IL NUOVO CIMENTO **41 C** (2018) 169
DOI 10.1393/ncc/i2018-18169-5

Colloquia: IWM-EC 2018

The FOOT (FragmentatiOn Of Target) experiment

S. M. Valle(1)(2), A. Alexandrov(3), B. Alpat(4), G. Ambrosi(4), S. Argirò(5)(6), M. G. Bisogni(7)(8), N. Belcari(7)(8), S. Biondi(9)(10), G. Bruni(9), N. Camarlinghi(7)(8), P. Carra(7)(8), P. Cerello(6), E. Ciarrocchi(7)(8), A. Clozza(11), S. Colombi(12)(13), G. De Lellis(3)(14), A. Del Guerra(7)(8), M. De Simoni(15)(16), A. Di Crescenzo(3)(14), M. Donetti(6)(17), Y. Dong(2)(1), M. Durante(12), A. Embriaco(2), M. Emde(18), R. Faccini(16)(15), V. Ferrero(5)(6), F. Ferroni(16)(15), E. Fiandrini(4)(19), C. Finck(20), E. Fiorina(22)(17), M. Fischetti(21)(16), M. Francesconi(7)(8), M. Franchini(9)(10), L. Galli(8), M. Garbini(9)(10)(22), V. Gentile(23), G. Giraudo(6), R. Hetzel(18), S. Hild(12), M. Ionica(4), K. Kanxheri(4)(19), A. C. Kraan(8), V. Lante(17), A. Lauria(3)(14), C. La Tessa(12)(13), E. Lopez Torres(6)(24), M. Marafini(22)(16), I. Mattei(2), A. Mengarelli(9), R. Mirabelli(15)(16)(22), M. C. Montesi(3)(14), M. C. Morone(25)(26), M. Morrocchi(8), S. Muraro(8), L. Narici(25)(26), A. Pastore(27), N. Pastrone(6), V. Patera(21)(16)(22), F. Pennazio(6), P. Placidi(4)(28), M. Pullia(17), L. Ramello(6)(29), R. Ridolfi(10), V. Rosso(7)(8), M. Rovituso(12), C. Sanelli(11), A. Sarti(21)(11)(22), G. Sartorelli(9)(10), O. Sato(30), S. Savazzi(17), A. Schiavi(21)(16), C. Schuy(31), E. Scifoni(12), A. Sciubba(21)(16)(22), M. Selvi(9), L. Servoli(4), G. Silvestre(4)(19), M. Sitta(6)(29), R. Spighi(9), E. Spiriti(11), G. Sportelli(8)(7), A. Stahl(18), S. Tomassini(11), F. Tommasino(12)(13), G. Traini(15)(16)(22), T. Valeri(3), M. Vanstalle(20), M. Villa(9)(10), U. Weber(31), A. Zoccoli(9)(10) and G. Battistoni(2)

(1) *University of Milano, Department of Physics - Milano, Italy*
(2) *INFN, Sezione di Milano - Milano, Italy*
(3) *INFN, Sezione di Napoli - Napoli, Italy*
(4) *INFN, Sezione di Perugia - Perugia, Italy*
(5) *University of Torino, Department of Physics - Torino, Italy*
(6) *INFN, Sezione di Torino - Torino, Italy*
(7) *University of Pisa, Department of Physics - Pisa, Italy*
(8) *INFN, Sezione di Pisa - Pisa, Italy*
(9) *INFN, Sezione di Bologna - Bologna, Italy*
(10) *University of Bologna, Department of Physics and Astronomy - Bologna, Italy*
(11) *INFN, Laboratori Nazionali di Frascati - Frascati (RM), Italy*
(12) *Trento Institute for Fundamental Physics and Applications, TIFPA-INFN - Trento, Italy*
(13) *University of Trento, Department of Physics - Trento, Italy*
(14) *University of Napoli, Department of Physics "E. Pancini" - Napoli, Italy*
(15) *University of Rome La Sapienza, Department of Physics - Rome, Italy*
(16) *INFN, Sezione di Roma 1 - Rome, Italy*
(17) *Centro Nazionale di Adroterapia Oncologica (CNAO) - Pavia, Italy*
(18) *Rheinisch-Westfälische Technische Hochschule (RWTH) University - Aachen, Germany*
(19) *University of Perugia, Department of Physics and Geology - Perugia, Italy*
(20) *Université de Strasbourg, CNRS, IPHC UMR 7871 - F-67000 Strasbourg, France*

