Determination of the Transient Time for Fission from a New Experimental Approach

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Abstract. Fission induced by peripheral heavy-ion collisions at relativistic energies is a powerful experimental approach to determine the dynamical delay of fission (transient time) due to dissipation. The fissioning nuclei produced by this method have small shape distortions, low angular momentum and high excitation energies at which this dynamical delay can be observed. These conditions allow for applying the model of Grangé and Weidenmüller to obtain a quantitative value of the transient time. Such approach was followed at GSI where the total and partial fission cross-sections and the widths of the charge distributions of the fission residues from a large number of nuclei were measured. The analysis of these data in the frame of an abrasion-evaporation code has lead to a transient time of $2.1 \cdot 10^{-21}$s when using a step function to describe the time dependence of the fission width. This result implies that excitation energies larger than 100 MeV are needed to observe this transient time.

1. INTRODUCTION

Dissipation leads to a delay time (transient time τ_f) for the nuclei to explore the deformation space from the ground state to the fission barrier. The aim of this work is to find experimental signatures on this transient time. For this the excitation energy of the nucleus should be high enough so that the transient time is longer than the statistical decay time predicted by the transition-state model of Bohr and Wheeler [1]. Intense and very diverse experimental work has been done to determine this transient time. However, this subject is still rather controversial and no clear agreement has been found until now. In [2] a strong influence of dissipation has already been observed at excitation energies as low as 40 MeV. On the other hand, in [3] no signature of fission hindrance is found up to excitation energies of approximately 100 MeV. The experimental approach we present here, based on fission induced by very peripheral heavy-ion collisions at relativistic energies, corresponds to an almost ideal scenario where the effects of dissipation and the consequent transient time for fission can be properly analysed. Firstly, this method allows for producing fissioning nuclei with excitation energies that are well above the limiting excitation energy were the transient time starts to be observed. Secondly, the deexcitation process of the fissioning nuclei can be described by means of the model of Grangé and Weidenmüller [4] that gives a quantitative estimation of the transient time τ_f to build up the fission decay width Γ_f up to its asymptotic value. Most theoretical codes apply two approximations for this time behaviour of Γ_f, in this work both of them are subject to critical analysis. The comprehensive experimental information gained at GSI on fission cross sections and element distributions from a wide range of systems is sensitive to the transient time τ_f and illustrates that the deduced value of τ_f strongly depends on the description used for the time dependence of Γ_f.

2. IDEAL SCENARIO FOR THE INVESTIGATION OF THE TRANSIENT TIME

An ideal scenario for investigating the transient time would be a heavy excited nucleus with only intrinsic excitation energy, i.e., only intrinsic degrees of freedom are excited and thus the nucleus has no deformation and no angular momentum. If the excitation energy of the nucleus is higher than the limiting excitation energy in which the statistical decay time and the transient time τ_f become comparable, the fission competition would set in after a time which is longer than the decay time of the nucleus for particle evaporation. Consequently, during the transient time the emission of particles is possible leading to a decrease of the excitation energy. Therefore, above the limiting excitation energy, the existence of a transient time would imply a considerably reduction of the fission probability respect to the predictions of the transition-state model.

The effects of dissipation are quantitatively analysed in the model of [4]. This model was developed recalling an old idea of Kramers [5]. According to Kramers, the fission process is considered as the evolution of the fission collective degree of freedom in the heat bath formed by the individual states of the nucleons. This process can be described by the Foker-Planck Equation (FPE) [6], which they solved numerically under the initial conditions of the ideal scenario described above. They obtained a time dependent fission width of the form:

$$\Gamma_f(t) = \Gamma^{BW} \cdot K \cdot f_{\tau_f}(t) \tag{1}$$

The first term of equation 1 Γ^{BW} is the fission width that is obtained by applying the transition-state model [1]. The second term K is the Kramers factor [5] given by the stationary solution of the FPE and the last term $f_\tau(t)$ is a time- and dissipation-dependent function. The two last terms of equation (1) reproduce how dissipation hinders the fission process. This can be seen in Figure 1 where the time dependence of the fission decay width given by an analytical solution of the FPE is depicted.

