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FOOT: FragmentatiOn Of Target Experiment

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Summary. — The main goal of the FOOT (FragmentatiOn Of Target) experiment is the measurement of the differential cross sections as a function of energy and direction of the produced fragments in the nuclear interaction between a ion beam (proton, helium, carbon, ...) and different targets (proton, carbon, oxygen, ...). Depending on the beam energy, the purpose of the measurements is twofold: in the [150-400] MeV/u range, the data will be used to evaluate the side effects of the nuclear fragmentation in the hadrontherapy treatment, while in the [700-1000] MeV/u range it will be used to optimize the shielding of spaceships for long term space missions. The experiment has been funded by the INFN since September 2017 and it is currently in the construction phase. An overview of the detector, of the results obtained in several beam tests and of the expected performances will be presented.

1. – Introduction

The main goal of the FOOT experiment is to provide cross section measurements necessary in two different fields: hadrontherapy and radioprotection in space.

In the last decade, a continuous increase in the number of cancer patients treated with Particle Therapy (PT) [1] has been registered, due to its effectiveness in the treatment of deep-seated solid tumors [2]. The main advantage of PT with respect to conventional radiotherapy with photons is the distribution of the deposited energy that is concentrated at a sharp depth inside the material at the Bragg peak, depending on the beam energy. At the end of the beam range the density of the deposited energy by a charged particle is larger compared to conventional photon beams and consequently the effect on the tumor, evaluated by the Relative Biological Effectiveness (RBE) is greater. When the charged particles travel through the patient, nuclear interactions occur producing nuclear fragments that can cause side effects in regions outside the tumor volume and vary the RBE. As a consequence a precise evaluation of this effect would increase the accuracy of the treatment. At the hadrontherapy energies ([150-400] MeV/u range), the most favoured nuclear process is the fragmentation between the nucleons of the beam and the target; this process generally provides several light fragments and on average one or two heavy fragments. At these energies, the probability to break the nucleons in quarks is negligible. Due to simple kinematical considerations, if the fragments derive from the target fragmentation they are produced almost at rest, while if they stem from the beam fragmentation they maintain almost the full kinetic energy per nucleon of the beam. In the former case the fragments have a very low range (tens of μm) and deposit their energy before reaching the tumor, while in the latter case, the range is longer than that the parent fragment's and the energy deposition can extend beyond the tumor. In both cases, the energy deposition is outside the tumor volume and can cause side effects, such as a new tumor, that need to be evaluated. For this purpose it is necessary to measure the differential cross section with respect to kinetic energies and direction of all the produced fragments with a precision of 5%. To accomplish this, the charge Z and mass number A identification, on top of energy and direction measurement, is needed. Since the fragments originating from the target fragmentation do no exit the target, FOOT overtakes this difficulty by means of the inverse kinematic approach: instead of studying the interaction of a proton beam with a target of C or O, it studies a C or O beam (with the same kinetic energy per nucleon of the proton) interacting on a proton target and then applyies a Lorentz transformation. This approach forces to use a proton target that, due to its gaseous state, drastically reduces the nuclear interaction probability; the adopted strategy is to use two targets, respectively, of C and C_2H_4 and to determine the cross section on proton by their difference [4].The inverse kinematic and the double target approaches induce uncertainties in the final differential cross section measurement that must be taken into account.

Regarding to the second FOOT mission, the XXI century will be characterized by a deeper exploration of the Solar System that will involve long term missions as the expedition to Mars. Health risks are associated to exposure to galactic cosmic radiation (GCR), that is very energetic (on average around 700-1000 MeV/u) and produces showers of light fragments and neutrons by nuclear fragmentation when hitting the spaceship shields. This suggests to study the differential cross section of the nuclear interaction between the GCR and the different materials composing the spaceship shields. Considering that the GCR are composed of 90% of protons, 9% of helium and the rest of heavy nuclei, the overlap with the measurements for hadrontherapy purposes is large, the main difference being the energy range.

