FISSION OF RADIOACTIVE BEAMS AND DISSIPATION IN NUCLEAR MATTER*

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The use of radioactive beams in inverse kinematics dramatically increased the number of isotopes which can be studied at excitation energies ranging from a few to several hundred MeV. Since this method is not subject to target restrictions, long isotopic and isotonic chains could be investigated, and hence, studies of the evolution of fission fragment charge yields, of total kinetic energies, as well as of the time scale of nuclear fission of highly excited compound nuclei with proton and neutron number of the fissioning nucleus, are possible.

1. Introduction

1.1. *Nuclear Fission and Radioactive Beams*

Nuclear Fission is one of the most fascinating reactions in nuclear physics and one of the best-studied (see e.g. [1]). The large-scale reorganization of all nucleons of an initial nucleus splitting into two fission fragments via extreme deformations, the influence of shell structure on the potential-energy surface governing the fission process, even-odd staggering in the elemental yields due to pairing, and the information the fission time scales reveal about the exchange of energy between collective and intrinsic degrees of freedom are just a few examples which explain the interest of the nuclear physics community in this reaction beyond the well-known applications.

Traditionally, most experiments used either neutrons or light charged particles for inducing fission in stable or long-lived heavy nuclei. The investigation of spontaneous fission was naturally limited to very heavy nuclei for which this decay channel is open. Here, the use of radioactive beams at relativistic energies of several hundred A MeV combined with the investigation

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of fission in inverse kinematics is a new and promising experimental approach which offers a number of advantages. The most important improvement is the access to a large number of highly-fissile nuclei. This allows studying the dependence of different observables for long isotopic and isotonic chains.

1.2. *Inverse Kinematics*

One of the key features of the investigation of fission with radioactive beams is the use of inverse kinematics. This is very important since it allows the use of thick targets ($\approx$ g/cm^2), therefore partially compensating low radioactive-beam intensities. Another advantage of the use of inverse kinematics, especially at relativistic energies, is the possibility of detecting both fission fragments with high efficiency, employing the fact that the two fission fragments are strongly focused in forward direction. A detection system of limited size covers therefore almost the full solid angle in the center-of-mass system. In addition, the large kinetic energies of the two fission fragments allow measuring the energy loss of both fission fragments independently. In combination with a time-of-flight measurement this can be used for the determination of the nuclear charge of both fission fragments with high accuracy. Access to the nuclear charge of both fission fragments is extremely difficult to achieve in normal kinematics [1]. The nuclear charge of the two fission fragments gives access to the nuclear composition at the scission point because the neutron-rich fission fragments are unlikely to loose protons in post-scission de-excitation. As will be discussed in the following, the sum of the fission fragment charges, compared to the charge of the projectile, is a measure of the excitation energy of the initial compound nucleus. This fact is exploited in the analysis of all data presented here.

1.3. *Research Fields of CHARMS*

The **C**ollaboration for **H**igh-**A**ccuracy Experiments on Nuclear **R**eaction **M**echanisms with Magnetic **S**pectrometers (CHARMS) [2] employs mostly the experimental facilities at the Gesellschaft für Schwerionenforschung (GSI) and especially the experimental capabilities of the Fragment Separator (FRS) [3]. The physics program of CHARMS is rather broad and ranges from questions concerning the momentum dependence of the nuclear equation of state to the physics which determines the production rates of radioactive beams in the next generation of radioactive beam facilities. CHARMS also works on nuclear fission and concentrates its attention to questions relating to the influence of nuclear shell structure and pairing on fission fragment yields, the influence of fission on the astrophysical r-process [4,5], and the dynamics of nuclear fission due to the influence of dissipation in nuclear matter (e.g. [6] and references therein). Some of the results will be presented here.

2. Experiment

The experiment consists of two parts: the production, preparation, and identification of secondary beams using the FRS and a dedicated set-up for the investigation of fission in inverse kinematics. A beam of 1 *A* GeV ^{238}U beam was used, which impinged on a 0.657 g/cm^2 Be target. While U and Th are the heaviest elements which can be used for the production of highly-fissile secondary beams from projectile fragmentation, it is especially the high beam energy which is important for a clean separation and identification of those heavy products. Even at primary beam energies of 1 *A* GeV not all of the reaction products are fully stripped. The identification and separation of the secondary beams in described in detail in Refs. [7,8].

At the focal plane of the FRS (see Fig. 1), a cocktail of radioactive beams, each ion identified in nuclear mass *A* and charge *Z*, impinges on an active target built from five natural Pb foils with a total thickness of 3.03 g/cm^2. The foils are set up as the electrodes of a sub-divided ionization chamber. An energy-loss measurement allows determining the location of a fission event as well as selecting fission events in the plastic scintillator which was located in front of the active target. The fission fragments are subsequently detected in a pair of scintillators, which act as fast fission trigger and a double ionization chamber which measures the energy-loss and the vertical and horizontal position of each fragment independently. A scintillator wall with an active area of about 1 m^2 is used as stop detector for a time-of-flight measurement of the two fission fragments. The start signal is provided by the scintillator in front of the active target. The time-of-flight measurement combined with the detected energy-loss results in a charge resolution of $\Delta Z = 0.4$ for both fission fragments. In addition the extraction of the mean total kinetic energy released in the fission process is possible. More details about the experimental approach can be found in Refs. [7,8].

