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M.Toppi, on behalf of the FIRST collaboration

Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati, Italy; Dipartimento di Fisica, Universitá di Roma Tor Vergata, Italy

E-mail: marco.toppi@lnf.infn.it

Abstract. The FIRST (Fragmentation of Ions Relevant for Space and Therapy) experiment at GSI laboratory took data in summer 2011, studying the collisions of a ^{12}C ion beam with Carbon and Au thin targets. The experiment main purpose is the double differential cross section measurement of the carbon ion fragmentation at energies that are relevant both for tumor therapy and space radiation protection applications (100-1000 MeV/u). The FIRST dataset contains carbon ions collisions on a 3.43 g·cm^{-2} carbon target (about 24 M events) and on a 0.96 g·cm^{-2} Au target (about 4.5 M events). The SIS (heavy ion synchrotron) was used to accelerate the ^{12}C ions at the energy of 400 MeV/u. The preliminary results of differential cross sections measurements as a function of angle and energy for carbon target, in the small angle region ($\theta < 5°$), are presented.

1. Introduction

The study of the nuclear fragmentation processes occuring in the interaction of highly energetic ions in matter is of great interest in basic research (e.g. to improve the understanding of hadronic showers development in the atmosphere) and in applied physics, in particular in particle therapy and space radiation protection fields. In particle therapy, ion beams slowing down in patient tissues undergo inelastic nuclear reactions and give rise to signficant yields of secondary fragments [1]. A more precise knowledge of the dose map due to the fragments mixed radiation fields with the required accuracy of $\sim 3\%$ is mandatory to achieve a better dose control, expecially when treating tumors nearby organs at risk. Nuclear fragmentation studies are of great interest also in the understanding of the ions component of the galactic cosmic radiation (GCR) effects on human space flight in the energy range of 100-1000 MeV/u (where GCR spectrum has a maximum) [2]. The current particle transport codes, used in particle therapy and space radiation protection applications, are not able to reproduce the measured fragments angular and energy distributions with the accuracy required for space and therapy applications [3]. The main limitation is the lack, or the large related uncertainty, of experimantal data [4]. For these reasons, various recent experiments aimed at double differential fragmentation cross sections measurements as a function of the angle and energy have been performed [5, 6], with a particular focus on the exploration of the energy region of interest for therapeutic application (100-400 MeV/u). The FIRST (Fragmentation of Ions Relevant for Space and Therapy) experiment has been performed at the SIS accelerator of GSI laboratory in Darmstadt with a ^{12}C ion beam at 400 MeV/u on carbon and gold targets [7]. Only the results

with the carbon target, relative to a data sample of ~ 25 M of detected incoming ^{12}C ions, are reported here.

2. The FIRST detector layout and performances

The FIRST apparatus (figure 1) is composed of several subdetectors optimized for the detection of all the charged fragments produced by the interaction of a ^{12}C ion with the carbon target up to a maximum aperture angle of 40° with respect to the beam axis. For each subdetector a wide dynamic range is required because the energy released by the fragments ranges from 2 mip (minimum ionizing particle) for protons to 100 mip for carbons. Moreover all the detectors along the carbon beam and the fragments trajectories were designed to minimize the secondary fragmentation inside them. A MC simulation of a ^{12}C beam at 400 MeV/u on a 3.43 g·cm^{-2} carbon target has been developed with the FLUKA code to optimize the FIRST detector: while most of the fragments go forward with small angles and, with about the same kinetic energy of the carbon beam, a not negligible fraction of the light Z=1,2 fragments are produced with large angles and a wider kinetic energy distribution. In FIRST a ^{12}C ion, before interacting with

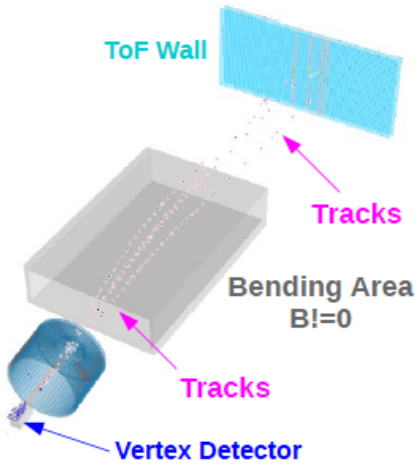

Figure 1. Fully reconstructed fragmentation event in the FIRST apparatus.

