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1. Introduction.

The evolution of a nucleus from its ground state until its scission into two fragments is governed by the variation of its potential energy as function of few relevant degrees of freedom as deformation and mass asymmetry. Two important deformation values are the ones corresponding to the saddle point, defining the fission barrier, and the scission point where the nucleus splits. The characterization of this potential energy is then crucial for the understanding of the fission process.

From an experimental point of view we can use few observables to characterize this potential energy. Fission probabilities give us access to fission barriers and the saddle point, fission yields provide information on the influence of the mass asymmetry degree of freedom, and kinetic energies of the fragments characterize its deformation at the scission point. Moreover, neutrons emitted by the fission fragments can be used to understand the energy sharing between the fragments, and gamma rays provide information on angular momentum.

Fission yields are interpreted in terms of fission modes, the so called super long or symmetric splitting and two asymmetric ones known as standard I and standard II [1-2]. The mass asymmetry of the final fragments, and then the origin of these fission modes, has been attributed to the quantum-mechanical nature of the atomic nucleus, in particular to its shell structure and the increase in binding energy caused when the proton and neutron composition of the fragments coincides with shell closures. According to this interpretation, the asymmetric splitting of actinides was understood as due to the double-shell closure around ^{132}Sn (Z=50 and N=82) together with the deformed shell closure at N~86. This interpretation also explained the symmetric narrow mass yields observed in ^{258}Fm. The symmetric mode can be explained in terms of a macroscopic approach (liquid-drop energies) and it becomes dominant as the excitation energy of the fissioning nucleus increases.

This interpretation of the asymmetric fission yields was questioned first by the observed dominance of partitions around Z=54 [3], and then by the unexpected asymmetric mass yields in ^{180}Hg [4]. Advanced model calculations based on the time-dependent Hartree-Fock approach [5,6] reconciled both pictures showing the strong impact of octupole-deformed shells at Z(N)=52,56 in fission. Since then, an intense activity on measuring fission yields is ongoing [7-11].

The new progress in measuring fission yields was mainly due to the use of the inverse kinematic technique to investigate fission [3]. The kinetic boost of the fission fragments makes it possible to overcome the impossibility of measuring the atomic number of the heavy fission fragment when produced at rest because of the fluctuations of the ionic charge state in energy-loss measurements of nuclei with high Z. This technique also gave access for the first time to the complete identification in atomic and mass number of both fission fragments [12]. Moreover, one can take advantage of fragmentation reactions induced by 238U projectiles at relativistic energies to produce a broad range of non-stable fissile nuclei that can be investigated [3]. The only limitation of this technique is the characterization of the fissioning nuclei in excitation energy.

The aim of subtask 2.5.2 was to demonstrate the validity of quasi-free proton knockout (p,2p), as a subrogate reaction, to investigate fission barriers and isotopic fission yields in inverse kinematics having access to the excitation energy of the fissioning nuclei. The idea is that using (p,2p) reactions the accurate measurement of the momenta of the two outgoing fragments can be used to determine the missing energy (excitation energy) of the reaction. It was then proposed to perform an experiment at the GSI/FAIR facility where the fission of ^{237}Pa would be investigated, impinging beams of ^{238}U at 500A MeV on la liquid-hydrogen target. One of the main outcomes of the experiment will be the investigation of the evolution of the fission yields with the excitation energy. This measurement was presented and approved by the GSI/FAIR PAC in 2019. The experiment was performed in March 2021, with almost one year delay with respect to the initial schedule because of the Covid-19 pandemic.

2. Experiment.

The purpose of the experiment was to perform complete kinematic measurements of the fragments produced in quasi-free proton scattering induced-fission of relativistic ^{238}U projectiles impinging a liquid-hydrogen target. These measurements require a complex experimental setup (see Fig. 1) to fully identify in atomic and mass number the two fission fragments but also to accurately determine the momenta of the two outgoing protons to reconstruct the missing mass of the reaction (excitation energy of the fissioning nucleus). Because of the Lorentz boost, the two fission fragments fly forward and can be identified in atomic number from the measurement of their energy loss, in a double Multi-Sampling Ionization Chamber (Twin_MUSIC), and their velocity from time-of-flight measurements using a start plastic scintillator and a large-area ToF-wall. The mass number of the fragments is obtained from the determination of their magnetic rigidity, using the large acceptance superconducting GLAD dipole, a high resolution (~200 μm) tracking the trajectories of both fragments with multi-wire proportional chambers (MWPC), and with accurate time-of-flight measurements (~40 ps). These measurements will also provide the kinetic energies of both fission fragments.