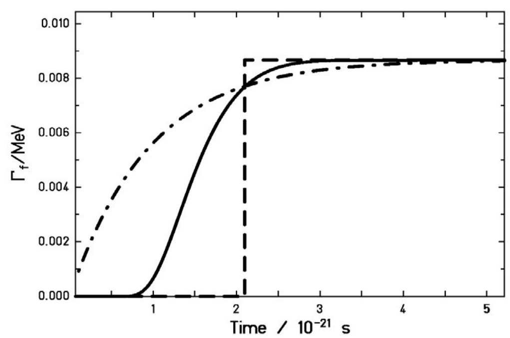

FIGURE 1. Fission decay width as function of time. The full line is the exact solution of the FPE for ^{238}U, T = 2 MeV and $\tau_f = 2.1\cdot10^{-21}$s with the nucleus potential approximated by a parabola that is truncated at the fission barrier and whose stiffness is determined according to the Liquid Drop Model [7]. The dashed-dotted line and the dashed line correspond to descriptions a) and b) respectively (see text).

The full line of Figure 1 shows how the fission width is completely hindered at the beginning of the process, then it rises up and at the time τ_f reaches 90% of the stationary value given by $\Gamma_f^{BW}\cdot K$. The inclusion of such description for $\Gamma_f(t)$ in a theoretical code is rather complicated and most of them contain one of the following approximations:

a) An exponential in growth function of the form $\Gamma_f(t) = \Gamma^{BW} \cdot K(1-\exp(-2.3t/\tau_f))$

b) A step function that switches from zero to the stationary value $\Gamma^{BW}\cdot K$ at the time τ_f

Both approximations are also represented in Figure 1.

3. EXPERIMENT

The production of fissioning nuclei with the initial conditions of the ideal scenario described in section 2 is not an easy task. Most of the experiments performed to investigate dissipation are based on fusion-fission or fast fission reactions [8,9]. In these reactions the composite systems produced after the collision are highly deformed and have a large angular momentum. This makes the description of the deexcitation process of such systems very difficult. For these reactions model [4] cannot be applied but rather more complicated codes like HICOL [10] are needed. On the contrary, heavy-ion fragmentation is a tool to excite fissile nuclei to very high excitation energies without too large shape distortions and without introducing large angular momentum ($\Delta L<20\hbar$) [11].

The radioactive-beam facility at GSI enabled the investigation of a large number of short-lived nuclei from ^{234}U down to ^{205}At and several stable uranium isotopes, covering a very interesting range of fissilities. After the production stage from the fragmentation of ^{238}U at 1 A GeV in a primary target and the identification stage [12], these nuclei were transmitted to the experimental set-up for fission studies, see figure 2. Fission was induced in inverse kinematics by collisions in a secondary target. The two fission fragments are focussed in forward direction and detected simultaneously in a double ionisation chamber. Because of the high energy of the fission fragments, they are fully stripped and the energy-loss in the chambers delivers a very accurate measurement of their charges. The velocity dependence of the energy-loss signals was corrected by means of the time of flight. In this way, total fission cross-sections as well as the charges of the fragments produced in each fission event could be measured.

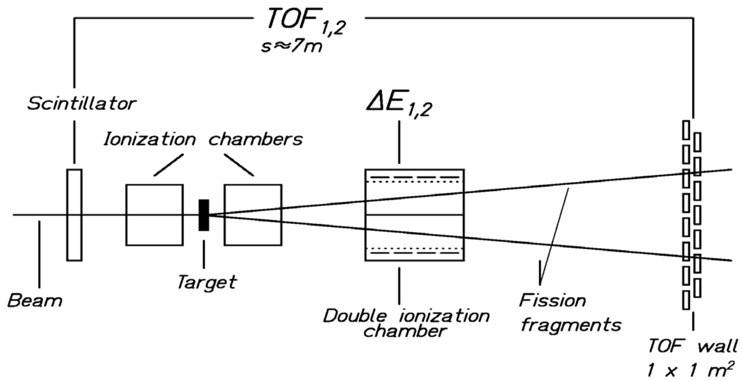

FIGURE 2. Experimental set-up for fission studies

4. RESULTS

Our results are based on the analysis of three increasingly complex measured quantities that are sensitive to the shape of $\Gamma_f(t)$ and to τ_f: Total fission cross sections, partial fission cross sections as function of the sum of the protons of the fission fragments and the widths of the charge distributions of the fission residues as a function of the sum of the protons found in the fragments. The sum of the charges of the fission fragments is directly related to the impact parameter and thus also to the excitation energy induced in the collision to the projectile spectator. The width of the charge distribution of the fission fragments is a direct measure of the temperature at which the nucleus fissions [13]. The experimental data are interpreted by comparing them with the GSI abrasion-ablation Monte-Carlo code ABRABLA [14,15]. This code consists on a first stage based in the abrasion model in which the conditions of the nucleus after the fragmentation reaction are calculated, and a second stage based on the statistical model that describes the deexcitation of the nucleus by particle evaporation and fission. In this second part the effects of dissipation are included via a time dependent fission width $\Gamma_f(t)$. We incorporated in the code the two approximations of $\Gamma_f(t)$ described in section 2 in order to compare them and investigate how the deduced transient time τ_f depends on the shape of $\Gamma_f(t)$. In all the calculations that will be shown the values of the level density parameters are calculated considering surface and volume dependencies as shown in [16]. For the fission barriers we assume the values of [17]. These theoretical values of both parameters have been experimentally confirmed in [18].