3. Low-energy Fission after Electromagnetic Excitation

The use of radioactive beams in inverse kinematics can be combined with two different reaction mechanisms which depend on the proton number of the target and the impact parameter of the reactions. High-*Z* targets and impact parameters larger than the sum the radii of projectile and target lead, at the given energies,

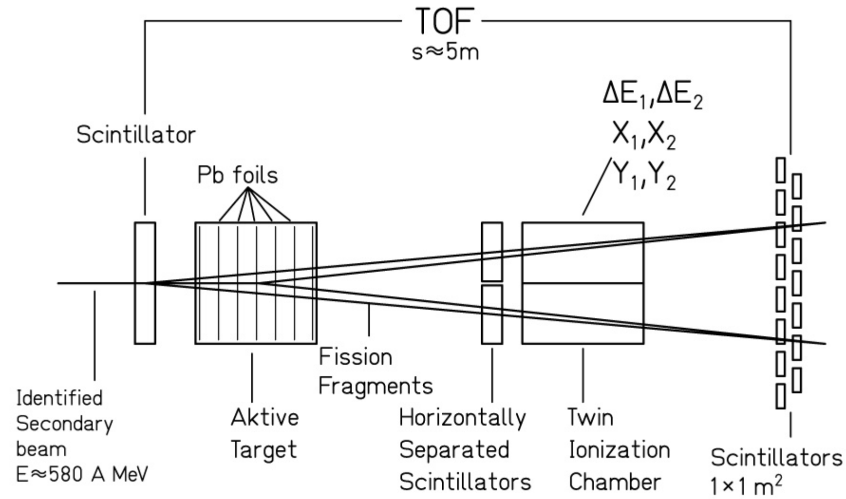

Fig. 1: Experimental set-up at the focal plane of the GSI Fragment Separator for the investigation of fission of secondary beams in inverse kinematics.

mostly to the electromagnetic excitation of giant resonances at excitation energies near the fission barriers of the nuclei in question [7]. Fission after electromagnetic excitation, selected by using again the sum of the charges of the two fission fragments [7,8], resulted in the first systematic study of the transition from symmetric fission near ^{208}Pb to the asymmetric fission processes of actinide nuclei. Surprisingly, this transition scales with the mass number of the fissioning nucleus in contrast to the expectation that shell effects in the neutron number dominate the structural effects in fission. The observed charge distributions can be described very well in a rather simple saddle point model, based on the curvature of the liquid-drop potential at the saddle, which is modified by two neutron shells, one at $N = 82$ and a deformed one at $N \approx 88$ [9]. The charge distributions are obtained by calculating the level density, and therefore the phase-space which is available for different charge splits. The model assumes that the distribution at the saddle point is not substantially altered on the way from the saddle to the scission point.

The presented experimental approach resulted also in information on the evolution of fission channels [10] which are characterized by different scission point configurations [11]. Other interesting results contain information on the influence of the ground-state shell effect on the fission probability of a compound nucleus [8].

4. Fission Dynamics and Radioactive Beams

Peripheral nuclear collisions lead to large excitation energies and are an ideal tool for the investigation of the exchange of energy between collective and intrinsic degrees of freedom, which is characterized by the reduced dissipation coefficient (see e.g. [12] for a review). While the transfer of energy from single-particle degrees of freedom into collective deformation is necessary for fission to occur, the inverse process reduces the amount of time the nucleus needs for its evolution from the initial compound nucleus deformation to the very elongated scission point. This exchange influences the fission process in several ways. Already Kramers pointed out [13] that, due to the statistical nature of that exchange, even nuclei beyond the saddle point might avoid fission, which reduces the total fission width.

Here, we focus on the transient time, which is the time the system needs to adjust to the available phase space, in a diffusion-like process which can be described mathematically by Fokker-Planck or Langevin type equations. This time scale is difficult to observe, and the method employed here is based on a measurement of the temperature of the initial compound nucleus and of the temperature at the saddle point. This is connected to the time it takes for the excited nucleus to reach the saddle point because the longer the transient time, the more time is available for the nucleus to reduce its excitation energy by particle evaporation before the saddle point is reached. Therefore, a longer transient time results in lower excitation energies at the saddle point. The measurement of the temperature of the compound nucleus is based on the measured sum of the charges of the two fission fragments. The number of abraded protons in the initial collision is a measure of the excitation energy which can be obtained by model calculations. Here the abrasion-ablation code ABRABLA [14] has been used. The measurement of the temperature at the saddle point can be obtained from the measurement of the width of the fission-fragment charge distribution which is related to temperature according to a relation which is based on a systematic by A. Ya. Rusanov *et al.*[15]:

$$\sigma_Z^2 = \left(\frac{Z_{fiss}}{A_{fiss}}\right)^2 \frac{T_{saddle}}{\frac{d^2V}{\left.\frac{dV^2}{d\eta^2}\right|_{\frac{A_{fiss}}{2}}}}$$

Here the charge distribution width is related to the ratio of nuclear charge (Z_{fiss}) to mass (A_{fiss}) of the fissioning nucleus, the stiffness of the potential (V) as function of the mass asymmetry (η). The physics behind this well-established equation is that a larger temperature allows the population of larger mass asymmetries. The term containing the charge-to-mass ratio of the fissioning nucleus converts this relation, which was made for the width of fission fragment mass distributions, into a relation for fission fragment charge distributions using the unchanged-charge density assumption.