The two outgoing protons are tracked with a two-layer silicon tracker with 2D segmentation and a pitch of 65 μm. The total energy of these protons is measured with a resolution of around 1% with the Califa calorimeter, composed for this experiment by more than 1500 CsI crystals. Moreover, the double gained of the Califa electronics make it possible to measure also gamma rays emitted in coincidence. The NeuLand neutron detector provides also the detection of neutrons emitted during the fission process. The measurement of the neutron multiplicity as function of the excitation energy will allow investigating the energy sorting between the two fission fragments.

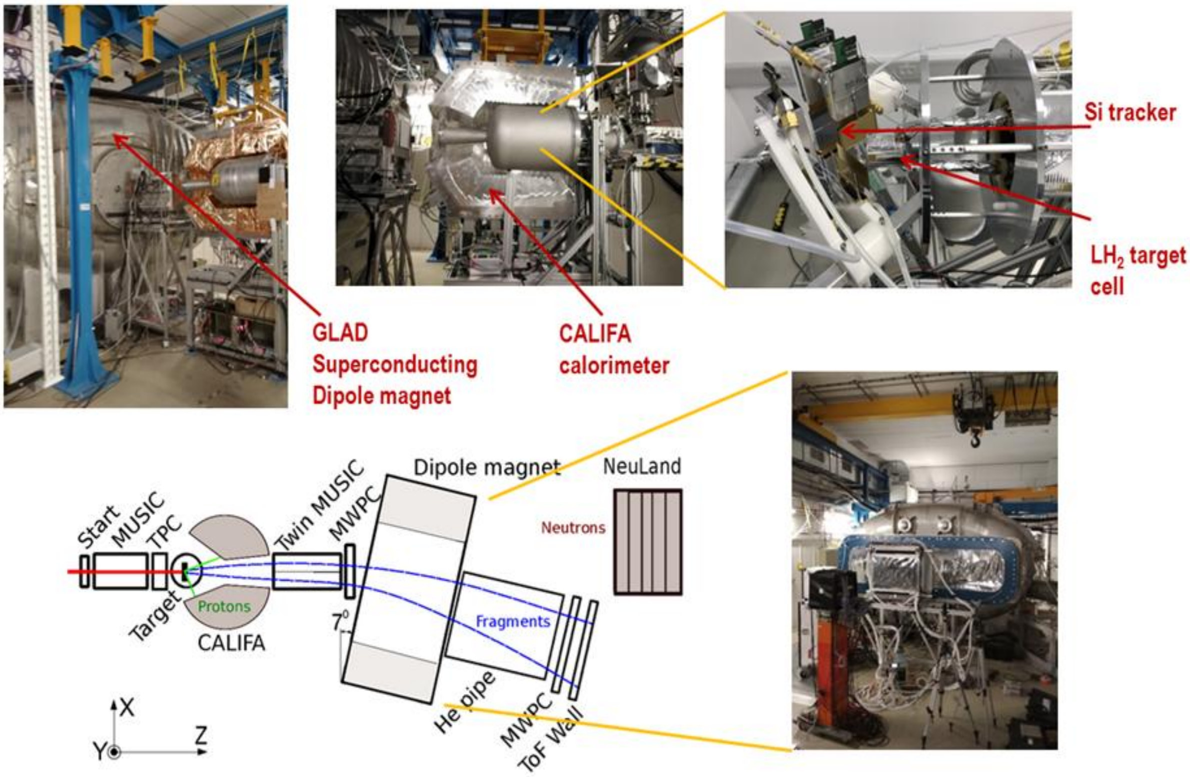

Figure 1. Schematic representation of the full experimental setup and pictures of some of the key detection systems.