(21) *University of Rome La Sapienza, Department of Basic and Applied Sciences for Engineering (SBAI) - Rome, Italy*
(22) *Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi - Rome, Italy*
(23) *Gran Sasso Science Institute - L'Aquila, Italy*
(24) *CEADEN - Havana, Cuba*
(25) *University of Rome Tor Vergata, Department of Physics - Rome, Italy*
(26) *INFN, Sezione di Rome 2 - Rome, Italy*
(27) *INFN, Sezione di Bari - Bari, Italy*
(28) *University of Perugia, Department of Engineering - Perugia, Italy*
(29) *University of Piemonte Orientale, Department of Science and Technological Innovation - Alessandria, Italy*
(30) *Nagoya University, Department of Physics - Nagoya, Japan*
(31) *Gesellschaft für Schwerionenforschung (GSI) - Darmstadt, Germany*

received 3 December 2018

Summary. — Particle therapy uses proton and ion beams to treat deep-seated solid tumors, exploiting the favorable energy deposition profile of charged particles. Nuclear interactions with patient tissues can induce fragments production that must be taken into account in treatment planning: in proton treatments target fragmentation produces low-energy, short-range fragments depositing a non-negligible dose in the entry channel, while in heavier-ion beam treatments long-range fragments due to projectile fragmentation release dose in tissues surrounding the tumor. The FOOT experiment aims to study these processes to improve the nuclear interactions description in next generation Treatment Planning Systems softwares and hence the treatments quality. Target (^{16}O and ^{12}C) fragmentation induced by 150–250 MeV proton beams will be studied via inverse kinematics: ^{16}O and ^{12}C beams (150–250 MeV/u) collide on graphite and hydrocarbon targets to provide nuclear fragmentation cross sections on hydrogen. The projectile fragmentation of these beams will be explored as well. The FOOT detector includes a magnetic spectrometer to measure fragments momentum, a plastic scintillator for ΔE and TOF measurements and a scintillating crystal calorimeter to measure fragments kinetic energy. These measurements will be combined to accurately identify fragments charge and mass.

1. – Introduction

Nowadays, Particle Therapy (PT) is an established technique to treat deep-seated solid tumors. Thanks to the favorable ions depth-dose deposition profile, it is indeed possible to precisely conform the dose release to the tumor volume, while efficiently sparing the healthy tissues surrounding the tumor. Moreover, thanks to the heavier-ions high Relative Biological Effectiveness (RBE), defined as the ratio of photon to charged-particle dose producing the same biological effect, PT is highly indicated in case of radioresistant tumors.

In clinical practice, proton RBE is set to a constant value of 1.1 regardless of the experimentally demonstrated RBE variations, which are due to complex and unclear dependencies on both physical and biological parameters. It has been suggested that an increase of the proton RBE can be caused by the nuclear reactions of the beam with the patient tissues [1]: inelastic interactions, in fact, can lead to the production of several low-energy and high-Z fragments. These fragments are characterized by significantly higher RBE values with respect to protons. The lack of information about the impact of target fragmentation on the RBE in PT is due not only to the complicated determination of fragments RBE with biological experiments but also to the lack of cross section data for the production of heavy nuclei after proton irradiation in the therapeutic energy range.

In case of $Z > 1$ ion beam therapy, nuclear interactions are also responsible for the production of low-Z projectile fragments, which travel farther than the primary beam and produce a dose tail beyond the Bragg peak position.

In clinical practice, target fragmentation is usually neglected, while projectile fragmentation is usually calculated by means of Monte Carlo (MC) codes. However, MC nuclear models prediction are not enough reliable to produce sound radiobiological models and therefore, since the fragments contribution to the overall released dose can be significant, a new study of their production cross sections is strongly needed to take their contribution into account during the treatment planning stage.

