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Study of (p,2p) fission reactions in inverse kinematics using the R3B set-up.

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Abstract. A new experimental fission approach is presented in the context of the R^3B (Reactions with Relativistic Radioactive Beams) collaboration, at the GSI/FAIR facility, in which knockout reactions in inverse kinematics are used to induce fission of ^{238}U that will allow to characterise the excitation energy of the fission process and all the fission products. The CALIFA (CALorimeter for In-Flight detection of γ-rays and high energy charged pArticles) calorimeter, a key part of the R^3B set-up, is used to reconstruct the momenta of the two protons from the (p, 2p) reactions. Preliminary results show that kinematic variables and first estimates for nucleon-removal cross sections are well reconstructed and in good agreement with other experimental measurements.

1 Motivation

Nuclear fission has been used as a tool for the study of nuclear properties since its discovery in 1939 by O. Hahn, F. Strassmann and L. Meitner after the irradiation of uranium nuclei by neutrons [1, 2]. The process can be understood as a complex mechanism in which a heavy nucleus splits into two smaller fragments, releasing a large amount of energy (compared with another nuclear reactions) and lighter particles, such as γ-rays and neutrons. The fission mechanism is governed by intrinsic and collective degrees of freedom. The latter can be divided into macroscopic and microscopic processes. The fission path followed by the system until it reaches the scission point is lead by a collective motion of its constituents and deformations, such as the elongation and mass asymmetry. In particular, at low excitation energies, the way the nucleus splits after the saddle point is strongly affected by its nuclear shell structure [3].

With the advance of nuclear reactions in inverse kinematics it was possible for the first time to measure

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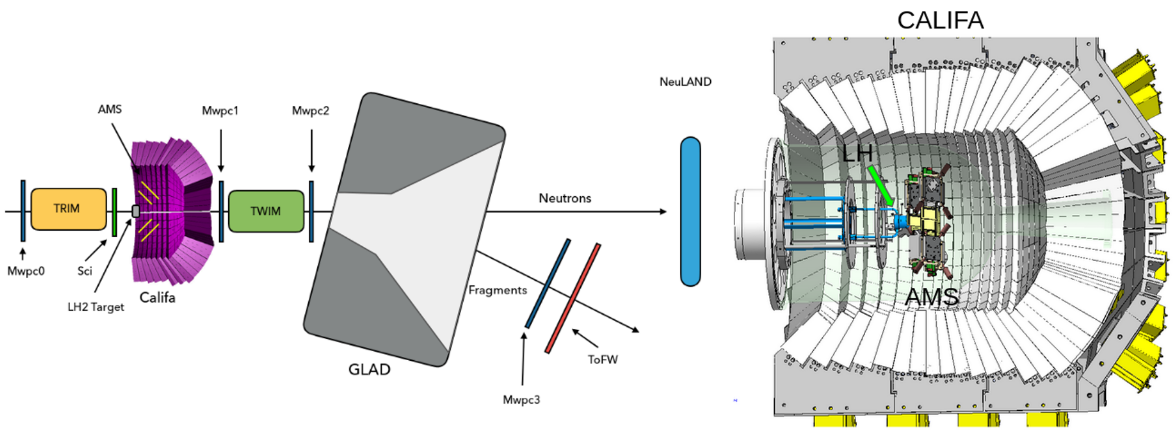

Figure 1: **(Left)** Top schematic view of the experimental set-up, in which the beam enters from left and impinges on the LH_2 target. Sizes are not to scale. **(Right)** CAD drawing of the CALIFA calorimeter, together with the AMS-type detectors and the LH_2 target.

simultaneously both fission fragments in terms of their charge and mass numbers [4, 5], which allowed for a complete kinematics measurement of the fission process. Such experiments made it possible to extract correlations between fission observables sensitive to the dynamics of the fission process at high excitation energies [6, 7] and to the nuclear shell structure at low excitation energies [8, 9]. With the development of new radioactive beam accelerator facilities more exotic nuclei are at the disposal of the experimentalists but, as they are typically short-lived rare isotopes, new methods are needed to measure fission barriers heights and fission yields. Coulomb-induced fission can be used to investigate fission of exotic nuclei at low excitation energies taking advantage of inverse kinematics, but the lack of reaction products prior to fission and the absence of information about the impact parameter makes not possible to study and characterize nascent fragments as a function of the excitation energy, which is assumed to be in a certain range. Transfer-induced fission allows a precise reconstruction of the excitation energy, but the cross section is much lower [10] compared with knockout reactions and the reaction is more peripheral, exploring only the outer shells of the nuclei.

Single-nucleon knockout induced fission reactions would overcome some of these limitations, allowing the study of this fission process at low excitation energies. At sufficiently high beam energies, quasifree scattering reactions become possible, with a strong localized interaction in which the knockout proton leaves a single hole state, producing an excited nuclear remnant, being this excitation released in the subsequent fission. The measurement of the two proton momenta allows to determine the excitation energy of the remnant prior to fission on an event-by-event basis and therefore a study of key fission observables, such as the mass and charge of both fission fragments, evaporated neutrons and fission probabilities, as function of the excitation energy.

