Fission studies in inverse kinematics with the R^3B setup

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Abstract. Nuclear fission is a complex dynamical process, whose description involves the coupling between intrinsic and collective degrees of freedom, as well as different quantum-mechanical phenomena. For this reason, to this day it still lacks a satisfactory and complete microscopic description. In addition to the importance of describing fission itself, studies of the r-process in astrophysics depend on fission observables to constrain the theoretical models that explain the isotopic abundances in the Universe. To improve on the existing data, fission reactions of heavy nuclei in inverse kinematics are produced in quasi-free (p,2p) scattering reactions, which induce fission through particle-hole excitations that can range from few to tens of MeV. In order to study the evolution of the fission yields with temperature, the excitation energy of the fissioning system must be reconstructed, which is possible by measuring the four-momenta of the two outgoing protons. Performing this kind of experiment requires a complex experimental setup, providing full isotopic identification of both fission fragments and an accurate measurement of the momenta of the two outgoing protons. This was realized recently at the GSI/FAIR facility and some of the results obtained for the charge distributions are presented in this work.

1 Introduction

The nucleosynthesis r-process is responsible for the synthesis of half of the elements heavier than Fe in the Universe. It is associated with high neutron flux scenarios such as supernovae or neutron star mergers, where rapid neutron captures followed by beta decays lead to the heavy neutron rich nuclear chart region where fission takes place. It was demonstrated that nuclear fission plays an important role in determining the final abundances of the r-process due to the so-called "fission cycling" phenomena, which limits the mass range of the r-process. Therefore, fission studies in the neutron-rich region are required in order to measure fission yields and fission barrier heights to im-

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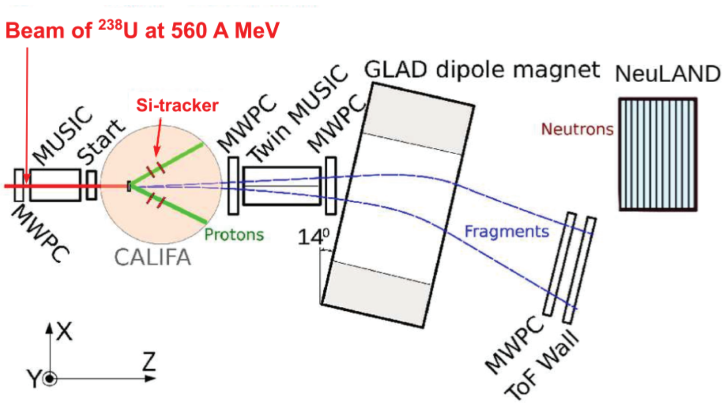

Figure 1. Schematic view of the experimental R^3B setup used in the present work to study quasi-free (p,2p) induced fission reactions.

prove r-process calculations [1, 2] and to obtain more accurate models for the observed isotopic abundances in the Universe.

In the last decade, unprecedented fission experiments have been carried out at the GSI/FAIR facility using the inverse-kinematics technique in combination with state-of-the-art detectors developed by the R^3B (Reactions with Relativistic Radioactive Beams) collaboration. For the first time in the history of fission, it was possible to simultaneously measure and identify both fission fragments in terms of their mass and atomic numbers [3, 4] and to extract correlations between fission observables sensitive to the dynamics of the fission process [5] and the nuclear structure at the scission point [6, 7].

However, previous studies based on either Coulomb excitation, transfer or fusion-fission reactions, were limited in terms of the reachable excitation energy and often limited to fissioning nuclei close to stablity. The excitation energy plays a fundamental role in the description of the process. Depending on the amount of available energy, different regions of the potential energy surface can be populated, leading to different fission paths and consequently to different fission yields distributions. The gradual weakening of the influence of shell structure on the fission yields with the increase of excitation energy can be quantified with the so-called suppression function [8], which minimizes the microscopic term of the energy-dependent effective potential. However, model parameters used in this approach are still not constrained due to the lack of data at different excitation energies. The experiment described in this work combined fission with quasi-free (p,2p) reactions, which allows to determine the excitation energy with stable and exotic nuclei. Thus, the new dataset will provide very valuable data to constrain the suppression function parameters. Another interesting question is the possible dependence of the energy sorting of the fission fragments on the excitation energy of the compound nucleus, since in direct kinematics studies with neutrons, the well known saw-tooth shape shows higher neutron multiplicities for higher incident neutron energies [9].

The ultimate scientific goal of this work is to investigate the energy dependence of the fission yields by using quasi-free (p,2p) reactions. Such data can be obtained combining the previous experimental setup with a silicon tracker based on AMS-type detectors [10] and the calorimeter CALIFA (CALorimeter for In-Flight detection of γ rays and high energy charged pArticles) [11].