4.1 Influence of $\Gamma_f(t)$

Figure 3 shows the nuclear-induced total fission cross sections of different Rn, Ra, Th and U isotopes at 420 A MeV in a lead target as a function of the neutron number. The overall smooth dependence of the cross sections with the neutron number is due to the high excitation energies of the fissioning nuclei that attenuate the shell effects and to the large variety of different nuclei with different fissilities and fission barriers that contributes to each data point. The data are compared with several calculations done with ABRABLA. The experimental data are reproduced either by using the step function of description b) for $\Gamma_f(t)$ shown in section 2 and a transient time of $\tau_f \approx 2.1 \cdot 10^{-21}$s or by using the exponential in-grow of description a) and a longer transient time of $\tau_f \approx 8.9 \cdot 10^{-21}$s. From this analysis we conclude that the deduced value of the transient time τ_f depends strongly on the function used to describe $\Gamma_f(t)$. Therefore, in order to compare different results for τ_f it is necessary to specify the form that has been used for $\Gamma_f(t)$.

The partial fission cross sections as a function of the sum of the charges of the fission fragments Z1+Z2 for the reaction of ^{238}U at 1 A GeV on CH_2 are depicted in Figure 4, full dots. Since the variable Z1+Z2 approximately corresponds to the charge of the fissioning nucleus, Figure 4 shows that in the reaction of one kind of beam with a target, a whole set of different fissioning elements from Z = 92 down to Z = 70 are produced. The cross sections decrease with decreasing Z1+Z2 because the fissility decreases with decreasing the charge of the fissioning nucleus.

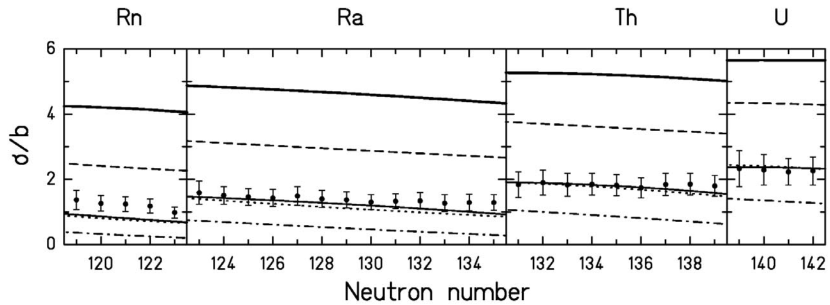

FIGURE 3. Experimental total nuclear-induced fission cross sections (black dots) as a function of the neutron number for different Rn, Ra, Th and U isotopes at 420 A MeV impinging on a lead target. The data are compared with the transition-state predictions (upper thick full lines) and with four other calculations. The dashed lines correspond to $\Gamma_f(t) = K\cdot\Gamma^{BW}(1\text{-}\exp(-2.3\cdot t/\tau_f))$ and $\tau_f \approx 2.1\cdot10^{-21}$s, the full lines to $\Gamma_f(t)$ as a step function and $\tau_f \approx 2.1\cdot10^{-21}$s, the dotted lines to $\Gamma_f(t) = K\cdot\Gamma^{BW}(1\text{-}\exp(-2.3\cdot t/\tau_f))$ and $\tau_f \approx 8.9\cdot10^{-21}$s, and the dashed-dotted lines to $\Gamma_f(t)$ as a step function and $\tau_f \approx 8.9\cdot10^{-21}$s.

These data are compared with the calculations that reproduced the total fission cross sections of figure 3. In this case, the combination step function for describing $\Gamma_f(t)$ and $\tau_f = 2.1\cdot10^{-21}$s (full line) fits the data, while description b) (dotted line) leads to important deviations from the data. Because of the better agreement with the data, in the following all the calculations are done with $\Gamma_f(t)$ as a step function according to description b) of section 2.

