

Nuclear fragmentation cross section measurements with the FOOT experiment

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Abstract. FOOT (FragmentatiOn Of Target) is an applied nuclear physics experiment that aims at a full characterization of the nuclear fragmentation processes of interest for Particle Therapy and Radiation Protection in Space. The physics program foresees a set of measurements in direct and inverse kinematics using particle beams and targets with composition similar to human tissues and spacecraft shielding materials. The final goal of the experiment is the measurement of double differential cross sections with respect to angle and fragment energy in the 100-800 MeV/u range with a precision better than 5%. The FOOT Collaboration is currently completing the development of the apparatus and data acquisition campaigns with partial setups have already started. In this paper, an overview of the current status of the experiment is given, together with a summary of the preliminary results obtained from the first measurements with ¹⁶O beams.

1 Introduction

Particle Therapy is an increasingly used technique for cancer treatment due to its effectiveness against deep-seated solid tumors. The main advantage with respect to conventional Radiotherapy is given by the specific energy loss profile of the beams used, which is perfectly suited to deliver a high dose to the cancerous region while sparing the surrounding healthy tissues and organs at risk.

One of the drawbacks of this technique is the potential contribution to biological dose given by nuclear fragments produced by the beam inside the patient. As a matter of fact, target and projectile fragments lead to an higher energy deposition outside the tumor, increasing the risk of radiation damage to healthy tissues. Moreover, the presence of nuclear fragments impacts the Relative Biological Effectiveness along the beam path inside the patient, especially in the case of protontherapy, where heavy, short range nuclei are produced in target fragmentation reactions. This implies that the production of nuclear fragments plays a non-negligible role in determining biological dose and collateral radiation damage, which has to be taken into account when preparing Particle Therapy treatment plans. However, the correct assessment of the contribution given by fragmentation ejectiles is currently difficult since the cross section data for the involved reactions are scarce or totally unavailable in literature. [1]

The characterization of nuclear fragmentation reactions is of great interest also for Radiation Protection in Space. Since there is no natural protection from cosmic radiation, astronauts are continuously exposed to a significantly higher dose rate than on the Earth surface. This increase in the environmental radiation has to be carefully

taken into account when planning long-term human space missions, such as the travel to Mars.

The main sources of space radiation are high energy protons and ⁴He ions produced in Solar Particle Events and Galactic Cosmic Rays ejected from supernovae. The energy spectrum of these particles spans over a wide energy range, from MeV to TeV, with a maximum around 100-800 MeV/u. The interactions of these particles can cause damage to astronauts and equipment either directly or through the secondary fragments produced in the spaceship. In the last years, space agencies such as ESA and NASA have been working on optimizing the composition of spacecraft hulls to shield as best as possible the environmental radiation. However, the reliability of Monte Carlo simulation tools as benchmarks for new shielding materials depends significantly on the availability of cross section data for the fragmentation reactions involved, which are currently only partially present in literature. [2]

In summary, an in-depth knowledge of the physical and biological effects caused by nuclear fragments is in fact of great interest for both the improvement of Particle Therapy treatment planning and the development of effective spacecraft shielding systems in long-term human missions in deep space (e.g. Mars explorations). However, the cross section data needed to accurately model the behavior of nuclear fragments in these fields are currently scarce or totally unavailable in literature. [3] The objective of the FOOT (FragmentatiOn Of Target) Collaboration is to fill in these gaps in nuclear databases. The physics program of the experiment foresees an extensive set of measurement campaigns with light ion beams, such as He, C and O, in the energy range of 100-800 MeV/u impinging on tissue-like and shielding material targets.

