NEW RESULTS ON DISSIPATION IN FISSION

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Abstract

Fission after very peripheral heavy-ion collisions at relativistic energies is a very powerful tool for the investigation of dissipation. Such approach has been followed at GSI where the total and partial fission cross sections of some stable and a large number of unstable nuclei have been measured. These data are sensitive to the description used for the time dependent fission decay width, $\Gamma_f(t)$, and to other model parameters like the fission barriers, B_f, and the ratio of the level-density parameters, a_f/a_n. The partial fission cross sections are not reproduced when an exponential in-grow function is used to describe $\Gamma_f(t)$ in the theoretical code. Moreover, a further preliminary analysis of the experimental data leads to a confirmation of the theoretical values predicted for B_f and a_f/a_n, and to a dissipation coefficient $\beta = 2 \cdot 10^{21}s^{-1}$ that corresponds to a transient time $\tau_f \cong 2 \cdot 10^{-21}s$.

1. Introduction

Dissipation in nuclei leads to fission time scales that exceed the prediction of the Statistical Model. Intense and very diverse experimental work has been done to determine these fission time scales. However, this subject is still rather controversial and no clear agreement has been found until now. The difficulties in the experimental determination of nuclear dissipation arise from the side effects (for example angular momentum) that most experiments present. The interpretation of these experiments requires very complicated models and that hampers the extraction of relevant information related to dissipation. 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 can be properly analysed. The diffusion model of Grangé and Weidenmüller [1] describes this scenario and leads to a transient time τ_f to build up the fission decay width, Γ_f, up to its asymptotic value. In most theoretical codes, approximations for this time behaviour of Γ_f are used; in this work the two most frequently used descriptions are subject to a critical analysis. The comprehensive experimental information gained at GSI on total fission cross sections and element distributions from a wide range of systems shows that the deduced dissipation strongly depends on the description used for the time dependence of Γ_f. Furthermore, these experimental data can also be used to determine further critical parameters governing the fission process, namely, the level-density parameter and the fission barrier.

2. An appropriate scenario for the investigation of dissipation in fission

An ideal scenario for investigating dissipation in fission is one in which the initial conditions of the fissioning nucleus are well defined and such that the consequent evolution of the system is determined by the dissipation. This would be the case for a heavy nucleus with the following initial conditions:

- high intrinsic excitation energy
- no deformation in fission direction, that is, the fission degree of freedom is not excited
- no angular momentum

Such a nucleus needs some time to deform and to cross the fission barrier. This time is determined by dissipation, that means by the rate with which the energy is transferred between intrinsic and collective degrees of freedom. While the nucleus deforms in fission direction, part of the intrinsic excitation energy is also consumed by particle emission. Consequently, the longer the time to reach the fission barrier, the lower is the probability that the system fissions. It is then clear that in such scenario fission cross sections are closely related to the strength of dissipation.

Grangé and Weidenmüller [1] recalling some old ideas of Kramers [2], developed a diffusion model to describe this scenario in a quantitative way. In their model, 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 Fokker-Planck Equation (FPE) [3,4] in which dissipation effects are included via the dissipation coefficient β which is defined as:

$$\beta = \frac{1}{E_{coll}^{equ} - E_{coll}} \left(\frac{\partial E_{coll}}{\partial t} \right) \tag{1}$$

Where E_{coll} is the intrinsic energy transferred to the collective degree of freedom and $E_{collective}^{equ}$ is the energy of the collective degree of freedom at thermal equilibrium. Grangé and Weidenmüller solved the FPE numerically with a realistic nuclear potential and under the initial conditions listed above. They obtained a time-dependent fission width of the form:

$$\Gamma_f(t) = \Gamma^{BW} \cdot K \cdot f_\beta(t) \tag{2}$$

The first term of equation 2, Γ^{BW} is the time- and dissipation-independent fission width that is obtained by applying the transition-state model of Bohr and Wheeler [5]. The second term K is the Kramers factor:

$$K = \sqrt{1+\left(\frac{\beta}{2\omega_0}\right)^2} - \frac{\beta}{2\omega_0} \qquad (3)$$

where ω_0 describes the potential curvature at the saddle point, and the last term $f_\beta(t)$ is a time-and dissipation-dependent function.