2 Experiment

This report is based on the first results obtained in an experiment performed at GSI in March 2021, by using a primary beam of ^{238}U delivered by the SIS18 synchrotron, which was guided to the experimental area and impinged on a liquid hydrogen target to produce quasi-free (p,2p) reactions at 560 MeV/u. The employed technique was the so-called inverse-kinematics, in which the heavy nucleus undergoing fission takes the role of projectile while the target is constituted by lighter nuclei. This methodology was developed at GSI and represents a major breakthrough in the characterization of fission fragments. The major advantage is that the fission fragments are emitted in a narrow cone in the forward direction with very high velocities, permitting to detect both fragments at the same time and to measure the isotopic yields. Using this methodology, previous fission experiments at GSI already provided complete isotopic identification of both fission fragments simultaneously [3, 4].

Since the main goal is to study the excitation energy dependence of the fission yields, the excitation energy is obtained via the aforementioned quasi-free (p, 2p) reactions, which are knockout reactions between protons of the target and protons bound in the heavy projectile nucleus. The products of the reaction are the two outgoing protons and the excited compound nucleus characterized by the particle-hole excitations created by the removed proton. This excited compound nucleus can then de-excite via fission or neutron evaporation. From the measurement of the four momenta of the two outgoing protons the excitation energy of the compound nucleus can be reconstructed using the missing energy method [12].

The experimental setup is displayed in the Fig 1. The detectors named as "MWPCs" in the scheme are multi-wire proportional chambers, which serve to track the trajectories of the particles along the setup. The "MUSIC" detectors are Multi-Sampling Ionization Chambers, used to obtain the charge of the ions by measuring the energy loss when they pass trough the gas filling the chambers. The time of flight is measured by two plastic scintillator detectors, one located before the target (named as "Star" in the scheme) and the ToF-Wall at the end of the setup. After the start scintillator, the ^{238}U beam enters the vaccum chamber and impinges onto the LH_2 target, where the (p, 2p) reaction takes place. To reconstruct the trajectory of the two protons, a silicon tracker is located inside of the chamber right after the target. The tracker includes two arms, each of them consisting of an array of three AMS-type [10] 0.3 mm thick double-sided silicon-strip detectors. To measure the energy of the protons, the CALIFA calorimeter [11] is placed surrounding the vaccum chamber. CALIFA consists of 1504 CsI(Tl) crystal scintillators covering a polar angle range between 22 and 90 degrees. After fission, the two fragments continue moving in the forward direction passing through the rest of the setup. The Twin-MUSIC ionization chamber is designed with two independent ionization chambers, and those two are divided into two sections, each one segmented into 16 anodes. This design allows to measure the atomic number of both fission fragments in coincidence. The two MWPCs, located upstream and downstream from the Twin MUSIC, serve to determine the horizontal angle of the fission fragments inside the Twin. Once inside the GLAD dipole, the fragments will follow different trajectories according to their magnetic rigidities. After GLAD, another MWPC measures the final positions of the fragments and the ToF-Wall detector composed by 28 plastic scintillators provides the time of flight with respect to the start signal. Neutrons emitted from the fission fragments are detected in NeuLAND (New Large-Area Neutron Detector) [13], located 15m downstream from the target. Using the measurements of charge, time of flight and trajectory, the mass of the fission fragments can be obtained employing the $\Delta E - B\rho - ToF$ technique, allowing therefore for full isotopic identification.

3 Results

Data analysis begins with the charge identification of both fission fragments given by the Twin-MUSIC. The correlation of the derived charges for both fission fragments Z_1 and Z_2 is shown in the Fig. 2 (top) in a two-dimensional cluster plot. Each diagonal of clusters in this figure corresponds to a different fissioning system produced in the reaction, and each cluster on the diagonal corresponds to a different pair of resulting fission fragments. Since the beam is $^{238}_{92}$U, when the desired quasi-free (p,2p) reaction takes place the excited compound nucleus is $^{237}_{91}$Pa, which corresponds to the diagonal of clusters enclosed by the red line. Nevertheless, it is important to notice that this diagonal does not only consist of ^{237}Pa systems, it contains also the contributions from other lighter Pa isotopes as well, since the ^{237}Pa can also de-excite via neutron emission and undergo fission after. It is also possible to obtain different excited Pa isotopes when the reaction inducing fission is not a quasi-free process. A selection of 80 degrees in the opening angle between the two protons serves to select and differentiate the quasi-free events.