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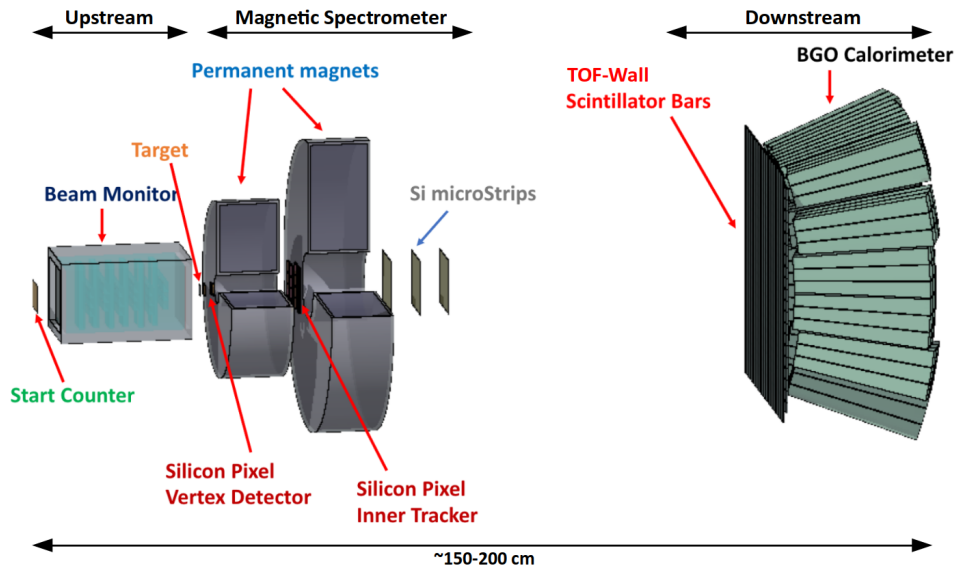


Figure 1: Scheme of the Electronic Setup of FOOT where the three main sections of the apparatus are highlighted.

2 The FOOT experiment

The final goal of the FOOT Collaboration is to measure the double differential cross section of fragmentation reactions with respect to angle and energy with a 5% uncertainty in both direct and inverse kinematics. To reach the desired resolution, FOOT has been conceived for a precise identification of the produced nuclear fragments through the measurement of their kinematic characteristics. Each detector has been studied to have the best possible resolution with the aim of performing measurements in inverse kinematics and with composite targets. To this purpose, the experimental setup has been developed with the capability of accurately characterizing both the primary beam and all the fragments produced in nuclear reactions with the target. [5]

A good knowledge of both primaries and reaction ejectiles is also fundamental to perform measurements in inverse kinematics. One of the goals of FOOT is the characterization of target fragmentation in protontherapy, which is extremely complicated due to the short range ($\sim 10\text{-}100\ \mu\text{m}$) of produced nuclei. This problem can be overcome in inverse kinematics i.e., in this case, studying the fragmentation of tissue nuclei (C, O) on hydrogenated targets, such as polyethylene or PMMA. Knowing the velocity of impinging particles, it is possible to reconstruct the reaction of interest ($p + \text{C/O}$) in direct kinematics through a Lorentz transformation.

Nevertheless, an additional challenge for target fragmentation measurements is the impossibility to employ a pure hydrogen target. Since FOOT will operate at relatively low beam rates ($\sim 5\text{-}10\ \text{kHz}$), a gaseous target would imply a very low reaction rate and thus an excessively long acquisition time. At the same time, a liquid hydrogen target would require a cryogenic system. This latter solution is of difficult application since particle beams employed in FOOT are usually available in clinical facilities. The solution proposed in FOOT is to perform the measurement

with composite and mono-atomic targets, such as C_2H_4 and C, and then extract the cross section of hydrogen as a difference. This technique has been employed and validated in previous measurement campaigns performed at GANIL [4], but it implies the need for high precision measurements of fragment kinematics.

One of the most challenging issues for the experiment is that the particle beams needed to perform the foreseen measurements can not be retrieved in a single facility. For this reason, FOOT has been conceived as a “table-top”, portable experiment while maintaining the needed precision for fragment kinematics measurements. The final system comprehends two setups with complementary purposes: one based on electronic detectors and one based on nuclear emulsions.

The Electronic Setup of FOOT is dedicated to the heavier fragments produced in the reactions of interest, i.e. particles with $3 \leq Z \leq 8$. Since these fragments are expected to be mainly emitted in the forward direction, the setup has an angular coverage of about 10° from the beam axis. A schematic picture of the setup is reported in Figure 1.