2 Experiment

The experiment was carried out at GSI on March 2021 using the R³B experimental set-up located at Cave-C, as shown in Fig. 1 (left). A primary beam of ^{238}U at 560 AMeV was delivered to the Cave from SIS18 impinging onto a 15-mm liquid hydrogen target. The CALIFA calorimeter [11, 12] is used together with a silicon tracker based on AMS-type detectors [13] to provide angular, energy and vertex reconstruction of the two scattered protons. The charge and the horizontal angle of the two nascent fragments is then measured by a double multi-sampling ionization chamber (Twin-MUSIC) detector [14]. Several multiwire proportional chambers (MWPC's) [15] are placed along the set-up, so a precise tracking of the beam and the fragments is possible. The large-acceptance superconducting dipole magnet GLAD bends the trajectory of each fragment, which in combination with a Time-of-flight wall [16] allows a mass spectroscopy study of the fragments. Finally, the NeuLAND (Large Area Neutron Detector) [17] can be used to reconstruct the neutron kinematics and to obtain the neutron multiplicities.

The CALIFA detector is composed of 2432 CsI(Tl) detection units (1504 currently installed) with right-pyramid frustum shape, and lenghts varying from 14 to 22 cm. A carbon-fibre structure acts as a honeycomb-like holder for the crystals. Each crystal is coupled on its back to a Large Avalanche Photo-Diode (APD) that collects the light output in the material. The detector is divided into two different parts. The barrel part has a cylindrical shape and is made of 1952 crystals, covering from 43° to 143° (right now up to 90°) in polar angle. The end-cap part comprises

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480 crystals with more irregular shapes, covering the range from 21° to 43°. This part is equiped with double-ranged preamplifiers, so both γ-rays and protons can be reconstructed using the same electronics and analysis software, whereas the barrel electronics only allows for a single-gain range that, for the present experiment, was set to the proton range.

3 Data analysis and results

After a proper calibration of the TWIM Music [18] and the CALIFA detector, the preliminary analysis of the reaction confirms that the proton pair can be properly correlated with the fission fragment charge distribution. Each proton is measured in coincidence in the CALIFA detector, so a kinematic line and an opening angle can be extracted.

The analysis comprises two reaction channels:

1. The knockout of a proton before fission: $^{238}U(p,2p)^{237}Pa$ + Fission.
2. The knockout of a proton and evaporation of neutrons, without fission: $^{238}U(p,2p)^{X}Pa$.

The observation of the two channels results in two very different opening angle distributions, as it can be seen in Figs. 2a and 2b. No fission events are more likely to come after a clean knockout of a proton from ^{238}U (i.e quasifree) with lower excitation energy, while fission events are produced mostly after a rescattering inside the incoming nucleus, so more energy is at disposal of the remanent making fission more probable. Selecting events with the quasifree condition, as illustrated in Fig. 3(a), in the fission channel and correlating then with the fragment charge distribution gives the evolution presented in Fig. 3(b) and 3(c) for quasifree and multi-knockout reactions, respectively. This proves that quasifree knockouts produce an asymmetric distribution of the fragments, with a larger contribution from the standard I and standard II fission modes, while a cut in the rescattered events shows a more symmetric distribution, with more contribution from the "super-long" (SL) fission mode. The next step would be then to reconstruct the reaction vertex and fine momenta of the scattered proton pair, so a direct calculation of the excitation energy can be performed using an invariant mass approach, as described in Ref [19].

3.1 Cross sections

Preliminary cross sections have been obtained by imposing the condition of two proton hits in the CALIFA calorimeter and, in the case of fission reactions, of two fission fragments in the spectrometer. For the fission channel selection we require fissioning systems with charge 91, which corresponds to fission fragments that fulfill the condition $Z_1+Z_2=91$. Additionally, we also request two hits in the segmented ToF wall located at the end of the R³B setup since it provides the fission trigger. The results obtained for the cross sections are listed in Table 1, which also includes the cross section measured in previous experiments performed with the GSI fragment separator.

Reaction	Cross sections (mb)
$^{238}U(p,2p)^{X}Pa$ (This work)	78 ±13
$^{238}U(p,2p)^{X}Pa$ ([20])	82.6 ±5.6
$^{238}U(p,2p) + Fission + QF$	24 ±8

Table 1: Preliminary cross section estimation for the two channels of interest. The uncertainties given for this work are purely statistical.

