The KENTROS Detector for Identification and Kinetic Energy Measurements of Nuclear Fragments at Polar Angles Between 5 and 90 Degrees

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Abstract– **KENTROS (Kinetic ENergy and Time Resolution Optimized on Scintillator) is a relatively compact detector that has been projected and constructed in the framework of the INFN FRAG and TPS experiments. KENTROS has been designed for energy deposition and time of flight measurements of charged particles. The detector ensures an angular coverage from about 5 degrees up to about 90 degrees polar angle in the laboratory frame. Recently KENTROS has been used as part of the FIRST experiment, devoted to measure double differential fragmentation cross sections, with the aim to detect light fragments produced in the nuclear fragmentation process.**

I. Introduction

Nuclear fragmentation reactions complicate both the hadrontherapy and the space radiation protection fields. In hadrontherapy the use of carbon ion beams has became an increasingly used technique in tumor treatments. Compared to conventional radiotherapy, it presents two main advantages: a maximum of dose deposition at the Bragg peak and an enhanced biological effectiveness. However, as carbon nuclei penetrate the human tissues, they may undergo inelastic nuclear reactions leading to the production of secondary fragments. Such fragments have different ranges and angular distributions with respect to the primary ions, thus the resulting spatial dose distribution, inside and outside the tumor region, differs from that of the primary beam. Moreover, the different linear energy transfer, LET, of the secondary ions with respect to the carbon beam results in a different biological effectiveness for the same delivered dose. Therefore, all these effects arising from the carbon fragmentation have to be correctly evaluated when planning a tumor treatment.

Similar problems related to nuclear fragmentation also affect the space radiation protection. Indeed, in planning space missions outside the Earth magnetic field, in order to correctly predict the radiobiological risks for the astronauts and the radiation damage for the instrumentation, a realistic estimation of the radiation field inside the space vehicles is mandatory.

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The radiation field is determined by the galactic cosmic rays and by the fragments produced in their interactions with the materials of the space vehicles and with the bodies of the astronauts. The accuracy of the simulation tools, which simulate in detail the physical interactions of particles as they pass through matter [1], is not sufficient to obtain the precision of about 2.5% on the deposited dose required by medical applications [2]. The largest uncertainty comes from the physical models and the lack in the fragmentation production cross sections. Several measurements of fragment yields and total cross section were made in the past [3], but double differential cross sections (DDCS), recently measured at intermediate energies [4], are scarce at relativistic energies.

In this context, the FIRST (Fragmentation of Ions Relevant for Space and Therapy) experiment is devoted to the measurement of the double differential cross section, with respect to kinetic energy and scattering polar angle, of nuclear fragmentation processes in the energy range between 100 and 1000 MeV/nucleon. A first run was performed at SIS accelerator of GSI laboratories in Darmstadt (Germany) during August 2011, using a 400 AMeV ^{12}C beam on carbon and gold targets. A detailed description of the experimental apparatus is reported in Refs. [5,6]. In particular, the interaction region [7] is composed by small area detectors surrounding the target, before the ALADiN horizontal bending magnet. The KENTROS detector is one of these detectors, specifically designed and built for the FIRST experiment. In this report we will give a detailed description of the KENTROS detector, showing preliminary results of data analysis.

II. THE DETECTOR

KENTROS is a detector built to measure the kinetic energy and time of flight of light charged particles emitted at polar angles larger than about 5 degrees. The active part of the detector is made of organic scintillator modules and scintillating fibers. The modules are realized using the EJ-200 fast scintillator by Eljen technology, which has a decay time of 2.1 ns, 10000 photons/MeV light yield, 425 nm wavelength of maximum emission, 1.58 refractive index, 4 meters attenuation length. The scintillating fibers are 1 mm diameter BCF-10 fibers by Bicron, which have a decay time of 2.7 ns, 8000 photons/MeV light yield, 432 nm wavelength of maximum emission, 1.6 core refractive index, 2.2 meters attenuation length. The signal is read using silicon photomultipliers (SiPM) by AdvanSiD, 4x4 mm^2 active area, that are relatively cheap and have excellent timing resolution. The scintillation light is driven from the modules to the SiPM through plexiglas light guides. The detector, whose schematic view is given in Fig. 1, has a cylindrical shape and is structured in three main parts depending on the different angular coverage: a Small Endcap, for particles with polar angles between 5 and 15 degrees, a Big Endcap, which cover the range between 15 and 36 degrees and a Barrel, for particles with polar angles between 36 and 90 degrees. A brief description of these parts will be given in the following subsections.

