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First inverse-kinematics fission measurements in a gaseous active target

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Abstract

The fission of a variety of actinides was induced by fusion and transfer reactions between a ^{238}U beam and ^{12}C nuclei, in the active target MAYA. The performance of MAYA was studied, as well as its capability to reconstruct the fission-fragment trajectories. Furthermore, a full characterization of the different transfer reactions was achieved, and the populated excitation-energy distributions were investigated as a function

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of the kinetic energy in the entrance channel. The ratio between transfer- and fusion-induced fission cross-sections was also determined, in order to investigate the competition between both reaction types and its evolution with the incident energy. The experimental results will be discussed with a view to forthcoming radioactive-ion beam facilities, and next-generation active-target setups.

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Keywords: Active target; Inverse kinematics; Fission; Surrogate reactions; Nucleon transfer; Fusion

1. Introduction

Accurate fission models remain today phenomenological [1], and they tend to fail when applied to unknown systems. Therefore, the requirements of fundamental and applied research in predictive power of models often remain unaccomplished. This status reflects the need of enlarging the body of data, and, more specifically, the number of fissioning systems available to experimental research.

From an applied perspective, many of the nuclei of interest for nuclear-energy applications are highly radioactive and difficult to study in the laboratory. Fundamental research reaches an even more exotic domain, and it requires model-dependent extrapolations. In nuclear astrophysics, the determination of reliable fission barriers and fission-fragment distributions is an urgent need for understanding nucleosynthesis processes [2]. Moreover, theoretical predictions of the fission barriers of exotic systems, whose existence would be caused by structural effects, drive the quest for superheavy nuclei [3].

In the framework of surrogate-reaction studies [4], nucleon-transfer reactions provide experimental access to fissioning systems that can not be investigated by standard neutron irradiation. This technique has been widely used to measure fission probabilities and to study actinide fission barriers [5]. It also allows the neutron-induced fission cross sections to be estimated when direct measurements are not available [6].

Transfer-induced fission experiments have traditionally employed very light projectiles, such as protons, deuterons, or helium, and actinide targets [7]. Under these circumstances, the transfer is restricted to a few nucleons, and only systems close to the limited available targets can be produced. A different approach has been developed at GANIL [8], which is based on an inverse-kinematics configuration. In a single experiment [9], the transfer of nucleons between a ^{238}U beam and a ^{12}C target produced a wide variety of neutron-rich fissioning systems. Using an accelerated heavy-ion beam, the kinematic boost of the fission fragments has brought new physical observables into the surrogate-reaction studies. Accurate measurements of the fission-fragment isotopic yields were performed [10,11], and unprecedented access to the scission-point configuration was obtained [12].

However, the excitation energy, the angular momentum, and the fission barrier of the compound nucleus influence its decay through fission [4]. In order to apply the data obtained via transfer reactions to scenarios where fission is induced by neutrons, the properties of the compound nucleus must be understood. Important examples of neutron-induced fission scenarios are nuclear reactors and, in the astrophysical domain, the r -process of nucleosynthesis.

In Ref. [9], the excitation-energy distributions and the fission probabilities of the actinides produced through $^{238}\text{U} + ^{12}\text{C}$ transfer reactions were measured. Additional information on the

reaction mechanism can be obtained by investigating the evolution with the incident energy [13, 14]. In a solid target experiment, the latter requires different energies of the primary beam.

Further development of transfer-induced fission experiments, in inverse kinematics, becomes particularly interesting in the view of the exotic heavy-ion beams expected at radioactive-ion beam facilities like HIE-ISOLDE [15]. A region between Tl and Pa isotopes will become accessible, in which the measurement of the fission barriers would be of major importance for the development of nuclear theories [16]. However, adapted experimental setups will be required, which allow to exploit relatively low beam intensities.

Active-target detectors, where the detection gas also acts as a target, appear as a promising choice to be explored. Such systems allow to increase the target thickness by one order of magnitude, with respect to solid target experiments. An additional advantage, unique to active targets, is that the slowing down of the beam in the gas allows to explore the evolution of the transfer mechanism with the incident energy, without the need of modifying the energy of the primary beam.

Furthermore, the two fission fragments can be simultaneously recorded, and a three-dimensional view of the process can be obtained on an event-by-event basis.

The aforementioned projects will imply challenging working conditions, which need to be first tested in the laboratory. The strong ionization induced by the beam could cause the malfunctioning of the setup [17]. Despite the risk of sparks and beam-induced signals, the space charge created by the beam could influence the electric drift field in the active volume, and the reconstruction of the trajectories would be distorted.

Moreover, the simultaneous detection of the transfer target-like products and fission fragments would exceed the dynamic range of the detector.

