



An Update on the FOOT Experiment

Programma anni futuri Richieste 2025 Sblocchi SJ

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The FOOT Collaboration (2025)

93+6 Authors, 33+2 Institutions

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Italy, France, Germany, Japan, Cuba, +India
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3 Continents (Europe, Asia, America)

INFN:

12 units (Ba, Bo, LNF, LNGS, Mi, Na, Pg, Pi, Rm1, Rm2, TIFPA, To)

66 researchers & 13 technologists

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28.9 FTE (25.5 researchers, 3.4 technologists)
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2025:

LNGS : Preparation/development of nuclear emulsions Calicut University (Kerala, India): participation to the analysis (MAECI - mobility of researchers)

Data taking campaigns already performed

Beam	Target	Energy MeV/u	Statistics (millions, electronic set-up only)	Integral Differential elemental	Integral Differential isotopic	direct	Inverse	Emul- sions	Campaign	Analysis status
0	С	200	0.06	angle	NO	YES	NO	Yes	GSI 2019	published
	C2H4	400						Yes	GSI 2020	
0	С	200	14.2	angle	NO	YES	NO	Yes	GSI 2021	
	C2H4	200	12.2							
	С	400	5.5							In the pub
	C2H4	400	6.5							phase .
He	С	100	18.5	angle	NO	YES	NO	No	HEID 2022	Only
		140	19.6							detector
		200	13.5							calib
		220	14.4							
С	С	200	4.1	angle	NO	YES	NO		CNAO 2022	Det calib.
С	С	200	3.2	Angle	YES	YES	YES	Yes	CNAO 2023	Started
	C2H4	200	2.0	Energy						

Vertex & Inner tracker – CNAO 2023



Vertex spatial resolutions



Magnet and Intermediate Tracker!



LNF measurements. 3D mechanical and magnetic model

- · Needed several iteration to get the real «as built»
- · Several tests for different «real positions» of M1 & M2
- · Permanent magnets BH curves from producer.



MSD status



A lot of effort to understand well the detector. W.r.t. the starting condition:

- Changes in firmware to reduce induced noise in the strips
- Optimized tracking of the pedestals (that might vary in a run)
- Updated definition of hit clusters with two thresholds (Seed, signal)
- Optimized spatial reconstruction, taking into account the eta-dependence
- Energy deposition calibrated w.r.t. the eta-dependence
- Checked all the samples from GSI 2021 to CNAO 2023





 $\mathbf{S}_{\text{L/R}}$ = two highest strips in cluster



Median ΔE on a track

In-flight interations can be well identified if they happens after MSD

η correction: multi-sensor energy loss





MSD-TW correlation





- Very good MSD-TW correlation!
- Possible to recognize many physics and
- reconstruction effects
 - Good correlation
 - Out-of-target fragmentation
 - **→** 2-α pile-up
 - ✤ Noise artifacts
- ✤ Event pile-up (?)

TOF Wall – Energy calibration – CNAO 2023

Routine calibration at each data taking: check of timings and energy deposits



60

40

50

fragmentation data

Calorimeter calibration



Set-up almost completed

Module holding mechanics to be substituted HIT2022: few modules calibrated with p, He, C, O CNAO2023: all modules calibrated with p & C





Charge dependence of the parametrization



GSI 2021 analysis – electronic set-up – ¹⁶O+C, 400 MeV/n

Few detector elements: SC, BM, TW (no VTX, ITR, MSD, CALO) «high» background from in-flight interactions Full analysis chain; MC closure test OK; $\frac{d\sigma}{d\theta}(Z) = \frac{1}{N_{prin}}$



 $\frac{Y(Z,\theta)}{N_{\text{prim}} \cdot N_{\text{TG}} \cdot \Delta \theta \cdot \varepsilon(Z,\theta)}$

