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Transient effects in fission investigated with proton-on-lead reactions in complete kinematic measurements

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Abstract

Proton-induced fission of ^{208}Pb has been investigated at 370, 500 and 650 *A* MeV in complete kinematic measurements. The experiment was performed at GSI Darmstadt where the combined use of the inverse kinematics technique with an efficient detection setup allowed to measure for the first time the atomic and mass number of both fission fragments. The performed measurement together with different model calculations allow us to investigate dissipative and transient effects in the fission process and the dependence on temperature and deformation of the dissipation strength β. The use of spallation reactions with lead projectiles favours this study due to its high excitation energy and low angular momentum.

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Keywords: Spallation reactions; Fission dynamics; Transient time; Neutron excess

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1. Introduction

More than 75 years ago, Otto Hahn and Fritz Stressmann discovered nuclear fission. Since then, considerable experimental and theoretical works have been undertaken on this process. A few months after the discovery of fission, Bohr and Wheeler derived a relationship for the fission width dependence on the excitation energy from simple statistical assumptions. However, the theory of Bohr and Wheeler did not allow to explain the high neutron multiplicities observed in recent experiments (Hinde et al. (1992)). Therefore, a dynamical description of the fission process seems more apropiate (Fröbrich et al. (1993)).

The description of fission as a dynamical process was already proposed by Kramers (Kramers (1940)), who introduced into fission process the concept of dissipation which represents the transformation of intrinsic energy into collective motion and is quantified by the dissipation strength β. Dissipative effects were clearly obserbed from pre- and post-scission neutron multiplicities (Hilsher and Rossner (1992)), γ ray (Hofman (1994)) and charged particles (Lestone (1993)). Recently, it has also been stablished that dissipative effects can explain fusion-fission cross sections at low excitation energies (Lestone and McCalla (2009)).

Unfortunately, Kramers' picture of fission fails at high excitation energies (Jurado et al. (2005)) where nuclei need a certain time (transient time or delay time) to explore the potential-energy landscape. Therefore, the stationary fission width is suppressed at shorter times (Grangé et al. (1983)) requiring a certain transient time to establish a quasi-stationary flux over the fission barrier. Transient time effects have recently been investigated within fission cross sections of spallation reactions (Jurado et al. (2003); Benlliure et al. (2006); Ayyad et al. (2014)). These works have shown evidences of transient effects at high excitation energies of proton- and deuterium-induced fission from subactinides to actinides.

However, after these important theoretical efforts, the nature and magnitude of nuclear dissipation and its dependence on temperature and deformation are still under debate (Lestone and McCalla (2009); Fröbrich and Gontchar (1998); Dioszegi et al. (2001); Jurado et al. (2004)). Moreover, the estimated values of β fluctuate between 2 and 30 $\times 10^{21}$ s^{-1}, depending on the experimental observable.

In this context, new experimental setups (Schmidt et al. (2000); Boutoux et al. (2013)) have been developed to obtain new observables to shed light on dynamical effects. From the first experiment (Schmidt et al. (2000)), new observables, such as the partial fission cross sections and the width of the charge distributions of the fission fragments as a function of the atomic number of the fissioning system, were investigated (Jurado et al. (2004); Schmitt et al. (2007)). These works concluded that the dissipation strength does not depend on the temperature. This same conclusion was recently obtained for proton-induced fission of ^{181}Ta (Ayyad et al. (2014)) with a dissipation parameter of 4.5×10^{21} s^{-1}.

In the present work, highly excited fissioning systems with compact shapes and low angular momentum are produced in spallation reactions. Using inverse kinematics, both fission fragments are identified for the first time in atomic and mass number. Concerning to the dynamical effects, we investigate previous observables such as the fission cross sections to obtain information about the value of the dissipation strength and its dependence on temperature. Moreover, we introduce a new experimental observable, the neutron excess, that seems to be sensitive to the dissipation beyond the saddle point. It is exploited to deduce a quantitative value for the dissipation strength from the saddle to the scission point. The new observable should help solving the questions on the dissipation strength beyond the saddle point and its variation with deformation.

2. Experiment

The experiment was performed at the GSI facilities in Darmstadt (Germany), where the SIS18 synchrotron was able to accelerate beams of ^{208}Pb at 370, 500 and 650 A MeV with an intensity around 10^5 ions/s. The reactions were produced in a cylindrical target filled with liquid-hydrogen (85 mg/cm^2). The use of the inverse kinematics technique facilitates the detection of both fission fragments because these ones leave the target with high kinetic energy, covering a narrow angular range in the forward direction. To register and identify both fission fragments an advanced detection setup (Rodríguez-Sánchez et al. (2013); Pellereau et al. (2013)) was mounted behind the target covering the complete angular range of the two fragments. This setup, together with a high precision tracking of trajectories, permits us to separate fission from other reaction channels and identify in atomic and mass number both fragments.

