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Characterizing Nuclear Fragmentation Reactions for Nuclear Physics Applications with the FOOT Experiment

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Abstract The cross-section measurement of nuclear fragmentation reactions of light nuclei (A < 20) is of great interest in current applied physics research. As a matter of fact, a complete understanding of such interactions would lead to an improvement in both Particle Therapy treatment planning systems and in risk-assessment for radiation exposure in long-term human Space missions. However, nuclear reaction databases lack the experimental measurements needed to accurately model nuclear fragmentation and, thus, calculations must rely on phenomenological models inherently subject to significant uncertainties. The FOOT (FragmentatiOn Of Target) experiment aims at a full characterization of the nuclear fragmentation reactions of interest for Particle Therapy and Radiation Protection in Space, i.e. in the energy range between 100 and 800 MeV/u. The experimental program comprehends an extensive set of measurements, in both direct and inverse kinematics, using ion beams and targets with composition similar to human tissues and spacecraft shielding materials. The final goal of FOOT is the measurement of double differential cross sections with respect to the emission angle and kinetic energy of the fragment with a precision better than 5%. The FOOT Collaboration has lately completed the development of the electronic apparatus, and several data acquisition campaigns have been already carried out with partial setups. This paper presents a brief overview of the current status of the experiment, together with a summary of the preliminary results obtained from the first measurements with ^{16}O beams impinging on thin graphite targets.

Keywords Particle Therapy, Radiation Protection, Nuclear Fragmentation, Cross section

INTRODUCTION

Particle Therapy is an external beam radiation therapy which employs light ion beams (atomic number $Z \leq 8$) for the treatment of deep-seated solid tumors. This technique is particularly effective for such cases due to the specific energy loss profile of the beams used, which can be exploited to deliver a high dose to the cancerous region while sparing the surrounding healthy tissues. One of the disadvantages of Particle Therapy is the production of nuclear fragments inside the patient, which contribute to the dose deposition outside the tumor volume and impact the Relative Biological Effectiveness along the beam path. However, as of today, the accurate assessment of this contribution to biological dose and collateral radiation damage is difficult since the cross-section data for fragmentation reactions are either limited or completely missing in literature [1].

Interest in nuclear fragmentation reactions extends beyond medical applications, particularly in the field of Radiation Protection for long term human missions in deep Space (e.g. travel to Mars). The absence of any natural protection leads to a significantly higher dose exposition for astronauts in space than on Earth surface. The planning of long-term explorations strongly depends on the careful consideration of the radiation exposure, mainly caused by Solar Particle Events and Galactic Cosmic Rays. Space agencies like NASA and ESA are constantly working on the optimization of spacecraft hulls to reduce the dose absorbed by astronauts, but the reliability of Monte Carlo benchmarks strongly depends on both the availability and accuracy of fragmentation cross section data, which are currently very scarce [2].

In summary, an accurate description of the behavior of nuclear fragments is inherently subject to

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significant uncertainties due to the lack of experimental data in nuclear databases [3]. The goal of the FOOT (FragmentatiOn Of Target) Collaboration is to address this issue by performing a set of fragmentation cross section measurements with light ion beams (He, C and O) in the energy range between 100 and 800 MeV/u impinging on tissue-like and shielding material targets.

THE FOOT EXPERIMENT

The aim of the FOOT experiment is to measure the double differential cross section of nuclear fragmentation reactions with respect to the angle of emission and kinetic energy of the fragments. The physics program of the experiment, reported in Table 1, foresees a set of data acquisitions with several beams and targets, with the final goal of reaching a 5% precision in cross section measurements for projectile fragmentation and of 10% for target fragmentation. To this purpose, the setup has been developed to characterize both the primary beam and secondary fragments, while also been able to perform measurements in direct and inverse kinematics.

Table 1. *Experimental physics program of FOOT*

Fragmentation	Research field	Beam	Energy [MeV/u]	Target	Kinematics
Projectile	Therapy	^{4}He	250	C, C_2H_4, PMMA	Direct
Projectile	Therapy	^{12}C	400	C, C_2H_4, PMMA	Direct
Projectile	Therapy	^{16}O	500	C, C_2H_4, PMMA	Direct
Projectile	Space	^{4}He	800	C, C_2H_4, PMMA	Direct
Projectile	Space	^{12}C	800	C, C_2H_4, PMMA	Direct
Projectile	Space	^{16}O	800	C, C_2H_4, PMMA	Direct
Target	Therapy	^{12}C	200	C, C_2H_4	Inverse
Target	Therapy	^{16}O	200	C, C_2H_4	Inverse

The particle beams needed to carry out the FOOT physics program (see Table 1) are available in different research and clinical facilities, meaning that the experimental apparatus has been designed to perform precise kinematics measurement while remaining as compact as possible and transportable. For this reason, the experiment comprehends two complementary setups (see Fig. 1): one based on electronic detectors (Electronic Setup), optimized for heavier fragments ($Z \geq 2$), and one based on nuclear emulsion films (Emulsion Cloud Chamber), optimized for lighter fragments ($Z \leq 3$).

