Transient Effects in Fission from New Experimental Signatures

B. Jurado,[1,*] C. Schmitt,[1] K.-H. Schmidt,[1] J. Benlliure,[2] T. Enqvist,[1,†] A. R. Junghans,[3] A. Kelić,[1] and F. Rejmund[1,*]
[1]*GSI, Planckstraße 1, 64291 Darmstadt, Germany*
[2]*Facultad de Fisica, Univ. de Santiago de Compostela, 15706 S. de Compostela, Spain*
[3]*Forschungszentrum Rossendorf, Postfach 510119, 01314 Dresden, Germany*
(Received 14 January 2004; published 12 August 2004)

A new experimental approach is introduced to investigate the relaxation of the nuclear deformation degrees of freedom. Highly excited fissioning systems with compact shapes and low angular momenta are produced in peripheral relativistic heavy-ion collisions. Both fission fragments are identified in atomic number. Fission cross sections and fission-fragment element distributions are determined as a function of the fissioning element. From the comparison of these new observables with a nuclear-reaction code a value for the transient time is deduced.

DOI: 10.1103/PhysRevLett.93.072501 PACS numbers: 24.75.+i, 24.10.–i, 25.70.–z, 25.75.–q

Introduction.—The process of equilibration of a highly excited nucleus in all its degrees of freedom is not yet well understood. A complete dynamical description of the equilibration process in terms of a purely microscopic theory is not possible to the present day due to the large number of degrees of freedom involved. For this reason, most of the current theoretical models are based on transport theories [1] where one distinguishes between collective and intrinsic degrees of freedom. The latter are considered in an average sense as a heat bath. The transfer of excitation energy between collective and intrinsic degrees of freedom is denominated dissipation and quantified by the dissipation strength β.

One of the most intensively investigated nuclear collective motions is the fission process. In the frame of a transport theory, fission is the result of the evolution of the collective fission coordinates under the interaction with the heat bath and an external driving force given by the available phase space. This evolution can be obtained by solving the Langevin equation or its integral form, the Fokker-Planck equation (FPE) [2]. In 1940, Kramers [3] described the nuclear fission process within a transport theory and derived the *stationary* solution of the corresponding FPE. Later, by solving numerically the *time-dependent* FPE, Grangé *et al.* [4] investigated the transient effects that arise from the relaxation of the collective degrees of freedom. Their results showed that it takes a so-called transient time τ_{trans}, until the fission-decay width reaches 90% of its stationary value.

The most frequently applied tools to measure nuclear times are the neutron clock [5] and the gamma clock [6]. They have yielded the majority of the available information on the time a nuclear system needs to cross the scission point. However, the mean scission time τ_{scission} is an integral value, including the transient time, the inverse of the stationary decay rate, and an additional dynamic saddle-to-scission time. Thus, τ_{scission} does not give direct access to the transient time τ_{trans} that is exclusively connected to the equilibration process of the compound nucleus in deformation space. Total fission or evaporation-residue cross sections have also been used to investigate dissipation at low deformation, but, as we will show later, they are not sufficient to determine transient effects in an unambiguous way. Besides, the experimental manifestation of transient effects is subject of controversy nowadays [7]. To clarify the situation, we emphasize that the observation of transient effects requires a reaction mechanism that forms excited nuclei with an initial population in deformation space far from equilibrium and an experimental signature that is specifically sensitive to the delayed population of transition states.

In the present work, highly excited fissioning systems with compact shapes and low angular momenta were produced in peripheral relativistic heavy-ion collisions. Using inverse kinematics, both fission fragments were identified in atomic number, enabling the measurement of fission cross sections and fission-fragment element distributions as a function of the fissioning element. In this way, we introduce two new experimental signatures that are selectively sensitive to transient effects. They are exploited to deduce a quantitative value for the transient time τ_{trans} from a comparison with a nuclear-reaction code where dissipation effects in fission are modeled in a realistic way. The new approach should help solving the questions on the strength of β and its variation with deformation [8–12] and temperature [9,13–15], which are intensively discussed.