The measured width can be compared with the Abrasion-Ablation model, which describes the entire reaction and contains a realistic analytical approximation of the numeric solution of the Fokker-Planck equation for an initially spherical compound nucleus [16]. Using radioactive beams, a rather large number of secondary projectiles between At and U can be investigated. Results (see Fig. 2) show that the model calculations describe the measured charge width for a large number of nuclei in a large excitation energy range. The best agreement is obtained with a reduced dissipation coefficient of $4.5 \cdot 10^{21}$ s^{-1} corresponding to a transient time of $(3.3 \pm 0.7) \cdot 10^{-21}$s. Calculations neglecting transient effects like the Bohr-Wheeler treatment of the fission channel or the quasistationary treatment of dissipation in fission as proposed by Kramers [13] fail to describe the data. An experiment performed under similar conditions for a ^{238}U projectile results in a transient time of $(1.7 \pm 0.4) \cdot 10^{-21}$s [16]. The only obvious difference which could explain the discrepancy of the two results seems to be the ground-state deformation of the initial compound nucleus. In the present work we investigated 45 highly-fissile secondary beams with ground-state deformations of $|\beta_2| \leq 0.15$, while the ground state of ^{238}U has $\beta_2 \approx 0.23$ (see Ref. [6] for more details). Calculations show that the initial deformation is almost preserved in the abrasion step of the reaction ($|\beta_2| \leq 0.15$), because the geometric overlap of projectile and target is rather small even for collisions resulting in a pre-fragment which lost a substantial number of nucleons with respect to the projectile. Changing the deformation of the pre-fragment via collective motion is slow because it is again governed by a diffusion-like process. On the other hand, thermalization of the available excitation energy is expected to be significantly faster than a collective motion. If this assumption holds, the ablation step in projectile fragmentation results in a compound nucleus which is characterized not only by high excitation energies, low angular momenta but also by a deformation which is close to that of the ground state of the initial projectile. This is the first experimental evidence for an influence of the initial deformation on the time the nucleus needs to reach the saddle point and was made possible by having access to beams with different ground-state deformations. Future plans include more detailed studies on this effect and improved calculations with an explicit treatment of the deformation of the excited nucleus.

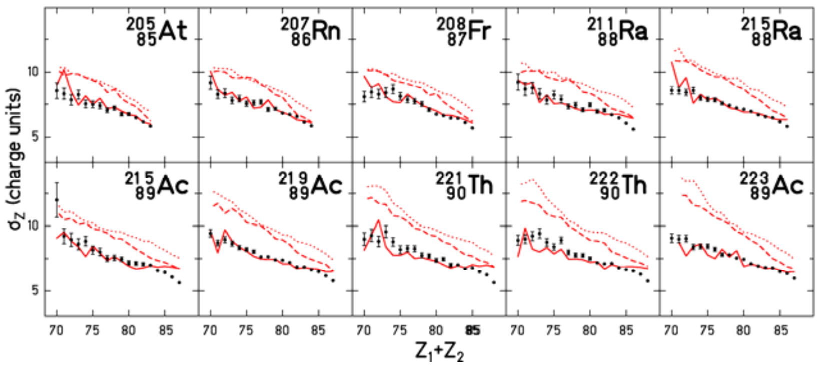

Fig. 2: The width of the fission fragment charge distributions measured for a number of isotopes with nearly spherical ground-state deformations as function of the sum of the charge of the two fission fragments. The data are compared to calculations using the abrasion-ablasion code ABRABLA. The dotted line shows a calculation based on Bohr-Wheelers transition state description of fission. The dashed line includes the quasistationary approach by Kramers. The full line is a calculation which includes transient time in nuclear fission and a reduced dissipation coefficient of $\beta = 4.5 \cdot 10^{21} s^{-1}$.

5. Outlook: R^{3}B and ELISe

The future of fission experiments using radioactive beams looks very promising. At GSI two large projects, which will be used with the new FAIR [17] facility will be optimized for the use of secondary beams.

While the setup for **R**eactions with **R**elativistic **R**adioactive **B**eams (R^{3}B) will measure in addition to the charge also the mass of both fission fragments. I will also be able to detect neutrons, light charged-particles, and gamma radiation. This will be especially useful for measuring the total kinetic energy release in fission and, hence, for a more precise picture on the evolution and properties of fission channels and their microscopic origin.

Especially for the investigation of fission at low excitation energies, the **EL**ectron-**I**on **S**cattering **e**xperiment (ELISe) will be of great importance, since here radioactive ions, circulating in a storage ring, will collide with an electron beam. From the detection of the scattered electrons the excitation energy can be determined. Mass and charge of the fission fragments will be accessible as well.

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