The present work is the first exploration of the capabilities of an active target to perform transfer-induced fission measurements, in inverse kinematics. The ^{238}U beam of GANIL was sent into the active target MAYA [18], and $^{238}\text{U} + ^{12}\text{C}$ transfer-induced fission reactions were analyzed.

In Secs. 2 and 3, the setup and the experimental procedure will be described. The data analysis and the results will be discussed in Secs. 4 and 5, respectively. The main technical aspects of the experiment, and the response of MAYA will be addressed. With a view to surrogate-reaction fission studies, the full reconstruction of transfer reactions will also be discussed. The latter provided the excitation energy of the fissioning system, which is crucial for the measurement of the fission-probability distributions and fission barriers [7,9]. The excitation energy populated by the transfer reactions was determined as a function of the kinetic energy in the entrance channel, and the competition between fusion- and transfer-induced fission cross sections was studied. The perspectives in a next-generation setup will be discussed in Sec. 6. Finally, the conclusions of this work will be summarized in Sec. 7.

2. Experiment

A ^{238}U beam was accelerated in the CSS1 cyclotron of GANIL [8] up to a kinetic energy of 6.55 MeV/u, and it entered the MAYA active target [18] through a 1 μm -thick Ti window. MAYA was filled with isobutane gas (iC_4H_{10}), at a pressure of 50 mbar.

Fusion reactions between ^{238}U and ^{12}C nuclei of the isobutane molecules produced ^{250}Cf with excitation energies between 36 and 49 MeV, depending on the location of the reaction vertex in the active target. Neutron-rich actinides ranging from U to Cm, with average excitation energies between 0 and 10 MeV, were obtained from the transfer of nucleons between ^{238}U and ^{12}C . In

Fig. 1. Transfer-induced fission event in the active target MAYA. An electrostatic mask along the beam axis protected the detection volume from the high ionization created by the ^{238}U beam. A two-dimensional image of the fission-fragment trajectories was provided by the pad plane, while the vertical coordinate was obtained from the electron drift times towards the amplification wires. The target-like transfer recoil was measured in 40, 500, and 700 μm -thick silicon detectors.

this case, the actinide products were accompanied by a target-like partner. Under the assumption of a binary reaction, the latter provided an unambiguous signature of each transfer channel.

Nuclear reactions between ^{238}U and ^1H were neglected. In the center-of-mass reference frame, the kinetic energy in the entrance channel barely reached half of the Coulomb barrier height, thus only electromagnetic interactions between ^{238}U and ^1H played a significant role.

The excited actinides produced in $^{238}\text{U} + ^{12}\text{C}$ fusion and transfer reactions decayed through fission with a certain probability. Fig. 1 shows the representation of a transfer-induced fission event in MAYA.

A detailed explanation of MAYA is provided in Ref. [18]. The electrons released by the fission fragments colliding with the atoms in the gas were driven by a strong electric field towards the amplification region, in the bottom of the detector. This region consisted of a grounded Frisch grid, and a set of amplification wires, which were parallel to the beam axis. A lower plane was occupied by 32×32 hexagonal pads of 5 mm side.

The electron cloud moving in the amplification region induced a signal in the pads, thus a two-dimensional projection of the fission-fragment trajectories was provided by the pad plane. The charge induced in the pads was treated by Gassiplex chips [19]. The readout was based on a *track and hold* procedure, in which the *track* signals were generated by the amplification wires.

Finally, the electron drift times towards the amplification wires provided the third spatial coordinate.

As represented in Fig. 1, three downstream walls of silicon detectors measured the energies and angles of the target-like products. The first wall was composed of eight double-sided silicon strip detectors (DSSSD), each 40 μm thick [20]. Each DSSSD had an area of $50 \times 50 \text{ mm}^2$, and was segmented in 16 front and 16 back strips of 3 mm pitch. Nine pad detectors, with an area of $70 \times 50 \text{ mm}^2$ each, and a thickness of 500 μm were placed behind. Finally, fifteen pad detectors,

with an area of $50 \times 50 \text{ mm}^2$ each, and a thickness of $700 \text{ }\mu\text{m}$ stopped the target-like products. A $177 \text{ }\mu\text{m}$ -thick mylar foil was placed in front of the DSSSD to protect the silicon detectors from being hit by the fission fragments.

3. Modifications to the MAYA setup

Specific modifications to the MAYA setup were required due to the high ionization created by the ^{238}U beam. Following the work of Ref. [17], an electrostatic mask was used to contain the electrons and positive ions produced by the beam, preserve the uniformity of the electric field, and minimize the risk of sparks in the detection volume.

The electrostatic mask is represented in Fig. 1 as a square tunnel around the beam axis. An upper and a lower plate, which were made of copper-clad epoxy FR4, acted as cathode and anode, respectively. They had a transverse dimension of 2 cm, and they were spaced 3 cm from each other. On both sides, tungsten wires maintained the gradient of voltage. A beam dump made of glass was located inside the electrostatic mask, at 220 mm from the MAYA entrance window.

