The FOOT experiment: current status and future perspective for nuclear fragmentation studies in particle therapy and space radiation protection

Sofia Colombi[1]*, on behalf of the FOOT collaboration*

[1]Istituto Nazionale di Fisica Nucleare (INFN), Section of Bologna, Bologna, Italy

Abstract. Nuclear fragmentation processes occurring in the beam-target interaction represent a potential source of hazard for humans' health both in particle therapy and space exploration. The FragmentatiOn Of Target (FOOT) experiment aims to characterize both beam and target fragments, and to measure with great accuracy nuclear fragmentation cross sections interesting in cancer therapy and in long-lasting interplanetary missions. In this paper, the fragments reconstruction capabilities of the FOOT experimental setup is reported. FOOT future perspective of providing useful data to improve the modelling of neutron interactions is also discussed.

1 Introduction

The two most relevant sources of radiation in the Solar System are Galactic Cosmic Rays (GCR) and Solar Particle Events (SPE). GCRs energy spectrum has a broad peak between 0.4 and 1 GeV/u, while the typical SPEs energies are below 150 MeV/u. The space radiation field, mainly composed of protons [1], is further modified by interacting with any material composing the spacecraft, including the passive shielding, which is nowadays considered the most effective countermeasure for mitigating radiation exposure. Recent studies [2] questioned the radioprotection advantage of using thicker passive shielding, showing that the build-up of neutrons actually increases the equivalent dose. The possible dominant role of secondary neutrons has a strong impact on the mission risk assessment and can potentially restrict the boundaries of space exploration. Improving the knowledge of nuclear processes relevant for space radiation protection perfectly matches the need in particle therapy. The latter employs protons and carbons beams at energies in the range [60-400] MeV/u to deliver a uniform dose in the tumor region, minimizing the damage to the surrounding healthy tissues. The characterization of both neutral and charged secondary particles produced in the nuclear patient-beam interaction has to be considered in the Treatment Planning System (TPS), in order to account also for the unwanted dose at the target volume edges and far away from the target region [3].

---

* Corresponding author: colombi@bo.infn.it

2 The FOOT experiment

The FOOT experiment has been designed to identify all the charged fragments produced in the primary beam collision with different targets, aiming to measure both projectile and target fragmentation. The latter is a challenging task due to the short range of the fragments (in the order of 10-100 μm), which results in a very low probability of escaping the target and be detected. To overcome this issue, FOOT relies on an inverse kinematic approach: fragmentation of different ion beams (like ^{12}C and ^{16}O) at 200-1000 MeV/n in hydrogen enriched targets will be studied. Therefore, the proton-nucleus cross sections is extracted by subtraction from data taken on C_2H_4 and C targets [4]. FOOT can also perform the direct measurement of projectile fragmentation cross sections induced by the beam on any targets, including for example dedicated materials for space radioprotection (e.g. Aluminum). FOOT includes a double experimental setup, exploring different angular regions of fragments emission. Below 10 degrees, an Electronic Setup (ES) is employed, while an Emulsion Cloud Chamber (ECC) is used for larger angles. Specifically, the ES consists in a pre-target monitor region to provide the trigger to the whole experiment and the start time for the Time-Of-Flight evaluation. Downstream of the target, there are three elements: i) a magnetic spectrometer for evaluating the production vertex and momentum (p) of the fragments through the tracking outside the magnetic field, ii) a scintillator detector to provide the stop signal for the Time-Of-Flight evaluation and the measurement of energy loss (ΔE) of the fragments, and iii) a calorimeter to measure the kinetic energy (E_{kin}) of all particles. In the following, the acronym *TOF* will refer to the time measured between the above mentioned start and stop signals. A detailed characterization of the ECC and all the detectors involved in the ES can be found in [5].

