Fragmentation-induced fission reactions of $^{236}$U in inverse kinematics to investigate the pre-fragment angular momentum parameterizations

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Abstract. In the last decades, measurements of spallation, fragmentation and Coulomb induced fission reactions in inverse kinematics have provided valuable data to accurately investigate the fission dynamics and nuclear structure at large deformations of a large variety of stable and non-stable heavy nuclei. The collected data were used to constrain dynamic and nuclear structure parameters of different de-excitation models, such as ABLA and GEF, but the data can also be used to constrain the parameterizations describing the pre-fragment properties after the nuclear collision, such as the angular momentum gained by the pre-fragment. In this work, the fissioning system yields are compared to calculations assuming different parameterizations for modeling the angular momentum gained by the compound nuclei. Our findings indicate that the parameterizations utilized by abrasion models clearly underestimate the angular momentum, resulting in the underestimation of the production of lighter fissioning systems.

1 Introduction

Nuclear fission is the clearest example of large-scale collective excitations in nuclei. Since its discovery by Hahn, Meitner, Strassmann and Frisch in 1939 [1, 2], the progress in the understanding of the fission process has been driven by new experimental results. Despite the recent theoretical progress in the investigation of fission, a complete description still represents a challenge in nuclear physics because it is a very complex dynamical process, whose description involves the coupling between intrinsic and collective degrees of freedom, emission of light particles and γ-rays, as well as different quantum-mechanical phenomena [3]. Therefore, its investigation requires complex experimental setups that allow for complete kinematics measurements of the fission products.

In the late 90’s, with the advance of heavy-ion accelerators, a new generation of experimental approaches for fission studies was developed. The use of the inverse kinematics technique permitted for the first time an in-flight identification of fission fragments in charge and mass number. The first measurements based on this technique were performed at the GSI facility in Darmstadt (Germany) using the fragment spectrometer FRS [4] to detect and identify one of the two fission fragments in charge and mass number [5]. The data provided relevant information on the fission process dynamics [6], resulted in the discovery of new isotopes and isomeric states [7], as well as providing production cross sections of more than 1000 nuclear fission residues [8–11]. The FRS spectrometer was also used to produce secondary radioactive beams of neutron-deficient actinides and preactinides between At and U elements [12] that impinged onto an active target to induce fission through Coulomb-excitation and fragmentation reactions. The fission fragments were identified in charge by a double ionization chamber. The charge distribution measurements provided relevant information on the transition from symmetric to asymmetric fission [12] and on the presaddle fission dynamics [13, 14].

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Recently, a great effort was made by the SOFIA (Studies On Fission with Aladin) collaboration at GSI [15, 16] to overcome the restrictions of conventional fission experiments and to provide complete isotopic measurements of both fission fragments inducing fission through spallation, fragmentation, and Coulomb-excitation reactions. A state-of-the-art experimental setup specially designed to investigate fission permits, by combining position, angle, energy loss and time-of-flight (ToF) measurements, to apply the $\Delta E-B$-ToF method to identify in coincidence both fission fragments in terms of their mass and atomic numbers. It became possible to extract correlations between fission observables sensitive to the dynamics of the fission process [17–20] and the nuclear structure at the scission point [21–24].

In this work, fission observables obtained from fragmentation-induced fission reactions of $^{236}$U in inverse kinematics are used for the first time to investigate the effects of the existing pre-fragment angular momentum prescriptions. Recently, it has been pointed out that the parameterizations used for modeling the angular momentum gained by the pre-fragments after a nucleus-nucleus collision underestimate by a factor of ten the measurements of high angular-momentum isomeric states populated in medium-mass and heavy nuclei [25–27]. These investigations were performed with medium-mass and heavy fragmentation residues at a few hundred MeV/u, in which one would expect low angular momenta because such residues are produced in peripheral collisions. In this case, we use fission reactions covering a large range of impact parameters to study the effects of the angular momentum from peripheral to more central collisions.

2 Experimental setup

The realization of this kind of experiment requires a complex experimental setup, providing an unambiguous identification of the secondary beams and a complete kinematics measurement of fission fragments. Such a measurement was performed in 2014 at the GSI facility by combining the fragment spectrometer FRS [4] and the SOFIA experimental setup. In the following, a detailed description of the experimental setup and some preliminary results are presented.

The SIS18-synchrotron was utilized to accelerate heavy ions of $^{238}$U at relativistic energies around 720A MeV. The secondary beams were produced by fragmentation reactions on a 1032 mg/cm$^2$ Be target mounted together with a 223 mg/cm$^2$ Nb stripper located at the entrance of the fragment separator FRS. The secondary beam of $^{236}$U was selected by the FRS operated as a momentum-loss achromatic spectrometer [28] and then guided to the experimental area Cave-C to induce fission reactions in an active target.

The SOFIA experimental setup, shown in Fig. 1, is divided into two parts, one to characterize the incoming projectile nuclei and another to measure the fission products. The first part consists of a triple multiple-sampling ionization chamber (MUSIC), a multi-wire proportional counter (MWPC) [29], and a plastic scintillator detector used to measure the time-of-flight (ToF) of the incoming projectiles and outgoing fission fragments. The combination of these detectors is used for the beam identification and to determine the beam position on the target.