In addition, the voltage on the cathode of MAYA was increased up to the sparking limit, so that the influence of a possible transverse electric field leaking out of the mask was limited.

3.1. Running modes during the experiment

Despite the electrostatic mask, sparks and beam-induced signals played a non-negligible role at high beam intensities, of approximately 10^6 pps. For this reason, two different running modes were considered, which divided the beam time in *fission* and *normalization runs*.

Fission runs. The beam intensity was increased up to several 10^6 pps, with the purpose of maximizing the fission rate. In order to withstand these intensity values, the voltage on the amplification wires, and thus the gain of MAYA, needed to be limited. As a consequence, only the fission fragments could induce a detectable track on the pads. The target-like products were only detected by the ancillary silicon detectors.

Normalization runs. The normalization of the fission data required the reconstruction of those reactions where the actinide product did not decay through fission. As shown in Refs. [7,9], this information would allow the determination of fission probabilities and fission barriers. However, the measurements of the target-like product provided by the ancillary silicon detectors were insufficient for a full reconstruction, and it was necessary to track the target-like nuclei in MAYA. Therefore, a higher amplification was used, which imposed a reduction of the beam intensity down to 10^5 pps.

4. Data analysis

This section addresses the analysis of the trajectories recorded in MAYA, and the full reconstruction of the $^{238}\text{U} + ^{12}\text{C}$ reactions. Different methods were applied for the analysis of fission and no-fission events. The first were mainly measured during the so-called fission runs, while the latter could uniquely be measured in the normalization runs.

4.1. Reconstruction of the fission events

A review of the main reconstruction algorithms developed for MAYA can be found in Ref. [21]. Among them, the Secant Hyperbolic Squared (SECHS) algorithm was used in this

Fig. 2. Fission event recorded during a fission run. Figure (a) shows the charge pattern on the MAYA pad plane, and the reconstruction of the two fission-fragment trajectories. The symmetry axis used by the SECHS algorithm is superimposed on each particle track. Longitudinal dashed lines indicate the borders of the electrostatic mask. Figure (b) shows the measurements provided by the amplification wires (Y), as a function of the position of each wire (X). The solid black line shows the reconstruction of the fission-plane angle (ϕ). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

work for the reconstruction of the fission-fragment trajectories on the pad plane. An example is provided in Fig. 2 (a). The SECHS method uses the intersection points of the particle trajectory with the symmetry axis of the hexagonal pads. Then, a linear fit provides the particle trajectory.

The reconstruction was completed by the drift-time measurements provided by the amplification wires. Using the electron drift velocity, these measurements were translated into position values. Then, the angle of the fission plane (ϕ) was determined, as shown in Fig. 2 (b). A discrepancy was observed between the results obtained for the two fission fragments. This effect was the consequence of a distorted electric field near the borders of the electrostatic mask, and it will be discussed in Sec. 5.1. A single fit of the two fission-fragment trajectories, in which only those amplification wires at more than 50 mm from the beam axis were considered, provided an accurate reconstruction of the azimuthal angle.

The reaction vertex was obtained as the intersection of the two fission-fragment trajectories on the pad plane. The vertical coordinate of the vertex was placed at the beam axis.

In order to reconstruct the $^{238}\text{U} + ^{12}\text{C}$ entrance channel, the energy lost by the ^{238}U projectiles in the MAYA entrance window and in the gas thickness crossed before the reaction occurred was taken into account. These calculations were based on LISE++ simulations [22,23].

Fig. 3. Transfer event recorded during a normalization run. Figure (a) shows the charge pattern on the MAYA pad plane, and the trajectory reconstruction. The latter included the position in the downstream strip detector (DSSSD), at $Z = 366$ mm. Longitudinal dashed lines indicate the borders of the electrostatic mask, while the vertical line shows the end of the MAYA active volume. Figure (b) shows the determination of the angle of the transfer-reaction plane (ϕ). The measurements provided by the amplification wires (Y) are represented as a function of the position of each wire (X).

In the exit channel of transfer reactions, the ensemble of ancillary silicon detectors was used as a telescope to isotopically identify the target-like products. As the latter were stopped in the 700 μm -thick silicon detectors, their total kinetic energies were also obtained. These measurements were corrected for the energy lost by the target-like nuclei in the gas, and in the mylar foil that protected the silicon detectors, which was also estimated using LISE++.

The angles of the target-like products were determined from the reaction vertex, and the positions measured by the silicon strip detectors.

4.2. Reconstruction of the no-fission events

As explained in Sec. 3, MAYA was operated with a higher amplification for measuring the target-like products. However, the risk of sparks and beam-induced signals limited the amplification that could be applied. In a significant number of cases, the signals induced in MAYA were below the detection threshold. Therefore, although a target-like nucleus was detected and identified in the ancillary silicon detectors, its trajectory could not be deduced.