Let us first consider the term Γ^{BW}. According to the transition-state model, the fission decay width is mainly given by the integral of the level density above the fission barrier (at the saddle point deformation), and the decay width for neutron evaporation is given by the integral of the level density over the ground-state deformation of the daughter nucleus. There are two key parameters that have to be defined a priori if this model is applied: the fission barrier, B_f, and the ratio of the level density parameters, a_f/a_n. Different reliable theoretical estimations of both parameters have been developed, for example, for B_f the calculations done in [6] and for a_f/a_n the formulation of reference [7]. In reference [7], the mass and deformation dependence of the level density leads to a value of a_f/a_n slightly larger than 1.

The two last terms of equation (2) reflect, how dissipation delays and hinders the fission process. These effects can be seen in figure 1, where the time dependence of the fission decay width obtained by solving the FPE when the nucleus potential is approximated by a parabola [8] that is truncated at the fission barrier is shown. This is in fact not a very realistic picture of the potential but it leads to an analytical solution of the FPE that

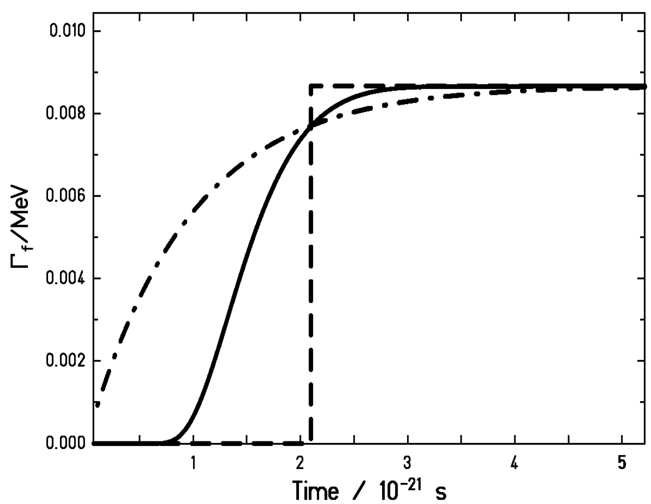

Figure 1: a) Fission decay with as function of time. The full line is the exact solution of the FPE for ^{238}U, T = 2 MeV and $\beta = 2\cdot10^{21}s^{-1}$ with the nucleus potential approximated by a parabola that is truncated at the fission barrier and whose stiffness is determined according to the Liquid-Drop Model [9]. The dashed-dotted line represents an approximation of $\Gamma_f(t)$ by the function $K\cdot\Gamma^{BW}(1-\exp(-2.3\cdot t/\tau_f))$. The dashed line is another approximation based on a step function that jumps to the stationary value $K\cdot\Gamma^{BW}$ at the transient time τ_f.

contains the main features of the numerical solution found by Grangé and Weidenmüller with a more realistic nuclear potential. 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 it reaches 90% of the stationary value given by $K \cdot \Gamma_f^{BW}$. Nevertheless, the inclusion of such description for $\Gamma_f(t)$ in a theoretical code is rather complicated, and most codes contain one of the following approximations:

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

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

Both approximations are also represented in figure 1. The step function underestimates the fission decay width at the beginning of the process while the description a) overestimates it and presents a too steep rise at the initial time. In the next section we compare both descriptions and investigate how the deduced dissipation coefficient depends on the shape of $\Gamma_f(t)$.

3. Experiment

Most of the experimental efforts to determine nuclear dissipation rely on the measurement of pre- and post-scission particle multiplicities and gamma spectra in fusion-fission and fast-fission reactions [10,11,12]. In such scenarios, a composite system with large deformation and high angular momentum is formed after the collision. The evolution of the system until it eventually fissions cannot be described by Grangé and Weidenmüller´s model since the initial composite system is highly deformed, which means that the fission degree of freedom has already some energy. In addition, the high angular momenta introduce further complications. Therefore, such reactions require sophisticated dynamical models like HICOL [13] to describe the process. Moreover, the inclusion of fluctuations in these models further represents a considerable difficulty.
In the present work we present an experimental approach followed at GSI that overcomes these difficulties. This approach is based on the study of fission induced by very peripheral heavy-ion collisions at relativistic energies. A schematic picture of the reaction can be seen in figure 2.

