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The FIRST experiment at GSI

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ABSTRACT

The FIRST (Fragmentation of Ions Relevant for Space and Therapy) experiment at the SIS accelerator of GSI laboratory in Darmstadt has been designed for the measurement of ion fragmentation cross-sections at different angles and energies between 100 and 1000 MeV/nucleon. Nuclear fragmentation processes are relevant in several fields of basic research and applied physics and are of particular interest for tumor therapy and for space radiation protection applications.

The start of the scientific program of the FIRST experiment was on summer 2011 and was focused on the measurement of 400 MeV/nucleon ^{12}C beam fragmentation on thin (8 mm) graphite target.

The detector is partly based on an already existing setup made of a dipole magnet (ALADiN), a time projection chamber (TP-MUSIC IV), a neutron detector (LAND) and a time of flight scintillator system (TOFWALL). This pre-existing setup has been integrated with newly designed detectors in the Interaction Region, around the carbon target placed in a sample changer. The new detectors are a

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Experimental methods
Instrumentation

scintillator Start Counter, a Beam Monitor drift chamber, a silicon Vertex Detector and a Proton Tagger scintillator system optimized for the detection of light fragments emitted at large angles.

In this paper we review the experimental setup, then we present the simulation software, the data acquisition system and finally the trigger strategy of the experiment.

1. Introduction

Particle therapy is a rapidly expanding field in cancer therapy, and generally exploits protons or carbon ions. Carbon ions combine significant advantages both in the physical dose-depth deposition pattern and in the biological effectiveness and may represent a significant breakthrough in radiotherapy [1]. Nuclear fragmentation cross-sections, as well as algorithms that deal with the transport of charged particle in matter, are essential for accurate treatment planning, as only roughly 50% of the heavy ions directed to the patient actually reach a deep tumor [2].

Transport of energetic charged particles in matter can be described either by deterministic codes, based on Boltzmann-type transport equations, or by Monte Carlo (MC) codes that sample the interaction process on a event-by-event basis, and both approaches rely on nuclear interaction cross-sections. The main applications of these transport codes for light ions ($Z \leq 10$) at medium energy (100–400 MeV/nucleon) are particle therapy in oncology [3] and radiation protection in space missions [4]. The cross-sections required for transport involve total yields and multiplicities and inclusive secondary energy spectra for one-dimensional transport or inclusive double-differential cross-sections in angle and energy for three-dimensional transport. For MC simulations, exclusive cross-sections may be needed for computer algorithms.

Treatment plans are generally based on deterministic codes such as the TRiP developed at GSI [5,6] or HIBRAC [7], but the great accuracy ($\leq 3\%$) required for medical treatment planning and sparing of normal tissues surrounding the tumors makes necessary several inter-comparisons of the codes with MC calculations [8–12]. All these calculations are based on measured nuclear fragmentation cross-sections of carbon ions in water or tissue-equivalent materials, mostly performed in the past in USA (BEVALAC and Berkeley), Japan (HIMAC in Chiba) and GSI in Germany (for a review see [13]). Most of these measurements are however limited to yields or total charge-changing fragmentation cross-sections, while the needed measurements of double-differential cross-section are scarce.

Not surprisingly, while fluence and total cross-sections are well described by current computer codes, the production of light fragments and their angular distribution is affected by large uncertainties and various codes may differ up to an order of magnitude in their predictions [14]. Similar problems are found in codes used for space radiation transport in shielding materials: despite several measurements of the fragmentation cross-sections related with space radio protection (reviewed in [15]), the angular distributions are not yet well reproduced. The same goes for the production of different He isotopes, mesons, and γ rays.

NASA is currently completing a large database [16] of measured nuclear fragmentation cross-sections including approximately 50,000 datasets, and has concluded that several experimental data are missing, including double-differential cross-sections for C-ions at energies below 400 MeV/nucleon, which are those needed also for improving treatment planning in therapy. It is therefore concluded that accurate measurements of double-differential cross-sections of light ions in the energy range 100–500 MeV/nucleon are urgently needed for improving transport codes to be used in cancer therapy and space radiation protection.

When a light ion impinges on a target nucleus, a fragmentation process can take place depending on the impact parameter between the colliding nuclei. The target fragments usually carry little momentum, while, in particular at high energies, the projectile fragments travel at nearly the same velocity as the beam ions and have only a small deflection, except for the lighter fragments (particularly protons and neutrons). In Figs. 1 and 2, the energy and angular distribution predicted by FLUKA Monte Carlo [17,18] for the fragments produced by a 400 MeV/nucleon carbon beam on graphite are shown: the number of all the particles produced in the target for a given run in a certain energy bin (N_{prod}) divided by the number of initial C-ions (N_{primC}), normalized by the bin width (MeV/n,sr) for the energy (angular) spectra, are shown as a function of the fragment energy (angle). As it can be seen the heavy fragments are forward peaked and keep the projectile velocity, while a huge amount of neutrons and protons are spread out over a wide range of angle and energy.

The FIRST setup [19], located at the Heavy Ion Synchrotron SIS of GSI in Darmstad, fulfills several requirements, as shown in the next section: suitable particle identification capability providing a $\Delta M/M \leq 10\%$ (where $M$is the fragment mass), tracking capability to measure angles and momenta of the produced charged fragments, large angular acceptance for low energy protons, and finally angular acceptance for the forward produced neutrons.

A 10% relative error on the fragment mass is mandatory in order to have a clear separation of all the ions and isotopes under study. The requirement on the fragment mass separation directly translates into performance requirements (time and momentum resolution) for all the detectors that are used in the FIRST setup. The mass measured in the spectrometer is given by $M = k|R|f(\beta)$ where $k = 0.3Z/m_0$ and $f(\beta) = \sqrt{1-\beta^2}/\beta = 1/\beta\gamma$. The relative error on $M$is hence related to the time and momentum resolutions by the relation

$$\frac{(\Delta M)^2}{M^2} = \frac{(\Delta p)^2}{p^2} + \gamma^2 \frac{(\Delta t)^2}{t^2} \tag{1}$$

where $(\Delta p)^2/p^2 = (\Delta R)^2/R^2$ has been used.

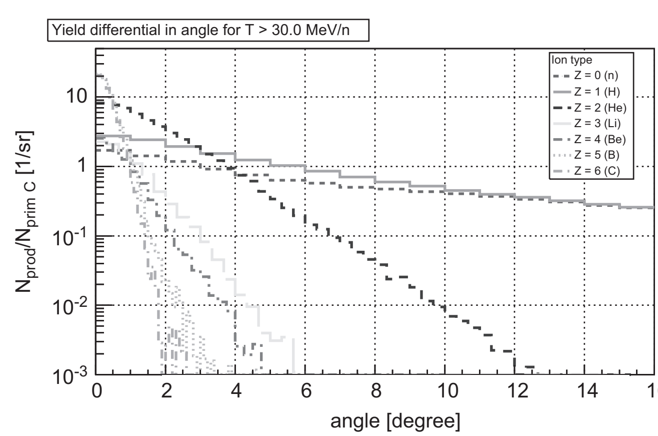

Fig. 1. Angular distribution of the fragments produced by a 400 MeV/nucleon carbon beam on 8 mm carbon target. N_{prod}/N_{primC} is the yield of fragments per primary carbon ion and steradian with a kinetic energy larger than 30 MeV/nucleon (FLUKA Monte Carlo).