The apparatus is made of three main sections. The upstream region, placed before the target, is dedicated to the characterization of primary particles. The Start Counter is a thin plastic scintillator foil that provides the trigger signal for the acquisition and the start time of each event. The Beam Monitor is an Ar/CO_2 drift chamber dedicated to measuring the momentum and direction of each primary. After the target, there is a Magnetic Spectrometer made of three silicon measuring stations, pixelated (Vertex and Inner Tracker) or stripped (Microstrip Detector), alternated with two permanent magnets. This section of the setup is dedicated to fragment track reconstruction, which allows to find the vertex of the interaction and to measure the momentum and angle of emission of each fragment produced in the reactions with the target. The downstream region, placed at about 1-2 m from the target, comprehends the

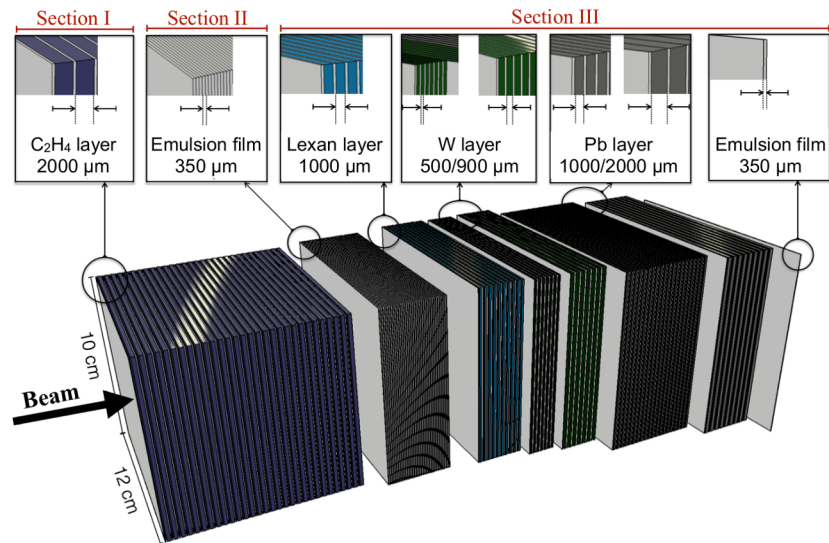


Figure 2: Schematic view of the Emulsion Cloud Chamber Setup of FOOT with its different sections.

TOF-Wall detector and a BGO Calorimeter. The first one is made of fast plastic scintillator bars and is dedicated to charge identification of fragments through energy loss and Time-Of-Flight measurements, while the second one measures the kinetic energy of each impinging particles to determine its mass. These two last detectors are also used to localize the endpoint of fragment trajectories.

The Electronic Setup has been conceived to fully reconstruct single primary events operating at beam rates up to 5-10 kHz. The data acquisition rate is fixed by the slowest components of the apparatus, i.e. the Vertex and Inner Tracker detectors, which have a maximum dead time of 500-600 μ s. With such characteristics, the expected maximum acquisition rate of the Electronic Setup is of the order of 1 kHz.

One of the key features of the Electronic Setup is its redundancy. To reach the desired resolution and keep systematic uncertainties as low as possible, the system will determine the charge and mass of the fragments with different methods. For example, the TOF, momentum and kinetic energy of the fragments are measured by three independent systems of the setup. Combining these three measurements two-by-two, it is possible to obtain three different values of the particle mass.

The setup dedicated to light fragments ($Z \leq 3$) is made of two components: the upstream region, made of the same Start Counter and Beam Monitor detectors of the Electronic Setup, and an Emulsion Cloud Chamber. This last component is sketched in Figure 2 and can be divided in three main sections.

The first section is made of nuclear emulsion films interleaved with layers of target material, such as polyethylene or carbon. Fragmentation reactions occur in this section, which is dedicated to the identification of the point of interaction between primaries and target. The length of this section is chosen so that the Bragg peak of primaries remains inside it, meaning that only nuclear fragments can reach the following sections. Moreover, the depth at which

the interaction occurs makes it also possible to accurately reconstruct the energy of the primary at the moment of the fragmentation. The second section of the ECC is made of nuclear emulsion layers and is dedicated to charge identification of fragments. The emulsion films in this section are thermally treated at different temperatures to enhance their sensitivity to ionization, enabling the possibility to discriminate particles with different charge. The third and last section of the ECC is made of emulsion films interleaved with lexan and high density material layers, such as tungsten and lead. This section is dedicated to the measurement of fragment momentum, which can be extracted from particle range and multiple Coulomb scattering.

3 Data acquisition campaigns

As of today, the FOOT Collaboration has carried out data takings with both partial and complete setups using ^{16}O , ^{12}C and ^4He ions impinging on C and C_2H_4 targets. A summary of the acquisition campaigns already performed is shown in Table 1.