The experimental setup is divided in two parts, one to characterize the beam and another one to determine the fission events. The first part consists of a plastic scintillator detector (Start), an ionization chamber and a time projection chamber. These last two detectors provide the beam identification and its position on the target, respectively.

The second part consists of a double ionization chamber (Twin MUSIC), two Multi-Wire Proportional Counters (MWPCs), A Large Acceptance DIpole magNet (ALADIN) and a Time-of-Flight Wall (ToF Wall). The Twin MUSIC has a central cathode that divides its volumen into two active parts. This detector provides ten energy loss and drift time measurements which allow us to obtain the atomic number of both fragments with a resolution below 0.45 units (FWHM) and their polar angles with a resolution below 0.5 mrad (FWHM). MWPCs, situated upstream and downstream the ALADIN magnet, provide the horizontal (X) and vertical (Y) positions of the fission fragments with a resolution below 300 μm and 3 mm (FWHM), respectively. Finally, the ToF Wall of 28 plastic scintillators allows us to measure the ToF of the fission fragments with a resolution around 40 ps (FWHM).

A complete kinematic measurement was achieved by adding two detectors for light particles. The first one was placed in front of the Twin MUSIC, which was used to measure the light charged particles, while the second one was placed behind the ALADIN magnet to measure the neutron multiplicities.

Full identification of fission fragments is made using a ray-tracing method coupled to GEANT4 simulations. The measured ToF together with the flight path reconstructed by tracking are used to deduce the velocity of the fragments. The x positions from the MWPCs and the angles from the Twin MUSIC give access to the curvatures of the trajectories, which provide the magnetic rigidity of the fragments taking into account the value of the magnetic field. The complete identification of fission fragments is performed by determining their mass numbers (A), which are deduced for each fission fragment from the magnetic rigidity, velocity and atomic number, according to the equation:

$$A = \frac{eZ}{u}\frac{B\rho}{\beta\gamma c} \qquad (1)$$

where Z is the atomic number provided by the Twin MUSIC, B is the magnetic field inside the magnet, ρ is the radius of the trajectory, u is the atomic mass unit, e is the electron charge, $\gamma = 1/\sqrt{1 - v^2/c^2}$, v is the velocity of the ion and c is the velocity of light.

Fig. 1 shows the identification of fission fragments of ^{208}Pb+p at 500 A MeV. In Fig. 1(a) we represent the mass over atomic-number spectrum for a atomic number Z = 40. This spectrum was calibrated with a previous measurement (Fernández-Domínguez et al. (2005)) from FRS, achieving a mass resolution around 0.63 units (FWHM) for mass number A = 93 and atomic-number resolutions below 0.45 units (FWHM). Finally, Fig. 1(b) shows a complete identification in mass and atomic number between Z = 35 and Z = 45.

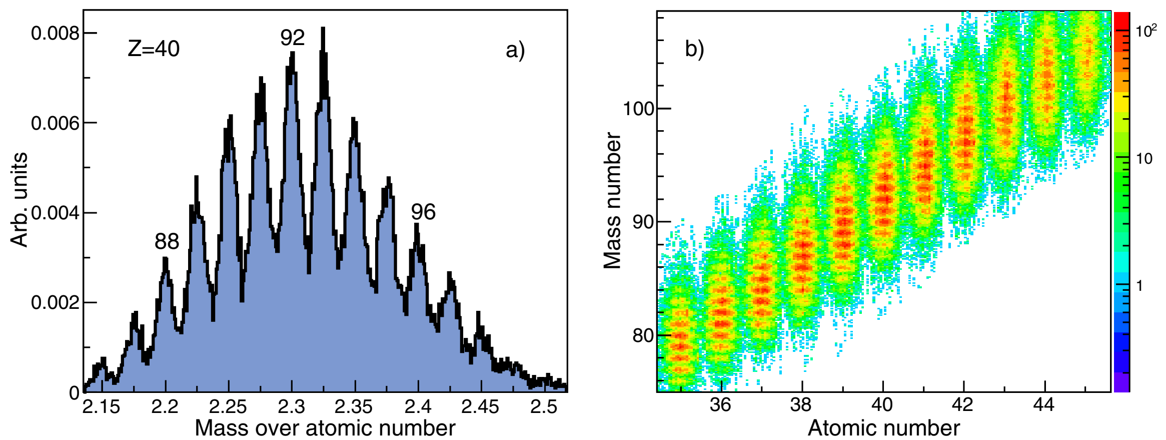

Fig. 1. (Color online) Identification in atomic and mass number of fission fragments of ^{208}Pb+p at 500 A MeV. (a) Mass over atomic number for fission fragments with Z = 40. The numbers over the peaks mean the mass number. (b) Complete identification of fission fragments.

