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Emulsion Cloud Chamber Technology to measure the Fragmentation of Carbon Ion Beams used in Hadron Therapy

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Abstract – **The use of Carbon ion beams in hadron therapy has become more and more used in recent years. Carbon ions present some advantages when compared to traditional radiotherapy, such as the dose-depth deposition that makes possible to reach critical anatomical sites and the biological effectiveness. The knowledge of the light fragments production yield and their angular distribution has a key role in the estimation of the dose profile in hadron therapy.**

We present a detector based on nuclear emulsions for fragmentation measurements that performs a sub-micrometric tridimensional spatial resolution, excellent multi-particle separation and large angle track recognition. Nuclear emulsions are assembled in order to realize a hybrid detector (Emulsion Cloud Chamber - ECC) made of 300 μ-thick nuclear emulsion films alternated with passive material, such as lead.

The data presented here have been obtained by exposing two ECC to the fragments produced by a 400 MeV/nucleon ^{12}C beam on a carbon target (GSI laboratory, Darmstadt, Germany). The ECC was exposed inside a more complex detector named FIRST in order to collect fragments with an angular distribution in the range 33°÷88° (with respect to the beam axis). Preliminary results on fragments momentum measurements performed either with the Multiple Coulomb Scattering and the range methods are reported here.

I. INTRODUCTION

The hadron therapy based on the use of Carbon ion beams has shown encouraging results in many different types of adult tumours during the last 20 years [1,2]. Clinical trials have proven the efficacy of charged particles radiotherapy in terms of improving both precisely dose localization and survival rates in a variety of tumours.

Many efforts have been performed to characterize the dose inside human tissue in case of incident ion beams, but the energy deposition of fragments and their angular distribution is not yet accurately established. This achievement has a key role to assess the results of the Monte Carlo (MC) simulations representing the basis of medical treatment planning.

In this study we used nuclear emulsions, already used for the OPERA experiment [3], performing sub-micrometric spatial resolution, excellent multi-particle separation and large angle track recognition, to measure the angular and the momentum distribution of the fragments produced by ^{12}C ions interaction.

In a previous analysis our group carried out a study for the charge measurements of fragments produced by the interaction of ^{12}C beam (400 MeV/nucleon) in a detector simulating the density of the human tissue [4,5]. A chamber made of nuclear emulsion films alternated with Lexan plates was exposed at the Heavy Ion Medical Accelerator (HIMAC) in Chiba (Japan). By analysing the grain density along the particle track on emulsion films, it was possible a charge separation of the produced fragments as shown in fig. 1 [4].

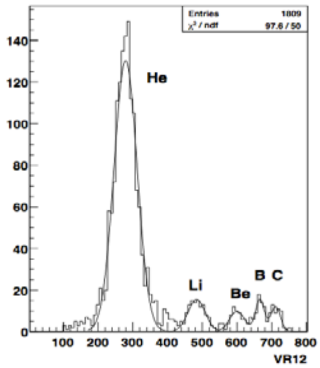

Fig. 1:Charge separation of the fragments generated along the detector by a ^{12}C ion beam (400 MeV/nucleon).

Table 1. Charge-changing cross section (mbarn) with the statistical and systematic errors.

Δz	1	2	3	4
σ	**2510**	**1170**	**1460**	**7510**
$\delta\sigma_{stat}$	140	90	105	240
$\delta\sigma_{sys}$	250	120	150	750

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In this study, we measured the Carbon ions charge-changing cross section analysing the Carbon interaction vertices and measuring the charge of all the outgoing fragments. The results in terms of charge-changing (Δz) cross-section are summarized in tab. 1 [4].

II. EXPERIMENTAL SET UP AND METHODS

The aim of this work is the measurement of the angular distribution and the momentum distribution of large angles fragments produced by a ^{12}C ion beam impinging on a carbon target. To this purpose we used a nuclear emulsion detector.