The FOOT (FragmentatiOn Of Target) experiment [2] of INFN (Istituto Nazionale di Fisica Nucleare) aims to investigate both target and beam fragmentation, with the purpose of providing new data for medical physicists and radiobiologists that are developing the new generation Treatment Planning Systems.

2. – Experiment goals and strategies

For kinematic reason, heavy fragments ($Z > 3$) are forward emitted and well contained within a cone of 10° semiaperture with respect to the beam axis, while, on the contrary, light fragments are scattered at larger angles, as confirmed by MC predictions. For this reason, it has been decided to design the FOOT apparatus with two different setups: an electronic experimental setup, finalized to the study of heavy fragments, and an emulsion chamber, that can measure light fragments emitted at larger angles.

The electronic FOOT detector has been optimized to study heavy ($Z > 3$) target fragment production in order to provide the differential cross sections for all the produced fragments. To this purpose, all fragments will be identified: their charge (Z) and mass number (A) will be determined, as well as their energy and emission angle. The main experimental difficulty in the measurement of the target fragmentation induced by protons is due to the low energy, and thus short range ($\sim$tens of μm), of the produced fragments. To overcome this difficulty, an inverse kinematic approach will be adopted: the fragmentation of tissue-like ion beams (C, O) impinging on a hydrogen-enriched target will be studied. In this way, secondary fragments will have a boosted energy and a longer range and, by applying the Lorentz transformation, it will be possible to switch from the laboratory frame to the "patient frame" [3]. Issues concerning the construction of a pure-hydrogen target can be bypassed by using two different targets: one made of carbon, while the other of a hydrogenated material, as for example C_2H_4. Differential cross sections on Hydrogen can be extracted by subtraction from the data obtained using a pure-C target [3] (fig. 1).

To measure the cross sections it is necessary to correctly identify the produced fragments charge and mass, their momentum p, kinetic energy E_k, time of flight (TOF) and energy release ΔE will be measured by the detector. The charge is retrieved from the Bethe-Bloch formula through the ΔE and β (derived from the TOF) measurements. Due

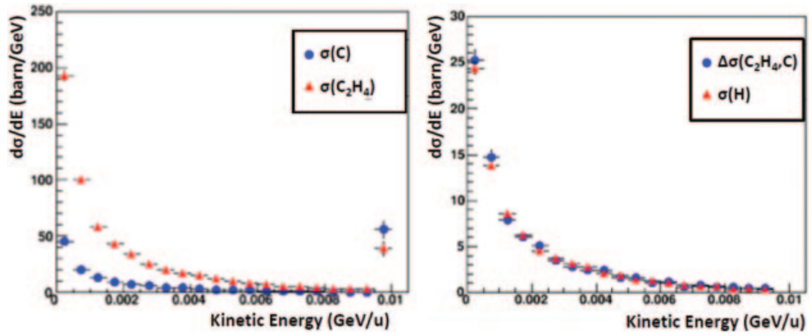

Fig. 1. – FLUKA simulation study of energy differential cross sections of C fragments in inverse kinematics for a ^{12}C beam on C and C_2H_4 target (left panel) and on H obtained by subtraction or directly on H target (right panel).

to the redundance of the FOOT detector, the number of mass A can be reconstructed in three ways, using the measurements retrieved from different sub-detectors:

1. time of flight + momentum:

$$A_1 = \frac{p}{uc\beta\gamma}, \tag{1}$$

2. time of flight + kinetic energy:

$$A_2 = \frac{E_k}{uc^2(\gamma - 1)}, \tag{2}$$

3. momentum + kinetic energy

$$A_3 = \frac{p^2c^2 - E_k^2}{2uc^2E_k^2}, \tag{3}$$

where β and γ are obtained from TOF and u is the atomic unit mass. The strategy used for the best determination of A considers two different global fit procedures: a standard χ^2 minimization approach and an Augmented Lagrangian method (ALM) approach [4] in which the masses obtained with the three methods are used as constraints.