If the charges Z_1 and Z_2 are added for each diagonal in this plot, the result is the distribution of the fissioning systems, which is shown in the Fig. 2 (top) inset. The peak with the highest statistics in the plot corresponds to $Z_1 + Z_2 = 91$ (Pa), and the peaks of the distribution are clearly observed for fissioning systems charges ranging from 80 to 94 (both included). The two peaks to the right of the 91 peak correspond to reactions in which neutrons might have

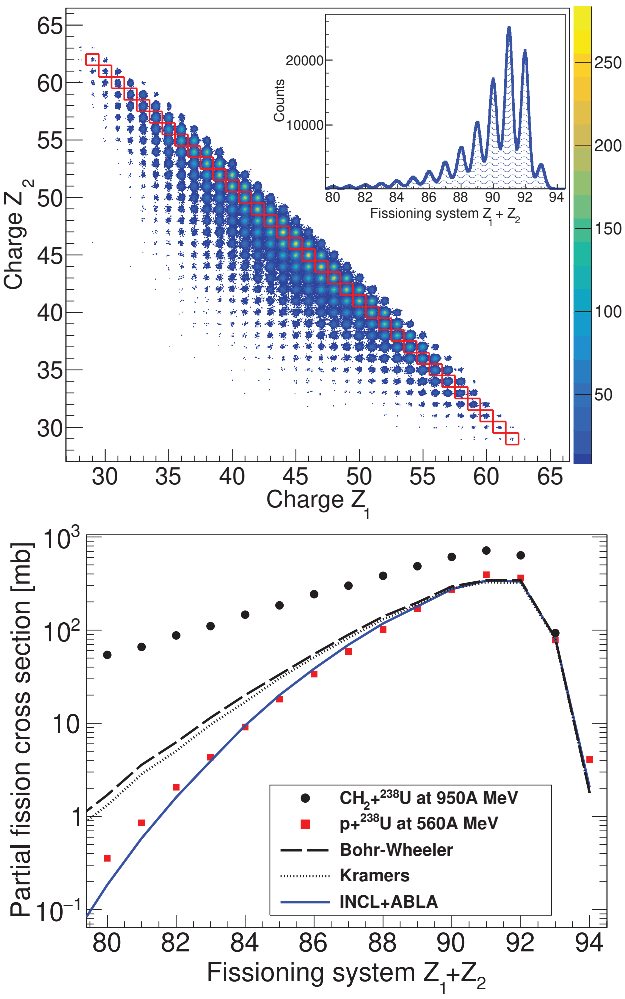

Figure 2. Top: Two-dimensional cluster plot of the charges Z_1 and Z_2 of both fission fragments for all fissioning systems. The inset shows the fissioning system distribution. Bottom: Partial fission cross sections for the different fissioning systems produced in this experiment (red squares, p+^{238}U) and comparison with theoretical models and fragmentation experimental data for the reaction CH_2 + ^{238}U at 950 MeV/u. .

been kicked out of the projectile nucleus, but no proton was removed. In particular, the systems with charge 93 correspond to the less likely case in which the projectile picks up one proton from the target. The peaks to the left of 91 originates from fissioning systems in which more than one proton was removed from the projectile when the (p, 2p) reaction took place.

The Fig. 2 (bottom) shows the fission cross sections for each fissioning system. To obtain this information, the statistics of each peak in Fig. 2 (top) inset is normalized to the total fission cross section measured in the present experiment, derived from an integration over all events where two fission fragments hit the ToF-Wall. The results obtained in this work are represented by red squares and compared with several theoretical models. The dashed line corresponds to the Bohr-Wheeler statistical model [14], the earliest attempt to describe fission. The dotted line corresponds to the Kramer's stationary solution [15], who pointed out that the fission rates provided by the statistical model might be overestimated by not taking into account the energy dissipation from intrinsic to collective degrees of freedom. Thus, a description of fission as a diffusion process was proposed. The experimental data from this work are compatible with the theoretical preditions by INCL+ABLA [16, 17] (solid line). This calculation describes the reaction and the following de-excitation processes as fission, by using a dynamical description based on the Fokker-Planck equation. This kind of dynamical model introduces a transient time at high excitation energies that delays the fission and thus lowers the fission rates in comparison with the precedent models. In addition, the data from this work are also compared with the data for the reaction CH_2+^{238}U at 950 MeV/u [18] (dots). In this case, fission is induced mainly after abrasion processes, which are more violent than the spallation ones used in this work, and thus it comes more likely that more nucleons are removed from the compound nucleus, resulting in larger partial fission cross sections for the lighter fissioning systems.

4 Conclusions

The first (p,2p)-fission experiment has been carried out at GSI/FAIR with projectiles of ^{238}U at energies of 560 MeV/u impinging on a liquid hydrogen target. The R^{3}B experimental setup allows to measure all the reaction products event by event. These complete kinematics measurements enable to correlate the fission yields with the excitation energy of the fissioning compound nucleus and to study the energy sharing between the two fission fragments. Additionally, this experiment permits to develop the data analysis and validate the methodology to use this approach in future experiments with exotic nuclei. At the current stage of the analysis the charge identification is completed and the fission cross sections for each fissioning system have been deduced and found to be compatible with theoretical calculations. The next steps will be the identification in mass number and the reconstruction of the excitation energy spectrum. In the near future further (p,2p)-fission experiments are planned to be carried out with exotic neutron-rich projectiles close to the neutron shell N=152 to obtain their fission yields and fission barrier heights for constraining r-process calculations.

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