3 Present performances results

In order to study the expected reconstruction capability of the ES, a study based on experimental-like data samples generated by Monte Carlo (MC) Fluka has been conducted. The samples has been produced by applying the present experimentally and analytically evaluated resolutions on *TOF*, p, ΔE and E_{kin} (i.e., $\sigma(TOF) \simeq 70$ ps, $\sigma(p)/p \simeq 3.7\%$ and $\sigma(E_{kin})/E_{kin} \simeq 1.5\%$) as a Gaussian smearing to the corresponding values predicted by MC. The produced fragment charge Z is then evaluated by combining the reconstructed ΔE and *TOF* measurements in the Bethe-Bloch equation [6, 7]. The results show that the precision on the charge reconstruction ranges between ~6% for hydrogen to ~2% for oxygen, allowing a clear identification of the particles produced in the nuclear beam-target interaction. Experimental data were collected in 2019 with a partial FOOT electronic setup at the GSI Helmholtz Center for Heavy Ion Research (Germany) with a 400 MeV/u ^{16}O beam impinging on a 5 mm graphite target (ρ=1.83 g/cm^3). The charge separation obtained on this real data sample is satisfactory and in agreement with the prediction of the MC-based study, thus confirming the goodness of the reconstruction method [8, 9]. The isotopic discrimination is obtained with a standard χ^2 minimization approach by performing a fit to the three reconstructed number of mass values. The latter were evaluated by combining *TOF*, p and E_{kin} measurements in different equations, as follows:

$$A_1 = p/(u\gamma\beta c) \qquad A_2 = E_{kin}/[(\gamma - 1)uc^2] \qquad A_3 = (p^2c^2 - E_{kin}^2)/(2uc^2E_{kin}) \qquad (1)$$

where u is the Unified Atomic Mass (~931.5 MeV), γ is the Lorentz factor, β is the fragment velocity provided by the tracking path (L) coupled with the *TOF* measurement as $\beta = L/(TOF \cdot c)$. An additional $\chi^2 < 5$ cut allows to discard the fragments whose kinetic energy

has been underestimated, without reducing the statistics more than ∼20%. Only A_1 provides a reliable number of mass estimation at higher primary beam energy (i.e., from 700 MeV/u), due to the greater probability of secondary fragmentation and neutrons emission inside the calorimeter, that corrupt the energy measurement. The method ensures a precision on the number of mass reconstruction ranging between ∼3.5% and ∼4.5%, for all the primary beam energies.

The reconstruction of the charge Z and number of mass A allows to uniquely identify the fth fragment generated in the beam-target interaction, therefore evaluating the corresponding yield Y_f. However, Y_f requires a *background* (Bkg) correction and the application of an *unfolding* (U) procedure [10] to account for the Z and A misidentification probabilities and the possible wrong counts of the produced fragments due to experimental effects. Afterwards, the differential cross-sections (CS) of such f^{th} fragment with respect to its production kinetic energy E_{kin} is retrieved as follow:

$$\sigma_f/dE_{kin} = (Y_f(E_{kin}) - Bgk_f)^U/(N_{prim}N_t\Omega_E\epsilon) \qquad (2)$$

where N_{prim} is the number of primary beam particles, N_t is the number of target scattering center, Ω_{Ekin} is the energy phase space, is the reconstruction efficiency. The total cross section is evaluated by integrating over the whole energy range. The procedure explained for the CS measurements has been applied to data samples produced with both C_2H_4 and C targets, in order to evaluate the result on a H target by difference. For all the targets, the results on the total cross section are compatible within the uncertainties with the MC predictions.

The contribution of each detector on the precision of the mass number determination has been evaluated by varying the resolutions on *TOF*, p and E_{kin} within a reasonable range around the current real values. The findings point out a strong dependence on the *TOF* precision, which can worsen the resolution on the number of mass determination of ∼0.4%/ps.

4 Future perspectives for neutrons detection

The increasing interest in more precise measurements of neutrons production has led the FOOT collaboration to investigate the possibility to characterize secondary neutrons generated by several projectiles-energy-targets combinations relevant for both particle therapy and space radioprotection. The present ES will allow to identify neutrons with the anticoincidence technique applied to the signals of the last two elements of the apparatus, namely a 6 mm thin plastic scintillator called ToF-Wall (TW) and a BGO Calorimeter (CAL) [5]. An uncharged particle impinging on the CAL will deposit either a very small or null amount of energy in the TW, due to the extremely low interaction probability. Therefore, the apparatus could identify neutrons in the CAL, and determine their kinetic energy with the *TOF* measurement. To estimate the amount of neutrons arriving in the CAL for detection but not produced in the target, a Fluka MC simulation of a 200 MeV/u ^{16}O beam impinging into a 5 mm C_2H_4 target has been studied. The results show that neutrons are largely produced in the setup detectors, as illustrated in Figure 1. In details, the main sources of neutrons are the permanent magnets and the calorimeter, that produce about two and four times the amount of neutrons originated in the target, respectively. However, only ∼20% of the overall neutrons generated will actually reach the CAL, due to the angular acceptance of the detector itself and the probability to interact with other elements of the apparatus or the walls of the irradiation room. Of those arriving in the CAL, the amount of neutrons generated inside the CAL itself is about eight times the production in the target, thus representing the main