Fig. 3 (a) shows the trajectory of a target-like product recorded in the pad plane. Longitudinal cuts can be observed, which were caused by the amplification and readout systems of MAYA.

In order to optimize the treatment of the pad-plane patterns, a dedicated algorithm was developed. As shown in Fig. 3 (a), an average position was calculated for each row of pads. A linear fit to these points was performed, which was conditioned by the position recorded in the silicon strip detectors.

By applying the aforementioned procedure, the trajectories of $8 \pm 5\%$ of the target-like products detected by the ancillary silicon detectors could be determined. This result is the average of the efficiencies obtained for the different target-like species, from ^4He up to carbon isotopes.

The reaction vertex was calculated as the intersection between the trajectory of the target-like nucleus and the beam axis.

The reconstruction of the transfer-reaction plane from the electron drift-times towards the amplification wires is provided in Fig. 3 (b). However, the three-dimensional scattering angle of the target-like nuclei was finally determined from the reaction vertex and the positions in the ancillary strip detectors. This choice allowed an accurate reconstruction, independent of the drift-time measurements, which were sometimes biased by beam-induced signals.

5. Results

5.1. Performance of the electrostatic mask

The ^{238}U beam lost approximately 20 MeV/cm along its path through the MAYA volume. As a result, approximately 7.7×10^5 electron-ion pairs/cm were created, per incident ion. For beam intensities of 10^6 pps, 7.7×10^{11} electron-ion pairs/cm/s were created along the beam axis. One of the purposes of the electrostatic mask was to avoid the distortion of the electric field in the detection volume, which would be induced by the space charge resulting from interactions of the beam with the gas.

The design of the electrostatic mask was previously tested in similar conditions, using a ^{136}Xe beam [17]. However, no drift-time measurements from the MAYA amplification wires were available at that time. In Ref. [17], the study of the electric-field uniformity was entirely based on the two-dimensional charge patterns recorded by the pad plane.

In the present work, complete three-dimensional trajectory reconstructions were achieved. The electron drift times were of particular interest. As shown in Fig. 2 (b), the expected back-to-back emission of the fission fragments was not reproduced by the experimental data. In Fig. 4, the angles of the fission plane reconstructed from ascending and descending fission-fragment trajectories show an average discrepancy of $4.2 \pm 0.3^\circ$.

Deformations of the electric field modified the trajectory of the ionization electrons. They produced an increase in the drift times towards the amplification wires near the borders of the electrostatic mask, which biased the ϕ reconstruction. As a result, the $|\phi|$ value was underestimated for the ascending tracks, and it was overestimated for the descending ones. The effect was stronger in the first, as the ionization electrons were more exposed to beam-induced field deformations.

As explained in Sec. 4.1, a simultaneous fit of the two fission-fragment trajectories, which only considered those amplification wires farther away from the beam axis, provided a correct determination of the ϕ angle. The difference between this fit and the measurement performed by each amplification wire is displayed in Fig. 5. This figure shows how the effect of the field deformations decreased as the distance from the beam axis increased. The influence of the field deformations reached a distance of 50 mm, while the maximum uncertainty induced in the wire measurements was approximately 4 mm. This last result represented 4% of the drift length from

Fig. 4. Comparison between the fission-plane angles reconstructed from the trajectories of the two fission fragments. The labels ϕ_{up} and ϕ_{down} represent the results obtained for the fission fragments emitted towards the upper and lower halves of the gas volume. Both fragments were simultaneously detected in each event. The red solid line represents $|\phi_{up}| = |\phi_{down}|$. The dashed black line represents $|\phi_{up}| = |\phi_{down}| - 4.2^\circ$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. The vertical axis represents the deviation of the drift-time measurements with respect to the reference trajectory. The latter corresponds to the fit of the experimental data, which excluded the amplification wires within a distance of 50 mm with respect to the beam axis. In the horizontal axis, the position of the amplification wires with respect to the beam axis is provided. The dashed line represents the average behavior of the data. No measurements were available from the wires covered by the electrostatic mask.

the horizontal plane including the beam axis. However, its influence on the trajectory reconstruction depended on the number of amplification wires that fired.

Furthermore, the ^{238}U beam induced signals in the vicinity of the beam axis, which were attributed to δ electrons in Ref. [17]. These signals were observed both in the normalization and in the fission runs, and they can be recognized on the charge patterns of Figs. 2 (a) and 3 (a).

Fig. 6 aims to determine the range of beam-induced signals, in the fission runs. The pads of MAYA were grouped in rows with respect to the beam axis. In (a) and (b), the number of fired pads and the total charge measured are represented as a function of the row position with respect to the beam axis, respectively. Beam-induced signals extended all along the longitudinal dimension of MAYA, thus they were characterized by the highest pad multiplicities.