2. – The FOOT Detector

Nuclear fragmentation produces both light and heavy fragments: the first are produced within a wide opening angle, while the second close to the beam direction. To detect both types of fragments, the FOOT detector consists of two different configurations: an emulsion chamber and an electronic setup (Fig. 1). The emulsion chamber setup covers an opening angle of ±70° optimized for the detection of fragments with $Z \leq 3$. The emulsion chamber setup is made of a pre-target region followed by an emulsion chamber [5]. In the pre-target region a plastic scintillator (Start Counter) detects the incoming beam and starts a time of flight (TOF) measurement; a drift chamber (Beam Monitor) measures the beam direction (necessary for the inverse kinematic approach) and recognizes possible nuclear fragmentation of the beam in the Start Counter. The emulsion chamber is composed of three different regions:

- the first made of C and C_2H_4 layers (as target) interleaved by emulsion films to detect the reaction vertex and the first track segment of the fragments;

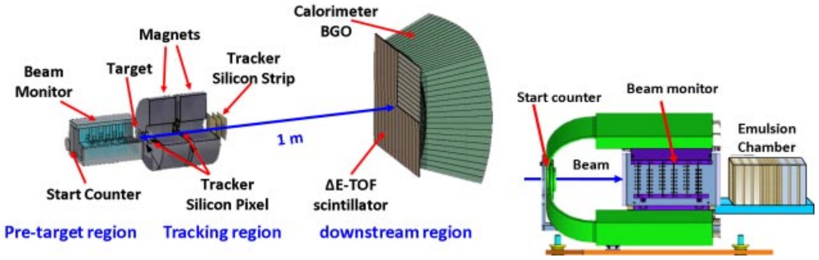

Fig. 1. – FOOT detector: electronic setup (left) and emulsion chamber setup (right).

- the second consists of only emulsion films for the charge identification:
- the third is made of Pb layers interspersed with emulsion films for momentum determination.

Similar emulsion chambers have been successfully used in the OPERA experiment.

The electronic setup of the FOOT detector [6] consists of a pre-target region, a tracking region and a downstream region. The pre-target region is the same as the emulsion chamber setup. The tracking region is composed of three stations of silicon detectors: the first (vertex) is composed of 4 layers of silicon pixels, the second (inner tracker) of two layers of silicon pixels and the third of three double layers of silicon strips. Between the three stations, two permanent magnets with a Halbach geometry are inserted providing a maximum field of 1 Tesla. The downstream region is composed of two orthogonal planes of thin plastic scintillator strips coupled to silicon photomultipliers for $\Delta E/\Delta x$ measurement and for the stop of the TOF. A calorimeter made of BGO scintillating crystals for the kinetic energy measurement is located at the very end of the apparatus. The experiment was devised as a table-top in order to cope with the dimensions of the possible experimental halls available at the CNAO, LNS, GSI and HIT treatment centers. The first data taking is foreseen in 2020.

Both the emulsion chamber and the electronic setups will be modified for the data taking at higher energy to keep the same acceptance for the studied fragments. The emulsion chamber will have a different geometry concerning the distribution of the layers, in particular the number of Pb planes of the last part will be increased in order to contain more energetic fragments. In the electronic setup, two modifications will be in order:

- the tracking system stations will be moved further away from each other in order to increase the magnetic analyzing power and consequently to improve the momentum (p) resolution;
- the plastic scintillator and the calorimeter will be moved to 2.9 m from the target (the standar position is at 1.0 m) to improve the β resolution maintaining the same resolution on the TOF.

Several beam tests have been performed on different components of the apparatus in order to check their performance. The plastic scintillator has been tested at CNAO with a proton and a carbon beam of various energies: the achieved accuracy on the TOF stop time was around 50 ps for carbon and about a factor 2 worse for protons [7]. Assuming to have the same precision on the Start Counter for the opening TOF, a final TOF precision of heavy fragments of 70 ps is expected. The precision reached on the deposited energy

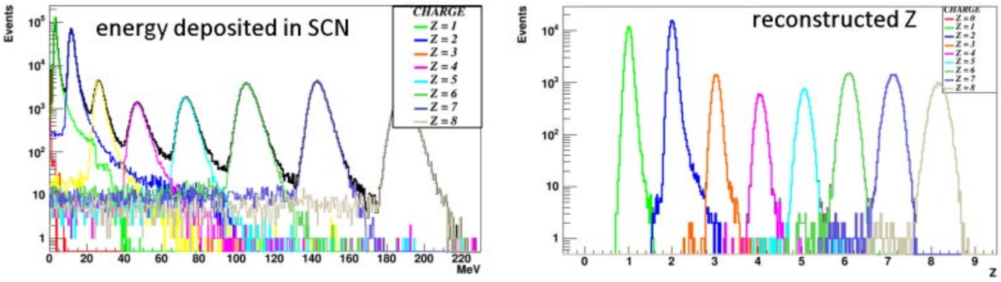

Fig. 2. – Released energy on the plastic scintillator (left) and Charge reconstruction (right).