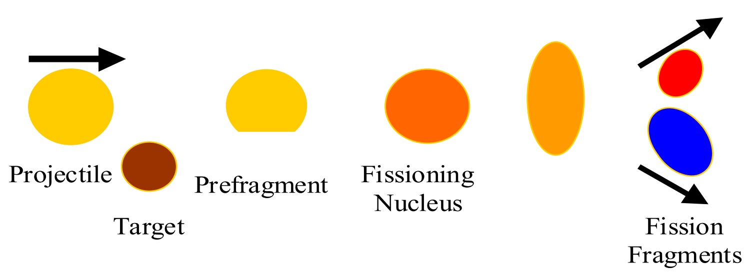

Figure 2: Reaction mechanism for the production of fissioning nuclei based on very peripheral heavy-ion collisions at relativistic energies.

In the interaction of the projectile with the target, a certain number of nucleons are removed, inducing an intrinsic excitation in the fragmented projectile. For large impact parameters heavy prefragments produced might also decay by fission. In the reaction of one kind of beam with the target, an interval of large impact parameters is possible and hence a whole bunch of different fissioning systems are produced by an abrasion-type reaction [14]. Because of the high energy involved in the reaction, these fissioning nuclei have small shape distortions, low angular momentum ($\Delta L<20\hbar$) [15] and high intrinsic excitation energies of several hundreds of MeV [16]. Such initial conditions allow the application of Grangé and Weidenmüller´s model to describe the evolution of the system.
Furthermore, 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 [17], these nuclei are transmitted to the experimental set-up for fission studies, see figure 3.

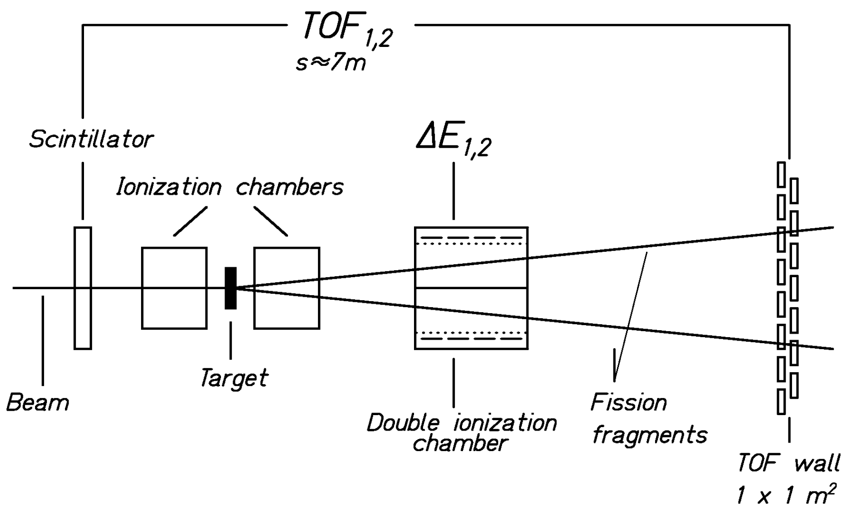

Figure 3: Experimental set-up for fission studies

Fission is 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. Figure 4 shows a scatter plot of the energy loss in the lower ionisation chamber versus the energy loss in the upper ionisation chamber for the reaction ^{238}U primary beam at 1 A GeV in a CH_2 target. The central peak inside the window corresponds to the fission events. In this way, fission events are discriminated against central collisions and random coincidences with beam particles.

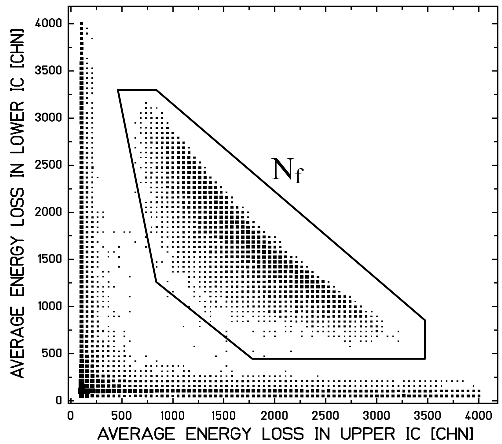

Figure 4: Scatter plot of the energy loss signals in the double IC. The applied condition selects the fission events N_f.