The TOF, ΔE and p resolutions obtained from various test beams have been included in the MC simulations in order to estimate the detector capability to identify the fragments. The momentum resolution is, at present, evaluated via MC simulations. The estimated resolutions are

- $\sigma(p)/p \simeq 4\%$ (uniform in all the energy spectrum),
- $\sigma(E_k)/E_k \simeq 1.5\%$ (uniform in all the energy spectrum),
- $\sigma(\Delta E)/\Delta E \simeq$ 3–10% depending on ΔE,
- $\sigma(\mathrm{TOF}) \simeq$ 70–140 ps depending on Z.

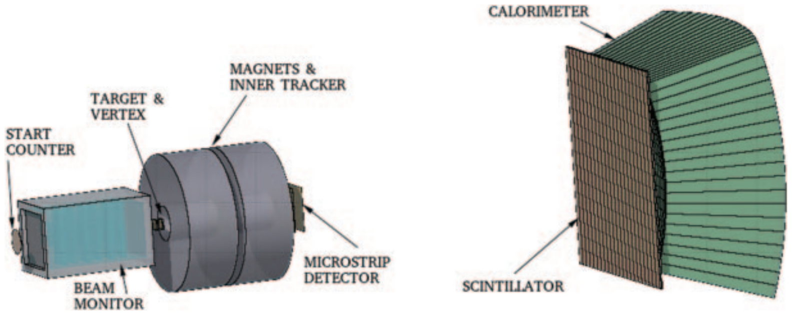

Fig. 2. – 3D view of the detector simulated by FLUKA.

3. – Electronic experimental setup

The planned experimental setup can be divided in three different regions (fig. 2):

- *Pre-target region.* A thin plastic scintillator counter provides trigger information and the TOF start, while a drift chamber acts as beam monitor to accurately measure the beam direction and position. The target is placed immediately downstream the beam monitor.
- *Magnetic spectrometer region.* Placed just after the target, a telescope of four layers of silicon pixel trackers provides the vertex reconstruction and the initial tracking. Then two cylindrical permanent magnets, realized in the Halbach configuration, provide the magnetic field (maximum value $\sim$0.9 T). Two additional layers of silicon pixel trackers placed in between the magnets and a telescope of three layers of orthogonally oriented silicon microstrips are placed between and beyond the magnets, respectively. All these tracking stations allow the measurement of fragments momentum.
- *Downstream region.* A detector made of two orthogonal planes consisting of 3 mm thick plastic scintillator bars measures ΔE and TOF. Finally, the measurement of kinetic energy is provided by a calorimeter made of about 300 BGO crystals, each one 24 cm thick.

The FOOT detector simulations have been built in the framework of the FLUKA MC code [5,6], and are currently used to optimize the design and to investigate the expected performances.

4. – Expected performances

A preliminary study of the detector performances on charge and mass resolution has been performed on the basis of the data obtained from FLUKA simulations, to which the above-mentioned resolutions have been applied.

The Z values are presented along with their resolutions in table I for some selected fragments (^{1}H, ^{4}He, ^{7}Li, ^{9}Be, ^{11}B, ^{12}C and ^{14}N), while the achievable resolutions on mass determination are reported in table II. As an example, in fig. 3 the ^{12}C mass obtained with the ALM fit, to which a χ^2 cut have been applied, is reported.

The resolutions obtained for heavy fragments charge and mass number determination are about 2% and 3%, respectively. This allows in the first case to make a wrong charge

TABLE I. – *True and reconstructed* Z *values of the selected fragments obtained for a 200 MeV/u* ^{16}O *ion beam impinging on a 2 mm thick* C_2H_4 *target.*

Fragment	^{7}Li	^{9}Be	^{11}B	^{12}C	^{14}N
Z	3	4	5	6	7
Z_{rec}	3.03 ± 0.08	4.05 ± 0.09	5.06 ± 0.10	6.09 ± 0.12	7.11 ± 0.14

TABLE II. – *True and reconstructed* A *values (*χ^2 *and ALM fits) of the selected fragments obtained for a 200 MeV/u* ^{16}O *ion beam impinging on a 2 mm thick* C_2H_4 *target.*

Fragment	^{7}Li	^{9}Be	^{11}B	^{12}C	^{14}N
A	7	9	11	12	14
A_{χ^2}	7.00 ± 0.31	8.99 ± 0.34	10.99 ± 0.44	11.99 ± 0.43	14.00 ± 0.48
A_{alm}	7.00 ± 0.31	8.98 ± 0.33	10.98 ± 0.44	11.98 ± 0.43	13.99 ± 0.48

definition in less than 1% of the reconstructed fragments and in the second one to have a good isotope separation (fig. 3).

