First experiment on fission transients in highly fissile spherical nuclei

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Abstract

A novel experimental approach for studying dissipative transient effects in nuclear fission has been developed at GSI, Darmstadt. Fragmentation of radioactive heavy-ion beams is employed to form highly fissile nuclei with spherical shape, and the specific sensitivity of the width of the fission-fragment nuclear charge distribution to the pre-saddle region is explored. A transient time of $(3.3 \pm 0.7) \cdot 10^{-21} s$ is deduced for initially spherical nuclei.

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Due to the difficulty inherent to pure microscopic calculations, nuclear dynamics is customarily portrayed by hybrid models, namely transport theories [1] which distinguish between collective and intrinsic degrees of freedom. The pertinence of such a picture in nuclear physics is widely recognized. In this frame, friction and diffusion forces lead to an exchange of energy between the various degrees of freedom of the system: While the former slows the motion down, the latter can re-inject heat into collective energy. The resulting subtle energy transfer matters not only in nuclear physics, but constrains the decay of meta-stable states also in fluid mechanics, chemistry or biology. Yet, in the nuclear medium, dissipative phenomena are complicated by quantum mechanics, and neither theory nor experiment did converge to a consistent picture so far.
As a typical large-scale amplitude motion involving a meta-stable state, fission is an

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excellent probe of nuclear dissipation. Once an excited system has been produced, the collective coordinates start adjusting to the potential-energy landscape, and the distribution of shapes inside the transitional saddle point develops towards quasi-equilibrium. After some time delay called the transient time τ_{trans} [2], all states in the quasi-bound region are populated according to the available phase space. Beyond the saddle, the strong Coulomb force drives the system to scission. The delay τ_{trans} until which fission sets in is closely related to the balance between friction and diffusion forces i.e. to the so-called dissipation strength β.
The ideal scenario for studying transient effects in fission consists of starting with an excited spherical nucleus [3]. In this case, the initial distribution probability of the system spreads out only under the influence of fluctuating forces, whereas driving and friction forces dominate along the saddle-to-scission descent. Aside from suited initial conditions, an accurate survey of fission transients calls for observables sensitive to the quasi-bound region. The width σ_Z of the distribution of the fission-fragment nuclear charge has shown to be strongly connected to the excitation energy E_{sad} at the saddle point [4]. Since E_{sad} is given by the number of particles evaporated prior to the saddle, it is primarily governed by the time the system needs to reach the barrier. Hence, σ_Z permits establishing a clock at the saddle point.
So far, achieving the above ideal scenario was impossible due to the unavailability of spherical highly fissile nuclei. This challenge has been overcome at GSI, Darmstadt, with the two-step mechanism illustrated in the left panel of Fig.1. Fragmentation of a primary ^{238}U beam produces a large variety of fissile nuclei. Among them, radioactive isotopes of At up to Th, with neutron numbers around N=126, are particularly interesting since they are spherical in their ground state. Thanks to the ability of the GSI Fragment Separator of identifying particles event-by-event, 45 of the uranium fragmentation products, those which are spherical, have been used as relativistic secondary beams which bombard a lead target. The second fragmentation reaction leads to nuclei which are initially still very fissile and nearly spherical, and possess up to high excitation energies as well as small angular momenta [3]. Fission of these systems, which precisely match the aforementionned ideal scenario, is studied by identifying in atomic number Z both fragments in coincidence [5].
The data set collected with a given secondary beam contains the nuclide production from fission of various nuclei formed by projectile-fragmentation. The experimental knowledge of the sum $Z_1 + Z_2$ of the nuclear charges of the two fission fragments permits classifying the data according to initial excitation energy and fissility [3]. The experimental fission-fragment nuclear charge width σ_Z are thus presented as function of $Z_1 + Z_2$. A sample of results is shown in the right panel of Fig.1.
In order to extract information on dissipation, model calculations are required. In this work, the abrasion-ablation code ABRABLA [6] which describes the whole fragmentation-fission process is used. Transient effects are accounted for via a realistic approximation of the time-dependent fission decay-width [7]. The reliability of the code has been assessed for various systems and observables [8]. As shown in Fig.1 for one example, the data are best described by $\beta = (4.5 \pm 0.5)\cdot 10^{21} s^{-1}$ independent on $Z_1 + Z_2$ i.e. independent on excitation energy and fissility. This observation holds for the whole set of data, see the figure. The progressive failure of calculations neglecting transient effects with decreasing $Z_1 + Z_2$ proves the crucial influence of fission transients at high initial temperature (above about 3 MeV) [3,9]: the absence of evaporation during a finite delay by assuming

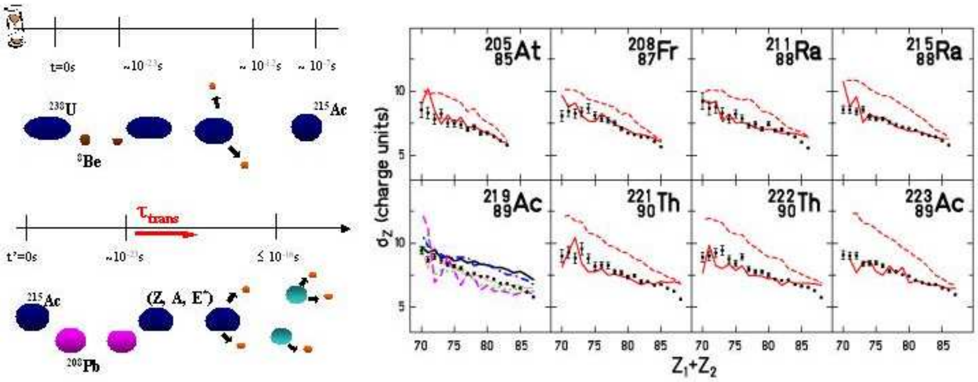

Fig. 1. Left: Illustrative drawing of the radioactive-beam production (up) and the subsequent fragmentation-fission reaction (bottom). Right: Width σ_Z as a function of $Z_1 + Z_2$ for a sample of radioactive beams. The data (dots) are compared with calculations including transient effects (full lines) or assuming instantaneous quasi-equilibrium (dashed lines) [3]. In both cases, β is set to $4.5{\cdot}10^{21}s^{-1}$. For ^{219}Ac as an example, the data are compared with calculations always including transient effects computed with various β's: 1 (full thick), 3 (thick dashed-dotted), 4.5 (full thin), 6 (thick dotted) and $7{\cdot}10^{21}s^{-1}$ (thick dashed). Staggering in the calculations is due to statistical fluctuations.

quasi-equilibrium is instantaneously reached - leads to too broad Z distributions. For initial spherical systems, the extracted β corresponds to a transient time of $\tau_{trans} = (3.3 \pm 0.7){\cdot}10^{-21}s$.

Thanks to a large experimental effort ensuring well-defined initial conditions and the measurement of a specifically sensitive signature, sizeable transient effects in fission of highly excited and fissile spherical nuclei could be un-ambiguously evidenced for the first time. The unusual size of the data set allowed a survey covering a wide excitation energy and fissility range. The controversy that exists so far on fission dynamics is to a large part related to the complex influence of initial deformation and temperature of the system in conventional approaches [9–11]. In addition, most popular observables [12] integrate the puzzling story up to scission. In the light of the present result, previous analysis might be revisited and apparent contradictions may be understood.

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