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Nuclear Fragmentation Cross-Section Measurements with the FOOT Experiment

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The main goals of the FragmentatiOn Of Target experiment are the measurements of double-differential fragmentation cross-sections of light particles ($Z < 10$) in the energy range between 100–800 MeV/u, which is of interest for hadron therapy and space radioprotection applications. The results will fill the gap in experimental data in this range, which is important for improving the treatment planning systems in particle therapy and for enhancing the reliability of risk-assessment models for space radioprotection. Two different setups were designed for this scope, and data have already been taken in several campaigns. In this paper, an overview of the apparatus is described, focusing on the preliminary results of cross-section measurements obtained with a ^{16}O beam at the GSI facility.

topics: FOOT (FragmentatiOn Of Target), nuclear fragmentations, cross sections measurements

1. Introduction

Particle therapy is a medical treatment based on the use of charged particle beams (usually protons and carbon ions) to treat deep-seated tumors in patients. According to how they interact with matter, the dose release is low and almost constant in the entrance channel and increases sharply near the end of the path where the tumor is situated, sparing the surrounding healthy tissues and organs. This represents the main advantage in comparison with conventional *radiotherapy*, and due to its effectiveness, *particle therapy* is becoming an important technique with an increasing number of treatment centers all around the world.

However, at the energy of clinical treatment (100–400 MeV/u), the incoming beam produces nuclear interactions while crossing the patient, generating fragments that change the biological dose. Specifically, short-range target fragments increase the local dose in the entrance channel, while projectile fragments have a range long enough to go beyond the tumor region. As a consequence, the energy deposition outside the tumor is higher than expected, causing collateral damage. Nuclear fragmentation cross-section measurements are then fundamental for a deep knowledge of these processes, which have to be taken into account when preparing particle therapy treatment plans.

Nuclear fragmentation has to be inspected even in the context of space radioprotection. The main sources of radiation in space are cosmic rays originating from astrophysical environments inside and outside the galaxy and particles generated by local outbursts on the Sun's surface. They are mainly protons and ^{4}He ions with a large energy spread, having a maximum of around 100–800 MeV/u, which can interact with astronauts and equipment. Long-term human missions in deep space are planned in the coming years by several space agencies, including ESA and NASA. It is then fundamental to preserve the astronauts' health and to prevent electronic damage from exposure to cosmic radiation, and in this scenario, the design and optimization of the spacecraft shielding require detailed knowledge of fragmentation processes.

At present, there is a lack of experimental data about nuclear fragmentation for light fragments ($Z<10$) in the energy range of 100–800 MeV/u, i.e., typical energies used in particle therapy [1] and relevant for space radioprotection [2]. To fill this data gap, the FOOT (FragmentatiOn Of Target) experiment [3] has been conceived with the main aim of measuring differential nuclear cross-sections of both target and projectile fragments in an extensive set of measurement campaigns using several beams, such as H, He, C, and O.

2. The FOOT experiment

The main aim of the FOOT experiment is to measure the double-differential cross-section in angle and energy of fragmentation reactions with