4. Results

The experimental set-up allows the measurement of total fission cross sections and partial fission cross sections, that means, fission cross sections as a function of the sum of the charges of the two fission fragments, Z1 + Z2. These two types of cross sections are used to investigate the influences of the shape of $\Gamma_f(t)$, and, in a preliminary attempt, to determine the dissipation coefficient and additional relevant model parameters like a_f/a_n and B_f.

4.1 Influence of $\Gamma_f(t)$ on the determination of β

Figure 5 shows the nuclear-induced total fission cross sections of Rn, Ra, Th and U isotopes at 420 A MeV in a lead target as a function of the neutron number. The lead target also induces low-energy fission after electromagnetic interaction. These electromagnetic-induced fission events have been disentangled from the nuclear-induced ones as described in ref. [18]. The nuclear-induced cross sections of figure 5 show a soft dependence with the neutron number, varying in a similar way as the fissility parameter: in an isotopic chain the cross sections decrease slowly with increasing neutron number and increase strongly with the atomic number of the projectiles. There are two main effects that lead to the overall smooth dependence of the cross sections with the neutron number. One is the high excitation energy of the fissioning nuclei that attenuates the shell effects and the other is the variety of different nuclei with different fissilities and fission barriers that contributes to each data point. Consequently, each point reflects the average of the structure effects of all the fissioning systems produced in the fragmentation reaction of one type of projectile. The experimental data are compared with several calculations performed with the GSI abrasion-ablation Monte-Carlo code ABRABLA [7,19,20]. We implemented in this code the approximations a) and b) for $\Gamma_f(t)$ [21,22] discussed in section 2. The full line of figure 5 corresponds to a calculation with the description b)

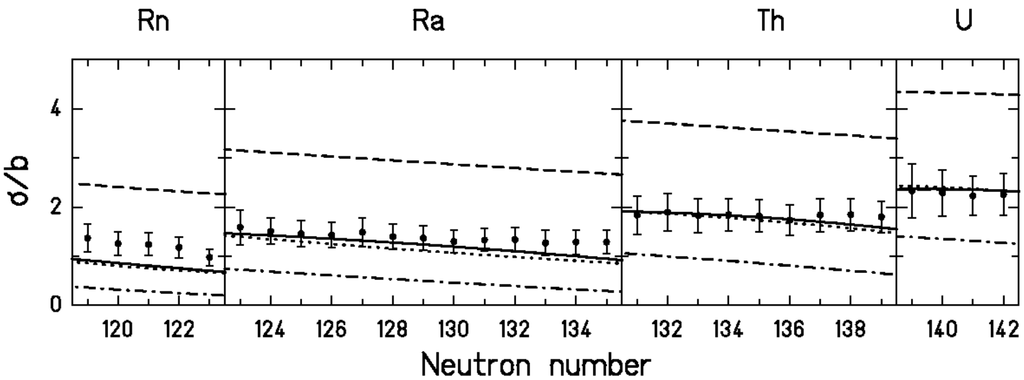

Figure 5: Experimental total nuclear-induced fission cross sections (black dots) as a function of the neutron number for different Rn, Ra, Th and U isotopes impinging on a lead target at 420 A MeV. The data are compared with four calculations with different descriptions of $\Gamma_f(t)$ and values of β. The dashed lines correspond to $\Gamma_f(t) = K\cdot\Gamma^{BW}(1\text{-}\exp(-2.3\cdot t/\tau_f))$ and $\beta = 2\cdot10^{21}s^{-1}$, the full lines to $\Gamma_f(t)$ as a step function and $\beta = 2\cdot10^{21}s^{-1}$, the dotted lines to $\Gamma_f(t) = K\cdot\Gamma^{BW}(1\text{-}\exp(-2.3\cdot t/\tau_f))$ and $\beta = 9\cdot10^{21}s^{-1}$, and the dashed-dotted lines to $\Gamma_f(t)$ as a step function and $\beta = 9\cdot10^{21}s^{-1}$