3. Results

3.1. Transient effects from fission cross sections

For the investigation of transient effects we have coupled two reaction codes. The Liège intra-nuclear cascade code INCL4.6 (Boudard et al. (2013)), which describes the fast interaction between the proton and the lead target as a series of nucleon-nucleon collisions leading to an excited remnant, is coupled to the statistical evaporation code ABLA07 (Kelić-Heil et al. (2008)). In this code, dissipative and transient effects in fission are described by using an analytical description of the time-dependent fission width as obtained from a Fokker-Planck equation describing the diffusion across the fission barrier.

In Fig. 2 we present different calculations compared with the cross sections measured for proton-induced fission of ^{208}Pb (Fig. 2(a)) and ^{209}Bi (Fig. 2(b)). The dot-dashed lines represent the result of a calculation taking into account dissipative effects with a value of the reduced dissipation parameter $\beta = 4.5 \times 10^{21}$ s^{-1}, but not considering transient effects. These calculations correspond to the description of the fission process proposed by Kramers (Kramers (1940)). As can be seen in the figures, these calculations clearly overestimate the fission cross sections at high proton energies. However, the calculations describe rather well the cross sections for proton energies below 200 MeV in both cases. This result is in agreement with other works (Lestone and McCalla (2009); Ayyad et al. (2014)), where the authors did not observe transient time effects for excitation energies below 100 - 150 MeV.

In the same figure, the solid lines correspond to calculations considering a time-dependent fission width using the same value for the reduced dissipation parameter ($\beta = 4.5 \times 10^{21}$ s^{-1}). As can be seen, these calculations nicely describe the complete excitation function of fission cross sections. The comparison with the calculations without transient effects would indicate that these effects appear at proton energies above 200 MeV, which corresponds to a mean excitation energy of 110 MeV.

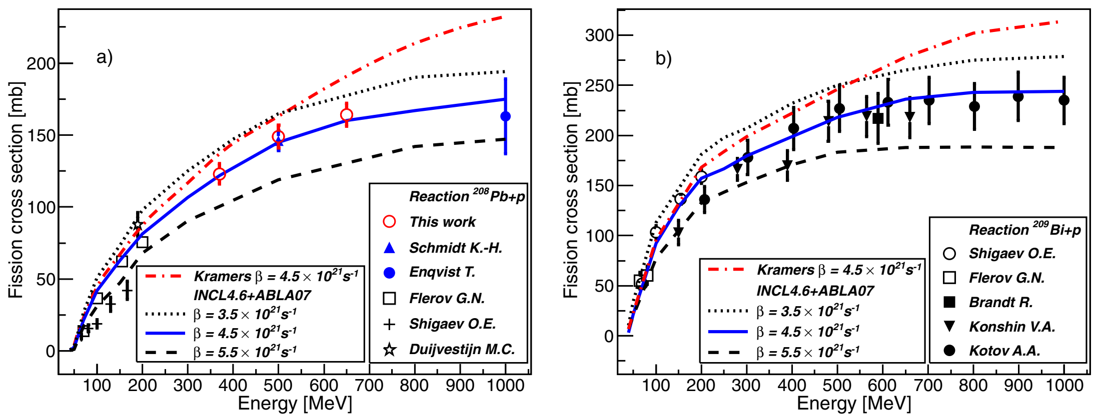

Fig. 2. (Color online) Dissipative and transient effects observed in fission cross sections. Different data in comparison to the dynamical description based on time-independent fission width given by Kramers (dot-dashed lines) and to calculations using INCL4.6+ABLA07 for different values of the reduced dissipation parameter β. (a) Proton-induced fission cross sections of ^{208}Pb obtained in this work (open circles) in comparison to other data (Rodríguez-Sánchez et al. (2013)). (b) Proton-induced fission cross sections of ^{209}Bi (Kotov et al. (2006); Shigaev et al. (1973); Konshin et al. (1966); Flerov et al. (1972); Brandt et al. (1972)).

The dotted and dashed lines in Fig. 2 represent similar calculations but with different values of the reduced dissipation parameter, $\beta = 3.5 \times 10^{21}$ s^{-1} and $\beta = 5.5 \times 10^{21}$ s^{-1} respectively. These additional calculations are used to illustrate that all cross sections of proton-induced fission of ^{208}Pb and ^{209}Bi can be described with the same value of the reduced dissipation parameter. Therefore, we do not obserbe any evidence for a temperature dependence of the dissipation strength. Moreover, the calculations for proton-induced fission of ^{209}Bi allow us to validate our parameters.

Our results for the onset of transient effects at excitation energies above 110 MeV and the temperature independence of the dissipation strength coincide with the ones obtained in other works (Lestone and McCalla (2009); Grangé et al. (1983); Ayyad et al. (2014); Schmitt et al. (2007)).