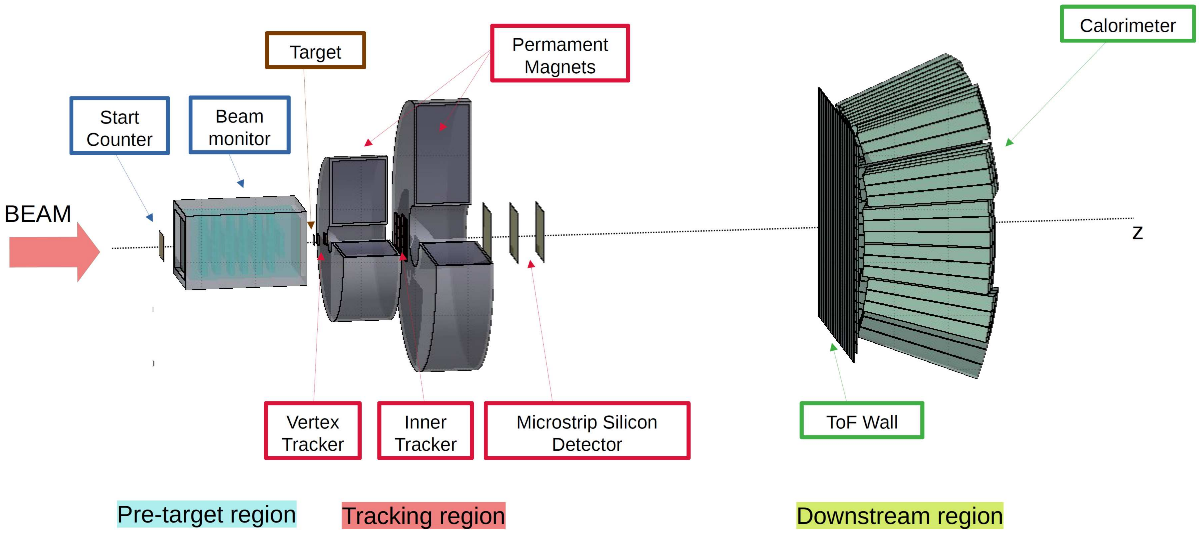

Fig. 1. Schematic representation of the FOOT electronic setup, organized in three main regions.

a resolution of 5% in both direct and inverse kinematics. It is a fixed target experiment in which beams of ions (such as ^{4}He, ^{12}C, ^{16}O) are shot against a target containing H, C, or O to simulate what happens during the beam–human interaction.

An important requirement of the FOOT experiment is its portability, which allows for performing data taking in experimental rooms in research centers scattered in different places. For this reason, the sizes and weights of detectors are important criteria to consider in the experimental design.

In order to obtain cross-section measurements, particle identification with accurate precision is required and can be obtained through the measurements of the kinematic characteristics of the particles. To reach this goal, the experiment consists of two setups with complementary purposes: one based on electronic detectors and one based on nuclear emulsions.

The FOOT electronic setup (ES) is optimized for particle identification of fragments with $Z \geq 3$ and an angular acceptance of $\pm 10^{\circ}$ with respect to the beam axis. A schematic representation is shown in Fig. 1. The ES is made of several subdetectors designed for charge and isotopic reconstruction of the fragments, organized into three main sections. The upstream region is suited to retrieve the features of the primary beam before impinging on the target. The *start counter* is a thin squared foil of plastic scintillator with an active surface of 5×5 cm^2 coupled with silicon photomultipliers (SiPMs) for light collection. It provides the trigger signal for the acquisition and start time for the time-of-flight (ToF) measurement of the particle, with a time resolution of the order of 50 ps. The *beam monitor* is a drift chamber filled with an 80/20% gas mixture of Ar/CO$_2$, made of 12 wire layers with three cells each, with a transversal shape of 16×10 mm^2. The aim is to measure the direction and the interaction point of the incoming beam and to discard pre-target fragmentation, with a spatial resolution of 100 μm.

After the target, there is the magnetic spectrometer made of silicon detectors interleaved by permanent magnets for track reconstruction. The *vertex detector* is a pixel silicon detector placed behind the target to reconstruct the origin point of the fragment. It consists of four layers of MIMOSA-28 sensors, each made of a matrix of 928×960 pixels of 20.7 μm pitch and 50 μm of thickness. The overall spatial resolution is of the order of 5 μm. In order to provide the tracking of the fragments among the magnets, the *inner tracker* is placed, made of two layers of 16 MIMOSA-28 sensors each. The third tracking station is given by the *microstrip detector* consisting of 3 planes of two perpendicular single-sided silicon detectors, each with an active area of 9.6×9.3 cm^2. The spatial resolution is about 40 μm. The two magnets with a diameter of 5 cm and 10.6 cm, respectively, are designed in Halbach configuration, generating a magnetic field B of a mean value of 1 T. They bend the trajectory of the charged fragments produced in the target to enable momentum measurement.