3. Results.

The main results obtained so far are the identification in atomic number of the two fission fragments produced in the reaction $^{238}U(p,2p)$fission and the identification of the two outgoing protons with the Califa calorimeter. The atomic number of the two fragments was determined from the measurement of their energy loss in the TWIN-MUSIC ionization chamber and their velocities from time-of-flight measurements. Fig. 2 shows a scatter plot of the atomic numbers of the two fragments identified in all fission reactions produced in collisions of ^{238}U projectiles at 500A MeV with protons. In the left panel of Fig. 3 we display the sum of the atomic numbers of both fragments, and in the right panel the distribution in atomic number of the fission fragments produced only in (p,2p) reactions ($Z_1+Z_2=91$). As observed the atomic numbers are determined with a resolution of $\Delta Z\sim0.4$.

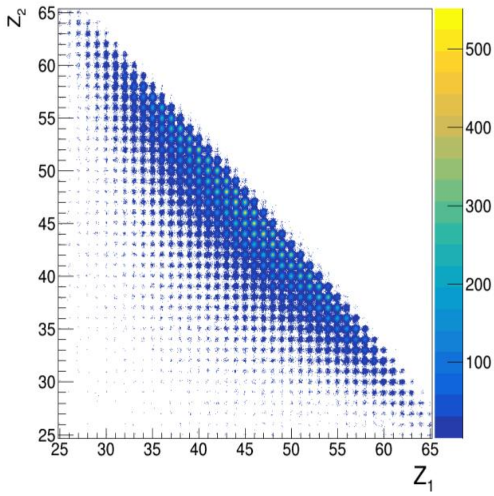

Figure 2. 2D correlation plot of the atomic numbers of the two fragments produced in all fission reactions induced by ^{238}U projectiles at 500A MeV impinging a liquid-hydrogen target.

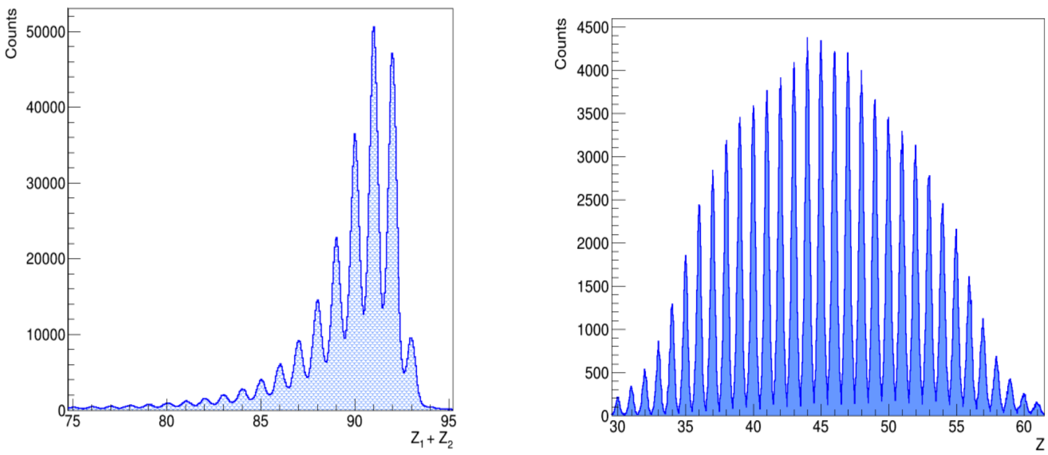

Figure 3.Left panel; Sum of the atomic numbers of the two fission fragments. Right panel; Atomic number distribution of the fission fragments fulfilling the condition of a proton knock out reaction ($Z_1+Z_2=91$).