GSI 2021 analysis – electronic set-up – ¹⁶O+C₂H₄, 400 MeV/n

Ongoing analysis of C2H4 Preliminary results





Emulsions: data analysis and cross section measurement

- Analysis of ¹⁶O @ 200 MeV/n on C and C₂H₄ targets almost completed:
 - Improvements in data-driven effects added on Monte Carlo reconstruction (background, misalignments, local distortion due to chemical development...)
 - · Evaluation of total and reaction cross sections
 - Evaluation of systematics effects by data-driven methods
 - Paper on cross section measurements with¹⁶O at 200 MeV/n on C, C₂H₄ and H in preparation





Integrated cross section H

Total reaction cross section

Total production cross section



Publications and papers in preparation (emulsions)

- Paper published on Charge identification of fragments produced in ¹⁶O at 200 327202 MeV/n and 400 MeV/n on C and C₂H₄ targets
- Paper on cross section measurements with¹⁶O at 200 MeV/n on C, C₂H₄ and H in preparation

¹⁶O ions at 200 MeV Nuclear reaction cross section on carbon and polyethilene targets measured by a nuclear emulsion detector

Abstract

Keywords: Particle therapy, nuclear emulsions, cross section, fragmentation

1. Introduction

Knowledge of nuclear reaction cross sections is crucial for an accurate evaluation of the dose in both charged particle therapy (CPT) and space radiation protection (SPR). Numerous studies have investigated the production of secondary fragments resulting from the fragmentation of primary ions; however, the available experimental data in the energy range 100-400 Mev/n for medical applications and greater than 700 MeV/n for SPR are still lacking. In Luoni et al. (2021) an up-to-date database collecting all published data for total nuclear reaction cross section was reported, together with the comparisons between experimental data and the parameterization utilized in transport codes The scarcity of measured nuclear cross-section data within the 100-400 MeV/n range is highlighted

The FOOT (FragmentatiOn Of Target) experiment () was designed to partially overcome such a crucial lack of data. Its objective is to measure the target fragmentation induced by protons on nuclei commonly found in human tissues, including hydrogen, carbon and oxygen, within the energy range relevant to therapeutic applications and space radiation protection. In this paper, we will provide the first measured nuclear cross-section data within XX-XX energy range.

2. Material and methods

The FOOT experiment aims to measure both projectile and target fragmentation, by means of detecting charged fragments generated in ion collisions with the most abundant elements in our organism (Carbon, Nitrogen, Oxygen). Of particular interest are the proton-nucleus (p-N) collisions, which are significantly challenging due to the extremely short range of the resulting fragments, of the order of tens of microns, resulting in a low probability of going out from the target

Target fragmentation cross sections are hence measured using an inverse kinematic approach, studying the interactions of a heavy ion beam impinging on pure and hydrogen-rich targets. Then, p-N cross sections are computed using the subtraction method, the feasibility of which has already been demonstrated in (Dudouet et al., 2013).

The FOOT measurements campaign foresees an extensive programme focused on the nuclear fragmentation of ⁴He, ¹2C ages are then converted into a grey scale of 256 levels, sent Prenting submitted to Nuclear Physics A

and ¹6O beams impinging on C and polyethylene (C₂H₄) targets, in the energy range 100-800 MeV/nucleon. The FOOT experiment employs two complementary setup

an electronic one for $Z \ge 3$ fragments at small angles ($\le 10^\circ$), and an emulsion spectrometer for $Z \le 3$ fragments over a wide angular range (≤ 70°). The whole detector design, expected performances (studied by FLUKA MC simulations) and the results of the preliminary test beams are described in a recent work (Battistoni et al., 2021).

2.1. Nuclear emulsion films

Nuclear emulsions are special photographic films composed of a large number of silver halide crystals (typically AgBr) dispersed in an organic gelatine. Each film consists of two sensitive layers deposited on both sides of a thick plastic base, resulting in a total thickness of about 300-400 µm. When a charged particle crosses the sensitive layer, the crystals along its trajectory are sensitised and give rise, after chemical development, to a sequence of dark silver grains. The grain density of a track segment keeps information on the local energy deposited. The nuclear emulsion films used in this data takings were produced in collaboration with Nagoya University (Japan) and Slavich Company (Russia). The mean thickness of the sensitive layers is 93 µm for Nagoya films and 77 µm for Slavich ones. Their sensitivity is 30 grains/100 µm for MIP particles. The thickness

of the plastic base is 179 µm and 198 µm, respectively After development, the analog images are digitised by New Generation Scanning System (NGSS) optical automatic microscopes (Alexandrov et al., 2015, 2016, 2017). The NGSS consists of a CMOS camera, a frame-grabber, a

