Fission studies with relativistic beams

K.-H. Schmidt[1*], P. Armbruster[1], J. Benlliure[2], C. Böckstiegel[3], H.-G. Clerc[3], T. Enqvist[4], A. Grewe[3], A. Heinz[1†], A. Junghans[1‡], J. Müller[3], F. Rejmund[5], S. Steinhäuser[3]

[1] GSI, Planckstr. 1, 64291 Darmstadt
[2] University of Santiago de Compostela, 15706 Santiago de Compostela, Spain
[3] IKDA, TU Darmstadt, Schloßgartenstr. 9, 64289 Darmstadt
[4] University of Jyväskylä, 40351 Jyväskylä, Finland
[5] IPN Orsay, IN2P3, 91406 Orsay, France

Abstract: We report on an experimental program to measure the nuclide production in fission in inverse kinematics. Using relativistic beams of primordial and radioactive nuclei, new experimental information the influence of shell effects on fission has been obtained. The transition from symmetric to asymmetric fission around ^{227}Th has systematically been mapped. The heavy asymmetric component was found to be astonishingly stable near N = 54 for all systems investigated.

1. Introduction

Since a few years, there is an experimental program in progress at GSI, Darmstadt, to systematically investigate the production of primary residues in relativistic nuclear collisions and in fission. A renewed interest in these reactions originates from future technical applications, e. g. in new-generation facilities for the production of secondary beams of nuclei far from stability. The installations at GSI offer unique conditions for these investigations by applying inverse kinematics and using secondary beams of short-lived fissile nuclei. Besides the heavy-ion synchrotron SIS18, which delivers projectiles up to ^{238}U at 1 A GeV, the in-flight spectrometer FRS [[1]] is the central tool for these investigations. Its role is two-fold: When using beams of primordial nuclides, delivered by SIS18, it is used to identify the reaction products in mass number A and atomic number Z as well as to measure their velocity with high resolution. In this case, only one reaction product can be detected at a time. When beams of radioactive nuclei are required, the FRS is used to separate and to identify the desired nuclear species from the projectile fragments produced in a primary target at the entrance of the FRS. In this case, the reaction to be studied was induced in a secondary target placed at the exit of the FRS, and the secondary reaction products were studied with an alternative set-up, consisting of a large ionisation chamber and a time-of-flight section, allowing to determine the atomic numbers and the velocities of both fission fragments simultaneously.

2. Results and Discussion

Experiments with the full identification of the fission fragments in A and Z have been performed for the systems ^{238}U + ^{9}Be [2], ^{238}U + ^{208}Pb [3,4,5], ^{197}Au + ^{1}H [6,7] and ^{208}Pb + ^{1}H [8] between 800 and 1000 A MeV. The evaluation of the data for other systems, *e.g.* ^{208}Pb + ^{2}H, ^{238}U + ^{1,2}H, ^{56}Fe + ^{1}H is in progress. These are the first experiments, which deliver a complete survey on the nuclide production in fission with full identification in Z and A. The use of different targets and several projectiles with different fissilities gives valuable information

* E-mail: k.h.schmidt@gsi.de
† Present address: Argonne Nat. Lab., Physics Div., build. 203, 9700 South Cass Avenue, Argonne, IL 60439, U.S.A.
‡ Present address: Nucl. Phys. Lab., BOX 354290, University of Washington, Seattle, WA 98195, U.S.A.

on nuclear dynamics, in particular on nuclear dissipation, *e.g.* ref. [9]. These data reveal systematic trends in the nuclide production for different systems. However, even in a specific projectile-target combination, the fission products emerge from a variety of different nuclei over a wide range of excitation energy. In the present contribution we concentrate on low-energy fission induced by electromagnetic interaction of a large number of systems using secondary beams. In this case, the fissioning system is rather well defined, so that specific information of the fission properties of selected systems can be deduced.