The last part of the electronic setup is the downstream region, at least 1 m away from the target, for identification of the fragments. In particular, the ToF *wall detector* is composed of two orthogonal layers of 20 plastic scintillator bars each, with an active area of 40×40 cm^2. Every bar is 0.3 cm thick and coupled at each edge to 4 SiPM, allowing the measurement of the energy loss $\mathrm{d}E/\mathrm{d}x$ needed for the charge reconstruction, the final time information for the ToF measurement, and the hit position for the track reconstruction. The time resolution is of the order of 100 ps, and the energy loss one is better than 5%, while the position precision is better than 8 mm. The calorimeter is the last detector

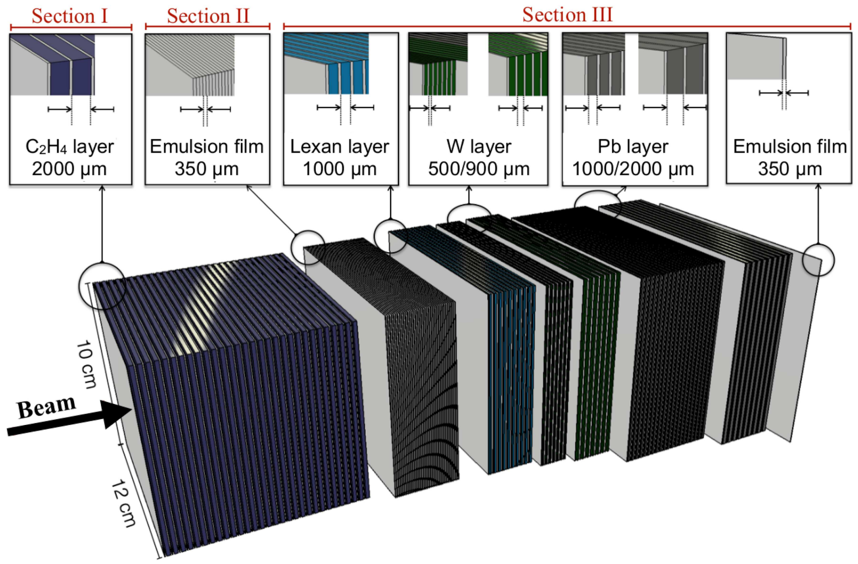

Fig. 2. Schematic representation of the FOOT emulsion cloud chamber, settled in three main sections.

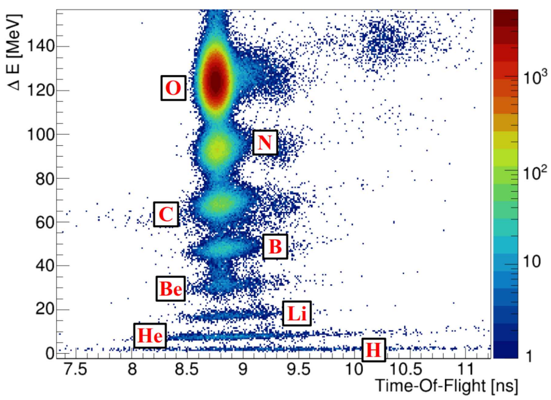

Fig. 3. Charge identification of fragments generated by a 400 MeV/u ^{16}O beam impinging on a 5 mm C target at GSI in 2021 as a relation between energy loss and ToF in the ToF-wall detector.

of the setup with the aim of measuring the kinetic energy of the fragment. It is made of 320 $Bi_4Ge_3O_{12}$ (BGO) crystals with a length of 24 cm and front and back sizes of 2×2 cm^2 and 3×3 cm^2, respectively. Every crystal is coupled to a matrix of 25 SiPM for light detection.

According to how the electronic setup is settled, the particle identification can be obtained by a two-by-two combination of detector measurements. This redundancy lets us reach the desired resolution and keep systematic uncertainties as low as possible, using the best combination method for the specific measurement.

The *emulsion setup* is focused on the reconstruction of light fragments ($Z \leq 3$) and is made of two components: the upstream region, made of the same *start counter* and *beam monitor detectors* of the electronic setup with the same purposes, and an emulsion cloud chamber (ECC), which is reported in Fig. 2. It is organized in three main regions.

The first part is made of nuclear emulsion films with dimension of 10×12 cm^2 interleaved with layers of target material where fragmentation reactions occur. From there, it is possible to retrieve the origin point of the fragment generated by the interaction between the beam and the target. The length of this section is chosen in such a way as to have the partial (almost 20%) absorption of primary particles, letting only the nuclear fragments reach the following sections. Moreover, it is made in such a way as to reconstruct the energy of the primary at the moment of the fragmentation.

The second section is made of nuclear emulsion layers with a depth of 350 μm, whose aim is charge identification of fragments. In order to increase the capability to distinguish particles with different charges during offline processing, a thermal treatment is applied to the layers in order to increase the dynamic range of the emulsion detector.