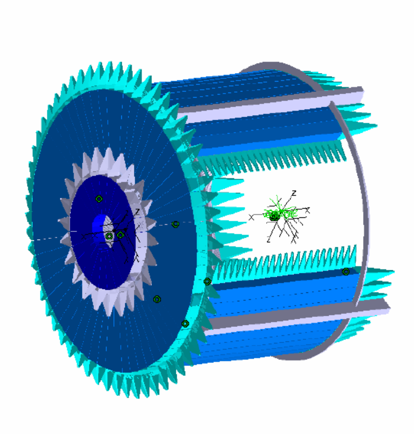

Fig. 1. A schematic view of the KENTROS detector.

A. Barrel

The active part of the barrel is composed by two layers. The external layer has a 74 cm external diameter, and it is made of 50 scintillator modules, 3.8 cm thickness, oriented in a direction parallel to the beam. Each module has 50 cm length and trapezoidal section, height 3.8 cm, lesser base 3.4 cm, greater base 3.8 cm. The azimuthal angle covered by each module is 6 degrees, therefore there should be 60 modules for a complete azimuthal coverage, however 10 modules are missing in order to allow access to the readout electronic of the internal layer. The scintillation light is collected only at one end of the modules, the one closer to the target.

The internal side is composed by 2 layers of 1 mm diameter scintillating fibers which are bent to form circles. Those fibers are grouped in 20 modules, each one containing 20 x 2 fibers. In the final configuration the presence of 25 modules will ensure the complete coverage of the barrel, from about 40 degrees to 90 degrees. In the FIRST setup a tracking detector [8] is used to reconstruct the fragment tracks up to about 40 degrees. Therefore the main function of this fibers layer is the measurement of the polar angle of the particle trajectory in the angular region that is not covered by the tracking detector. A precise measurement of the particle impact point on the detector is also important for time of flight evaluation. The scintillation light at one end of each module collected by a plexiglas lightguide and driven to a SiPM.

B. Big and Small Endcap

The big endcap has the shape of a disk with a hole. The internal and external diameters are 28 and 74 cm, respectively. It is composed by 60 trapezoidal scintillator modules, having 3.5 cm thickness along the beam direction, 3.8 cm greater base, 1.39 cm lesser base, 23 cm height.

The small endcap, like the big one, has the shape of a disk with a hole, with 10 cm internal diameter and 30 cm external diameter. It is composed by 24 trapezoidal scintillator modules, having 3.87 cm greater base, 1.28 cm lesser base, 10 cm height.

The scintillation light at the external end of each module is collected by a plexiglas lightguide and driven to a SiPM.

III. TIME OF FLIGHT VS ENERGY LOSS MEASURENTS

An example of the measured time versus deposited energy of the detected particles is shown in Fig. 2. for a small endcap module.

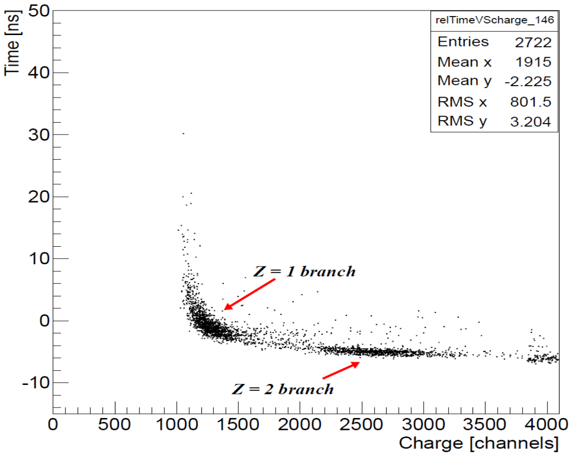

Fig. 2. Time versus charge spectrum for a small endcap scintillating module.