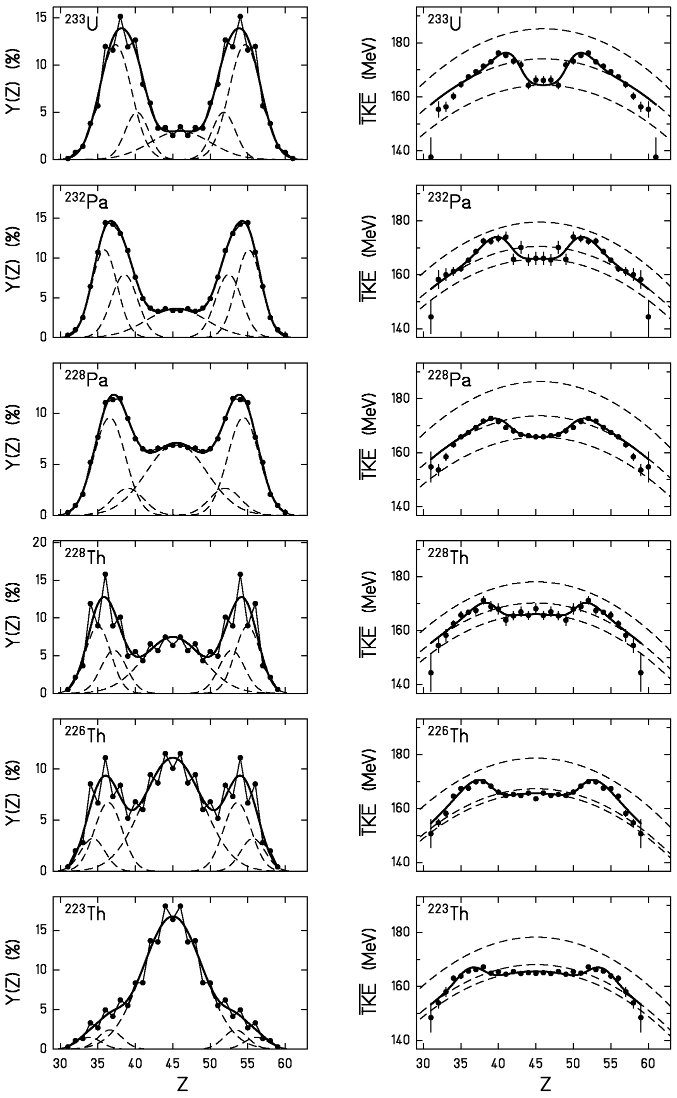

Fig. 1: Element yields (left part) and average total kinetic energies (right part) as a function of the fission-fragment nuclear charge. The data points are compared to the result of a simultaneous fit (full lines) to both quantities with 3 fission channels. The super-long, standard I, and standard II channels correspond to the symmetric, the inner asymmetric and the outer asymmetric peaks (dashed lines), respectively, in the yields and to the lower, upper and middle curve (dashed lines), respectively, in the total kinetic energies.

Low-energy fission ($<E^*> \approx 11$ MeV) of secondary projectiles between ^{205}At and ^{234}U, induced by electromagnetic interaction with lead target nuclei has been used to systematically investigate the influence of nuclear shell structure on the collective motion from saddle to scission in a particularly interesting region [10], only scarcely studied before because suitable targets did not exist. Fig. 1 shows the fission-fragment element distributions and the total kinetic energies (TKE) of 6 selected systems. These data, showing a drastic variation of the yield distributions, are particularly well suited to test the concept of fission channels, elaborated by Pashkievich [11] and Brosa et al. [12]. The yields and the TKE distributions can well be fitted with the three fission channels (Standard I, Standard II and Super-long), which are known to describe the previously measured fission-fragment distributions of all systems from thorium to fermium, except a few very neutron-rich systems close to ^{264}Fm. The good reproduction of the data means, that the fission-channel concept is confirmed. Note, that the yield distribution is described as the sum of Gaussian distributions, attributed to the different fission channels, while the total kinetic energies are understood as the weighted average of the values of the different channels. The variation of the total kinetic energy of a specific fission channel with atomic number of the fission fragment is given by the expected variation of the Coulomb repulsion of the nascent fragments at scission, while keeping the deformation fixed.

In accordance with the fission-channel concept, the yields of different components in the fission-fragment distribution vary strongly, presumably due to variations in the potential-energy landscape near the barrier, while their properties, *e.g.* TKE values, mean mass asymmetry and others, which are attributed to shell effects in the nascent fragments, prove to be rather universal. However, fig. 2 illustrates one inconsistency with the previous understanding: While the asymmetric fission channels, Standard I and Standard II, have been attributed to the spherical neutron shell at $N = 82$ and to the strongly deformed neutron shell at $N = 86$ to 90, the position of the asymmetric peak appears to be remarkably constant at proton number $Z = 54$. It is an open question, whether this is an indication for a shell at $Z \approx 54$ at large deformation, which does not appear in available shell-model calculations. We hope that most advanced dynamical calculations of the fission process, based on multi-dimensional Langevin equation (*e.g.* ref. [13]), will soon be able to include shell effects and thus will allow the studying of this question on an elaborate theoretical basis.

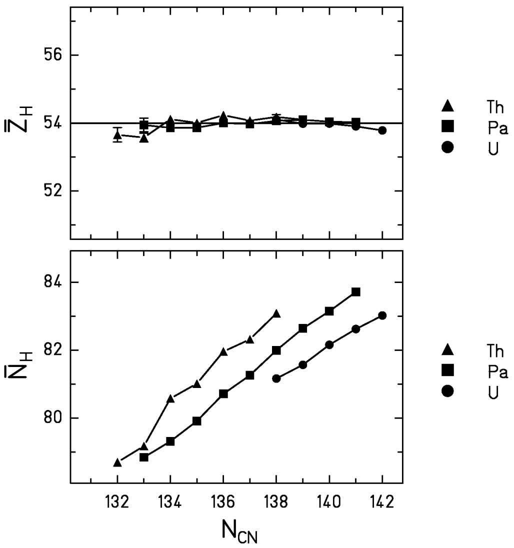

Fig. 2: Mean position of the heavy asymmetric component in atomic number, measured, (upper part) and neutron number, estimated by the UCD assumption, (lower part).

3. Conclusion

Relativistic beams of primordial and short-lived nuclei have opened up new possibilities for the investigation of nuclear fission over a large range of excitation energy. This contribution concentrates on structures in element and total-kinetic-energy distributions for a large number of fissioning systems which provide stringent tests for our understanding of shell structure at large deformation and for the fission dynamics. The data can be reproduced in the frame of the schematic fission-channel concept of fission dynamics.

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