GPU board for image processing, a 3D movable stage, an optical system, an illumination system, a motion control unit, and a workstation to perform on-line and off-line processes thanks to the software LASSO (De Lellis et al., 2007, 2011; Lauria et al., 2015; ?; ?). With this configuration, it has a scanning speed of 60 cm²/h. Moving the focal plane of the objective through the film thickness, a sequence of tomographic images 800×600 um2 of each field of view is obtained, where the images are taken with steps of 1.75 um (see fig.2 left). The acquired imto a GPU board, bosted in the control workstation, and analysed to search for sequences of aligned grains which will form a segment of the track. The segment in a single film is called "base-track". The grain density is digitized to pixel counts of CMOS images whose pixel size is 0.35 × 0.35µm. The sum of the nixel brightness along each base-track is named "Volume" and used to identify a track charge at a later stage. Track segments with tangents of polar angles (hereafter "slope") less than Imrad were recorded, and the average detection efficiency of a track segment is > 90%. The positional and angular resolutions are 1/m and 1 mrad, respectively, EORSE METTIAMO 2 e 2.5 PER COERENZA CON SMEARING?

2.2. The nuclear emulsions Spectrometers The nuclear emulsion spectrometers are Emulsion Cloud

Chambers (ECC) (Kanlon et al. 1952) detectors constructed with a well-known technique that involves a sequence of nuclear emulsion films interleaved with passive material, arranged perpendicular to the incoming particles. This configuration creates a compact setup that functions as a finely subdivided sampling calorimeter, allowing for the high-resolution reconstruction of charged tracks originating from interactions in space. The characteristics of the ECC used for the EOOT experiment have already been described in detail in Montesi et al.

(2019); Galati et al. (2021, 2024), and are briefly summarized here for clarity The ECC is composed of three sections, each dedicated to a specific task (see Figure 1). The first section (S1) is designed for interaction vertex reconstruction and consists of 30 alternat-

ing layers of nuclear emulsion films and target material: Carbon (1 mm thick) or Polyethylene C:H4 (2 mm thick). We will refer to the ECC containing the Carbon target as ECC1 and the one with the Polyethylene target as ECC2. The second section (S2) is aimed at fragments' charge identification and is composed of 36 nuclear emulsion films, which undergo to specific thermal treatments before chemical development. The third section (S3), dedicated to momentum measurement, includes a sequence of emulsions and materials with increasing thickness and density: lexan (1mm thick), tunesten (0.5 and 0.9mm thick), and lead (1mm and 2mm thick). The results reported in this paper involve sections S1 and S2.

Two ECCs were assembled at CERN and transported in a refrigerated box by train to the GSI facility in Germany. After exposure, the ECCs (still assembled) were taken to the University of Naples for S2 thermal treatments processes and all chemical developments. 2.3. Experimental set-up at GSI

Two beam exposures were performed in cave A of the GSI

Helmholtzzentrum für Schwerionenforschung facility in Darmstadt (Germany) in April 2019, using a 16O primary beam with kinetic energy of 200 MeV/n. The beam impinging on the ECC was monitored by the Start

Counter, which is based on a thin plastic scintillator, to count the incident particles, and by the Beam Monitor, which consists of a drift chamber to provide their spatial distribution (Battistoni et al., 2021).