The upstream region of FOOT has been operational since 2019, allowing for the first physics runs with the ECC in 2019 and 2020 at the GSI facility in Darmstadt. For these data acquisitions, the thermal treatment and scanning of the emulsions has been finalized and more acquisition campaigns are foreseen for 2023.

Instead, the Electronic Setup is still being completed and data takings have been carried out only with partial setups. The completion of the apparatus and the first acquisitions with the full setup are foreseen for 2023, when the construction of the tracking system and the BGO Calorimeter will be finalized.

In the following sections, an overview of the preliminary results obtained with ^{16}O beams at GSI is given for the two experimental setups.

Year	Facility	Beam	Energy [MeV/u]	Target	Setup
2019	GSI	^{16}O	200, 400	C/ C_2H_4	Emulsion
2019	GSI	^{16}O	400	C	Electronic
2020	GSI	^{12}C	700	C/ C_2H_4	Emulsion
2021	GSI	^{16}O	200, 400	C/ C_2H_4	Electronic
2021	CNAO	^{12}C	200	C/ C_2H_4	Electronic
2022	HIT	^4He	100, 140, 200, 220	C	Electronic

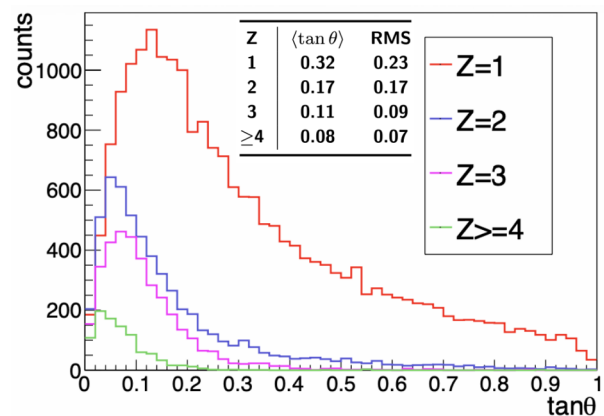
Table 1: Summary of the data takings performed by the FOOT Collaboration up to now with the two setups

4 Preliminary results

A data taking campaign has been performed at the GSI (Darmstadt, Germany) facility with the ECC in 2019-2020 using a ^{16}O beam on graphite and polyethylene target. In this occasion, the apparatus has shown very promising performance in terms of charge identification and track reconstruction of the produced fragments. Figure 3 shows an example of the reconstructed charge for each fragment identified in the emulsions for a ^{16}O beam at 200 MeV/u on a C_2H_4 target as a function of the emission angle. The results shown here refer only to the tracks correctly reconstructed in the emulsion layers of Section II (see Figure 2). The charge of each track has been associated with a twofold analysis. For tracks with lower ionization density, i.e. MIP cosmic rays and $Z \leq 2$ fragments, an event selection cut-based analysis was applied. The thermal treatment of emulsions makes MIP tracks vanish in most of the films, so that they do not produce tracks involving more than one layer. The remaining $Z = 1$ and $Z = 2$ tracks can be distinguished comparing the ionization density of single tracks in consecutive layers with different thermal treatment. For all the other tracks with higher ionization density, the charge was assigned through a Principal Component Analysis procedure. The charge identification strategy and overall capabilities of the ECC setup are described in detail in [6].

As expected, the fragments with lower Z are emitted at a larger angle and all the distributions fall to zero in the forward direction. Moreover, it is possible to notice that the ECC becomes less sensitive as charge increases and that it is impossible to discriminate between fragments with $Z \geq 4$. This is a direct consequence of the saturation of silver grain densities inside the emulsion films at higher ionization densities.

Figure 4 shows the preliminary differential cross section results obtained for the same data sample. Since all the measurement uncertainties are still being evaluated, the two distributions have been normalized to one to highlight their shape, while the final cross section values will be provided in a dedicated paper. Due to the good charge identification capabilities shown by the ECC, it will be possible to obtain the same results for each of the identified Z . Moreover, these results will also allow to extract the first set of cross section values for nuclear fragmentation on hydrogen.