The third and last section of the *emulsion setup* is made of emulsion films interleaved with high-density materials such as lexan (1000 μm thick), tungsten (500 μm), and lead (1000 μm). From particle range and multiple Coulomb scattering of the fragments with the layers, it is in fact possible to achieve momentum measurements. By putting together the measurements of the several regions, a complete track reconstruction can be achieved.

3. Preliminary results

Up to now, both setups have been used in different experimental campaigns, employing beams of ^{16}O, ^{12}C, and ^{4}He against targets of C and C_2H_4.

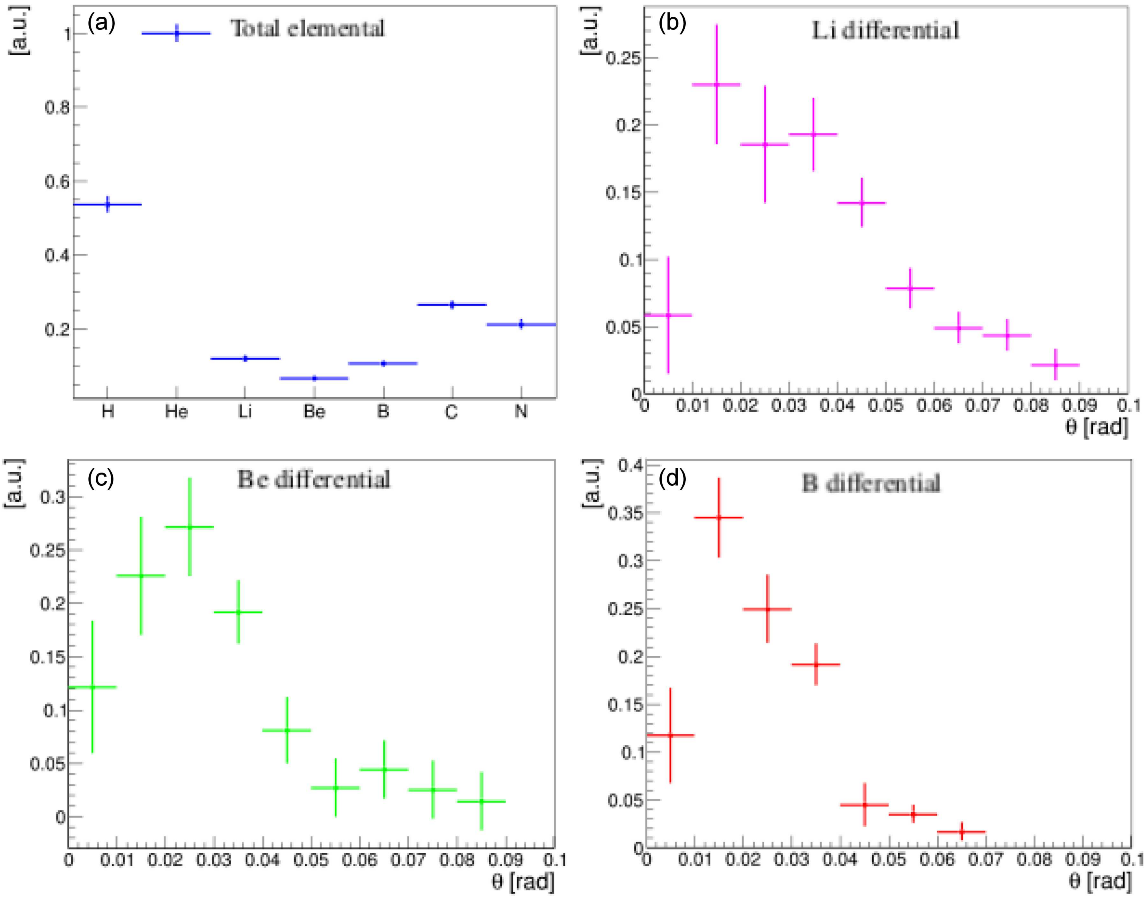

Fig. 4. Total (a) and differential (b–d) cross-section distributions for a 400 MeV/u ^{16}O beam impinging on a C target at GSI in 2021 obtained with the FOOT electronic setup. The shape of the distribution (a) is normalized to the most frequent charge, while the distributions (b–d) are normalized to unit.