4 Conclusions

The first (p,2p)-fission experiment has been carried out at the GSI/FAIR facility with projectiles of ^{238}U at 560A MeV impinging on a liquid hydrogen target. The R³B experimental set-up is used to perform complete kinematics measurements of the reaction.
The reconstruction of the (p,2p) reactions with the CALIFA calorimeter shows the presence of two kinematical

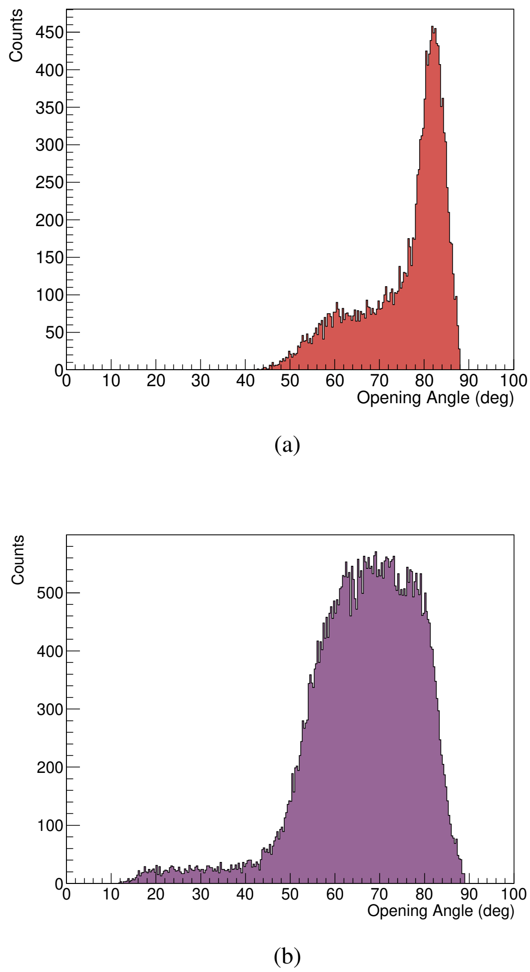

Figure 2: (a): Opening angle distribution for the two scattered protons in the case of a knockout without fission. (b): Opening angle distribution for the two scattered protons in the case of a knockout-induced fission.

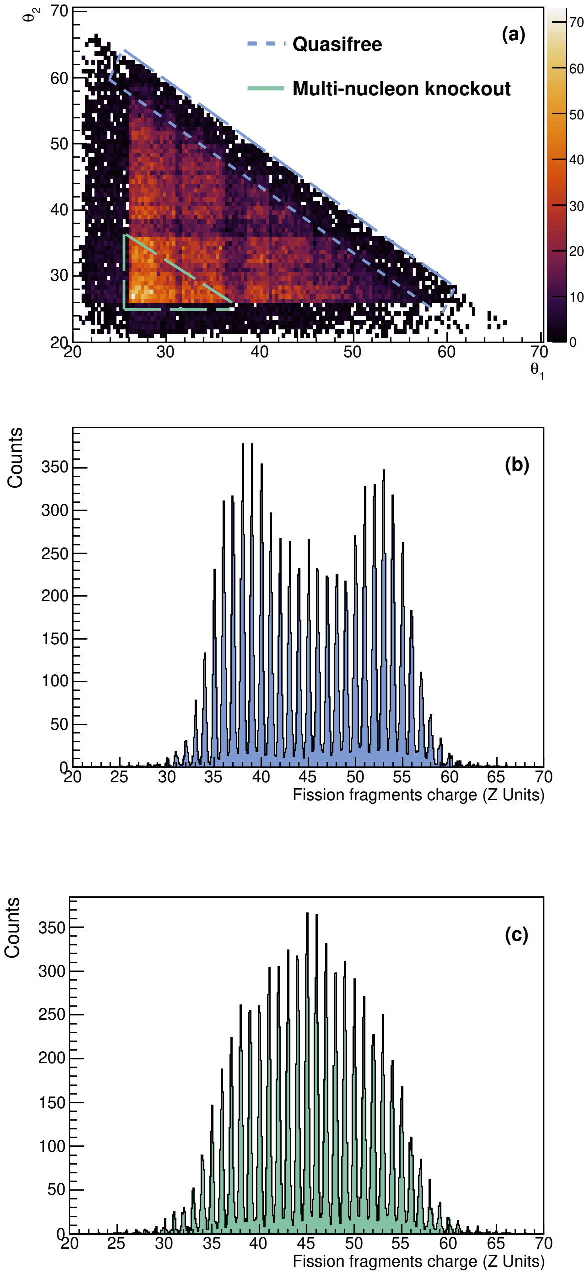

Figure 3: (a) Polar angle correlation of outgoing protons with the angular ranges selected to investigate the fission yields evolution with the opening angle. (b) Charge distribution for quasi-free (p,2p) fission reactions. (c) Charge distribution for multi-nucleon knockout reactions.

regions related to quasi-free scattering reactions close to opening angles of 80° and re-scattering at smaller angles. The correlation of these two kinematic regions with the charge distribution of the fission fragments shows a clear evolution from asymmetric to symmetric fission related to low and high excitation energies, respectively. Finally, inclusive cross sections for the two channels of interest have been extracted for the first time deploying the large acceptance and complete-kinematics capabilities of the R^3B set-up. This analysis proves the validity of the method for future studies with more exotic beams, allowing the study of fission observables as a function of the excitation energy.

Acknowledgments

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