A. Emulsion Cloud Chamber - ECC

The nuclear emulsion films used for this analysis are the same employed in the OPERA experiment for the study of neutrino oscillation [3]. Fuji company produced the films needed for OPERA experiment in collaboration with the group of Nagoya University. The collaboration gave rise to first industrial production of nuclear emulsions with high sensitivity (about 30 grains/100 μm for MIPs – Minimum Ionizing Particles). The OPERA emulsion films consist of 44 μm thick emulsion layers deposited on both sides of a 205 μm thick plastic support with a sensitive surface of 12.5 × 10.0 cm^2.

The ECC was built as a sequence of nuclear emulsion films and lead plates. The structure developed for this study can be divided in two sections: a first section consisting of 6 nuclear emulsion films put at the top of a second section consisting of 55 nuclear emulsion films interleaved with 1 mm thick lead plates (fig. 2). The overall ECC dimensions are 12.5(length)×10.0(width)× 7.3 (height) cm^3.

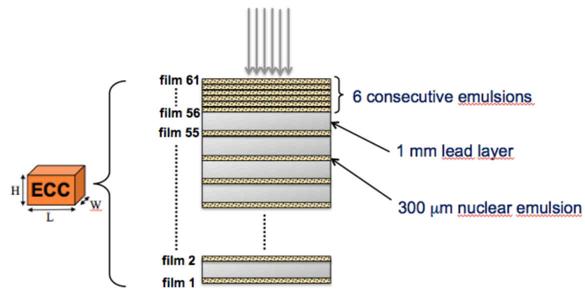

Fig. 2. Details of the ECC structure.

B. ^{12}C ion beam exposure

Our ECC detectors were dedicated to study the 400 MeV/nucleon ^{12}C ions beam fragmentation on 8 mm thick carbon target in the framework of the FIRST (**F**ragmentation of **I**ons **R**elevant for **S**pace and **T**herapy) experiment [6,7]. The FIRST apparatus was installed at SIS accelerator of GSI laboratory in Darmstadt and is dedicated for the measurements of different ions fragmentation cross sections at different energy (energy range 100÷1000 MeV/nucleon).

The FIRST detector can be divided into two main blocks: an Interaction Region and a Large Detector Region. In the Interaction Region is present a detector named KENTROS (Kinetic ENergy and Time Resolution Optimized on Scintillator) for the measurements of the fragments TOF (Time Of Flight) and energy release [6].

We have installed two ECC chambers into the KENTROS detector as indicated in fig. 3. The distances with respect to the incident ^{12}C beam on the carbon target are shown in fig. 4. The top surface of the ECC detectors was 16.5 cm below the axis beam.

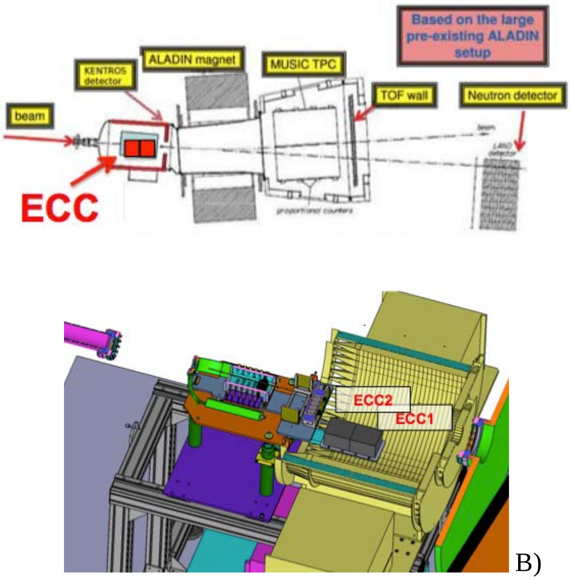

Fig. 3: A) Schematic layout of the FIRST experiment at GSI. The location of two ECC detectors is highlighted; B) Zoomed view of the KENTROS region with the ECC detectors.

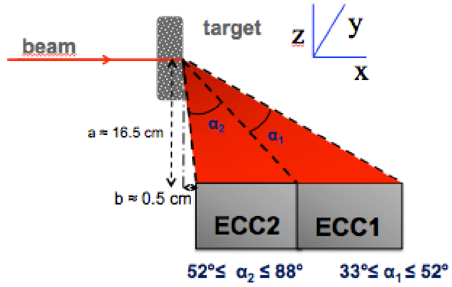

Fig. 4: Layout of the ECC detectors, the ^{12}C beam and the target; relative distances and the angles with respect to the beam axis are indicated (along x axis).