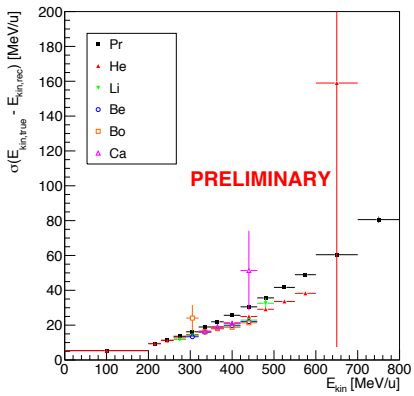

Figure 2. Kinetic energy resolution vs kinetic energy for each fragment charge.

the target, impinges on the start counter (SC), a thin scintillator that provides the number of carbon ions, the trigger of the experiment and start for the Time of Flight (ToF) measurement, and goes throught a drift chamber, that measures the direction and the impact point on the target [8]. The fragmentation vertex produced in the interaction with the target is reconstructed with a silicon pixel detector (VD) that has a track angular acceptance of $\theta = \pm 40°$ [9, 10]. The fragments produced with polar angle $\theta < 5°$ enter in the angular acceptance of the ALADIN dipole magnet. The trajectory and the momentum of the fragments are reconstructed using the magnetic bending provided by the ALADIN magnet, by measuring the ToF and matching the fragment position on the ToF-Wall (TW), a large area hodoscope formed of two scintillator layers [11]. The tracking algorithm uses an iterative procedure that matches the VD tracks and the TW hits detected in each event. Special care is needed while performing the extrapolation from the VD to the far away (~ 6 m) TW. The VD excellent tracking resolution, < 10 µm and < 50 µm in the (x, y) plane and along the beam axis (z) respectively, translates in an angular resolution of ~ 1 mrad for each fragment and plays a crucial role in reducing the amount of random combinations made up with wrongly matched tracks and hits (combinatorial

background). For each reconstructed global track the charge is measured by the TW and the VD, the ToF is measured by the TW and the SC, the particle path (L) and the rigidity (pc/Z) are determinated by the tracking algorithm, allowing a measurement of the fragment speed $\beta = L/(c \cdot ToF)$. The fragment mass is computed as $Mc^2 = pc/\beta\gamma$ where γ is the Lorentz factor and the mass resolution is:

$$\frac{\Delta M}{M} = \sqrt{\left(\frac{\Delta p}{p}\right)^2 + \left(\gamma^2 \frac{\Delta ToF}{ToF}\right)^2} \tag{1}$$

The ToF resolution was measured to be about 800 ps for each fragment charge. The momentum resolution depends essentially on the spatial resolution along x direction of VD (< 10 µm) and TW (~ 7 mm) and it worsens with higher fragment momentum as shown in figure 2 where the kinetic energy resolution is displayed for the different fragments charges.

3. Cross section measurements

The double differential cross section in angle and kinetic energy for the i-th isotope ${}^{Z}_{A}X_i$ with charge Z and mass number A is defined as:

$$\frac{d^2\sigma_i}{d\Omega dE}(\theta, E) = \frac{Y_i(\theta, E)}{N_C \times N_{TG} \times \Delta\Omega \times \Delta E \times \epsilon_{trk}(\theta, E)} \tag{2}$$

where the number of carbon impinging on the target N_C is measured by the SC, the number of

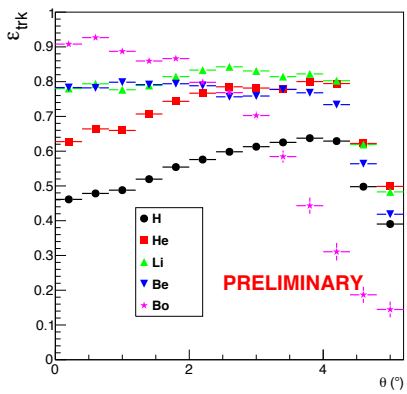

Figure 3. Tracking efficiency vs fragment angle θ.

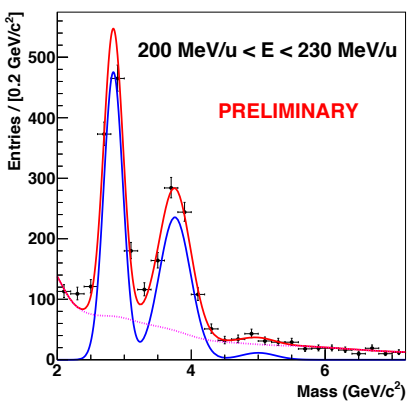

Figure 4. Fit result for charge Z=2 mass spectra in an energy bin.