Figure 1: The nuclear emulsion spectrometer structure consists of three sec-tions, each designed according to different physics objectives: vertexing, fragx 14 cm x 30 cm), made with a 3D printer, which is light-shielded and has a 2.5cm x 2.5 cm window for beam entry

The beam size and intensity were optimized to ensure that the surface of the ECC corresponding to the scanning area was irradiated uniformly with an appropriate density. The number of 16O ions impinging on the detector was evaluated as a trade-off between avoiding interaction pile-up in nuclear emulsion films (with a maximum occupancy of approximately 1000 particles/cm2) and and achieving large statistics. The 16O ms had Gaussian shapes with a typ. FWHM of 6 mm, and the irradiation was performed on a square of 24 mm side, in a grid of 25×25 spots with 1 mm step size, starting from the cen tre and following a squared spiral shape. The nominal fluence was 3100 ions/cm2 and 3200 ions/cm2 for C and C2H4 targets

Nuclear emulsion films are sensitive to charged particles from the time of production until their chemical development. During this period, they accumulate tracks from cosmic rays and environmental radioactivity. To minimize unwanted back ground, the films were transported in a random order before detector assembly. This randomization ensures that cosmic ray tracks accumulated during transport do not align in a way that allows them to be reconstructed as penetrating tracks. However, they can still contribute to the background if there is a random association of two or more aligned base-tracks. The cosmic rays integrated while the ECCs were assembled, instead, are used for align films during the tracks reconstruction, as will be outlined in section 2.6.

2.4. Charge identification The Volume of a track, defined as the sum of the pixel brightness of all its base-tracks in arbitrary units, is proportional to the energy loss of particles within a specific range At high ionization levels, the grain density saturates, hinder ing charge measurements. To address this, thermal treatments were applied to induce controlled fading, as described in previous works De Lellis et al. (2007, 2011); Lauria et al. (2015) **ORIGINAL RESEARCH article** Front, Phys., 29 January 2024 Sec. Nuclear Physics Volume 11 - 2023 | https://doi.org/10.3389/fphy.2023.1327202

Charge identification of fragments produced in ¹⁶O beam interactions at 200 *MeVI n* and 400 MeV/n on C and C₂H₄ targets





2 Material and methods

secondary fragments

2.1 The nuclear emulsion detector

A detailed description of the nuclear emulsion spec available in Ref. [11]. For the sake of clarity, a brief description is reported in the following. Nuclear emulsion spectrometers have as Emulsion Cloud Chamber (ECC) structure, which is composed of the following three sections (see Figure 1):

thicknesses and densities, is designed to stop fragments and measure their momentum by combining ind from their range and Multiple Coulorr · Vertexing section consisting of 30 reachest envolution film Scattering (MCS) [16] interleaved with layers of target passive material (C or C.H.) is designed to reconstruct the vertices where Nuclear emplaion films, which are the active part of the primary ions interact with atoms of the target and produce detector, consist of two sensitive layers (each 70 µm thick) deposited on both sides of a 210 am thick plastic bas

before chemical development

· Charge identification section, consisting of 36 nuclea

emulsion films (divided into 9 cells), is designed to

dentify the charge of the fragments that cross it through

dedicated thermal treatments of the nuclear emulaion films

Momentum measurement section, consisting of a securice

nuclear emulsion films and passive layers of differen

NIT emulsions first results

- Access to the direct kinematics of p+C fragmentation cross sections
- All the emulsions from the Pilot test have been scanned with the fast optical microscope
- Developed a strategy to identify target fragmentation events: more than 1500
 events reconstructed so far
 Proton

3D displays of reconstructed events





Developments/problems:

35720 35700 5680

14920

- Improved optics for the scanning microscopes
- Tracks and interactions are clearly seen
- Vertices can be easily reconstructed
- Impinging proton track is weak
- Emulsion preparation and development to be studied carefully

α clustering physics with nuclear emulsions

- Nuclear cluster structures can be probed by studying preferential dissociation channels (such as ${}^{16}O \rightarrow 4 \alpha$)
- lpha clustering has not been thoroughly explored in the energy regime accessed by FOOT
- Analysis on-going with 2019 FOOT emulsion DATA (${}^{16}O @ 200 \text{ MeV/n}$ on carbon and polyethylene targets)
- The detection of correlated He pairs (relative angle $< 25 \ mrad$) is used to measure the production of ${}^{8}Be_{g.s.}$ in the fragmentation of the oxygen nucleus



