the saddle-to-scission point [9]. 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 sections 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 use of the light particle multiplicities in the ER channel as further constraint grounds, however, also on the reliability of the statistical model to reproduce such multiplicities when all the necessary experimental constraints are given and this is not demonstrated yet. 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 friction parameter, and contribute to a better comprehension of the origin of nuclear viscosity. In this framework, 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 this presentation we will report on our analysis of the reaction $200\text{MeV } ^{32}\text{S} + ^{100}\text{Mo}$ leading to the composite system $^{132}\text{Ce}$ at $E_x = 122$ MeV and fusion angular momentum $L_{\text{fus}} = 72\hbar$, derived from the measured fusion cross section in the sharp cut-off approximation. We will show the inability of the SM to provide an estimate of the fission time scale when the evaporation residue 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 three-dimensional (3D) Langevin approach [10] will be discussed. It will prove to be a method that better reproduces the overall multitude of data.

3. Experimental procedure and data analysis

The experiment was performed at the XTU Tandem - ALPI Superconducting LINAC accelerator complex of the Laboratori Nazionali di Legnaro. A $200\text{MeV}$ pulsed beam of $^{32}\text{S}$ of about 1 pnA intensity was used to bombard a self supporting $^{100}\text{Mo}$ target 300 $\mu$g/cm thick. A beam burst with frequency of about 1.25 MHz and duration of about 2 ns was used.

![Figure 1. Schematic layout of the 8πLP apparatus](image)

We used the BALL and the WALL sections of the 8πLP apparatus [11], shown schematically in figure 1, to detect light charged particles (LCP). The WALL consists of 116 telescopes placed at 60 cm from the target and covers an angular range from 2° to 24°. The BALL consists of 7 rings placed coaxially around the beam axis each with 18 telescopes which amount to a total number of 126 telescopes covering an angular range from 34° to 166°. The telescopes of the BALL are made out of a 300 $\mu$m Si detector mounted in the flipped configuration (particle entering from the ohmic side) backed by a 3 mm CsI(Tl) crystal. The rings are labelled from A to G going from backward to forward angles. Each ring covers an angular opening of about 17°. The experimental method consists in measuring LCP in coincidence with both fission fragments and with the ER.

The fission fragments were detected in the telescopes of the ring F and G of the BALL. The Pulse Shape Discrimination technique allows the separation between heavy fragments and LCP stopping in the same detector. Evaporation residues were detected through 4 Parallel Plate Avalanche Counter modules (figure 1). Each one covers a forward angle between 2.5° and 7.5°, and subtends a solid angle of about 0.3 msr. A 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 lighter 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.

In a separate experiment the ER cross section was measured by means of the electrostatic deflector of LNL and the FF cross section was measured with the double-arm time-of-flight spectrometer CORSET [12] at LNL as well.
For the system $^{32}\text{S} + ^{100}\text{Mo}$ at $E_{lab} = 200$ MeV we have measured most of the relevant quantities in the ER and FF channels: proton and alpha particle energy spectra and multiplicities, ER and FF cross sections as well as mass and total kinetic energy distributions of fission fragments. To extract the pre- and post-scission integrated multiplicities, particle energy spectra have been analyzed considering three evaporative sources: the composite nucleus prior to scission (CE) and the two fully accelerated fission fragments (F1 and F2). We used a well established procedure which employs the Monte Carlo statistical code GANES [13,14].