Experiment.—In very peripheral collisions of relativistic ^{238}U ions, delivered by the SIS18 heavy-ion accelerator of GSI, with a lead target and a $(CH_2)_n$ target, fissile nuclei were produced with high excitation energy and small deformation. This reaction mechanism induces only a small angular momentum $<20\hbar$ [16], which avoids additional complications in describing the process. The experimental setup, especially conceived for fission studies in inverse kinematics [17], is schematically illustrated in Fig. 1. When the projectile fragment fissions, the two fission fragments are emitted in forward direction and

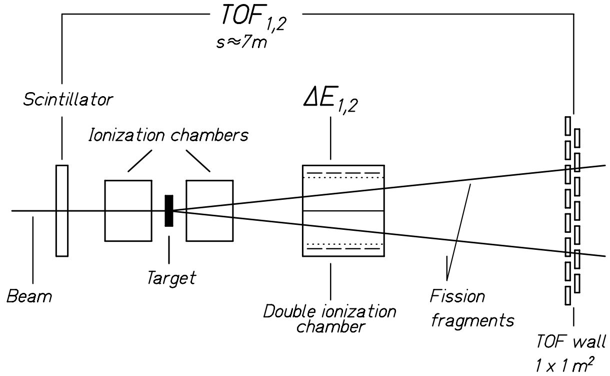

FIG. 1. Experimental setup for fission studies in inverse kinematics with a 1 A GeV ^{238}U primary beam.

detected simultaneously in a double ionization chamber that delivers a very accurate measurement of their nuclear charges.

The charge identification of both fission fragments enabled us selecting the fission events according to the excitation energy induced in the nuclear collision. The sum of the nuclear charges of the fission fragments $Z_1 + Z_2$ is a very significative quantity, being essentially identical to the charge of the fissioning nucleus. Indeed, dynamical calculations performed with the Langevin Monte Carlo code of [18] show that charged-particle emission between saddle and scission is negligible for the systems investigated here. Calculations with the ABRABLA code [19,20] revealed that evaporation of charged particles from the fission fragments is a very rare process as well. Moreover, the charge of the fissioning system is strongly correlated to the charge of the projectile fragment and hence, it gives a measure of the centrality of the collision. Consequently, lower values of $Z_1 + Z_2$ imply smaller impact parameters and higher excitation energies induced by the fragmentation process.

The first signature we exploited to measure $\tau_{\rm trans}$ is given by the partial fission cross sections, i.e., the fission cross sections as a function of $Z_1 + Z_2$. At high excitation energies, particle decay times become smaller than $\tau_{\rm trans}$, and the nucleus can emit particles while fission is suppressed. Therefore, for the lightest fissioning nuclei (lowest values of $Z_1 + Z_2$) transient effects will lead to a considerable reduction of the fission probability. The second signature is based on the element distribution of the fission fragments that result from a given fissioning element. According to empirical systematics [21], the variance σ_A^2 of the mass distribution of the fission fragments is a measure of the saddle-point temperature $T_{\rm saddle}$. Although this systematics has been established on the basis of experimental data for moderate excitation energies, experimental results from heavy-ion induced fission [22] as well as recently performed two-dimensional Langevin calculations [23] indicate that the linear correlation between σ_A^2 and $T_{\rm saddle}$ remains valid at higher excitation energies. Because of the strong correlation between the mass distribution and the charge distribution of the fission fragments, a linear relation also holds for the variance of the element distribution σ_Z^2 and $T_{\rm saddle}$. For the lower values of $Z_1 + Z_2$, transient effects will reduce the temperature of the system at saddle, and, consequently, they will decrease the width of the corresponding element distributions [24].

Results.—To deduce quantitative results on transient effects, the experimental observables need to be compared with a nuclear-reaction code. The code we use is an extended version of the abrasion-ablation Monte Carlo code ABRABLA [19,20]. It describes the nuclear reaction in three stages: In the first stage, the characteristics of the projectile residue after the fragmentation are described in ABRA according to the abrasion model. The second stage accounts for the simultaneous emission of nucleons and clusters (simultaneous breakup) that takes place due to thermal instabilities when the temperature of the projectile spectator exceeds some 5.5 MeV [25]. After abrasion or eventually the consecutive breakup, the ablation code ABLA models the deexcitation of the system through an evaporation cascade. The relaxation process of the compound nucleus in deformation space was considered by introducing a *time-dependent* fission-decay-width $\Gamma_f(t)$. For this purpose we have implemented in the third stage of ABRABLA a description of $\Gamma_f(t)$ that is based on an approximate solution of the FPE [26,27]. In Table I, the measured total nuclear fission cross section in the reaction ^{238}U + Pb at 1 A GeV is compared with the values obtained from ABRABLA calculations performed with three different treatments of the fission-decay width. The total nuclear fission cross section has been obtained subtracting the electromagnetic contribution given by Rubehn *et al.* [28] from the experimental total fission cross section. Apart from the new analytical description of [26], Table I includes the predictions of two other expressions for the fission-decay width that do not consider any transient effect. In one calculation, we applied the Bohr-Wheeler transition-state model [29], and in the other we used Kramers's solution Γ_K for the stationary fission-decay width. The calculation with the transition-state model overestimates the cross section. With Kramers's stationary decay width, the total fission cross section can be reproduced, although a considerably higher

TABLE I. Total nuclear fission cross section of ^{238}U(1 A GeV) on Pb in comparison with different model calculations.