Figure 3: Charge reconstructed by the ECC for the fragments produced by the interaction of an ^{16}O beam at 200 MeV/u on a C_2H_4 target. The data shown here refer to the data acquisition campaign at GSI in 2019. [6]

For what concerns the Electronic Setup, the results obtained so far are relative to the data acquisition carried out the GSI facility in July 2021, where a beam of ^{16}O ions at 200 and 400 MeV/u was sent on graphite and polyethylene targets. 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. However, the only tested and fully functioning components were the Start Counter, Beam Monitor and TOF-Wall, so the preliminary cross section evaluation was performed using just the information from these detectors.

Figure 5 shows an example of the charge identification capabilities of the ΔE -TOF system of the Electronic Setup, made of the Start Counter and TOF-Wall detectors. The results shown refer to the 400 MeV/u ^{16}O beam on a 5 mm C target. Here, the charge separation is achieved correlating the energy lost by fragments in the TOF-Wall detector and their Time-Of-Flight through the whole setup. It can be noticed that the energy loss of particles can be reconstructed with good accuracy (~ 3 -4%) over a wide energy range. At the same time, the TOF resolution of the system varies from 200 ps for lighter particles to 45-50 ps for primary O ions. With such high precision, the system proved to be capable of also measuring lighter fragments ($Z \leq 2$).

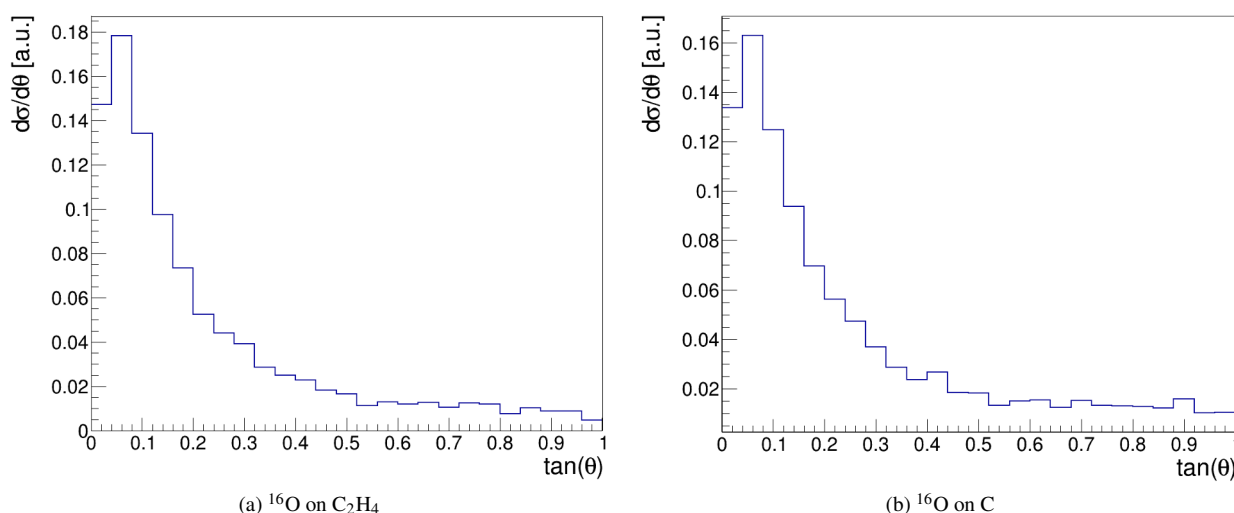


Figure 4: Differential cross section curves for O at 200 MeV/u impinging on PE and C targets obtained with the ECC setup of FOOT from the acquisition campaign at GSI in 2019. Here, the integral of the curves is normalized to be unitary.

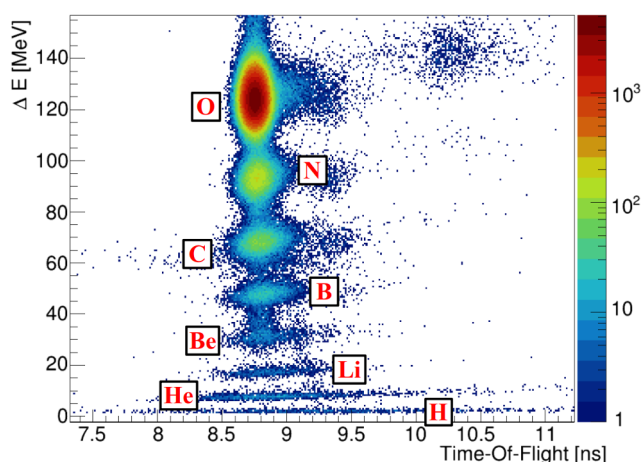


Figure 5: Charge identification of the nuclear fragments produced by a ^{16}O beam at 400 MeV/u impinging on a 5 mm C target with the ΔE -TOF system of FOOT. The energy and time resolution of the system provides good charge discrimination between the particles. The data shown here have been acquired at GSI in 2021.