The full set of data is shown in Table 1 along with the results of the SM calculations performed with the code PACE2_N97 [15] and with a 3D Langevin dynamical code [10, 16] which implements the one-body and two-body dissipation models. The dynamical model is coupled with the statistical model Lilita_N97 to simulate the emission of LCP from ER and from the composite system before scission (pre-scission emission). The symbols are as follows: the multiplicities of the protons and alpha particles in the ER channel are, respectively, $M_p$ and $M_\alpha$ (ER); $M_p$ and $M_\alpha$ (PRE) are the prescission multiplicities. $\sigma_{ER}$ and $\sigma_{FF}$ are, respectively, the ER cross section and the FF cross section; $<\text{Mass}>$ and $\sigma_{\text{Mass}}$ are the mean and the standard deviation of the measured mass distribution, respectively; $<\text{TKE}>$ and $\sigma_{\text{TKE}}$ are the mean and the standard deviation of the measured TKE distribution, respectively.

| Table 1. Comparison of measured observables (Exp.) and the best predictions of the code. One-body is obtained with full one-body dissipation, two-body with viscosity parameter $\mu = 0.46$ TP. |
|---|---|---|---|---|---|---|---|---|
| Exp. | $M_p$ (ER) | $M_\alpha$ (ER) | $M_p$ (PRE) | $M_\alpha$ (PRE) | $\sigma_{ER}$ (mb) | $\sigma_{FF}$ (mb) | $<\text{Mass}>$ (u) | $\sigma_{\text{Mass}}$ (u) | $<\text{TKE}>$ (MeV) | $\sigma_{\text{TKE}}$ (MeV) |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Exp. | 0.9 (0.14) | 0.56 (0.09) | 0.055 (0.007) | 0.038 (0.005) | 828 (50) | 130 (13) | 66 | 15.4 | 90.9 | 11.4 |
| SM | 1.44 | 1.64 | 0.058 | 0.034 | 813 | 143 | |
| OneBody | 1.198 | 0.556 | 0.064 | 0.0399 | 786 | 150 | 65 | 14.6 | 82.1 | 7.2 |
| TwoBody | 1.18 | 0.57 | 0.059 | 0.031 | 758 | 178 | 65.5 | 14.9 | 79.4 | 7.3 |

4. Statistical model analysis
We analyzed the measured quantities in Table 1 with the SM implemented in the code PACE2. The original code has indeed been extended with the inclusion of new options for the level density and the transmission coefficients as well as the possibility to account for a fission delay according to the prescription widely used in the literature [1]. The fission delay parameter $\tau_d$ is used in such a way that the fission probability is zero up to the time $\tau_d$ and has the full Bohr-Wheeler value subsequently.

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 assuming $a_c = A/9$, $a_f/a_c = 1.04$, liquid drop model (LDM) yrast line and optical model (OM) transmission coefficients [17-19], without any delay. The parameter $a_c$ 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, in contrast with the systematics [3], although a different combination of input parameters does not exclude the presence of a relatively small fission delay. On the other hand, with the same 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 supposed as a reliable tool to estimate the fission time scale through the pre-scission light particle multiplicities.

In order 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 transmission coefficients. Calculations have been carried out adopting three different and well known prescriptions for the yrast line: 1) Gilbert Cameron [20], 2) LDM and 3) sharp rigid sphere (RS) with radius parameter $r_0 = 1.2$ fm. Different prescriptions have also been used for the level density ($\alpha_\nu$), yrast line (YR) and the transmission coefficients (TC); see Table 2.

| Prescription | $\alpha_\nu$ | YR   | TC   |
|--------------|-------------|------|------|
| a)           | $A/6$       | RS   | OM   |
| b)           | $A/12$      | LDM  | OM   |
| c)           | $A/6$       | RS   | FS   |
| d)           | $A/6$       | LDM  | OM   |

Figure 3. Measured evaporative (ER) and pre-scission (PRE) charged particle multiplicities together with the FF and ER cross sections (full lines indicating lower and upper limits of the uncertainty), compared to the predictions of the statistical model (symbols connected by lines to guide the eye) using prescriptions: a), b), c) and d) reported in Table 2. See text for details.

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| d)           | $A/6$       | LDM  | OM   |
density parameter \( a_f \): 1) a constant value ranging from \( A/6 \) to \( A/12 \), 2) inclusion of shell effects [21] with a damping term [22] as a function of the excitation energy and 3) a temperature dependent prescription [23]. Transmission coefficients derived from: 1) optical model and 2) fusion systematics (FS) [24] have been used. Different values of fission delay and \( a_f / a_\nu \) have been adopted to modulate particle-fission competition. Calculations have been constrained by the sum of the measured evaporation residue and fission cross section \( \sigma_{\text{ fus}} = \sigma_{\text{ ER}} + \sigma_{\text{ FF}} = 958 \text{ mb} \).