contribution to the background neutrons. However, the mean kinetic energy of neutrons coming from the target is almost a factor four times higher with respect to the neutrons generated in the CAL. Therefore, a convenient detection energy threshold (e.g., 50 MeV) will help to clean up the neutral particle spectrum from the background contribution, thus selecting only the high-energy neutrons originating from target. A further option currently under investigation regards the possibility to add one or more liquid scintillators specifically designed for the detection of fast (i.e., >1 MeV) neutrons due to the excellent pulse shape discrimination properties [11]. Thanks to their compactness, they will be easy to move to different angles
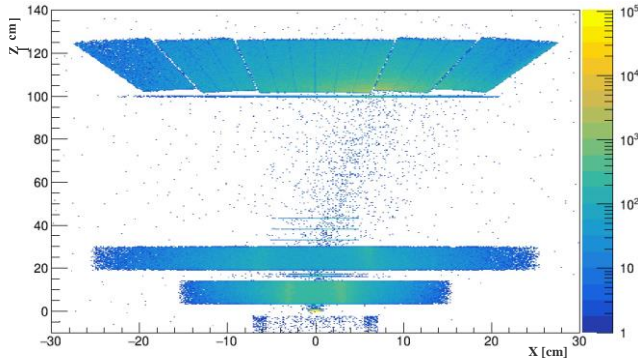

Figure 1. 2-D plot representing the production point of all the neutrons generated in the ES. Z and X are the direction parallel and traversal to the beam direction (in cm), respectively. All the detectors composing the setup presented in Sec.4 are evident. The principal sources of neutrons (i.e., the target placed at -0.25<Z<0.25., the magnets placed at 5<Z<29.5 and the calorimeter placed at 102<Z<126) are clearly visible.

with respect to the primary beam position. Therefore, neutrons production at several angles will be investigated as required for the evaluation of differential cross sections with respect to the emission angle.

5 Conclusions

The FOOT experiment will contribute to increase the knowledge of nuclear processes of charged particles and neutrons production at intermediate energies (200-1000 MeV/u), providing precious experimental data for risk assessment in future space missions and in the development of particle therapy. MC studies suggest a precision in the identification of the produced fragments good enough to accurately reconstruct the differential cross sections with respect to their production kinetic energy. The analysis of the first experimental data collected validates the reconstruction method. The experimental campaigns foreseen in the near future will not only provide data to enforce the reliability of the proposed reconstruction method, but will also deeply investigate the possibility to upgrade the experimental setup to study secondary neutrons production.

References

[1]   P. M. O'Neill et al., IEEE Transactions on Nuclear Science **57**, 3148–3153 (2010)

[2]   T. C. Slaba et al., Life Sciences in Space Research **12**, 1–15 (2017)

[3] M. Hultqvist et al., Phys. Med. Biol. **55**, 6633-53 (2010)

[4] J. Dudouet et al., Phys. Rev. C **88**, 16 (2013)

[5] G. Battistoni et al., Front. Phys. **8**, 555 (2021)

[6] H. Bethe, Ann. Phys. **397**, 325-400 (1930)

[7] F. Bloch, Z. Physik **81**, 363-76 (1933)

[8] A.C. Kraan et al., Nucl. Instrum. Meth. A **1001**, 165206 (2021)

[9] S. Colombi et al., Phys. Scr. **96**, 114013 (2021)

[10] G. D'Agostini, Nucl. Instrum. Meth. A **362**, 487-498 (1995)

[11] C.A. Goulding et al., LANL Technical Note LA-N2TN-87-201 (1987)