(step function) and $\beta = 2\cdot10^{21}s^{-1}$. This combination shows a very good agreement with the data. However, the combination $\beta = 2\cdot10^{21}s^{-1}$ and description a) (exponential in-grow) clearly overestimates the cross sections, dashed line in figure 4. The reason is that this description of $\Gamma_f(t)$ allows for fission already at the very beginning of the deexcitation process, see figure 1. Nevertheless, the reproduction of the total fission cross sections with description a) is also possible if we increase the transient time by increasing β up to $9\cdot10^{21}s^{-1}$, this is represented in figure 5 by the dotted line. Finally, the dashed-dotted line shows that the combination $\Gamma_f(t)$ according to b) and $\beta = 9\cdot10^{21}s^{-1}$ underestimates the cross sections because fission has been too long hindered. From this analysis we conclude that the deduced value of the dissipation coefficient β depends strongly on the function we use to describe $\Gamma_f(t)$. Therefore, in order to compare different results for β it is necessary to specify the form that has been used for $\Gamma_f(t)$.
The partial fission cross sections for the reaction of ^{238}U at 1 A GeV on CH_2 are depicted in figure 6, full dots. Since the variable Z1+Z2 essentially represents the charge of the fissioning nucleus, these results show what we have already mentioned above, namely, that in the reaction of one kind of beam with a target a whole set of different fissioning elements from Z = 92 down to approximately Z = 65 are produced. The cross sections decrease with decreasing Z1+Z2 because the fissility decreases with decreasing charge of the fissioning nucleus. These data are compared with the two calculations that reproduced the total fission cross sections of figure 5. In this case, only the combination step-function for describing $\Gamma_f(t)$ and $\beta = 2\cdot10^{21}s^{-1}$ fits the data, while description b) leads to important

deviations from the data. The sensitivity of the experimental data suggests that a realistic treatment of the time dependent fission width $\Gamma_f(t)$ is necessary in order to give a reliable value for the dissipation coefficient β. 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).

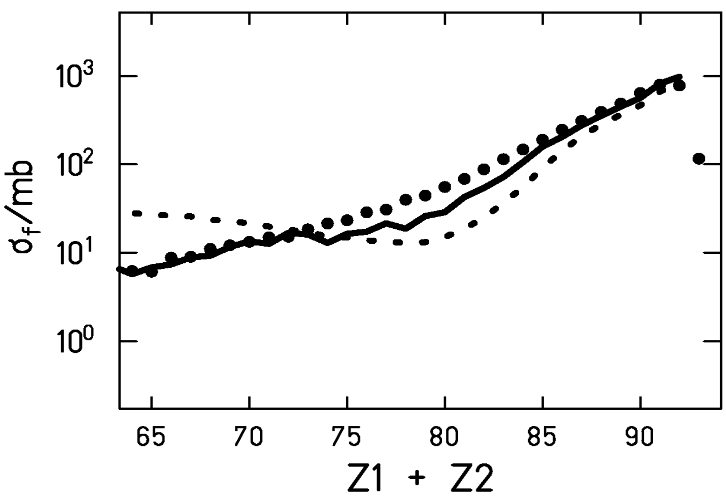

Figure 6: Experimental partial fission cross sections for ^{238}U impinging on CH_2 at 1 A GeV (full dots) in comparison with two calculations. The full line corresponds to a calculation done with $\Gamma_f(t)$ as a step function and $\beta = 2 \cdot 10^{21} s^{-1}$, and the dotted line to a calculation with $\Gamma_f(t) = K \cdot \Gamma^{BW}(1-\exp(-2.3 \cdot t/\tau_f))$ and $\beta = 9 \cdot 10^{21} s^{-1}$