In figure 3 we show the multiplicities for protons and alpha 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 \( a_f / a_\nu \). We report in the figure the results corresponding to the prescriptions labeled as a), b), c) and d), whose peculiarities are reported in Table 2. The prescriptions a), b), c) and d) presented here have been chosen among the many combinations for which calculations have been performed as they allow to explore the full range of variability of the calculated values of the observables under examination. No fission delay has been included in the calculations.

In figure 3 we infer that the SM strongly overestimates proton and alpha particle multiplicities in the ER channel for this system, irrespective of the input parameters and the prescriptions used for the level density and transmission coefficients. Same result is confirmed by the calculations performed with the well known codes Lilita_N97 [25] and Gemini [26]. 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 statistical model particle multiplicities predictions, resulting in a larger overestimation. On the other hand, the comparison of the measured proton and alpha particle energy spectra with the SM shows no evidence of nuclear deformation.

It should be pointed out that the overestimate in the ER channel found for the present compound system was found also in other systems of similar mass. We have in fact compared 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 have been measured. From calculations performed by us, once again we find that the SM overestimates protons and alpha particle multiplicities in the ER channel which makes us to suspect that the SM is behaving surprisingly at variance with what expected.

5. 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 [10, 27] which describes the fission process by using a 3D Langevin stochastic approach. This coupling was necessary in order to allow the evaporation of light particles from the composite system during the evolution along trajectories in the phase space. At the moment we have performed several sets of calculations for the system \( ^{32}S + ^{100}Mo \) at \( E_{\text{lab}} = 200 \text{ MeV} \) assuming different prescriptions of transmission coefficients and level densities for particle evaporation, and by modulating the values of the strength of the one-body and two-body dissipation schemes. From Table 1 we see that the model is able to reproduce most of the measured quantities, including the ones in the ER channel, assuming full one-body dissipation, and with a viscosity parameter \( \mu \) independent upon the temperature but dependent on the deformation of the fissioning system. In order to obtain a similar agreement with two-body dissipation, the unrealistic value of viscosity parameter \( \mu = 0.24 \text{ TP} \) had to be used, as already found in Ref. [28]. The full one-body dissipation implies a transient times for fission in the range of \( 23-25 \times 10^{-21} \text{s} \).

In figure 4 we show how the reduced friction coefficient 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 the red line (\( K_s = 1 \)), namely, full one-body dissipation. The two-body dissipation case is represented by the black line. It is clear that one-body dissipation shows a stronger dependence on the deformation. Furthermore, the viscosity 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 5 for the case of \(^{132}\text{Ce}\). 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 nuclear dissipation. The extension of the time distribution may also explain why different time scales are extracted with the statistical model approach when different probes are used.

**Figure 4.** Friction coefficient as a function of the deformation of the fissioning nucleus in the case of the one-body dissipation mechanism. The black solid line is the functional dependency expected in the case of the two-body.

**Figure 5.** Time distribution of all the fission events for the nucleus \(^{132}\text{Ce}\).

6. Conclusions and perspectives

Our study on the system 200MeV \(^{32}\text{S} + ^{100}\text{Mo}\) highlights the inadequacy of the SM in describing the LCP particle multiplicities in the ER channel. Same analysis performed on data from literature in the region of mass number \(A \approx 150\) and excitation energy \(E_x \approx 100-200\) MeV, for the ER channel, provides similar conclusions. 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 repurpose 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, 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 important is the isospin degree of freedom. In [27] 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 also consider the possible dependence of the nuclear viscosity on the temperature. Consequently, experiments should be designed to explore this particular aspect. Both these developments are currently in progress.

7. References

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