Experiment	$\sigma_f^{\rm nucl} = (2.16 \pm 0.14)\ b$
Bohr-Wheeler	$\sigma_f^{\rm nucl} = 3.33\ b$
Γ_K, $\beta = 2 \times 10^{21}$ s^{-1}	$\sigma_f^{\rm nucl} = 3.07\ b$
Γ_K, $\beta = 6 \times 10^{21}$ s^{-1}	$\sigma_f^{\rm nucl} = 2.19\ b$
$\Gamma_f(t)$ Ref. [26], $\beta = 2 \times 10^{21}$ s^{-1}	$\sigma_f^{\rm nucl} = 2.09\ b$
$\Gamma_f(t)$ Ref. [26], $\beta = 6 \times 10^{21}$ s^{-1}	$\sigma_f^{\rm nucl} = 1.48\ b$

value of the dissipation coefficient, $\beta = 6 \times 10^{21}\ \mathrm{s}^{-1}$, is needed than in the dynamical calculation where $\beta = 2 \times 10^{21}\ \mathrm{s}^{-1}$ is sufficient to reproduce the data. Actually, the dynamical calculation reproduces the experimental value rather well with a dissipation strength in the range $\beta \sim 1 - 3 \times 10^{21}\ \mathrm{s}^{-1}$ due to the smooth variation of the transient time with β in the critically damped region around $2 \times 10^{21}\ \mathrm{s}^{-1}$ [30]. Nonetheless, the last line of Table I shows that a strength as high as the one necessary to reproduce the data with Γ_K is excluded. The results of Table I demonstrate that total fission cross sections allow identifying an overall reduction of the fission probability. However, they do not allow discriminating between a stationary description of fission and a time-dependent approach including transient effects.

Figure 2 represents the partial fission cross sections [Fig. 2(a)] and the standard deviations of the element distributions [Fig. 2(b)] measured in the reaction of $^{238}U + (CH_2)_n$ as a function of the sum of the nuclear charges $Z_1 + Z_2$ of two fission fragments. The experimental data are compared with calculations using the same descriptions for the fission-decay width as in Table I. In addition, several calculations have been performed that include transient effects according to the time-dependent fission width of [26] with different values of β.

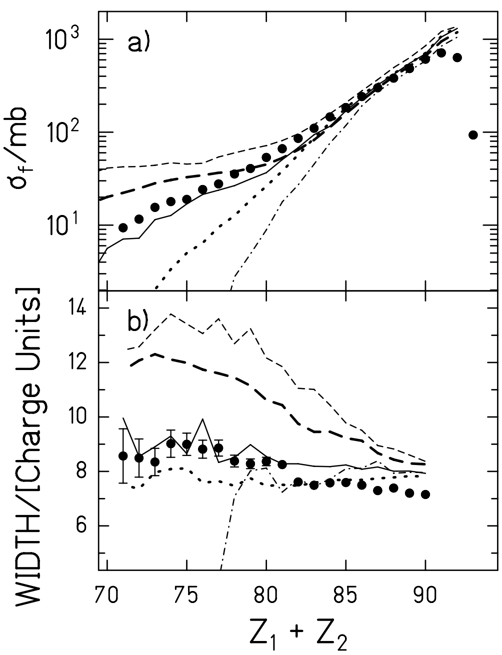

FIG. 2. (a) Partial fission cross sections and (b) partial widths of the fission-fragment element distributions for the reaction of $^{238}U(1\ A\ \mathrm{GeV})$ on $(CH_2)_n$ in comparison with several calculations. The thin dashed and the thick dashed lines are obtained by applying the Bohr-Wheeler transition-state model and Kramers's stationary solution with $\beta = 6 \times 10^{21}\ \mathrm{s}^{-1}$, respectively. The solid, the dotted, and the dashed-dotted lines show calculations using the $\Gamma_f(t)$ function of Ref. [26] with $\beta = 2 \times 10^{21}\ \mathrm{s}^{-1}$, $0.5 \times 10^{21}\ \mathrm{s}^{-1}$, and $5 \times 10^{21}\ \mathrm{s}^{-1}$, respectively. The staggering in these curves and the strong decrease of the dashed-dotted curve below $Z_1 + Z_2 = 78$ are due to statistical fluctuations of the Monte Carlo calculations.