Both in (a) and (b) of Fig. 6, the horizontal projection of a selected range of the vertical axis provided the size of the region affected by beam-induced signals. In average, the latter can be described by a distribution centered on the beam axis, with $\sigma = 16.1 \pm 0.9$ mm.

Fig. 6. Study of the beam-induced signals in the fission runs. In (a) and (b), the pad multiplicity and the total charge measured by each row of pads are represented as a function of the position with respect to the beam axis, respectively. The vertical dashed lines indicate the borders of the electrostatic mask. The horizontal dashed lines indicate the regions selected to investigate the range of beam-induced signals. The inset plots show the horizontal projections of these regions.

In Fig. 7, a similar analysis is provided for the normalization runs. In this case, the region of beam-induced signals can be described by $\sigma = 12.1 \pm 2.1$ mm.

5.2. Characterization of $^{238}\text{U} + ^{12}\text{C}$ transfer reactions

Fig. 8 shows the isotopic identification of the target-like products provided by the ancillary silicon detectors. The energy lost in the 500 μm -thick detectors is represented as a function of the energy lost in the 700 μm -thick detectors. Graphical cuts on this figure were used to select the different reaction channels: $^{12}\text{C}(^{238}\text{U}, ^{238}\text{U})^{12}\text{C}$, $^{12}\text{C}(^{238}\text{U}, ^{237}\text{U})^{13}\text{C}$, $^{12}\text{C}(^{238}\text{U}, ^{236}\text{U})^{14}\text{C}$, $^{12}\text{C}(^{238}\text{U}, ^{239}\text{Np})^{11}\text{B}$, $^{12}\text{C}(^{238}\text{U}, ^{240}\text{Pu})^{10}\text{Be}$, $^{12}\text{C}(^{238}\text{U}, ^{241}\text{Pu})^9\text{Be}$, $^{12}\text{C}(^{238}\text{U}, ^{242}\text{Pu})^8\text{Be}$, $^{12}\text{C}(^{238}\text{U}, ^{243}\text{Am})^7\text{Li}$, and $^{12}\text{C}(^{238}\text{U}, ^{246}\text{Cm})^4\text{He}$.

In the case of $^{12}\text{C}(^{238}\text{U}, ^{241}\text{Pu})^8\text{Be}$, as a result of the decay of ^8Be , two kinematically correlated ^4He nuclei were found in the exit channel. The pileup of these two ^4He products in the silicon detectors can be recognized in Fig. 8. When the two ^4He products hit the same 500 μm -thick and 700 μm -thick detectors, they populated the same region of the identification plot as ^7Li . The transfer channels were thus disentangled using the granularity of the silicon strip detectors.

In addition to the aforementioned reaction channels, protons were also identified in Fig. 8. These events, which were not in coincidence with fission, were assigned to the elastic scattering

Fig. 7. Study of the beam-induced signals in the normalization runs. In (a) and (b), the pad multiplicity and the total charge measured by each row of pads are represented as a function of the position with respect to the beam axis, respectively. The vertical dashed lines indicate the borders of the electrostatic mask. The horizontal dashed lines indicate the regions selected to investigate the range of influence of beam-induced signals. The inset plots show the horizontal projections of these regions.

Fig. 8. Energy lost by the target-like products in the 500 μm -thick silicon detectors versus the energy lost in the 700 μm -thick detectors. The identification of the target-like products associated with the different reaction channels is indicated. The labels (i) designates the pileup of the two ^4He nuclei produced in the decay of ^8Be . Specifically, (1) and (2) denote the pileup in the 500 μm -thick and 700 μm -thick detectors, respectively, while (3) stands for the pileup in both detectors.

Fig. 9. Kinematics of the $^{12}\text{C}(^{238}\text{U}, ^{238}\text{U})^{12}\text{C}$ events measured in the normalization runs. (a) Total kinetic energy of ^{12}C nuclei as a function of the scattering angle. (b) Reconstructed excitation-energy distribution.

between the beam and H atoms of the isobutane gas filling the MAYA volume. This conclusion is in agreement with the observations reported in Ref. [9].

Under the assumption of a binary reaction, the kinetic energy and the scattering angle of the target-like nuclei were used to reconstruct the kinematics in the $^{238}\text{U} + ^{12}\text{C}$ exit channels, and thus the excitation energy.

In the normalization runs, $^{12}\text{C}(^{238}\text{U}, ^{238}\text{U})^{12}\text{C}$ reactions were used to investigate the resolution of the setup. In Fig. 9 (a), the kinetic energy of ^{12}C products is plotted as a function of the scattering angle. As shown in Fig. 9 (b), the reconstructed excitation-energy distribution is dominated by elastic-scattering events. The width of this distribution, $\text{FWHM} = 5.4$ MeV, provided an estimation of the excitation-energy resolution. From this result, an angular resolution of approximately 2° was deduced, which indicated an uncertainty of approximately 24 mm in the determination of the reaction vertex. The latter corresponds to the size of three pads of MAYA, and it reflects the limited quality of the pad-plane patterns registered for target-like products.