The ECC detectors were located in such a way to collect ^{12}C fragments emitted with a large angular distribution with respect to the beam axis. The range of the angular distribution with respect to the beam axis are 33°÷ 52° (for ECC1) and 52°÷ 88° (for ECC2). Indeed large angle particles are dominated by protons and, to some extent, by alpha particles [7]. The measurement of protons at a large angle could be used to monitor the delivered dose, provided the cross-section is well known. The measurement of the large angle proton cross-section is indeed the motivation of our work.

The chemical development was carried out at the facility at the LNGS (L'Aquila, Italy). After the development, nuclear emulsions were brought to the OPERA Laboratory at the University of Napoli where they have been analyzed by automated microscopes with a dedicated software operating at a speed of 40 cm^2/hour [8].

C. Track reconstruction

Charged particles crossing the emulsion ionize silver bromide crystals which, after film developing and scanning, are reconstructed as a sequence of black dots forming a micro-track in a single emulsion layer. Two micro-tracks can be connected to define a base-track in a single film (a film is composed by two emulsion layers on a plastic base); connecting base-tracks in two or more films a volume-track can be reconstructed.

For each particle track it is possible to determine, thanks to the high resolution of the nuclear emulsions [9], the x-y spatial coordinates and the slope (θ_x, θ_y).

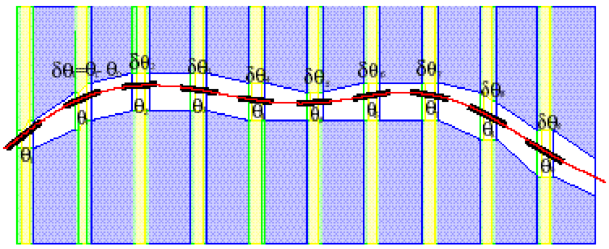

Fig. 5: Schematic view of a volume-track formed by a sequence of base-tracks with their angular measurements in a section of a ECC detector.

The availability of several angular measurements along a volume-track makes possible to calculate the particle momentum by the Multiple Coulomb Scattering (MCS) method (fig. 5). The following formula is at the basis of the MCS method:

$$p\ (MeV/c) = \frac{13.6}{\beta\, \delta\theta\ (mrad)} \sqrt{\frac{x}{X_0}}$$

where p is the particle momentum, β is the particle velocity, x is the traversed distance, X_0 is the radiation length in the material and δθ is the base-tack angular resolution along the volume track.

In our analysis, we assumed X_0= 5.6 mm as the scattering is dominated by the 1 mm thick lead. The angular resolution of the emulsions (the base-track direction is measured with an accuracy of few mrad) allows the reconstruction of the charged particles momentum in the range 0.2÷2 GeV/c with 20% or better accuracy.

For the momentum calculation, we have also performed an analysis based on the reference data supplied by NIST [10] for the particles range determination.

III. RESULTS

At the present, we have completed the analysis of 61 films of the ECC detector indicated as ECC2 in fig.4. The angular distribution of the ^{12}C fragments is reported in fig. 6. Each point of the distribution represents a volume track reconstructed in the ECC detector: the points confined in the region outlined in red represent the signal, the others are due to cosmic rays interacting in the detector. In order to evaluate the cosmic rays contribution to the signal, we selected a region, with the same size of the signal, in a symmetric position (see blue box in fig. 6).