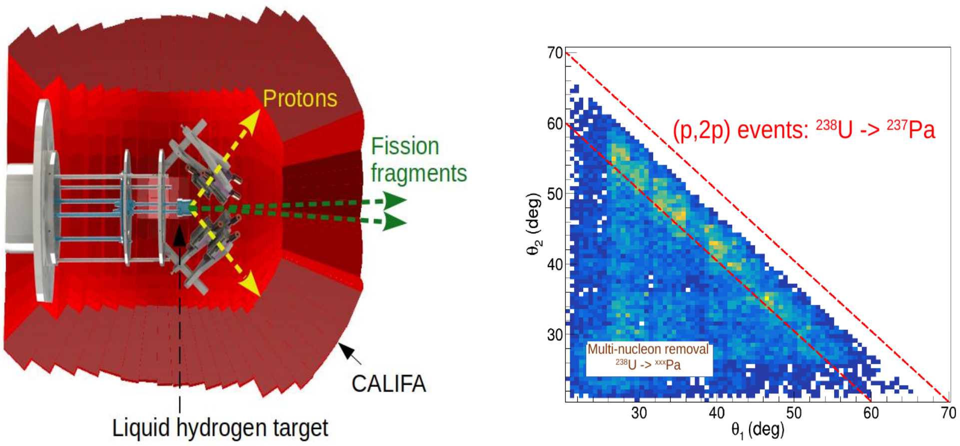

Figure 4.Left panel; schematic representation of the detection of the two protons produced in (p,2p) reactions using the silicon tracker and the calorimeter CALIFA. Right panel; measured correlation between the polar angles of the two protons produced in ^{238}U(p,2p) reactions at 500A MeV.

The two protons produced in the (p,2p) reactions were identified using the Califa calorimeter as illustrated in the left panel of Fig. 4. In the right panel of Fig. 4 we report the polar angle correlation between these two protons. The free (p,2p) scattering would correspond to a value of the relative polar angle of 90^{o}. Because of the kinematic conditions in our experiment the observed maximum value of relative polar angle around 80^{o} corresponds to the (p,2p) quasi-free scattering. Those are reactions where the knocked out proton from ^{238}U scapes without interacting with the other nucleons, producing a hole in the Fermi energy distribution of the nucleons in ^{238}U. The difference in energy between the orbital occupied by the knocked out proton and the Fermi level corresponds to the excitation energy gained by the residual nucleus, ^{237}Pa, undergoing fission.

All other cases with a relative polar angle between the two protons smaller than 80^{o} correspond to collisions where the knocked out proton rescatters with other nucleons in ^{238}U. This rescattering increases the excitation energy gained by the residual nucleus, ^{237}Pa. This effect is illustrated in Fig. 5 where we represent the measured distribution in atomic number of the fission fragments produced in ^{238}U(p,2p) reactions for different values of the relative polar angle between the two protons. As can be seen, in quasi-free (p,2p) reactions ($\Delta\theta$ ~80^{o}, left panels) the distribution in atomic number of the fragments is asymmetric, as expected for low-energy fission. However, when rescattering occurs (($\Delta\theta$ <80^{o}, central and right panels) the distribution becomes symmetric as expected for higher energy fission. Indeed we observe how the larger the rescattering (the lowe the relative value of the polar angle), the more symmetric is the distribution in atomic number of the fission fragments and the higher the excitation energy of the fissioning nucleus.This result clearly demonstrates how we can use (p,2p) reactions to select the excitation energy of the fissioning system.

Another important result is the cross section for fission-induced in proton quasi-free scattering on ^{238}U which amounts to some 25 mb. This value is relatively small compared to neutron-induced fission but still sufficiently large to perform statistically significant measurements with stable and unstable beams in a reasonable time.