atoms in the target per unit surface N_{TG} is known and $\Delta\Omega$ and ΔE are the angular and energy phase space factors, accounting for the cuts applied in each θ, E bin. The study of the tracking efficiencies $\epsilon(\theta, E)$ has been performed on the full MC simulation: for each fragment charge, the efficiency is defined as the ratio between the number of reconstructed tracks and the number of MC generated tracks emerging from the target in the magnet angular acceptance (see figure 3). $Y_i(\theta, E)$ are the fragments yields for a given isotope ${}^{Z}_{A}X_i$ in an angular (energy) bin. The fragment yields $Y_i(\theta, E)$ are measured fitting the reconstructed mass spectra for each charge and angular (energy) bin using an unbinned extended maximum likelihood approach in which the signal and background yields are fitted as well [12]: the signal is modeled with a gaussian PDF and the backgroud PDFs are extracted from the MC simulation. Figure 4 shows the fit result

for Z=2 and 200 MeV/u $< E <$ 230 MeV/u where the blue curve is the sum of all the signal gaussian PDFs and the magenta line represents the background PDF. The preliminary single differential cross sections in angle and energy have been obtained for each fragment charge and for each isotope. As an example in figures 5, 6 the angular and energy cross sections for the helium isotopes are shown: the error bars are only accounting for the statistical uncertainty, since the calculation of the systematic uncertainties is still ongoing. A paper containing all the distributions and the tabulated results is in preparation.

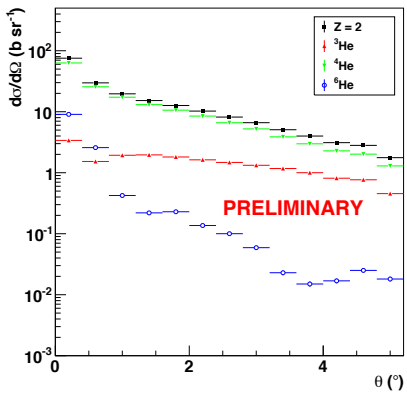

Figure 5. Angular fragmentation cross sections for helium isotopes.

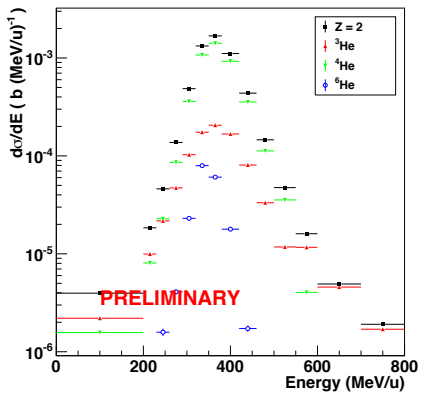

Figure 6. Energy fragmentation cross sections for helium isotopes.

4. Conclusions

The preliminary differential fragmentation cross sections results in angle and energy for a ^{12}C beam at 400 MeV/u on a carbon target in the low angle ($\theta < 5°$) range have been obtained with the FIRST apparatus. Given the very large fragmentation statistics available, the analysis effort is currently focused on the final assessment of the systematic uncertainties related to the PDFs modeling inside the fit, the combinatorial background subtraction and the reconstruction algorithm tuning and efficiency. Future analysis plans foresee the measurements of the full double differential cross sections, together with the benchmarking of MC softwares and analytical algorithms currently used for treatment planning applications.

References

[1] Schardt D *et al* 1996 *Adv. in Space. Res.* **17** 87-94.
[2] Durante M and Cucinotta F 2011 *Rev. Mod. Phys.* **83** 1245.
[3] Bohlen T *et al* 2010 *Physics in Medicine and Biology* **55** 5833–47.
[4] Patera V 2011 *Nuovo Cimento* C **34** 6.
[5] De Napoli M *et al* 2012 *Physics in Medicine and Biology* **57** 7651-7671.
[6] Dudouet J *et al* 2013 *Physical Review* C **88** 024606.
[7] Pleskac R *et al* 2012 *Nucl. Instrum. Methods Phys. Res.* A **678** 130-138.
[8] Abou-Haidar Z *et al* 2012 *JINST* **7** P02006.
[9] Rescigno R *et al* 2014 *Nucl. Instrum. Methods Phys. Res.* A **767** 34-40.
[10] Spiriti E *et al* 2011 *Nucl. Phys. (Proc. Suppl.)* B **215** 157161.
[11] Introzzi R *et al* 2013 *DOI:10.1109/NSSMIC.2013.682944, Conference: C13-10-26.*
[12] Verkerke W and Kirkby D P 2003 *arXiv:physics* 0306116.