($\Delta E/\Delta x$) resulted in the $3 - 10\%$ range from carbon to protons. A sizeable part of the Calorimeter (145 crystals) has been tested at the HIT center with a proton, helium and carbon beams at different energies resulting in a energy resolution of about 1.5% for heavy fragments. At the moment the resolution of the tracking system has not been evaluated yet at a beam test, but only through a detailed simulation with Fluka [8]: the obtained p resolution is about 4% in all momentum range. All these resolutions have been included in the Monte Carlo (MC) simulation to estimate the probability of the fragment identification.

3. – Fragment identification

A fragment is uniquely identified when its charge and mass number are correctly measured.

The charge is measured inverting the Bethe-Bloch formula after the measurements of the deposited energy in the plastic scintillator ($\Delta E/\Delta x$) and TOF (from the same scintillator and the Start Counter). The energy released in the scintillator and the corresponding charge of the fragments are presented in Fig. 2 for a ^{16}O beam of 200 MeV/u on a C_2H_4 target (Fluka simulation). The distributions of the released energy of the charged particles are well separated allowing a correct charge assignment for 99% of the events. The obtained resolution of the charge determination is 2% for heavy fragments ($Z \geq 3$). Similar performance has been obtained at higher energies, for example in a simulation of ^{16}O beam of 700 MeV/u on a C_2H_4 target.

The redundance of the FOOT apparatus allows us to reconstruct the mass number in three different but correlated ways:

$$A_1 = \frac{p}{u\beta\gamma} \qquad A_2 = \frac{E_{kin}}{u(\gamma - 1)} \qquad A_3 = \frac{p^2 - E_{kin}^2}{2uE_{kin}} \tag{1}$$

where u is the atomic mass unit, β is the relative velocity with respect the light speed, γ is the Lorentz factor, p the momentum, E_{kin} the kinetic energy and A_1, A_2 and A_3 are the mass number derived from TOF plus tracking, TOF plus calorimeter and tracking plus calorimeter information respectively. A better precision is reached performing a kinematic fit that uses all the information from each A_i at the same time. Two different fit strategies have been used: a standard χ^2 fit and an Augmented Lagrangian Method (ALM) Fit [9]. The results of the two approaches are very similar, and for brevity

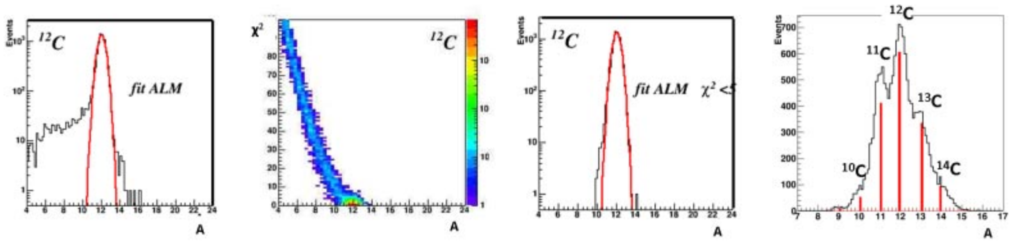

Fig. 3. – Example of ^{12}C mass number A reconstruction for a simulation of $^{16}O(200\ MeV/u)$ on a C_2H_4 target. The first plot is referred to the A reconstruction with ALM, the second is the χ^2 distribution with respect A, the third is the A reconstruction with $\chi^2 < 5$ and the last all the produced carbon isotopes reconstructed with ALM with $\chi^2 < 5$.

only the ALM is reported. The A resolution obtained from ALM was 3% for the heavy fragments (first plot of Fig. 3 for a typical ^{12}C fragment) from a simulation of ^{16}O with an energy of 200 MeV/u. A tail of badly reconstructed events is present due to the missing energy of neutrons produced in the nuclear interaction between the fragment and the BGO material of the calorimeter: these events have a large χ^2 of the fit (second plot of Fig. 3), so the tail can be removed with an appropriate χ^2 cut (here $\chi^2 < 5$) obtaining a clean distribution (third plot in Fig. 3). The obtained resolution on A allows the different isotopes of each charged fragment to be separated (last plot of Fig. 3 for the case of a carbon fragment). This makes us confident for future measurements on the differential cross sections of the all produced fragments. A similar performance was also obtained with a 700 MeV/u ^{16}O beam on a C_2H_4 target.

4. – Conclusion

The main goal of the FOOT experiment is to measure the differential cross sections of the produced fragments in the nuclear interaction between a ion beam (p, He, C, O, ...) and a target (p, C, O, ...). The measurements will be performed at two different energy ranges (150-250 and 700-1000 MeV/u) in order to improve the accuracy of Planning Systems for hadrontherapy treatment and to optimize the shielding of spaceships for long term missions. The experiment is in the construction phase and several beam tests have already been performed with satisfying results. The current simulation demonstrates the feasibility of the measurements.

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