For comparison, the excitation-energy resolution achieved in the solid-target experiment of Ref. [9] was $\text{FWHM} = 2.7$ MeV. In that case, the angular resolution was slightly below 1° . In order to achieve this result, the resolution of the reconstruction of the reaction vertex must be improved by approximately a factor of two. This objective was accomplished in the fission runs, where an uncertainty of a few mm was associated with the reconstruction of the reaction vertex.

The excitation-energy distributions obtained in the fission runs are displayed in Fig. 10, where the different transfer–fission channels can be compared. These results cover a wide range of total

Fig. 10. Excitation-energy distributions measured in transfer-induced fission events. These data correspond to total kinetic energies in the entrance channel between 55 and 69 MeV, in the center-of-mass reference frame.

kinetic energies in the entrance channel, namely between 55 and 69 MeV, in the center-of-mass reference frame.

In Table 1, the mean value and the width of the each distribution are provided. The $^{12}\text{C}(^{238}\text{U}, ^{238}\text{U}^*)^{12}\text{C}$ channel corresponds to the inelastic scattering of the beam, and it should be considered separately from the transfer reactions. The latter show an increase in the excitation energy with the number of transferred nucleons, as observed in Refs. [14,17].

5.3. Evolution of $^{238}\text{U} + ^{12}\text{C}$ reactions with the energy in the entrance channel

The slowing down of the beam in the gas filling the volume of MAYA was used to investigate transfer-induced fission reactions as a function of the available initial energy.

Table 1

Characterization of the excitation-energy distributions measured in inelastic- and transfer-induced fission events. The mean value ($\langle E_x \rangle$) and the width (σ_{E_x}) of the distributions shown in Fig. 10 are provided. The column $\Delta E_x / \Delta E_{cm}$ represents the average increase of excitation energy with respect to an increase of the entrance-channel kinetic energy, in the center of mass. It was calculated from a linear fit to the results given in Fig. 11. The last column represents the value of $\Delta E_x / \Delta E_{cm}$ predicted by a simple model, which considers the Coulomb forces at the distance of closest approach [24]. In this calculation, $Z_{1,2,3,4}$ are the number of protons in the projectile, target, actinide, and target-like nuclei, respectively.

Reaction	$\langle E_x \rangle$ (MeV)	σ_{E_x} (MeV)	$\frac{\Delta E_x}{\Delta E_{cm}}$	$\frac{Z_1 Z_2 - Z_3 Z_4}{Z_1 Z_2}$
$^{12}\text{C}(^{238}\text{U}, ^{238}\text{U}^*)^{12}\text{C}$	4.3 ± 0.4	5.3 ± 0.4	0.9 ± 0.4	0
$^{12}\text{C}(^{238}\text{U}, ^{237}\text{U}^*)^{13}\text{C}$	2.2 ± 1.3	6.3 ± 1.7	1.3 ± 1.4	0
$^{12}\text{C}(^{238}\text{U}, ^{236}\text{U}^*)^{14}\text{C}$	2.8 ± 0.3	3.5 ± 0.3	0.7 ± 0.6	0
$^{12}\text{C}(^{238}\text{U}, ^{239}\text{Np}^*)^{11}\text{B}$	1.6 ± 0.2	3.0 ± 0.2	0.5 ± 0.3	0.16
$^{12}\text{C}(^{238}\text{U}, ^{241}\text{Pu}^*)^9\text{Be}$	3.9 ± 0.2	4.3 ± 0.1	0.8 ± 0.4	0.32
$^{12}\text{C}(^{238}\text{U}, ^{240}\text{Pu}^*)^{10}\text{Be}$	4.6 ± 0.1	3.6 ± 0.1	0.7 ± 0.3	0.32
$^{12}\text{C}(^{238}\text{U}, ^{243}\text{Am}^*)^7\text{Li}$	10.0 ± 1.7	8.1 ± 2.4	1.1 ± 0.2	0.48

Using LISE++ [22] simulations, the energy of the ^{238}U projectiles was calculated at the position of the reaction vertex. The total kinetic energy in the $^{238}\text{U} + ^{12}\text{C}$ entrance channel was then determined in the center-of-mass reference frame, on an event-by-event basis. The region covered by this experiment extended from approximately 7% above the Coulomb barrier, down to 18% below.

In Fig. 11, the excitation-energy distributions measured in the different transfer–fission channels are plotted as a function of the total kinetic energy in the entrance channel, $E_{cm} = E_{cm,^{238}\text{U}} + E_{cm,^{12}\text{C}}$. The results from Ref. [9], at $E_{cm} = 69.7$ MeV, are also plotted.

