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Nuclear physics experiment for hadrontherapy application

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Summary. — Nuclear fragmentation processes are relevant in different fields of basic research and applied physics and are of particular interest for light ion tumour therapy by means of light ions beam, and for space radiation protection applications. The FIRST experiment at SIS accelerator of GSI laboratory in Darmstadt, has been designed for the measurement of different ions fragmentation cross sections at different energies between 100 and 1000 A MeV. The first data taking of the FIRST experiment was carried out in summer 2011 and will be focused on the analysis of the 200–400 A MeV 12C beam fragmentation on thin (5 mm) graphite target. The experiment is performed by an international collaboration made of institutions from Germany, France and Italy. A total of 33 shifts were granted for the measurement of the C+C, C+Au and O+C reactions during summer 2011.

PACS 25.70.-z – Low and intermediate energy heavy-ion reaction.
PACS 87.53.-j – Effects of ionizing radiation on biological systems.
PACS 87.55.-x – Treatment strategy.

1. – Introduction

The interaction of light ions with matter is a subject of interest in the fields of astrophysics, radiobiology, radiation medicine, and radiation protection [1]. In particular the effect of the transport of light energetic ions ($Z \leq 9$ and $E \leq 400\,A$ MeV) in tissue-like matter is extremely important for cancer therapy with charged particles (hadrontherapy) [2], a field in rapid expansion and pioneered in Europe at GSI [3].

Normally, less than 50% of the carbon projectiles actually reach the tumor in therapy, and this makes very clear that a precise knowledge of the fragmentation cross sections is necessary for treatment planning [4]. An accurate description of the fragmentation of heavy ions is important also to understand the effects of the high-Z component of galactic cosmic radiation (GCR) on humans in space [5] and for shielding in space and in accelerator environments. The energy spectrum of the GCR peaks around 1 GeV/n, and among the different heavy ions, ^{56}Fe attracted the greatest interest, because its contribution in terms of dose equivalent can be even greater than that attributed to galactic protons [6]. When a heavy ion impinges on a target, it undergoes fragmentation processes depending on the impact parameter between the colliding nuclei. The target fragments carry little momentum. 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. Both in hadrontehrapy and space radiation protection, specific computer codes are used to calculate the beam transport in matter [7]. Deterministic codes are quick and are commonly used in practical situations. They include TRiP [8], developed at GSI and used by SIEMENS for hadrontherapy in Europe or HZETRN [9], used by NASA for spacecraft shielding design. On the other hand, Monte Carlo codes, such as FLUKA [10], GEANT4 [11], PHITS [12], or SHIELD-HIT [13], have also been applied both to therapy and space problems. However, total and partial fragmentation cross sections are the critical inputs for transport codes, and the limited experimental data on cross sections, expecially on thin target, make up the highest uncertainty in these codes. To check that the physics in the models is correct, it is essential to understand the reactions and transport of particles and ions, not only the production of fragments but also evaporation products, *e.g.*, protons and neutrons.

2. – Fragmentation and hadrontherapy

Given this general landscape, experiments for the determination of double differential cross sections for reactions of heavy ions on different target material present in tissue, spacecraft shielding and electronic devices need to be performed. The multiplicity distributions of secondary particles and the production of evaporation residues and light fragments should be validated to make sure the physical models included in the transport codes can reproduce the observations. The total reaction cross sections are essential in the determination of the mean free paths of the transport particles in the transport codes, and must therefore be calculated with great accuracy. However, measurements of total reaction cross sections including all reactions channels (*e.g.*, de-excitation through gamma-ray emission, target excitation) are missing and should be performed. A number of measurements of fragmentation cross sections in the $(Z; E)$ range (4–56; 200–1000 MeV/n) have been performed in the past [14] with several targets. These measurements do not include all the information that is required to benchmark the codes, namely energy and angular distribution, with their correlations. If we focus on the hadrontherapy application, namely on ^{12}C projectiles fragmentation on thin oxigen or carbon target at 200–400 A MeV kinetic energy, a further constraint on the needed knowledge is given by the need to measure this distribution with an accuracy of the 5% level to match the terapeutical prescription. In figs. 1 and 2 are shown the kinetic energy and angular distribution foreseen by FLUKA for the fragments produced by a 400 A MeV carbon beam on 5 mm graphite target. As can be seen, the heavy fragment are forward peaked, while a huge amount of neutron and proton are spread out on a wide range of angle and energy. The experimental setup that has been built for these measurements has a suitable particle identification capability, that must provide a $\frac{\Delta M}{M} \leq 20\%$ (M is the fragment mass), tracking capability with magnetic analyzing power to measure angles and momentum of the produced charged fragments, a large angular acceptance for low energy protons, and a forward angular acceptance for the produced neutrons, as will be shown in the next section.