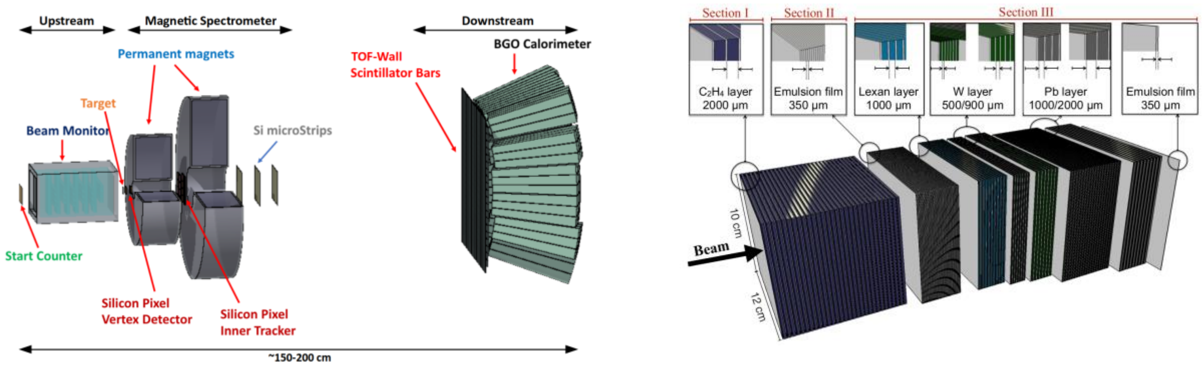

Figure 1. *Schematic view of the Electronic Setup (left) and of the Emulsion Cloud Chamber (right) of FOOT*

The Electronic Setup is made of three main sections. The first one (upstream) is devoted to the characterization of the impinging primaries. It contains a thin plastic scintillator (Start Counter), which provides the trigger and the start time for Time-Of-Flight (TOF) measurements, and a drift chamber (Beam Monitor), which measures the position and direction of the primaries hitting the target. The second region, placed right after the target, is a magnetic spectrometer made of three silicon measuring stations, either pixelated (Vertex and Inner Tracker) or stripped (Microstrip Detector), alternated with two permanent magnets. This region tracks all generated nuclear fragments and performs the momentum measurement. The last region (downstream) comprehends two layer of plastic scintillator bars (TOF-Wall), devoted to the charge identification through energy loss and TOF measurements, and a BGO Calorimeter which measures the kinetic energy of the fragments. With these measurements it is possible to obtain a complete identification (in charge and mass) of the detected particles.

The Emulsion Setup of FOOT comprehends the upstream region of the Electronic Setup in combination with an Emulsion Cloud Chamber (ECC), which is also divided in three sections. Section 1 is made of nuclear emulsion films interleaved with layers of target material (e.g. C or C_2H_4) and is thick enough to stop primaries. This section is devoted to the identification of interaction vertices and to the evaluation of projectile energy at the moment of the fragmentation. Nuclear fragments have longer range with respect to the primaries and can travel to Section 2, which is dedicated to charge identification. This section is made only of emulsion films which are then thermally treated at different temperatures to enable particle discrimination. Section 3 is instead made of alternating layers of emulsions and high-density materials (e.g. W or Pb). Its purpose is to measure the fragment momentum from multiple Coulomb scattering and particle range [4].

The Electronic Setup of FOOT has been employed in several data taking campaign with partial configurations. The full setup has been first tested in 2023, with the first physics measurement carried out at the end of 2024. The upstream region of FOOT is fully functional since 2019, allowing for the first acquisition campaigns with the ECC in 2019 and 2020. The emulsion thermal treatment and scanning has been finalized for these acquisitions and more campaigns are foreseen for the future.

In the following section, some preliminary results from data acquisitions with ^{16}O ions with both the setups of FOOT are reported.