As expected, the Bohr-Wheeler transition-state model overestimates both observables, confirming their sensitivity to dissipation. The calculation performed with the constant decay width of Kramers overestimates the observables as well. This demonstrates that these new observables are clearly sensitive to transient effects. In particular, the rather fast decrease of the partial fission cross section for the lowest values of $Z_1 + Z_2$ and the weak increase of the width of the element distribution with decreasing value of $Z_1 + Z_2$ directly prove the suppression of fission at high excitation energies. For both observables, the best description is obtained with the approximation of [26] and $\beta = 2 \times 10^{21}\ \mathrm{s}^{-1}$ (solid line) corresponding to critical damping [30] and thus to the shortest transient time $\tau_{\mathrm{trans}} \approx (1.7 \pm 0.4) \times 10^{-21}$ s. The full data can be described with a constant value of β over the whole range of $Z_1 + Z_2$. Thus, we do not find any indication for a temperature dependence of the dissipation strength. In all calculations shown in Figs. 2 and 3, the contribution from the hydrogen part of the $(CH_2)_n$ target has been determined with CASCABLA, previously used in Ref. [31]. CASCABLA is a fast simplified version of the intranuclear cascade code INCL3 [32] coupled to the break-up stage and the ablation stage of ABRABLA. For $Z_1 + Z_2 < 84$, fission events from carbon-induced reactions prevail.

Fission after charge pickup at $Z_1 + Z_2 = 93$ is not treated in ABRABLA, and therefore does not appear in the model calculations. Moreover, the model does not consider the multihumped structure of the fission barrier for the actinides. This might explain why the data at $Z_1 + Z_2 = 91$ and 92 are overestimated. However, this disagreement does not affect the conclusions drawn in the present work as transient effects manifest only at lower values of $Z_1 + Z_2$.

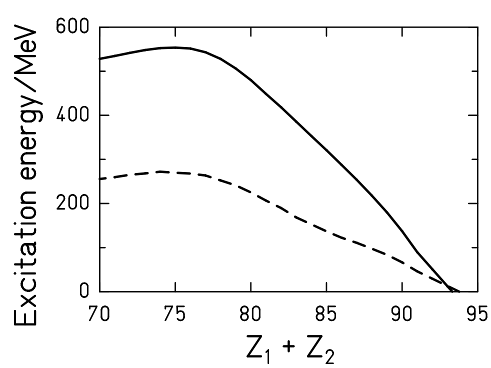

FIG. 3. Calculated mean excitation energies of the prefragment right before entering the ablation stage (solid line) and at the fission barrier (dashed line) for the reaction $^{238}U(1\ A\ \mathrm{GeV})$ on $(CH_2)_n$ as a function of $Z_1 + Z_2$. The dashed line has been obtained using the description of Ref. [26] with $\beta = 2 \times 10^{21}\ \mathrm{s}^{-1}$.

Figure 3 shows the mean excitation energy of the prefragments right before entering the ablation stage and at the fission barrier as a function of $Z_1 + Z_2$ as calculated by ABRABLA and CASCABLA. Up to $Z_1 + Z_2 \approx 76$ the excitation energy increases with decreasing $Z_1 + Z_2$ and then it decreases gradually. The reason for this decrease is that the projectile fragments undergo a simultaneous breakup, setting a limit of 5.5 MeV to the temperature with which the fragments enter the ablation stage. The influence of the breakup on the fission process is thoroughly discussed in [33]. From Fig. 3 we deduce that, although the initial excitation energies can be as high as 550 MeV, transient effects suppress fission above 300 MeV.

Conclusion.—We studied projectile-fragmentation–fission reactions and introduced two new experimental signatures, the partial fission cross sections and the partial widths of the fission-fragment element distributions, to observe transient effects in fission. These observables exploit the influence of the excitation energy on the fission probability and on fluctuations of the mass-asymmetry degree of freedom. We have interpreted the data with a nuclear-reaction code that includes a time-dependent treatment of the deexcitation process. The treatment is based on an analytical approximation to the fission-decay width that results from the solution of the Fokker-Planck equation. The comparison of the experimental observables with model calculations indicates that, for the range of excitation energies considered, the collective nuclear motion up to the saddle point is critically damped.

These new signatures have opened a new road to answer still open questions on the dissipation strength and its variation with deformation and temperature. In the near future, we plan to extend these investigations to projectiles between uranium and lead in order to separately vary fissility and induced energy by using secondary beams, presently available at GSI. Further progress in this field is expected when advanced installations, e.g., in the planned FAIR or RIA future projects, will become available. They will allow to extend the isospin range of secondary beams and to add new capabilities for mass identification and light-particle detection, aiming for kinematically complete experiments with a measure of excitation energy in individual events.

