NUCLEAR FISSION STUDIES IN INVERSE KINEMATICS WITH THE R³B SETUP AT THE GSI-FAIR FACILITY*

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Received 30 November 2022, accepted 11 January 2023,
published online 22 March 2023

Despite the recent experimental and theoretical progress in the investigation of the nuclear fission process, a complete description still represents a challenge in nuclear physics because it involves the coupling between intrinsic and collective degrees of freedom as well as different quantum-mechanical phenomena. In the last decade, unprecedented fission experiments have been carried out within the Reactions with Relativistic Radioactive Beams ($\mathrm{R^3B}$) Collaboration at the GSI facility by using the inverse kinematics technique in combination with state-of-the-art detectors especially designed to measure the fission products with high detection efficiency and acceptance.

DOI:10.5506/APhysPolBSupp.16.4-A29

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], progress in the understanding of the fission process has been driven by new experimental results. However, 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.

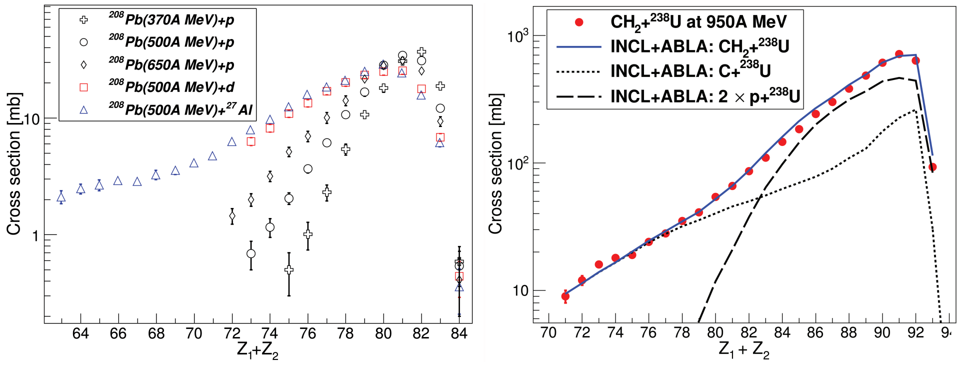
In the late 90s, the use of the inverse kinematics technique permitted for the first time an in-flight identification of fission fragments in charge and mass number. The first measurements based on this technique were

[*] Presented at the Zakopane Conference on Nuclear Physics, *Extremes of the Nuclear Landscape*, Zakopane, Poland, 28 August–4 September, 2022.

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], discovery of new isotopes and isomeric states [7], as well as production cross sections of more than 1000 nuclear fission residues [8–10]. The FRS spectrometer was also utilized to produce secondary radioactive beams of neutron-deficient actinides and preactinides between the At and U elements [11] that impinged onto an active target to induce fission through Coulex and fragmentation reactions, being the fission fragments identified in charge by a double ionization chamber. This set of data provided relevant information on the transition from symmetric to asymmetric fission [11] and on the presaddle fission dynamics [12]. Recently, a great effort was made by the SOFIA (Studies On FIssion with Aladin) Collaboration at GSI [13, 14] to provide complete isotopic measurements of both fission fragments inducing fission through spallation, fragmentation, and Coulex reactions. A state-of-the-art experimental setup based on a large-aperture dipole magnet, multi-sampling ionization chambers, multi-wire proportional counters, and highly segmented plastic scintillator ToF walls allowed for the first time to simultaneously measure and identify both fission fragments in terms of their mass and atomic numbers, as well as to extract correlations between fission observables sensitive to the dynamics of the fission process [15–18] and the nuclear structure at the scission point [19–22].

2. Fission dynamics at R^3B

In Fig. 1 (a), the partial fission cross sections of the different reactions measured during the fission campaign performed in 2012 are compared to illustrate the evolution with the projectile kinetic energy and with the target size. These measurements are also compared to previous ones performed by Ayyad and collaborators [23] for the ^{208}Pb+d reaction at 500 A MeV (open squares). The maximum value for the partial fission cross sections is always found close to the projectile atomic number ($Z_1 + Z_2 = 82$). The cross sections decrease with decreasing $Z_1 + Z_2$ because for the lighter fissioning systems, the fission barriers become higher and also because the smaller impact parameters are less likely. The partial fission cross sections of the lightest fissioning systems are expected to increase with the violence of the reaction (either projectile kinetic energy or mass number of the target nuclei) because more nucleons are removed from the projectile. One can also see that fission from single and double charge-exchange reactions $Z_1 + Z_2 = 83$ and $Z_1 + Z_2 = 84$, respectively, were also measured. These charge-exchange reactions are expected to be peripheral reactions that can occur by the exchange of a virtual pion between the colliding nucleons (quasielastic charge exchange) or the excitation of a nucleon resonance decaying by pion emission (inelastic charge exchange).



(a) (b)

Fig. 1. Partial fission cross sections as a function of the atomic number of the fissioning system ($Z_1 + Z_2$) for the reactions: (a) ^{208}Pb+p at 370 A, 500 A, and 650 A MeV, ^{208}Pb+d at 500 A MeV, and ^{208}Pb+Al at 500 A MeV; (b) ^{238}U+CH$_2$ at 950 A MeV. In figure (b), the data are compared to calculations performed with the INCL+ABLA models [24, 25].

The data shown in Fig. 1 (a) together with the widths of the charge distributions and the average neutron excess of the fission fragments as a function of the fissioning system were used to constrain the nuclear dissipation parameter β at small and large deformations, obtaining a dissipation parameter of 4.5×10^{21} s^{-1} [16, 18]. In Fig. 1 (b), the calculations constrained in the previous works are compared to a more complex fission reaction induced by a polyethylene target (CH$_2$), where the calculations for the contributions from H$_2$ and carbon are also displayed with dashed and dotted lines, respectively. Clearly, one can see that the coupling of the INCL+ABLA models [24, 25] also provides a good description.

3. Conclusions and perspectives

The SOFIA-R^{3}B experimental setup has been used for the first time to perform complete kinematics measurements of all fission products. The total and partial fission cross sections, the widths of the charge distributions of the fission fragments, as well as the neutron excess of the fission fragments were utilized to constrain the nuclear dissipation parameter at small and large deformations. The same theoretical calculations also describe more complex fission reactions induced by polyethylene targets.

Recently, this approach has been improved by combining the previous experimental setup with the calorimeter CALIFA (CALorimeter for In-Flight detection of γ-rays and high-energy charged pArticles) and the neutron detector NeuLAND (New LArge Neutron Detector) developed by the R^3B collaboration, which allow us to measure the γ-rays and light particles in coincidence with the fission fragments. Moreover, these new detectors will allow for using quasi-free $(p, 2p)$ and (p, np) scattering reactions to induce fission and get direct access to the excitation energy of the fissioning systems with high precision.

This work was supported by the Regional Government of Galicia under the postdoctoral fellowship ED481D-2021-018.

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