Future: 2025-2027

- At the moment there is no portable competing experiment with FOOT \rightarrow no external improvements on cross section measurements.
- We are still working towards differential cross sections for hadrontherapy
- C+C, C+C2H4, O+C, O+C2H4 in different conditions at Ekin < 400 MeV/n
 -A lot of interest also for higher energies for radioprotection (O+C, O+C2H4 at > 500 MeV/n)
- -At CNAO there is a broad interest on 4He: both for therapy and for diagnostics

Far Future (>2027)

- O-O cross section (for space radioprotection) and Ca+C cross sections (for hadrontherapy) are also very interesting in their fields

Foreseen data taking campaigns

Beam	Target	Energy MeV/u	Integral Differential elemental	Integral Differential isotopic	Direct	inverse	Emul- sions	Campaign
С	C C2H4	100-200	Angle Energy	YES	YES	YES	YES (NIT?)	CNAO 2025
0	С	500-700 (?)	Angle Energy	YES	YES	YES	YES	GSI 2026
С	C C2H4	200-300	Angle Energy	YES	YES	YES	-	CNAO 2026
Ρ	С	100-220	Angle Energy	YES	YES	-	NIT	CNAO 2026
С	C C2H4 PMMA	320-400	Angle Energy	YES	YES	YES	YES	CNAO 2027
He	C C2H4 PMMA	200- 400(?)	Angle Energy	YES	YES	YES	YES	CNAO 2027

Richieste finanziarie 2025

Capitolo	Richieste (k€)	Voci principali
Inventariabile	0	Finanziati su PRIN/MAECI o altro
Consumo	47	NA: chim x emulsioni, LNF: mecc+schede,
Apparati	0	Finanziati su PRIN/MAECI o altro
Trasporti	5	BO, LNGS, MI, PI
Missioni	144	Tutti: prese dati a CNAO, meeting di collaborazione, tests, calibrazioni. NO GSI
Pubblicazioni	0	Finanziati su MAECI, principalmente
Totale	195	per una spesa pro capite di 6.7 k€/FTE

Storico richieste: 2017: 274 k€, 2018: 815k€, 2019: 868 k€, 2020: 545 k€, 2021: 389 k€ 2022: 434 k€, 2023: 317 k€, 2024: 286 k€

Algoritmo missioni

- . Viaggio ITA (AR): 220€, viaggio EU (AR): 440€
- . Giorno ITA, giorno EU: 180€
- · 2 Meeting di collaborazione ITA (per molti)
- · Presa dati 1-4 persone per sede
- Trasporti per BO, LNF, MI, PI, TO (>1 m³, >200 kg, sicurezza)

Richieste consumo 2025

Sede	Richieste (k€)	Voci principali
BO, LNF, MI, PI, RM1, RM2, TIPFA, TO	17	Metabolismi laboratorio (2 k€/sede in media)
LNGS	5	Prodotti chimici per emulsioni / smaltimento
BO, LNF	8	Schede elettroniche (DAQ, Nuovo VTX)
LNF	5	Sensori MIMOSA di riserva
NA	11,5	Emulsioni e reagenti chimici
Totale	46,5	

Richieste addizionali & sblocchi

Nessuna richiesta addizionale! \rightarrow In caso di necessità ci aiuteremo tra le sezioni

Prossime prese dati: CNAO – Novembre 2024 – (+BTF prenotata per fine novembre)

SJ totali: 70 k€ - Richieste sblocco 48 k€, restituzione di 22 k€

Richieste di sblocco	Richieste (k€)	Sezione/voci principali
SJ missioni x CNAO	23.0	Varie sedi coinvolte (non tutte)
SJ Bonus dottorandi	24.5	BO (da usare per il CNAO)

Milestones

Milestone	Data	
Proceeding/articolo con risultati preliminari campagna 2023 set- up elettronico	31-dic-2025	
Proceeding/articolo con risultati preliminari emulsioni 2023	31-dic-2025	
Test su fascio del nuovo rivelatore di vertice	31-dic-2025	
Test su fascio di un prototipo di nuovo TofWall	31-dic-2025	
Sottomissione lavoro strumentale FOOT	31-dic-2025	
Proceeding/articolo R&D su emulsioni NIT per FOOT	31-dic-2025	

Grazie per l'attenzione!