A detailed description of the analysis procedure for charge identification and of the ΔE -TOF system performances is given in [7].

Figure 6 shows the preliminary cross section results obtained for ^{16}O at 400 MeV/u on a 5 mm C target. The analysis process used to obtain such results is described in detail in [8], but only the information from the upstream region and the TOF-Wall detector were used. As for the ECC results, the shown distributions are all normalized, with the aim of showing the actual cross sections in a dedicated paper. What can be noticed is that the shape of the distributions varies strongly with the charge of the detected fragment, with the lighter ones being emitted at higher angles. The same procedure will be applied to the data ac-

quired with the polyethylene target and the first results for hydrogen will also be calculated.

5 Future developments

As of today, the emulsion setup is the only apparatus that has been completed and has acquired data with the full system. Instead, the Electronic Setup is still being developed and data have been acquired only with partial setups. The completion of this system is foreseen for next year, when the Magnetic Spectrometer and the BGO Calorimeter will be finalized, with the first full data acquisition expected for late 2023.

The FOOT Collaboration is also currently working on the possible upgrades of the two setups. For what concerns the ECC setup, the possibility to employ Nano Imaging Trackers for direct target fragmentation measurements is being studied. These devices are made of very thin layers of nuclear emulsion gel ($\sim 70 \mu\text{m}$) with grains at the nanometric scale. [9] With this type of emulsion, it is possible to reconstruct tracks as short as 100 nm, granting the needed sensitivity to study short-ranged fragments produced in target fragmentation. The NIT films will be mounted on a plastic base, creating a configuration where target and tracking device coincide. A setup based on NIT films is currently being prepared at the Gran Sasso National Laboratories and it will be used in a beam test at the CNAO facility in late 2022 [9].

Concerning the Electronic Setup, one of the upgrades currently under study is the inclusion of dedicated neutron detectors. The nuclear fragmentation processes occurring in both Particle Therapy and Radiation Protection in Space produce a significant amount of neutrons and understanding their behavior is crucial for an accurate radiation risk assessment. The FOOT setup has been conceived to focus on charged fragments, but two possible solutions are currently being considered. The first is the inclusion of additional detectors dedicated to neutrons, made of BC-501A