It is possible to distinguish two different branches in the figure, depending on the charge of the detected particles. The Z = 2 particles, which have a greater energy loss in the scintillator, release enough energy to generate a prompt readout TDC response. As a consequence, the energy signal is almost time independent for these particles. On the other hand, the Z = 1 particles, especially the ones at greater energies, release less energy in the module, giving rise to a time delay between the arrival of the particle on the module and the TDC response: this is the time walk effect. In order to correct the time versus charge plot for this time effect we performed a fitting procedure using a polynomial function plus an exponential one, then subtracting the fitting function from the experimental data on a event by event basis. The procedure has been applied to all the KENTROS scintillating modules, with specific differences related to the analyzed detector. As an example, the result of the described procedure is shown in Fig. 3 for a small endcap module.

Due to the different SiPM gains, the Z = 1 and Z = 2 peaks in the charge distributions are not centered at the same value in all the modules. Therefore, in order to superimpose the time-charge distributions for all the modules of a specific subdetector. the charge equalization was performed.

Fig. 4 shows the time of flight versus deposited energy after the time walk correction for all the Small Endcap modules superimposed. It is possible to distinguish the three branches of the Z=1 isotopes, protons, deuterons and tritos, as well as the Z=2 region after the punch through.

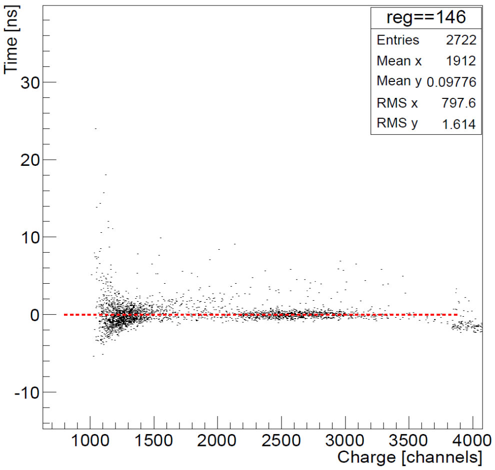

Fig. 3. Time versus charge distribution after the time walk correction.

Full lines represent theoretical calculations performed by using energy loss calculations and the predicted mean time of flight of the particles as a function of the kinetic energy.

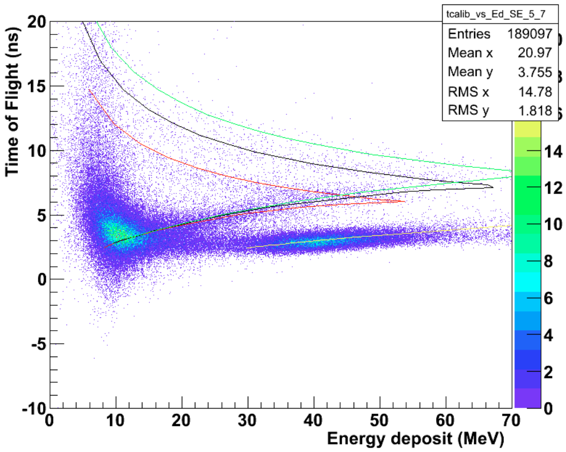

Fig. 4. Time of flight versus energy loss for all the Small Endcap modules superimposed. Full lines represent theoretical calculations for protons (red line), deuterons (black line), tritons (green line) and alpha particles (yellow line).

IV. CONCLUSIONS

The FIRST experiment was designed for the measurement of double differential fragmentation cross sections, with respect to energy and scattering polar angle, for light ions in the range between 100 and 1000 MeV/nucleon. The main goal is to reduce the lack of data on DDCS measurements, which are crucial for hadrontherapy and for radiation protection in space missions. The experiment was setup at the GSI laboratory in Darmstadt (Germany) and a first data taking took place during August 2011 with a 400 MeV/nucleon ^{12}C beam hitting a carbon target.

Among the different detectors used in the experiment, the KENTROS detector was devoted to the identification and kinetic energy measurements of light fragments emitted at angles between 5 and 90 degree in the laboratory frame. Data analysis, which is still ongoing, has involved the time walk correction of all the time-charge distributions and the charge equalization of all the modules. New procedures, attempting to improve our preliminary results, are currently under study.

Future developments of the FIRST experiment will involve fragmentation measurements of different projectiles of interest for hadrontherapy and space radiation protections on different targets.

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