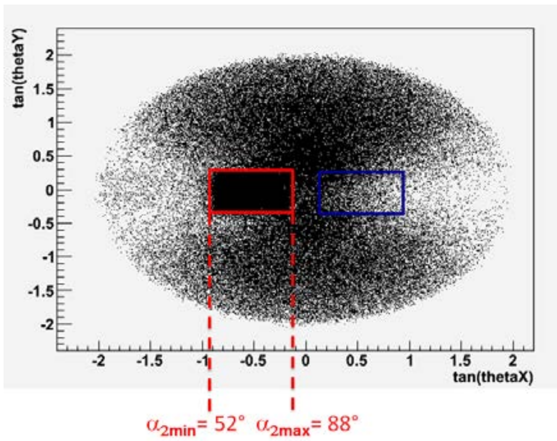

Fig. 6: Analysis distribution of the ^{12}C fragments obtained by the ECC2: the X axis is the x projection of tan (θ) and the Y axis is the y projection of tan (θ), where θ is the angle of a volume track with respect to the orthogonal axis to the emulsion surface (i.e. the detector surface). The region delimited by the red box corresponds to the particles signal, while that in the blue one is the cosmic rays signal. The range of α_2 angle (the angle with respect to the ^{12}C beam) is also indicated in the region signal.

In fig. 7, we plotted the number of tracks passing through each emulsion film as a function of the film position. We defined a track as a path containing, at least, three base-tracks aligned, with no more than two holes.

In the plot there are two curves: the red one represents the tracks whose slope belongs to the signal region; the blue one plots the number of tracks due to the cosmic rays contribution.

Analyzing the red curve, it is possible to distinguish three regions:

Region A (plate 61÷56): corresponding to the first 6 adjacent emulsion films, where, being no passive material, the number of tracks is almost constant;

Region B (plate 55÷15): corresponding to the central part of the ECC, where the number of tracks shows an exponential decrease due to the absorption in the lead;

Region C (plate 14÷1): corresponding to the downstream films, where only cosmic rays are present.

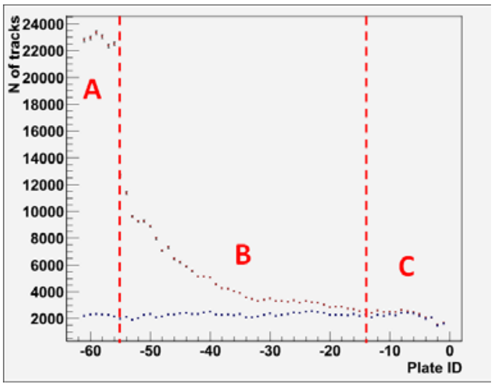

Fig. 7: Number of tracks as a function of film number (plate ID); the signal tracks are plotted in red and the cosmic rays tracks are plotted in blue. The region A, B and C are explained in the text.

We have also estimated the massive range (g/cm^2) distribution of the particles inside the volume detector (fig. 8); the black curve represents the tracks of the signal region and the blue one is relative to the cosmic rays contribution. As we expected, only 50% of signal tracks goes beyond 4 g/cm^2 and almost all of them are absorbed within 50 g/cm^2. The peak at the end of the distribution corresponds to the particles passing through the whole ECC.

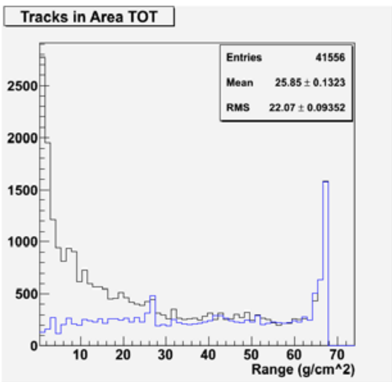

Fig. 8: Distribution of the massive range tracks. The black curve is relative to the signal and the blue one is for the cosmic rays.

The tracking efficiency has been evaluated as the ratio between the number of base-tracks reconstructed in a volume track and the number of crossed films.

The dependence of the efficiency on the tracks slope is reported in fig. 9 for the signal (black dots) and cosmic rays (blue dots). The differences in the efficiency curves is due to the different ionization produced in the ECC by the signal tracks with respect to the cosmic rays tracks. The mean energy of the signal particles is lower than the mean energy of the cosmic rays, and for this reason the ionization due to the signal particles is higher than the cosmic rays.

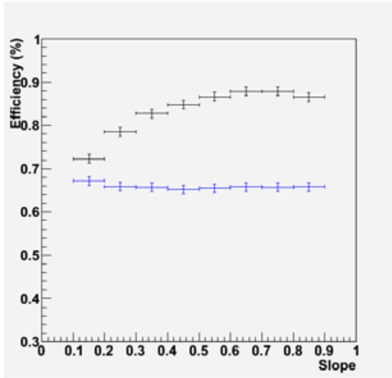

Fig. 9: Track efficiency evaluated on signal (black dots) and on cosmic rays (blue dots) as function of the tracks angle tangent.