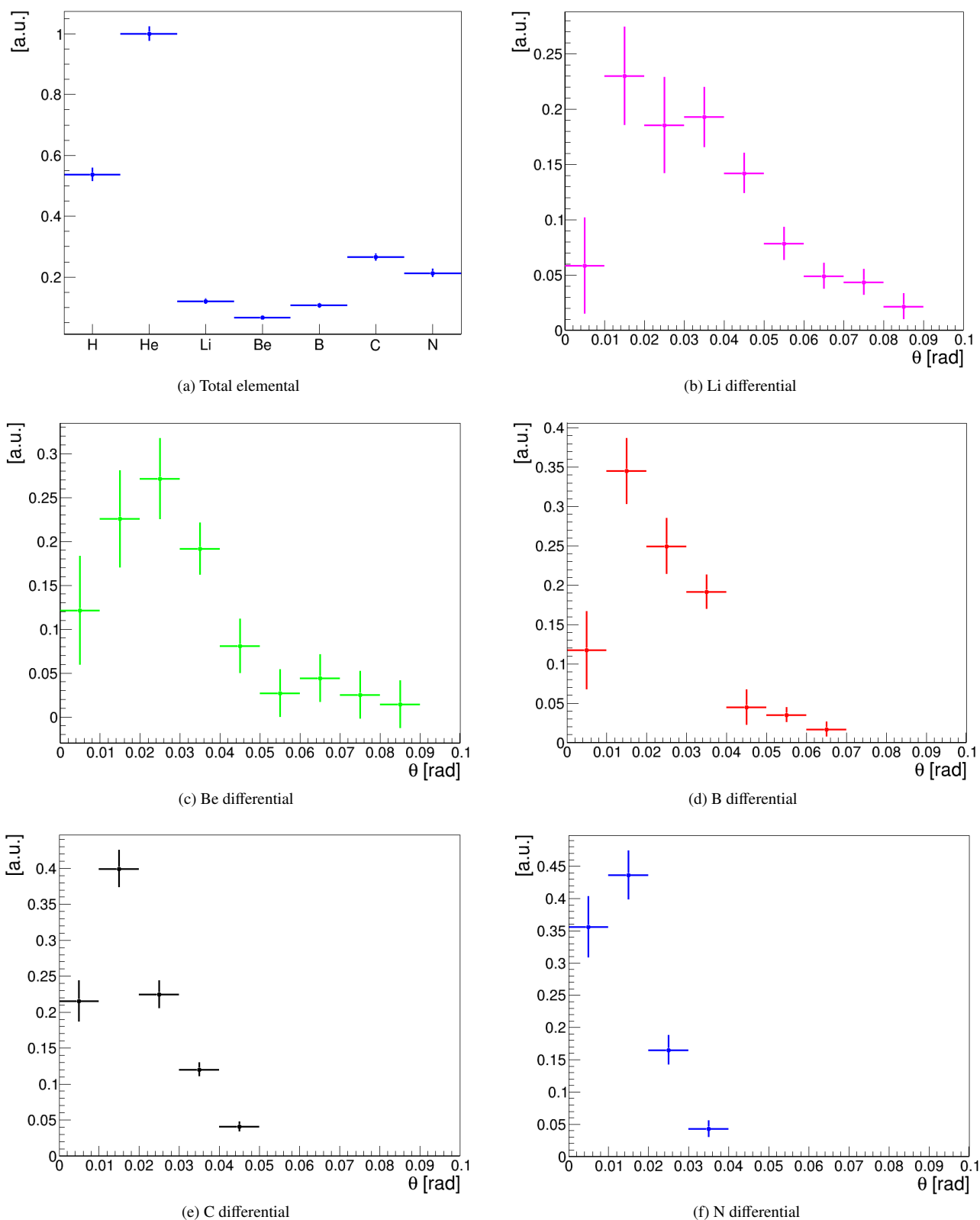


Figure 6: Cross section curves obtained for a 400 MeV/u ^{16}O beam impinging on a 5 mm C target obtained with the Electronic Setup of FOOT: (a) total elemental cross section and (b)–(f) differential (angle) cross section curves for the different charged fragments. In figure (a) the yields of each fragment have been normalized to the most frequent charge, while in (b)–(f) the curves are normalized to have unitary integral. The results are relative to the data acquisition campaign performed at GSI in 2021.

liquid scintillators. These devices have good n- γ discrimination capabilities and, using a plastic scintillator in front as veto for charged particles, it is possible to completely disentangle signals coming from neutrons. The second proposed solution is an upgrade of the BGO Calorimeter which consists in coupling single crystals with a plastic scintillator and collect their signals in phoswich mode. With such configuration, a charged fragment interacting in the crystal will produce a signal with both a fast and a slow component coming from the plastic and BGO scintillators respectively. Conversely, a neutron will only produce signal in the BGO, making it possible to disentangle charged and neutral particles.

The final goal of the FOOT upgrade is to reach a detection efficiency of 5-10% for neutrons between 50 and 200 MeV. A data acquisition dedicated to the accurate characterization of the two systems under study (BC-501A liquid scintillators and phoswich BGO crystals) has been performed in 2022 at the n_TOF facility at CERN and the analysis is currently ongoing. [10]

6 Conclusions

The preliminary results obtained by the FOOT experiment have shown to be promising. Both setups have demonstrated good charge identification capabilities and the first cross section calculations are ongoing. The final results are currently being finalized and will be published in a dedicated paper after a careful evaluation of all the systematic effects is performed. Nevertheless, the obtained

preliminary results are a good starting point for the upcoming data acquisition campaigns.

Future data takings with both the ECC and the Electronic Setup are already scheduled for late 2022 and 2023. The last developments of the setups are currently being completed and an acquisition campaign with the full Electronic Setup is foreseen for 2023. Moreover, the first tests for direct target fragmentation measurements with NIT will be held in 2023 and the inclusion of neutron detectors in the Electronic Setup is already under study.

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