4.2 Preliminary attempt to determine a_f/a_n and B_f

References [6,7] are two examples of elaborated theoretical estimations of B_f and a_f/a_n, respectively. However, the value of a_f/a_n is difficult to determine experimentally, and some theoretical studies predict a dependence of B_f from temperature [23,24]. Even more, the deduced value of the dissipation coefficient β itself depends on the values used for B_f and a_f/a_n. Consequently, it is interesting to investigate if our experimental observables can also be used to determine these other model parameters. We proceeded in the following way: For a given combination of the parameters a_f/a_n and B_f/B_f^{Sierk}, where B_f^{Sierk} are the values of the fission barriers according to reference [6], the value of β is determined so that the total fission cross sections of figure 5 are reproduced. There are a priori certain values of a_f/a_n and B_f that we do not consider: Since all the theoretical predictions point to a reduction of the fission barriers due to temperature, the tentative values of B_f/B_f^{Sierk} should be always smaller than one, and due to the larger deformation at the saddle point a_f/a_n should be always larger than one. There are many different combinations of a_f/a_n, B_f, and β that reproduce the experimental total fission cross sections of figure 5. Five examples of these combinations are listed in table 1. However, only the first of these combinations, the one with a_f/a_n and B_f according to the theoretical predictions and $\beta = 2 \cdot 10^{21} s^{-1}$ reproduces the partial fission cross sections, see figure 7.

a_f/a_n	B_f/B_f^{Sierk}	β
Reference [7]	1	$2 \cdot 10^{21} s^{-1}$
1	0.8	$2 \cdot 10^{21} s^{-1}$
Reference [7]	0.8	$4 \cdot 10^{21} s^{-1}$
1	0.6	$9 \cdot 10^{21} s^{-1}$
1.14	1	$9 \cdot 10^{21} s^{-1}$

Table 1: Examples of different combinations of model parameters that reproduce the total fission cross sections

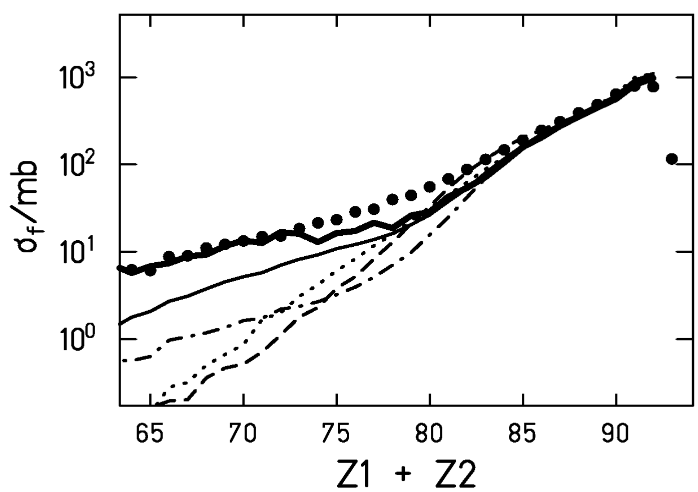

Figure 7: Experimental partial fission cross sections for ^{238}U at 1 A GeV on CH_2 in comparison with the five combinations listed in table 1. The thick full line represents the first combination, the dashed-dotted line the second combination, the thin full line the third, the dashed line the fourth and the dotted line the fifth combination.

All the calculations fit to the experimental data for large values of Z1+Z2 (from Z1+Z2 = 92 to approximately Z1+Z2 = 84), these points correspond to the heaviest fissioning systems which have low excitation energies. For lower values Z1+Z2 the systems acquire more and more excitation energy. At high excitation energies, neutron evaporation is a very fast process, so that large fission delays τ_f will lead to a considerable reduction of the fission cross sections. The solution of the FPE [3] gives a minimum of the transient time $\tau_f \cong 2 \cdot 10^{-21} s$ at $\beta \cong 2 \cdot 10^{21} s^{-1}$. This explains why all the calculations with $\beta > 2 \cdot 10^{21} s^{-1}$ result in too low cross sections for the lightest fissioning elements. In the case of the second combination of table 1, the cross sections are lower than the experimental

values despite the corresponding minimum value for τ_f. This is mainly due to the lower value of $a_f/a_n = 1$ that leads to smaller fission probabilities at high excitation energies.
Figure 8 shows these results schematically. The x-axis represents the values of a_f/a_n and the y-axis the values of B_f/B_f^{Sierk}. The points correspond to the five combinations tested and specified in table 1, and the lines describe all the combinations of the two parameters a_f/a_n and B_f that lead to the same value of β.