We thank David Boilley and Anatoly Ignatyuk for fruitful discussions. This work has been supported by the European Union in the frame of the HINDAS project under Contract No. FIKW-CT-2000-0031 and by the Spanish MCyT under Contract No. FPA2002-04181-C04-01. One of us (C. S.) is thankful for support by the Humboldt Foundation. The work profited from a collaboration meeting on "Fission at Finite Thermal Excitations," sponsored by the ECT* ("STATE" Contract).

*Present address: GANIL, Blvd. H. Becquerel, B.P. 5027, 14076 Caen, France.

†Present address: CUPP project, P.O. Box 22, 86801 Pyhäsalmi, Finland.

[1] H. A. Weidenmüller, Prog. Part. Nucl. Phys. **3**, 49 (1980).
[2] H. Risken, *The Fokker-Planck Equation* (Springer, Berlin, 1989).
[3] H. A. Kramers, Physica (Amsterdam) **7**, 284 (1940).
[4] P. Grangé, *et al.*, Phys. Rev. C **27**, 2063 (1983).
[5] D. Hilscher and H. Rossner, Ann. Phys. (Paris) **17**, 471 (1992).
[6] P. Paul and M. Thoennessen, Annu. Rev. Nucl. Part. Sci. **44**, 65 (1994).
[7] H. Hofmann and F. A. Ivanyuk, Phys. Rev. Lett. **90**, 132701 (2003); K.-H. Schmidt *et al.*, nucl-th/0307097.
[8] P. Fröbrich and I. I. Gontchar, Phys. Rep. **292**, 131 (1988).
[9] S. Yamaji, F. A. Ivanyuk, and H. Hofmann, Nucl. Phys. **A612**, 1 (1997).
[10] I. Dioszegi *et al.*, Phys. Rev. C **63**, 014611 (2001).
[11] N. P. Shaw *et al.*, Phys. Rev. C **61**, 044612 (2000).
[12] G. Chaudhuri and S. Pal, Eur. Phys. J. A **18**, 9 (2003).
[13] V. A. Rubchenya *et al.*, Phys. Rev. C **58**, 1587 (1998).
[14] D. J. Hofman, B. B. Back, and P. Paul, Phys. Rev. C **51**, 2597 (1995).
[15] G. A. Souliotis *et al.*, Phys. Rev. C **57**, 3129 (1998).
[16] M. de Jong, A.V. Ignatyuk, and K.-H. Schmidt, Nucl. Phys. **A613**, 435 (1997).
[17] K.-H. Schmidt *et al.*, Nucl. Phys. **A665**, 221 (2000).
[18] K. Pomorski, J. Bartel, J. Richert, and K. Dietrich, Nucl. Phys. **A605**, 87 (1996).
[19] J.-J. Gaimard and K.-H. Schmidt, Nucl. Phys. **A531**, 709 (1991).
[20] A. R. Junghans *et al.*, Nucl. Phys. **A629**, 635 (1998).
[21] S. I. Mulgin, K.-H. Schmidt, A. Grewe, and S.V. Zhdanov, Nucl. Phys. **A640**, 375 (1998).
[22] M. G. Itkis and A. Yu. Rusanov, Phys. Part. Nuclei **29**, 160 (1998).
[23] D.V. Vanin, G. I. Kosenko, and G. D. Adeev, Phys. Rev. C **59**, 2114 (1999).
[24] J. Benlliure *et al.*, Nucl. Phys. **A700**, 469 (2002).
[25] K.-H. Schmidt *et al.*, Nucl. Phys. **A710**, 157 (2002).
[26] B. Jurado, K.-H. Schmidt, and J. Benlliure, Phys. Lett. B **553**, 186 (2003).
[27] The validity of the approximation of Ref. [26] over a wide range of dissipation strength and temperature has been meticulously investigated and confirmed in B. Jurado *et al.*, nucl-ex/0302003 [Nucl. Phys. A (to be published)]. This study clearly demonstrates that the doubts emitted in H. Hofmann, Phys. Lett. B **567**, 189 (2003) are founded on a severe misunderstanding of the approach and therefore not relevant.
[28] Th. Rubehn *et al.*, Phys. Rev. C **53**, 3143 (1996).
[29] N. Bohr and J. A. Wheeler, Phys. Rev. **56**, 426 (1939).
[30] K.-H. Bhatt, P. Grangé, and B. Hiller, Phys. Rev. C **33**, 954 (1986).
[31] T. Enqvist, *et al.*, Nucl. Phys. **A686**, 481 (2001).
[32] J. Cugnon, *et al.*, Nucl. Phys. **A620**, 475 (1997).
[33] B. Jurado *et al.*, nucl-ex/0403004.