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The FOOT experiment: A first measurement of nuclear fragmentation cross section for hadrontherapy

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Summary. — The FOOT experiment has been conceived with the main aim of measuring double differential fragmentation cross sections of light fragments ($Z < 10$) in the energy range between 100 MeV/u and 800 MeV/u, typical for hadrontherapy and space radioprotection applications. The results will overcome the lack of experimental data in order to improve the Treatment Planning Systems in hadrontherapy treatments and to enhance the accuracy of risk-assessment models for space radioprotection. In this paper, the analysis strategy for the measurement of elemental and angular differential cross sections is shown, focusing on data acquired at GSI in 2021 with a 400 MeV/u ^{16}O beam impinging a graphite (C) target. A Monte Carlo closure test is introduced in order to verify the reliability of the aforementioned procedure.

1. – Introduction

Hadrontherapy is a medical treatment based on the delivery of beams of charged hadronic particles towards deep-seated tumors in a patient. According to its favorable depth-dose profile, the release of dose is low in the entrance channel and increases sharply near the end of the particle range, the Bragg peak. Hence, in hadrontherapy it is possible to tune the beam energy in order to release the heaviest amount of dose in the tumor region, sparing healthy tissues and organs around it [1]. However, some issues need to be faced in the calculation of treatment plans, among which the inability to exactly evaluate the contribution of nuclear fragments as a consequence of the beam interaction with the body nuclei [2]. The research topic of nuclear fragmentation is shared even with the field of space radioprotection [3]. The interest of public and private space agencies in long space missions is increasing: several of them are planned in the next years, among which the NASA mission to Mars within 2030. Nevertheless, some of the main aspects to be faced are astronauts' health and electronics prevention from risks linked to space and cosmic radiation, the main source of fragmentation processes [4].

2. – The FOOT experiment

The main goal of the FOOT (FragmentatiOn Of Target) experiment [5] is the measurement of differential nuclear fragmentation cross section of ion beams against specific targets, in order to fill the gaps in experimental data in the energy range between 100 MeV/u and 800 MeV/u, for hadrontherapy and space radioprotection interest. The measurement of the target fragmentation cross section can be achieved by applying the inverse kinematic approach. The experiment consists of an emulsion spectrometer and an electronic setup, which is discussed below.

The FOOT electronic setup is optimized for particle identification of fragments with $Z \geq 3$ and an angular acceptance of $\pm\ 10°$ with respect to the beam axis. It is made of several subdetectors designed for charge and isotopic reconstruction of the fragment. The apparatus is currently in operation in a reduced setup. Namely, in the GSI 2021 data taking the following detectors were present: the Start Counter (SC) and the Beam Monitor (BM) are respectively a scintillator and a drift chamber that extracts the characteristics of the primary beam before impinging the target (TGT); the Vertex (VTX) and the Microstrip Detectors (MSD) are silicon detectors for the global tracking reconstruction; the ToF Wall (TW) is a scintillator for the charge reconstruction and a module of calorimeter (CALO) is present for kinetic energy measurements (see fig. 1).

In particular, the detectors used in the analysis are: SC and TW for charge reconstruction and VTX and MSD for tracking reconstruction. The SC is a thin squared foil of EJ-228 plastic scintillator with an active surface of $5 \times 5\,\text{cm}^2$ coupled with 48 $3 \times 3\,\text{mm}^2$ SiPMs for light collection. It provides the start time for the Time of Flight (TOF) measurement of the particle which ends up to the TW, with an overall time resolution of the order of 50 ps for the heaviest fragments. The VTX is placed after the target to identify the starting point of the fragments. It is made of four layers of a single MIMOSA-28 sensor based on MAPS technology. Each plane is made of a matrix of 928×960 pixels of $20.7\,\mu$m pitch and $50\,\mu$m of thickness. The overall spatial resolution is of the order of $5\,\mu$m. The second tracking station is given by the MSD, consisting of 3 planes of two perpendicular single-sided silicon detectors, each with an active area of $9.6 \times 9.3\,\text{cm}^2$. The spatial resolution is about $40\,\mu$m. The TW is made of two orthogonal layers of 20 plastic scintillator bars with an active area of $40 \times 40\,\text{cm}^2$. Every bar is 0.3 cm thick and coupled at each edge to 4 SiPM, allowing for the measurement of the energy loss dE/dx needed for the charge reconstruction.

Fig. 1. – Schematic view of the FOOT setup used during GSI 2021 data taking. It consists of the Start Counter (SC), the Beam Monitor (BM), the target (TGT), the Vertex (VTX), the Microstrip Detectors (MSD), the ToF Wall (TW) and the calorimeter (CALO).

3. – Analysis strategy

The following analysis is focused on data collected at GSI in 2021 of a 400 MeV/u ^{16}O beam impinging a graphite (C) target, using the electronic setup with the aforementioned characteristics. The aim is the measurement of elemental total cross sections and the angular differential cross section for every fragment.