The second part consists of two MWPC detectors, a double multi-sampling ionization chamber (Twin MUSIC), a large acceptance dipole magnet (ALADIN), and a large ToF wall. The Twin MUSIC chamber has a central vertical cathode that divides its volume into two active regions (left and right) both of which are divided into two sections (up and down). Each section is then segmented in 16 anodes that provide 16 independent energy-loss and drift-time measurements. This segmentation allows us to obtain the atomic number of our fission fragments with a resolution better than 0.38 charge units full width at half maximum (FWHM) and the angles on the X-Z plane with a resolution around 1 mrad (FWHM). MWPCs, situated in front and behind the dipole magnet, provide the horizontal (X) and vertical (Y) positions of the fission fragments. The MWPC situated in front of the dipole magnet provides the X and Y positions with a resolution of around 200 $\mu$m and 1.5 mm (FWHM), respectively, while the MWPC situated behind the dipole magnet provides those positions with a resolution of around 300 $\mu$m and 2 mm (FWHM), respectively. The ToF wall consists of 28 plastic scintillators that allow to measure the ToF of the fission fragments with respect to the start signal provided by the plastic scintillator located at the entrance of the experimental setup with a resolution of around 40 ps (FWHM) [30]. The ALADIN magnet was set to a magnetic field of around 1.6 T and its gap was filled with helium gas at atmospheric pressure to reduce the energy and angular straggling of the fission fragments.

The atomic number of the fission fragments is deduced based on the fact that the energy loss is proportional to the atomic number squared. In Fig. 2 we show the measured atomic-number correlation plot in the twin-MUSIC detector, where the energy lost by the fission fragments was corrected by the corresponding ToF measurements. The achieved resolution is better than 0.38 charge units...
3 Results

The fission yields as a function of fissioning system $Z_1 + Z_2$ are displayed in Fig. 3(a), which were obtained by normalizing the counts of each fissioning system to the total number of fission events. The data are compared to model calculations based on the intranuclear cascade code INCL++ [31] coupled to the de-excitation model ABLA++ [32], which have been benchmarked with different observables obtained from spallation-induced fission reactions [35]. In this case we consider different parameterizations for the description of the angular momentum. First, we compare the data to standard INCL calculations where the angular momentum is obtained from energy and momentum conservation applied during the nucleus-nucleus collision, as explained in Refs. [33, 34]. Second, we calculate the angular momentum by using the phenomenological parameterization introduced in the abrasion-ablation model ABRABLA07 [36], which is based on Goldhaber’s prescription [37].

One can see clearly in the Fig. 3(a) that the calculation based on the abrasion parameterization (solid line) underestimates the fission yields for the lighter fissioning systems, whereas the standard INCL calculation (dashed line) gives a better description. This discrepancy can be explained in terms of the angular momentum gained by the fissioning compound nuclei, as shown by the INCL predictions (dashed line) in the Fig. 3(b). Whereas the fragmentation residues are produced with an average angular momentum around 16h and a tail that can populate values up to 70h, the fissioning systems can reach higher angular momenta up to 140h, with an average angular momentum around 42h. This fact is in contradiction with the abrasion model. The latter predicts that fragmentation residues and fission pre-fragments are produced with the same angular momentum distribution (red dotted line).

Finally, according to these calculations, one can interpret that in fragmentation reactions induced by light target nuclei the pre-fragments could cover a large range in angular momentum, reaching values up to 140h. This large angular momentum favours the fission channel since it reduces the fission barrier height down to zero, as shown in Ref. [38], increasing the fission probabilities.

4 Conclusions

The fragment spectrometer FRS was combined with the SOFIA experimental setup to study fragmentation-induced fission reactions of $^{236}$U in inverse kinematics. A secondary beam of $^{236}$U at 650A MeV was produced and selected with the fragment spectrometer FRS and guided to the experimental area to induce fission reactions of $^{236}$U in an active target. The SOFIA experimental setup was then used to perform complete kinematics measurements of the two fission fragments. In this work, we focus on
the charge distributions of the fission fragments and their correlations to obtain the atomic number of the fissioning systems. These yields are compared to intranuclear cascade calculations based on INCL model using the standard description for the pre-fragment angular momentum distributions and also to phenomenological prescriptions used in abrasion models like ABRABLA07. The comparison reveals that the abrasion parameterization underestimates the fission yields for lighter fissioning systems produced with large angular momentum, whereas the INCL standard parameterization based on energy and angular momentum conservations gives a better agreement.

Further experimental studies on Coulex, spallation and fragmentation induced fission reactions within the R3B (Reactions with Relativistic Radioactive Beams) collaboration have been carried out recently, measuring the charge and mass distributions for many short-lived neutron-deficient nuclei in the region between Re and Th. The new set of data could be used to systematically investigate the fissioning system as a function of the neutron-to-proton asymmetry or isospin. This investigation could also be combined with new approaches based on quasi-free scattering reactions to induce fission reactions of neutron-deficient and neutron-rich nuclei, which will provide direct access to the excitation energy of the fissioning system. Therefore the current and future experiments look very promising to accurately measure fission yields for many exotic nuclei and to study their evolution with the excitation energy.

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