D. Momentum measurement

The momentum has been calculated by two different methods: the Multiple Coulomb Scattering and the range.

The MCS method has been applied for tracks passing through the first 6 films and having at least three base-tracks in the second section of the ECC2.

In fig. 10, the momentum distribution evaluated by the MCS method is shown for signal tracks.

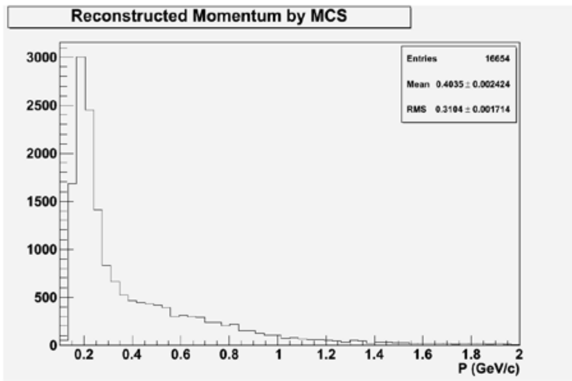

Fig. 10: Distribution of reconstructed momentum by MCS method considering the signal tracks.

The range method has been used for tracks not included in the MCS selection and stopping within the ECC2. The corresponding distribution is reported in fig. 11.

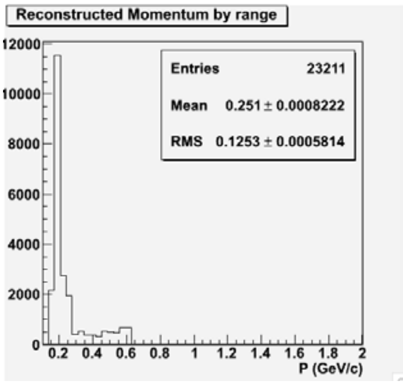

Fig. 11: Distribution of reconstructed momentum by range method considering the signal tracks.

IV. OUTLOOK

In this work we measured, by the use of two ECC detectors, the angular distribution and the momentum distribution of large angles particles produced by a ^{12}C ion beam impinging on a carbon target. At present we have completed the analysis of one of the two ECC exposed. In the next future, we are going to complete the analysis of the second ECC detector. The whole analysis will lead to the measurement of the differential cross-section for large angle fragments produced by the interaction of ^{12}C ion beam.

V. ACKNOLEDGMENTS

We would like to acknowledge the FIRST collaboration.

REFERENCES

[1] http://enlight.web.cern.ch/media/highlights.

[2] H. Tsujii et al. (2014), "Carbon-Ion Radiotherapy Principles, Practices, and Treatment Planning ", Springer Ed.

[3] R. Acquafredda, et al., OPERA Collaboration, "The OPERA experiment in the CERN to Gran Sasso neutrino beam", J. Instrum., vol. 4, 2009, P04018.

[4] G. De Lellis et al., "Measurements of the fargmentation of Carbon nuclei used in hadron therapy", Nuclear Physics, vol. A 853, 2011, pp. 124-134.

[5] G. De Lellis et al., "Emulsion Cloud Chamber tecnique to measure the fragmentation of high-energy carbon beam", Jinst, 2, 2007, P06004.

[6] C. Agodi et al., "FIRST experiment: Fragmentation of Ions Relevant for Space and Therapy", Journal of Physics, vol. 420, 2013, 012061.

[7] R. Plesak et al., "The FIRST experiment at GSI", NIMA, vol. 678, 2012, pp.130-138.

[8] A. Alexandrov et al., "Further progress for a fast scanning of nuclear emulsions with Large Angle Scanning System", 2014 *JINST* **9** C02034.

[9] N. Agafonova et al., "Momentum Measurement by multiple Coulomb scattering method in the OPERA lead emulsion target", New Journal of Physics, vol. 14, 2012, 013026.

[10] http://physics.nist.gov/PhysRefData/