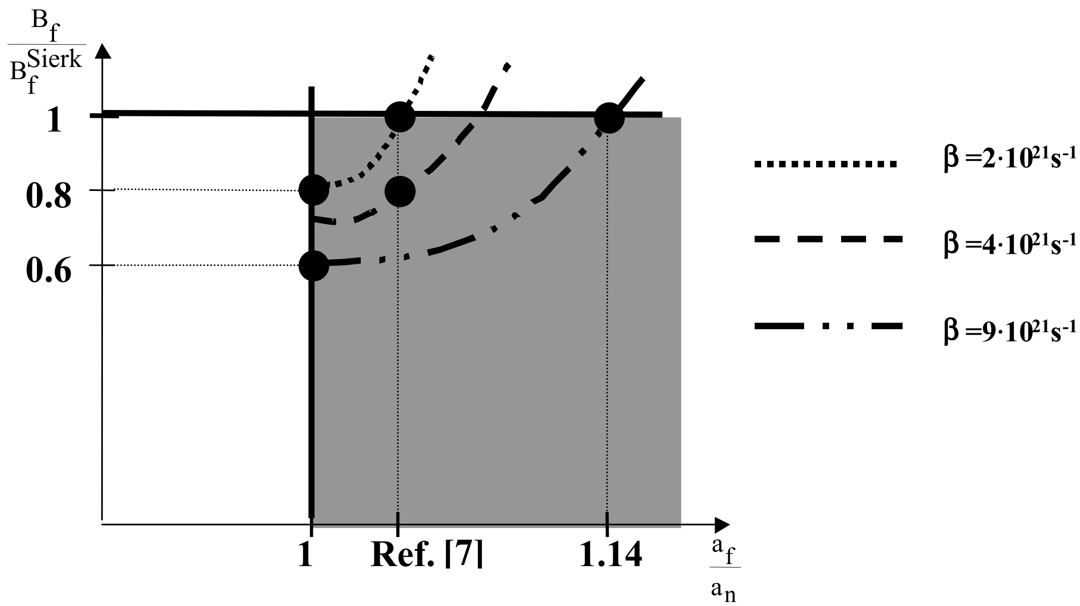

Figure 8: Schematic plot of the possible combinations for the parameters a_f/a_n and B_f/B_f^{Sierk}. The dashed area represents all the combinations that are allowed a priory. The dots represent the combinations listed in table 1 and the curved lines all the combinations of the two parameters that lead to the same value of β

According to our previous arguments, all the combinations outside the $\beta = 2\cdot10^{21}s^{-1}$ line, that is, all the points with lower values of B_f/B_f^{Sierk} and higher values of a_f/a_n than the points lying on the $\beta = 2\cdot10^{21}s^{-1}$ line, and the combinations that are inside it but with $a_f/a_n \cong 1$ will give too low partial fission cross sections for the lightest fissioning elements. Therefore, we conclude that the theoretical expectations for B_f and a_f/a_n given by [6,7] are confirmed.

We would finally like to stress that the values found for B_f, a_f/a_n and β have been determine experimentally without any assumption. This shows the great potentiality of the experimental observables that we have measured. A recent work of K.X. Jing and co-workers [25] based on the measurement of cumulative fission probabilities of neighbouring isotopes has lead to an experimental estimation of the same parameters that is in very good agreement with our results. For the transient time, however, only an upper limit could be determined, because only excitation energies up to 150 MeV were reached. The work we presented here and the one presented in reference [25] are two examples of approaches that are very well suited for the determination of the dissipation coefficient for low deformations, that is, from the ground state up to the saddle point.

Conclusions

A new and very appropriate approach for the investigation of dissipation in fission has been presented. 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, namely high excitation energy, small shape distortion, and low angular momentum, fit to the initial conditions assumed by Grangé and Weidenmüller in their theoretical model. This represents important advantages with respect to the more commonly used approaches, and relevant information on dissipation can be extracted. We have shown that the deduced dissipation coefficient β 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 the essential feature of the solution of the Fokker-Planck equation, namely the practically complete suppression of fission up to the transient time. Our experimental observables are also sensitive to the ratio of the level density parameters, a_f/a_n, and the fission barriers B_f. A preliminary attempt to determine these parameters as well as β has lead to a confirmation of the values of B_f and a_f/a_n predicted by [6] and [7], respectively. For the dissipation coefficient we obtain a value of $\beta = 2\cdot 10^{21}s^{-1}$ that corresponds to a transient time $\tau_f \cong 2\cdot 10^{-21}s$ which is in agreement with some latest works done in this field [25,26].

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