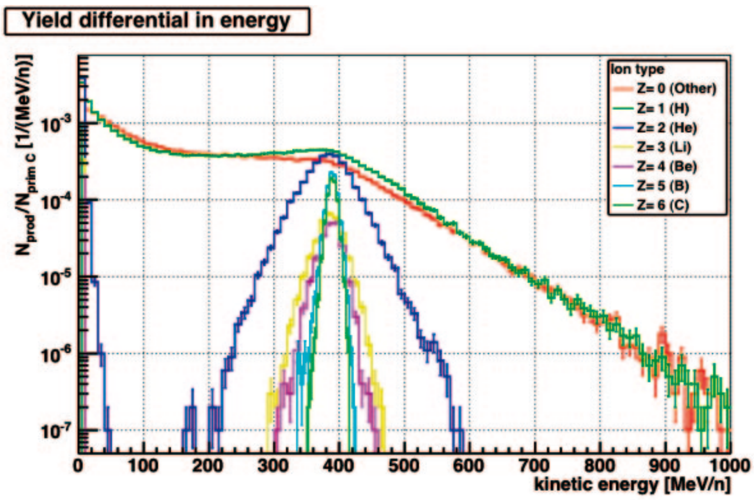

Fig. 1. – Kinetic energy distribution of the fragments produced by a 400 A MeV carbon beam on carbon target.

3. – The experimental setup

The FIRST [15] experiment (Fragmentation of Ions Relevant for Space and Therapy) consists of several subdetectors, see table I, divided in two main blocks of detectors: the interaction region (IR) and the magnetic region (MR). The two regions are very different in dimensions of the corresponding detectors: impinging beam and produced fragments are studied in the IR within some tens of centimeters from the target, while the apparata

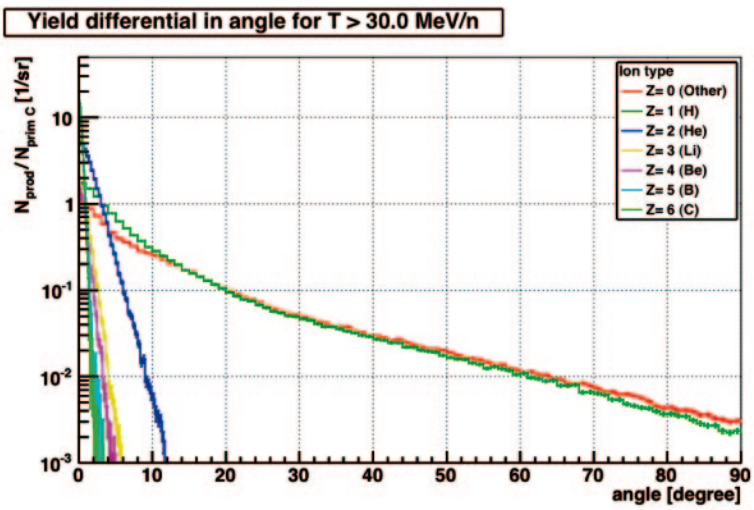

Fig. 2. – Angular distribution of the fragments produced by a 400 A MeV carbon beam on carbon target.

TABLE I. – *Overview of subdetectors of the FIRST experiment.*

Interaction Region (before bending by ALADiN spectrometer)		
Start counter	Scintillator	Start of TOF
Beam Monitor	Drift Chamber	Beam impact point on target and direction
Vertex Detector	Silicon Pixel	Fragment emission angle from target
KENTROS	Scintillator	TOF, ΔE and coarse impact point
Large Detector Region (after bending by ALADIN spectrometer)		
TP-MUSIC IV	Time Projection Chamber	ΔE, Fragment emission angle after bending
TOFWALL	Scintillator	Stop of TOF, ΔE and coarse impact point
Veto Counter	Scintillator	Veto detector, TOF, ΔE
LAND2	scintillator	Neutron TOF, ΔE and impact point