The data indicate an increase in the energy dissipation with the energy in the entrance channel, and an evolution with the number and nature of the nucleons transferred. In order to provide a quantitative description of the overall trend of the data, a linear fit was performed. The values of the slope ($\Delta E_x / \Delta E_{cm}$) are summarized in Table 1. For reference, the predictions of a simple transfer model, which considers the Coulomb forces at the distance of closest approach [24], are reported in Table 1.

An accurate interpretation of Fig. 11 must consider the combined effect of the transfer cross-sections and the fission probabilities. The dependence of the latter on the excitation energy explains the differences with respect to Ref. [9], in $^{12}\text{C}(^{238}\text{U}, ^{236}\text{U}^*)^{14}\text{C}$, and $^{12}\text{C}(^{238}\text{U}, ^{239}\text{Np}^*)^{11}\text{B}$.

The results of Ref. [9] correspond to inclusive transfer measurements, which included all the possible decays of the actinide in the exit channel. In the present work, the selection of fission events favored the excitation of the actinides above the fission barrier, located at approximately 6 MeV [25]. The crossing of the fission barrier may also explain the change of slope observed in Figs. 11 (c) and (d).

In the case of $^{12}\text{C}(^{238}\text{U}, ^{241}\text{Pu}^*)^9\text{Be}$, and $^{12}\text{C}(^{238}\text{U}, ^{240}\text{Pu}^*)^{10}\text{Be}$, at $E_{cm} = 69.7$ MeV, the transfer reaction mainly populates a region above the fission barrier [9], where the fission probability does not change abruptly. As a consequence, a good agreement is observed between this work and Ref. [9].

Finally, the competition between transfer- and fusion-induced fission cross-sections was investigated. In Fig. 12 (a), the numbers of recorded fusion–fission and transfer–fission events are plotted as a function of the energy in the entrance channel.

Fig. 11. Excitation energy (E_x) as a function of the total entrance-channel kinetic energy (E_{cm}), in the center of mass. The average excitation-energy values are represented as black points. The horizontal bars represent the size of the E_{cm} bins used to perform the calculations. The vertical bars represent the standard deviation of the excitation energy. The results from Ref. [9] are displayed as red triangles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In the case of transfer reactions, the geometric efficiency for the detection of target-like products was accounted for by means of specific simulations. The setup geometry was fully implemented, and a phenomenological description of the angular distributions populated by the transfer reactions was included. The evolution of the latter with the incident energy was parameterized according with the data reported in Ref. [13]. A scale factor was included, in order to reproduce the average angles previously observed in $^{238}\text{U} + ^{12}\text{C}$ reactions [9].

Depending on the distance with respect to the MAYA entrance window, the efficiency values varied from 0.005 to 0.04. Due to the limited accuracy of the description of the transfer kinematics, these estimations are affected by an uncertainty of approximately 40%. The latter was

Fig. 12. In (a), the number of recorded fusion- and transfer-induced fission events is represented as a function of the total kinetic energy in the entrance channel, in the center-of-mass reference frame (E_{cm}). In (b), the ratio $\sigma_{tr}/(\sigma_{fus} + \sigma_{tr})$ is plotted, where σ_{fus} and σ_{tr} represent the fusion- and transfer-induced fission cross-sections, respectively. The transfer data were corrected for the geometric efficiency of the detection of target-like products in the ancillary silicon detectors. The fusion data were corrected for the transfer reactions where the target-like products were not detected. The error bars account for the statistical uncertainties, and for the uncertainty of the efficiency corrections. The dashed line indicates the value of the $^{238}\text{U} + ^{12}\text{C}$ Coulomb barrier.

obtained comparing the efficiency results provided by different parametrizations of the transfer angular distributions.

In Fig. 12 (a), those events where none of the ancillary silicon detectors was fired were interpreted as fusion–fission reactions. They were corrected for the number of transfer–fission events where the target-like nucleus was not detected.

The results provided in Fig. 12 (a) do not only reflect the evolution of the cross section, but also the influence of the geometric efficiency of the setup for the detection of the fission fragments, which evolves with the position of the reaction vertex. However, transfer–fission and fusion–fission events are expected to be similarly affected by this effect. Although different angular distributions of the fission fragments can be expected for both reaction types, in the center of mass, the high velocities of this experiment focused the fission fragments in the forward direction. Therefore, the angular distributions are similar in the laboratory reference frame.

On this basis, the ratio between the fusion–fission and transfer–fission distributions provided in Fig. 12 (a) was chosen as the relevant observable to investigate the competition between the two reaction types.