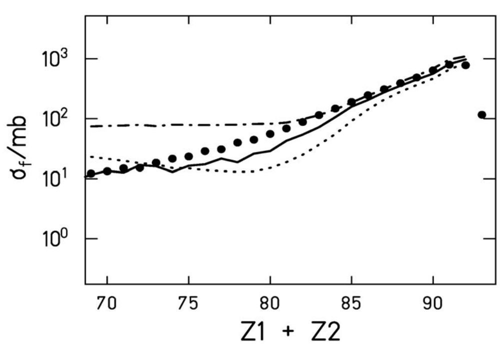

FIGURE 4. Experimental partial fission cross sections for ^{238}U impinging on CH_2 at 1 A GeV (full dots) with three calculations. The dashed-dotted line is a calculation done according to the transition-state model, the full line is a calculation done with $\Gamma_f(t)$ as a step function and $\tau_f = 2.1\cdot10^{-21}$s, and the dotted line a calculation with $\Gamma_f(t) = K\cdot\Gamma^{BW}(1\text{-}\exp(-2.3\cdot t/\tau_f))$ and $\tau_f \approx 8.9\cdot10^{-21}$s.

4.2 Transient time τ_f

From Figures 3 and 4 it can be seen that the transition-state model over predicts either the total fission cross sections as well as the partial fission cross sections for small values of Z1+Z2, i.e., for high excitation energies. These figures also show that a transient time of $\tau_f \approx 2.1\cdot10^{-21}$s is needed to reproduce both quantities. In figure 5 the width of the charge distributions of the fission fragments as a function of Z1+Z2 (a quantity which approximately corresponds to the charge of the fissioning nucleus) are represented among various ABRABLA calculations with different values of τ_f. Again the transition-state model does not reproduce the widths for the higher excitation energies and a transient time of $\tau_f \approx 2.1\cdot10^{-21}$s gives the best description of the data. From the solution of the FPE it follows that this value of τ_f corresponds to the minimum value of τ_f possible if dissipation effects are included. This value of τ_f is in good agreement with some recent results appeared in [18]. According to the statistical model, at excitation energies that go from ca. 100 to 150 MeV depending on the fissioning nucleus, the neutron decay time coincides with the transient time. Hence, for lower excitation energies the effects of the transient time cannot be observed, this agrees with reference [3].

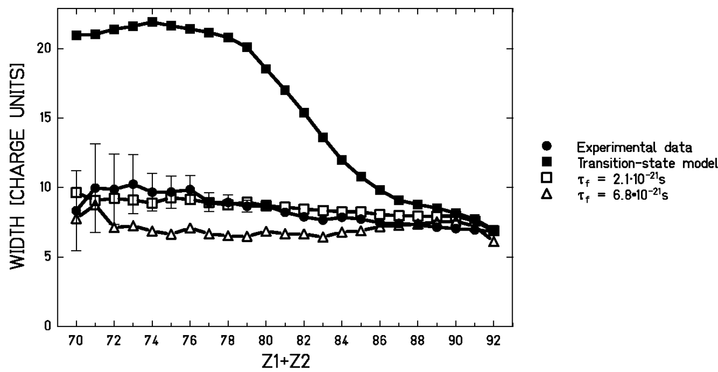

FIGURE 5. Widths of the charge distribution as a function of Z1+Z2. The experimental data are the black dots, the black squares are a calculation with the transition-state model, the white squares a calculation with $\tau_f \approx 2.1\cdot10^{-21}$ s and the white triangles a calculation with $\tau_f \approx 6.8\cdot10^{-21}$ s.

5. CONCLUSIONS AND OUTLOOK

We have presented a new and very appropriate approach for determining the transient time for fission. In this approach performed at GSI fission is induced by peripheral heavy-ion collisions at relativistic energies. The initial conditions of the fissioning nuclei in such reactions allow for applying the model of [4]. This represents important advantages with respect to the more commonly used methods and allows determining τ_f reliably. We have shown that the deduced value of τ_f depends strongly on the description used for the time-dependent fission decay width $\Gamma_f(t)$. The most widely used description of $\Gamma_f(t)$, an exponential in-grow function, does not reproduce our data, because it fails to describe practically complete suppression of fission up to the transient time. All our data are reproduced when a transient time of $\tau_f \approx 2.1\cdot10^{-21}$ s is assumed. This implies that for nuclei with excitation energies lower than 100 MeV the transient time is still a too tiny effect to be observed.

Yet, it is important to remark that the evaporation code used might not describe properly the reactions occurring at the highest excitation energies. Nonetheless, nuclear dynamics in the range of excitation energies above the 4 MeV per nucleon is the subject of current research. The R3B-project that will be developed in the next years at GSI will allow for the full identification of light and heavy products and the determination of the full kinematics of all reaction products. In this way a complete study of nuclear reactions in the energy range where fission begins to be hindered up to the range where another deexcitation channel like break-up occurs will be possible.

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