5. – Additional goals of FOOT experiment

Complementary light fragments ($Z \leq 3$) measurements will be achieved by means of an emulsion chamber [7] (fig. 4). It will in fact provide measurements of fragments emitted in a cone with semiaperture up to 70°, which are mainly protons, deuterons, tritons, helium and lithium ions. In this setup, the pre-target region of the electronic setup will be employed to monitor the incoming primary beam, while the emulsion chamber will act both as target and fragments detector: in the first section target layers (C or C_2H_4) are alternated with emulsion films to reconstruct the interaction vertex, the second one will be made only by emulsion films to provide charge reconstruction, while in the last one the emulsion films are interleaved with Lead layers to measure fragments energy and momentum.

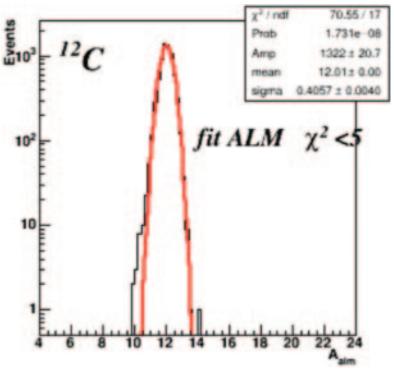

Fig. 3. – Example of ^{12}C mass determined by applying both the ALM fit and a χ^2 cut.

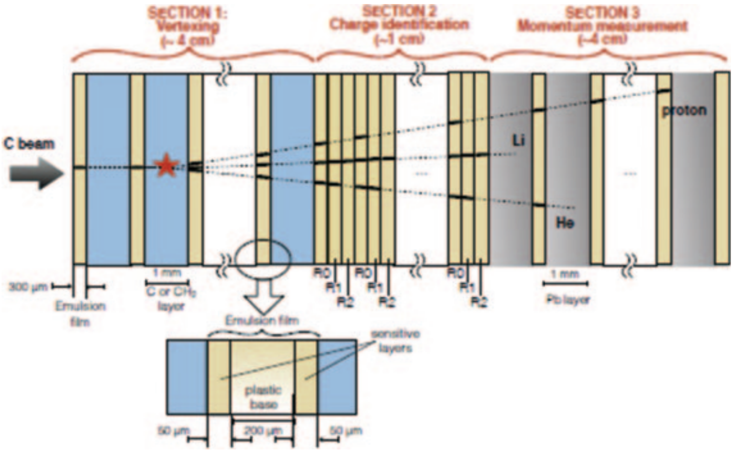

Fig. 4. – Scheme of the emulsion spectrometer detector.

Data that will be acquired by means of the electronic setup can also be studied in terms of direct kinematics, thus providing projectile (C and O) fragmentation cross sections, which are required to improve nuclear reactions description presently available in Treatment Planning Systems. Moreover, along with the study of cross sections relevant in hadrontherapy, also an investigation of the fragmentation induced by higher-energy beams will be performed, in order to provide data of interest for space radioprotection.

6. – Conclusions

The FOOT experiment's aim is to measure target fragmentation cross sections, in order to improve the protontherapy treatment quality. To this purpose, an inverse kinematics strategy will be adopted and two experimental setups, an electronic setup for heavier fragments measurement, and an emulsion cloud chamber for the lighter ones, are currently under development. Optimization and performances of the detectors are currently studied by means of FLUKA simulations and the outcomes are promising. Besides target fragmentation, the experiment will also provide projectile cross sections which are relevant in heavy ion therapy. In addition, by considering the operation of FOOT at higher energies, useful results for the development of radioprotection for long duration and far from earth space missions will be achieved.

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