3.2. Dissipative effects from neutron excess

Another fundamental question about the dissipation parameter is the dependence on deformation, which has been investigated in other works (Fröbrich and Gontchar (1998); Dioszegi et al. (2001)). This dependence is related with the fission dynamics beyond the saddle point, where it is very known that the compound fissioning system needs certain time to evolve from the saddle to the scission point. During this time, fissioning nuclei have the posibility of evaporating neutrons.

This time was firstly calculated by H. Hofmann (Hofmann and Nix (1983)), who obtained an analytical solution based on the dynamical picture of Kramers. Following their solution, the saddle-to-scission time (τ_{ssc}) can be calculated according to:

$$\tau_{ssc} = \left(\left[1 + \left(\frac{\beta}{2\omega_0} \right)^2 \right]^{1/2} + \frac{\beta}{2\omega_0} \right) \tau^0_{ssc} \tag{2}$$

where ω_0 is the frecuency of the inverted oscillator potencial at the saddle point, β is the reduced dissipation parameter and τ^0_{ssc} is the non-dissipative saddle-to-scission time that is also described in Ref. (Hofmann and Nix (1983)).

With the idea of investigating the dissipative effects between the saddle and the scission point, we have implemented this equation in the evaporation code ABLA07 (Kelić-Heil et al. (2008)). In this preliminary calculations we propose as observable the neutron excess, which is obtained as the mean number of neutrons over the atomic number. This observable is displayed as a function of the atomic number in Fig. 3 for ^{208}Pb+p at 500 A MeV. In this figure, we compare our measurement (open squares) with previous measurement performed by B. Fernández (open circles) (Fernández-Domínguez et al. (2005)) at FRS, where they only measured one fission fragment. As can be seen, our measurement (open squares) is in agreement with previous one.

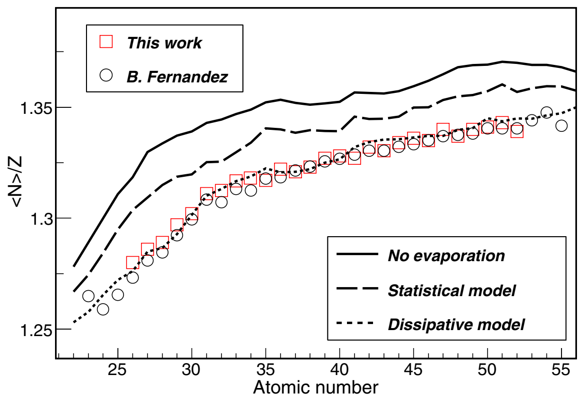

Fig. 3. (Color online) Dissipative effects obserbed on neutron excess for the reaction ^{208}Pb+p at 500 A MeV obtained in this work (open squares) in comparison with previous measurement (open circles) (Fernández-Domínguez et al. (2005)). The full line represents a calculation considering no evaporation between the saddle and the scission point. The dashed line corresponds to a calculation based on statistical model and the dotted line represents a calculation using the dissipative model based on the dynamical picture of Kramers.

The neutron excess is compared with a calculation considering no evaporation effects (solid line) between the saddle and the scission point. As can be seen in the figure, this calculation clearly overestimates the neutron excess for both measurements. This overestimation indicates the need of a saddle-to-scission time. Taking into account this fact, we also compare the data with a calculation considering the non-dissipative saddle-to-scission time (τ^0_{ssc}), which is represented by dashed line. This calculation also overestimates both measurements and therefore this result clearly indicates the need of dissipative effects. Finally, we compare the data with a dissipative calculation (dotted line) for a reduced dissipation parameter of 9×10^{21} s^{-1}. This calculation clearly describes both measurements and confirms a deformation dependence of the dissipation parameter, which was pointed out in other works (Fröbrich et al. (1993); Paul and Thoennessen (1994)). However, the value of the dissipation parameter and its dependences could depend on the used model, for this reason the verification of this result with other calculations (Grangé et al. (1983); Fröbrich and Gontchar (1998)) should be performed as a future work.

4. Summary and Conclusions

In the present work, we have investigated proton-induced fission of ^{208}Pb in inverse kinematics using a highly efficient detection setup, which permitted to measure for the first time the atomic and mass number of both fission fragments. These new data allow us to investigate dissipative and transient effects using model calculations. Fission cross sections and neutron excess as observables seem to be sensitive to these effects and allow us to deduce the value of the dissipation parameter, obtaining values of 4.5×10^{21} s^{-1} and 9×10^{21} s^{-1} for the pre- and post-saddle, respectively. Moreover, the calculations for the fission cross sections of ^{208}Pb and ^{209}Bi allow us to conclude that the dissipation parameter does not depend on the temperature and to confirm the transient time effects at high excitation energies. These preliminary calculations performed for the neutron excess show a dependence of the dissipation parameter with the deformation, which was observed in other works.

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