PRELIMINARY RESULTS

A data taking campaign with a ^{16}O beam at 400 MeV/u impinging on a graphite target has been carried out at the GSI (Darmstadt, Germany) facility with part of the Electronic Setup. During this acquisition the setup was still under construction, so the used system comprehended the full upstream region, part of the tracking system, the TOF-Wall detector and a prototype of the Calorimeter.

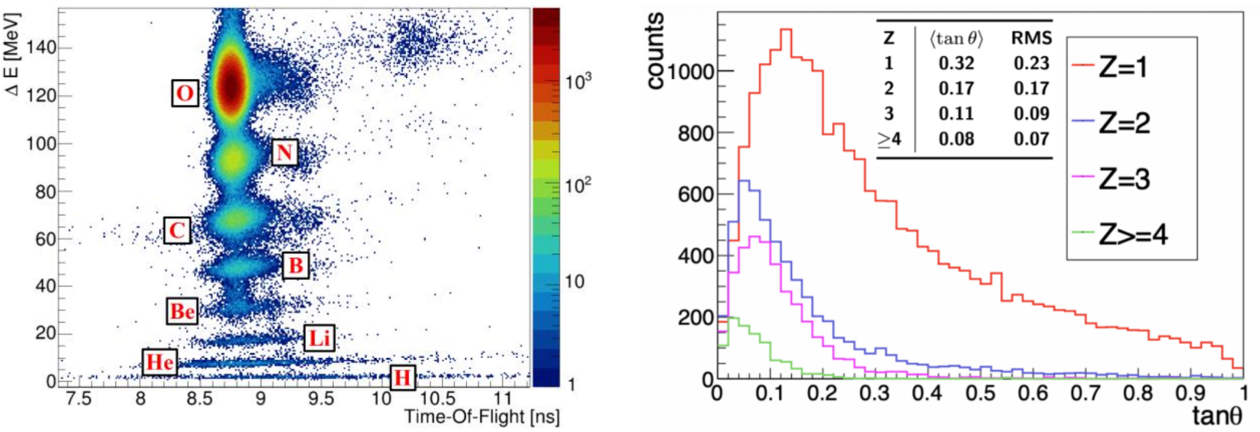

Figure 2. *Charge identification through ΔE and TOF measurements in the Electronic Setup (left) and emission angle for different fragment charge in the Emulsion Cloud Chamber (right)*

The results in Fig. 2 (left) show the charge identification capabilities of the Electronic Setup, which rely on the energy loss (ΔE) and TOF measurements obtained from the Start Counter and TOF-Wall detectors. Here, the resolution reached by the apparatus is of 3-4% for ΔE and ranging from 50 to 200 ps for TOF measurements of heavier and lighter fragments, respectively. With such precision, the different charges are clearly separable, and the setup has shown that it is possible to properly detect and reconstruct also He (Z=2) fragments. H ions (Z=1) are also recognized by the ΔE-TOF system, with a decrease in detection efficiency given by the lower energy deposition in the TOF-Wall. Further details on the system and on the analysis procedure for charge identification can be found in [5].

For what concerns the ECC, charge identification is obtained using a twofold analysis of the tracks identified in Section 2 of the apparatus. Tracks with low ionization density, i.e. $Z \leq 2$ fragments and background cosmic rays are treated using a cut-based analysis. Most of the tracks coming from cosmic rays vanishes after the thermal treatment of emulsions, so that they do not produce signals in consecutive layers. The remaining $Z = 1$ and $Z = 2$ tracks are then separated by comparing the ionization density in consecutive emulsion layers with different thermal treatments. Instead, tracks with higher ionization density are treated separately through a Principal Component Analysis Procedure. The results shown in Fig. 2 (right) have been obtained with a 200 MeV/u ^{16}O beam on a C_2H_4 target. As expected, lighter fragments have a wider angular distribution, while heavier particles are emitted mostly in the forward direction. It can be noticed that, in this case, the ECC is not capable to separate $Z \geq 4$ fragments to the very high ionization density. A detailed description of the charge identification strategy can be found in [6].

CONCLUSIONS

The FOOT experiment has just completed the development of its two complementary setups. The preliminary results obtained with partial versions of both setups have shown to be promising, with very good fragment charge identification performance. These capabilities will be used to extract the first double differential cross section measurements for nuclear fragmentation reactions of light ions. The results are currently being finalized and will be published in dedicated papers.

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