that detects the fragments, after magnetic bending, in the MR have typical dimension of meters. Following the beam path, the interaction region is made of a Start Counter (SC) scintillator that provides the start to the Time-Of-Flight measurement (TOF), a drift chamber Beam Monitor (BM) that measures the beam trajectory and the impact point on the target, a robotized target system, a pixel silicon Vertex Detector (VD) to track the charged fragments emerging from the thin target and a thick scintillator system, KENTROS (Kinetic ENergy and Time Resolution Optimized on Scintillator), that detects the large angle light fragments. Due to the reduced dimension all the interaction region is in air. This choice greatly helps the design and the running of the IR detectors, increasing the out of target interaction probability only by 5%. With the noticeable exception of the large angle protons and a little fraction of He, most of the fragments are produced in the forward direction with the same β of the beam (see fig. 1). These $Z \geq 2$ fragments are then in the magnetic acceptance of the ALADIN dipole magnet and after the benfing enter in the MR being detected by the large volume Time Projection Chamber (TP) MUSIC IV that measure track directions and energy release. A large area system of scintillators (TOFWALL) provides the measurement of the impinging point and the arrival time of the particles. In correspondence of the non interacting beam path after the TOFWALL we have the Veto Counter, a scintillator stack analyzing the carbon beam. Finally the Large Area Neutron Detector (LAND2), made of a stack of scintillator counters, gives information about the neutrons the are emitted within a narrow angle with respect to the beam ($\simeq 5°$–$10°$). Particular care must be taken to match the information of the IR with that ones collected by the MR. In particular the charged ions tracks detected by VD, MUSIC and TOFWALL. A careful alignement can be achieved between these tracking devices using the copious events with non interacting carbon ions.

The main features of the beam provided by the SIS accelerator are the rate, in the range of the kHz and a Gaussian shape in the transverse plane of $\simeq 5$ mm size (FWHM).

4. – DAQ and Trigger

The readout is handled by Multi Branch System (MBS), a general DAQ framework developed at GSI [16]. In MBS several intelligent bus controllers (CES RIO), running under the real-time operating system LynxOS, perform the readout of the digitization modules of the individual crates when triggered by dedicated trigger modules. All the trigger modules, one in each readout crate, are connected via a trigger bus to distribute the trigger and dead-time signals and to ensure event synchronisation. Data collected by single controllers are broadcast via Ethernet to an event-builder where they are merged and saved in the standard GSI format. A set of client-server applications allows to control the data acquisition, to configure the detector settings by remote and to perform on-line monitoring of the data quality. MBS can handle easily the different Front End Electronics standards used by the different subdetectors: FASTBUS, CAMAC and VME. The expected dead time due to trigger signal formation and readout is of the order of ms per event due to several factors as drift time in the MUSIC, conversion time in the digitization modules and transfer data time from the electronics to the readout controllers and from the controllers to the event builder via TCP/IP. An efficient trigger system is then essential to select the fragmentation events and to keep the counting rate at a level where the inefficiencies due to the dead-time are minimized.

The complexity of the experimental setup requires that the individual trigger signals from each detector are logically combined with different criteria. The final trigger decision is based on the coincidence of trigger from the Start Counter with trigger of any of TOFWALL, LAND, KENTROS and downscaled Veto Counter. In order to suppress events in which the carbon projectile does not interact with the target, coincidences between the Start Counter and the Veto Counter can be rejected. An additional unbiased trigger condition based on the Start Counter trigger alone is also foreseen with tunable down-scale factor to estimate the efficiency of the other trigger conditions.

5. – Conclusions

An increasing demand for a comprehensive knowledge of the processes involved in the interaction of two light ions is emanating not only from basic research but also from applications in fields such as hadron therapy or radiation protection studies in space missions. For this purpose the FIRST experiment at GSI laboratory has been setup by an international collaboration between several institutes and universities from Germany, Italy and France. The collaboration was formed at GSI in December 2008 and in February 2009 a proposal for the FIRST experiments was already presented in front of the G-PAC and approved. The setup has acceptance both for the heavier forward peaked fragments and for the large angle light fragment component due to the use of several detectors using different technique. Data taking with 400 A MeV carbon projectiles on graphite target took place during summer 2011 in cave C.

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