The angular differential cross section is empirically defined as follows:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\theta}(Z) = \frac{Y(Z,\theta) \; - \; B(Z,\theta)}{N_{beam} \; N_{target} \; \Omega_\theta \; \epsilon(Z,\theta)}, \tag{1}$$

where $Y(Z,\theta)$ and $\epsilon(Z,\theta)$ are respectively the number of detected fragments (yield) and the reconstruction efficiency for a given charge Z, B is the background present in each fragment production, Ω_θ is the phase space, N_{beam} is the number of primaries impinging the target and N_{target} is the number of interaction centres in the target per unit surface. The total elemental cross section can be obtained by integrating eq. (1),

$$\sigma(Z) = \int_0^{\theta_{max}} \frac{\mathrm{d}\sigma}{\mathrm{d}\theta}(Z)\, d\theta \; = \; \frac{Y(Z) \; - \; B(Z)}{N_{beam} \; N_{target} \; \epsilon(Z)}, \tag{2}$$

where θ_{max} represents the maximum angular acceptance of the detector, which is of the order of 8° for the GSI 2021 setup.

The upcoming studies concern Monte Carlo (MC) data generated by the FLUKA code to simulate detectors and beams with the GSI 2021 campaign setup, in order to study efficiencies and performances of the analysis procedure.

3·1. *Fragment identification.* – The fragment charge is reconstructed using the information given by SC and TW, namely TOF and dE/dx. According to them, the charge identification algorithm discriminates the fragment by considering the different dE-ToF curves described by the Bethe Bloch formula for every charge [6].

The reconstruction of the trajectory is performed using the fragment positions measured in the VT and MSD planes. The global tracking algorithm being used is based on the Kalman Filter model, in which the estimation of the parameters of interest (position, direction and momentum of a track) is improved by adding hits in an iterative way [7].

The main sources of investigated background are due to misreconstruction of both charges and tracks as a consequence of inefficiencies of the aforementioned algorithms.

3·2. *Track efficiency.* – The efficiency of the tracking algorithm has been computed as follows:

$$\epsilon(Z) = \frac{N_{track}(Z)}{N_{true}(Z)}, \tag{3}$$

where $N_{track}(Z)$ represents the number of reconstructed particles by the global tracking and $N_{true}(Z)$ the generated MC true ones. Since reconstructed tracks correspond to fragments which leave a signal in VTX, MSD, and TW in the angular acceptance of the setup, the particles used in MC studies were selected among primary fragments generated in the TGT with a kinetic energy E $>$ 100 MeV/u, enough to go beyond the target and to reach the end of the apparatus.

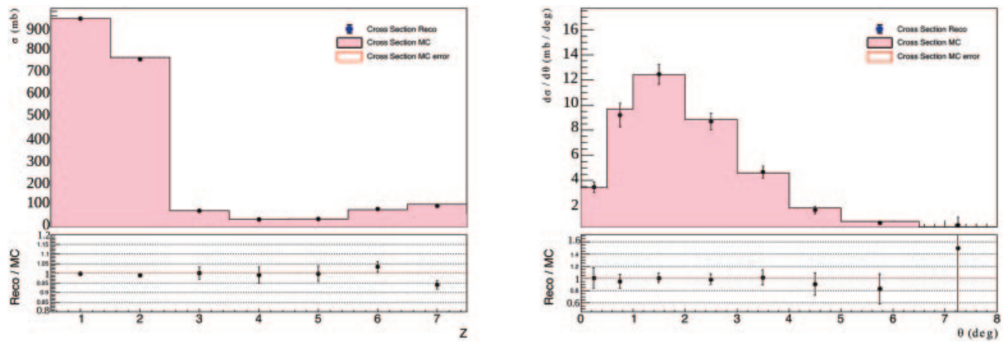

Fig. 2. – Elemental fragmentation fiducial cross section (left) and angular differential cross section of $Z = 4$ (right) in comparison with MC generated particle distribution and their ratio.

4. – Results

The described procedure was tested on MC data simulating the GSI setup, in order to verify the analysis chain. In fig. 2, the fiducial elemental fragmentation cross section (left) and the angular differential fragmentation cross section for $Z = 4$ fragments (right) are reported. The cross sections measured by a MC data-like dataset (black dots) are compared with an independent MC generated one (red columns) and the ratio for every measurement is also reported. When inspecting the total elemental cross sections, the ratio value is very close to one for all the charged particles, showing that the adopted analysis procedure is solid. For what concerns the angular differential cross section, the ratio of the two dataset values is very close to one, worsening for high angles where the statistics is poor and the reconstruction algorithm is less reliable. The angular differential cross sections of the other fragments show a similar behaviour.

5. – Conclusions

The analysis strategy for fragmentation cross section measurements of a 400 MeV/u ^{16}O on a graphite (C) target is presented, using MC dataset generated by FLUKA to simulate the GSI 2021 campaign setup of the FOOT experiment. The closure test between a MC data-like reconstruction and a MC generated one shows high correspondence between them, highlighting the reliability of the analysis strategy that has been followed. New improvements are foreseen, in order to enhance the performance of the procedure before the application to experimental data of GSI 2021 campaign and those foreseen in the future.

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