In Fig. 12 (b), the ratio $\sigma_{tr}/(\sigma_{fus} + \sigma_{tr})$ is plotted, where σ_{fus} and σ_{tr} are the fusion-fission and transfer-fission cross sections, respectively. At the position of the Coulomb barrier, $\sigma_{tr}/(\sigma_{fus} + \sigma_{tr}) \sim 0.05$, i.e., fusion-induced fission is approximately 20 times more probable than transfer-induced fission. This ratio seems to stabilize at energies above the Coulomb barrier, while, at sub-barrier energies, the relative cross section of the transfer channels increases. Such a behavior is in good agreement with Ref. [13].

6. Perspectives in next-generation setups: ACTAR TPC

The forthcoming active target and time-projection chamber ACTAR TPC [26] can be considered as an evolution of MAYA. This new detector will be based on the MICROMEAS [27] technology, and will use GET electronics [28].

In the context of fission studies, ACTAR TPC will allow to solve some of the difficulties encountered in this work.

In the first place, the detection of target-like nuclei will be improved. The longitudinal cuts of the target-like tracks induced by the amplification and readout systems of MAYA, which were discussed in Sec. 4.2, will not occur in ACTAR TPC. In this case, as the pads will be read individually, the charge pattern on the pad plane will not be geometrically biased.

Moreover, the difficulties for recording the trajectories of target-like products in MAYA prevented the determination of fission probabilities. The measurement of this observable requires to run with higher amplification at high beam intensities, a challenge that could be achieved by ACTAR TPC. In ACTAR TPC, the use of MICROMEAS, combined with the possibility of polarizing the pads individually, will allow to set different gain regions. Moreover, the use of GET will allow further modification of the gain associated with each pad, at the electronic level. As a result, different gain regions could be established in the detector. A low amplification could be used in the vicinity of the beam axis, which will protect the system against beam-induced signals. The use of a higher amplification outside this region will allow the accurate tracking of the target-like products. The results discussed in Sec. 5.1 suggest that this region of higher amplification should be a few cm from the beam axis. However, in ACTAR TPC, the improvement of the induction process will reduce the artificial spread of the pad-plane pattern, with respect to the measurements performed in MAYA. As a consequence, the region affected by beam-induced signals will be smaller.

In addition to the measurement of fission observables, detailed investigations of the transfer mechanism and its evolution with the excitation energy are foreseen. With respect to the results presented in Sec. 5.3, the measurement of all transfer events, independent of the subsequent decay of the reaction products, would bring important, and complementary information. The use of different beams and detection gases would provide a variety of projectile/target data, which will be of importance for the development of heavy-ion transfer theories.

Further improvement to the electrostatic mask would also be of interest. A simple upgrade would be to add a second plane of wires, in order to reduce the transparency of the mask to the space charge created by the beam. A set of magnets inside the electrostatic mask could also be of interest, in order to contain the δ electrons produced by the beam.

7. Conclusions

The first inverse-kinematics fission measurements in a gaseous active target were performed by sending a ^{238}U beam into the active target MAYA. The fission of a variety of actinides was

induced by fusion and transfer reactions between the ^{238}U projectiles and ^{12}C nuclei of the gas filling MAYA.

This experiment required specific modifications to the MAYA setup, due to the extreme working conditions created by the ^{238}U beam. An electrostatic mask was placed along the beam axis, and the amplification of the detector was limited. A remarkable response of the setup was achieved at beam intensities of several millions of pps, which allowed the accurate reconstruction of the fission-fragment trajectories.

Beyond probing the feasibility of fission measurements, the experimental results have identified the main aspects to be considered for the preparation of future experiments. Evidence of a distorted electric field was found over a distance of 50 mm from the beam axis, which established the limits of the performance of the electrostatic mask. In addition, beam-induced signals were observed along the borders of the electrostatic mask, which extended over a few cm from the beam axis.

The detection of target-like products was especially challenging due to the weak signals left in MAYA. A higher amplification was necessary, which could only be achieved at the cost of scaling down the beam intensity by one order of magnitude. The low beam intensity and the limited efficiency prevented the determination of the fission-probability distributions. However, the main difficulties were identified and possible solutions were discussed. Measurement of fission probabilities will better suited in next-generation active target systems, such as ACTAR TPC.

Furthermore, a complete characterization of the different $^{238}\text{U} + ^{12}\text{C}$ transfer channels was achieved. The slowing down of ^{238}U projectiles in the gas was used to explore the dissipation of energy as a function of the energy in the entrance channel. The competition between fusion- and transfer-induced fission cross-sections was also investigated. A thorough analysis of these results will be the subject of future articles, which will deepen our understanding of the transfer mechanism.

In summary, this work showed the capabilities of active targets for investigating the fission process and the mechanism of nucleon transfer in reactions induced by heavy-ion beams. Used in an inverse-kinematics configuration, active-target setups will definitely be powerful tools to exploit the heavy radioactive-ion beams that will be provided by forthcoming facilities.

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