From the perspective of the future data takings, the overall ECC detector is completely operational, while the ES is partially under construction, with the finalization foreseen by the end of 2023. In the following, the preliminary results obtained with ^{16}O beams at GSI (Darmstadt, Germany) with both setups are shown.

The results of the ES concern data acquired at the GSI facility in July 2021 on a beam of ^{16}O of 200 MeV/u and 400 eV/u of kinetic energy. The apparatus operated in a reduced setup, but adequate for a cross-section evaluation, and consisted of the full upstream region, part of the tracking system, the ToF-wall detector, and a part of the calorimeter. The charge reconstruction was achieved thanks to the high performance of the ΔE-ToF system composed of the *start counter* and the ToF-wall. In Fig. 3, the charge separation of fragments generated by a 400 MeV/u ^{16}O beam on a 5 mm C target is shown, considering the correlation between $\mathrm{d}E/\mathrm{d}x$ in the ToF-wall and ToF of the particle crossing all the detectors [4]. It is possible to infer that the system is able to measure the charge of the particles with a high resolution, discriminating even light fragments with $Z \leq 3$. In particular, the energy loss accuracy is of the order of 3–4%, while the ToF resolution decreases from 200 ps for lighter fragments to 45–50 ps for the ^{16}O particles.

Figure 4 shows the preliminary total and angular cross-section measurements [5] of 400 MeV/u ^{16}O beam impinging on a 5 mm C target. Since the contributions due to uncertainties and systematic are under investigation, the distributions are normalized in order to emphasize their shape, leaving the final cross-section values for a dedicated paper. What can be verified is that the most abundant generated fragments are the lightest ones, while the angular distribution varies strongly with the charge of the particle.

The ECC apparatus successfully performed a data-taking campaign at the GSI (Darmstadt, Germany) facility in 2019 and 2020 using a ^{16}O beam on C and C_2H_4 targets. Figure 5 reports the tangent of the angle with respect to the beam direction of fragments, separated according to their charge for a 400 MeV/u ^{16}O beam on a C_2H_4 target. The reported tracks are the ones well reconstructed in the second section of the apparatus, while the charge has been distinguished by employing the ionization

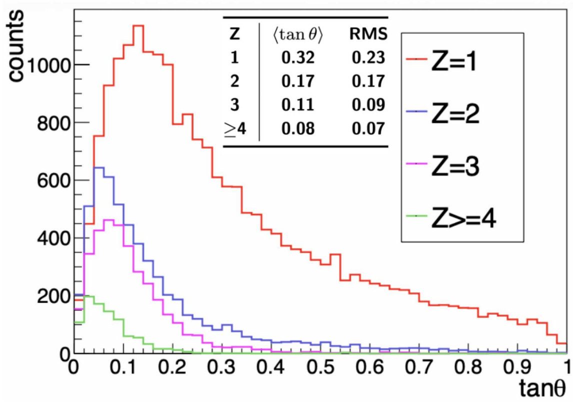

Fig. 5. Charge reconstruction of fragments generated by a 200 MeV/u 16O beam impinging on a 5 mm C_2H_4 target at GSI in 2019.

sensitivity of the second section of the apparatus (for $Z \leq 2$) and further analysis procedures [6]. In particular, the sensitivity of the apparatus is not suited for heavier fragments (for $Z \geq 4$), whose discrimination is not the purpose of this detector. What can be noticed is that the angular distribution becomes wider for lighter particles.

4. Conclusions

The main aim of the FOOT experiment is the measurement of double-differential fragmentation cross-sections in order to overcome the lack of experimental data on light fragments ($Z \leq 10$) in the energy range between 100–800 MeV/u, which is important for the applications in *particle therapy* and space radioprotection. To reach this goal, two different setups were designed, and very promising preliminary results were obtained for each. In both cases, good charge identification performances were found, and cross-section measurements were achieved. The final values will be published in a dedicated paper once all the effects have been investigated.

New data taking will be carried out in the future campaigns foreseen for 2023 and 2024, when the experimental setups will be totally assembled. In particular, the magnets and *calorimeter* of ES will be finalized by the end of 2023.

In conclusion, the reported results lay the foundation structure for data analysis that will be applied also to further data takings, when the experimental setups are completed and enhanced for new measurements.

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