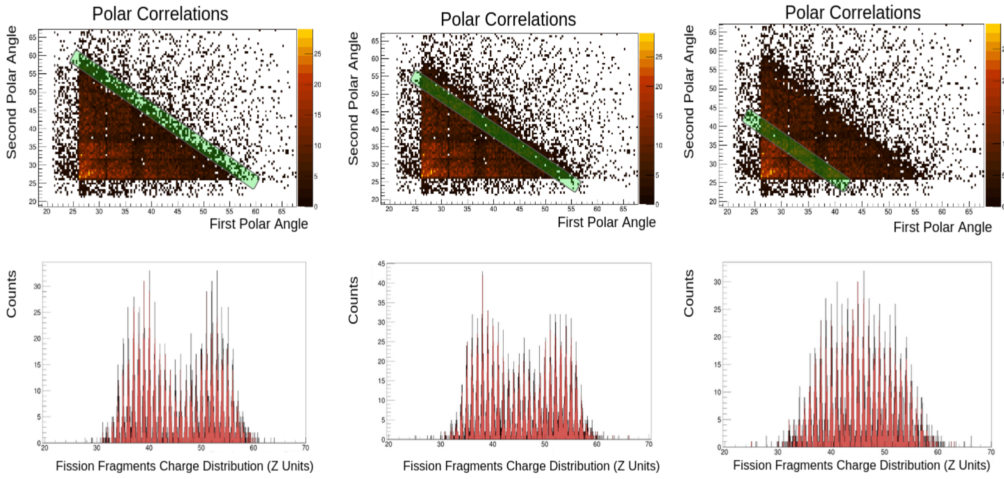

Figure. 5. Upper panels: Relative polar angle between the two outgoing protons in ^{238}U(p,2p) reactions. Lower panels. Distribution in atomic number of the fission fragments as function of relative polar angle between the protons (larger to smaller relative angles from left to right).

4. Conclusions.

A pioneering experiment to investigate fission using quasi-free proton scattering on heavy nuclei in inverse kinematics was successfully conducted at GSI/FAIR in March 2021. The complex and advances experimental setup used in this experiment makes possible for the first time complete kinematic measurements where all reaction products are fully identified and their momenta accurately determined. In particular, the two outgoing protons and fission fragments are fully identified in atomic and mass number, and their kinetic energies are accurately determined. Moreover, neutrons and gamma rays emitted in coincidence are also identified and their energies measured with good accuracy.

At the present stage of the data sorting we have obtained and excellent resolution measurement of the atomic number of the two fission fragments. The two outgoing protons have also been identified and their angle and momenta determined with the Califa calorimeter. The scatter plot between the polar angles of the two outgoing protons shows a clear correlation for relative angles around $\Delta\theta \sim 80^{o}$, which is a clear signature for the quasi-free scattering of protons in the reaction ^{238}U(p,2p).

The charge distribution of the fission fragments produced in proton knock out reactions on ^{238}U shows a symmetric and broad distribution while low energy fission of ^{238}U produces an asymmetric distribution. This difference is explained by the relatively high excitation energies induced by the proton knock-out process. The selection of fission events induced by quasi-free scattering ($\Delta\theta \sim 80^{o}$) shows, however, an asymmetric charge distribution of the fission fragments.

Next steps in the data sorting are the identification in mass number of the fission fragments, the determination of the excitation energy induced in the reaction from the accurate determination of the momenta of the two outgoing protons using the silicon tracker, the identification of neutrons with the NeuLand detector, and the measurement of the gamma rays with the Califa detector.

Despite the sorting of the data is still ongoing, the results obtained so far confirm that quasi-free proton scattering can be used to induce fission at low excitation energies with cross sections sufficiently large (~25 mb) to use this technique to investigate low-energy fission in complete kinematic measurements in inverse kinematics for a large range of stable and unstable fissile nuclei. These measurements will open the possibility for systematic measurements of fission barriers and fission yields but also to the characterization of neutrons and gamma rays emitted in coincidence.

References.

[1] U. Brosa, Phys. Rev. C 38, 1944 (1988).

[2] F.-J. Hambsch et al., Nucl. Phys. A 491, 56 (1989).

[3] K.-H. Schmidt et al. Nucl. Phys. A 665, 221 (2000).

[4] A.N. Andreyev et al., Phys. Rev. Lett. 105, 252502 (2010).

[5] G. Scamps and C. Simenel, Nature 564, 382 (2018).

[6] G. Scamps and C. Simenel, Phys. Rev. C 100, 041602(R) (2019).

[7] I. Tsekahnovich et al., Phys. Lett. B 790, 583 (2019).

[8] B.M. Swinton-Bland et al., Phys. Rev. C 102, 054611 (2020).

[9] E. Prasad et al., Phys. Lett. B 811, 135941 (2020).

[10] A. Chatillon et al., Phys. Rev. Lett. 124, 202502 (2020).

[11] C. Schmitt et al., Phys. Rev. Lett. 126, 132502 (2021).

[12] E. Pellereau et al., Phys. Rev. C 95, 054603 (2017).