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Measurements of the ^{16}O cross section on a C target with the FOOT apparatus

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Summary. — In particle therapy (PT) nuclear interactions of the beam with the body cause fragmentation of both the projectile and target nuclei. Fragmentation processes need to be taken into account when planning a PT treatment, but the evaluation of their impact is limited because of the lack of experimental data. The FOOT (FragmentatiOn Of Target) collaboration designed an experiment aiming to the measurement of the differential cross sections of interest in PT. In this paper, an overview of the FOOT experiment, the experimental setup and the measurement strategy will be discussed. In addition, preliminary results of a 400 MeV/u ^{16}O beam impinging on a C target will be presented.

1. – The FOOT experiment

The FOOT project is an applied nuclear physics experiment aiming to measure the fragmentation cross sections of relevance for particle therapy and radioprotection in space applications. The final goal of the experiment is to measure the double differential cross section of nuclear inelastic reactions in the energy range of PT (up to 250 MeV for protons and 400 MeV/u for ^{12}C and ^{16}O). The FOOT main goal is to perform the charge identification with an accuracy of 2–3% and to measure the fragments kinetic energy spectra with an energy resolution of about 1–2 MeV/u. Also the mass has a significant role, since it influences the fragments range, therefore the isotopic identification accuracy has to reach the accuracy level of about 5%. These requirements drove the development of the FOOT experimental setup.

2. – Experimental setup

The FOOT setup consists of an upstream region composed by the pre-target detectors and by a region, including the target, for the tracking and the identification of the fragments based on a magnetic spectrometer, coupled with detectors for tracking. A

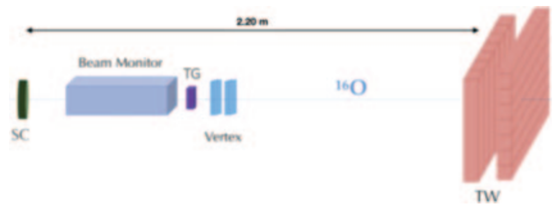

Fig. 1. – Schematic view of the 2019 GSI data taking setup.

description of the setup used during data taking at the GSI Heavy Ion Research Center in Darmstadt (Germany) in April 2019 will be provided in the following paragraph. The available detectors were (see fig. 1): the Start Counter (ST), the Beam Monitor (BM), the Vertex (VTX) and the Tof Wall (TW) (see fig. 2). During data acquisition, due to a problem with the DAQ, it has not been possible to synchronize the data collected by the VTX with the rest of the apparatus. For this reason, the VTX is not used for the analysis reported here.

2˙1. *Start Counter*. – The Start Counter is made of a thin squared foil of plastic scintillator 250 μm thick and with 5 cm transverse size.

To provide light tightness, the scintillator foil is held by means of an aluminum frame enclosed in a black 3D printed box, where two squared windows are placed in correspondence of the scintillator field of view. The produced light is collected laterally by 48 SiPMs and the acquired waveforms are analyzed offline with a constant fraction discriminator technique to extract event start time t_0. The SC, placed 44 cm upstream of the target (TG), provides the trigger signal to the whole experiment, the measurement of incoming ion flux to be used for the cross section measurement and the reference time for all the other detectors to allow the TOF measurement in combination with the TW scintillator detector. A time resolution of the order of $\sigma(t) \geq 60$ ps has been measured using only one of the four channels of the device.

2˙2. *Beam Monitor*. – The Beam Monitor is a drift chamber consisting of twelve layers of wires, with three drift cells per layer, operating at atmospheric pressure in Ar/CO2, 80/20% gas mixture. The efficiency of the detector was measured to be approx 90% for C ions and the mean track spatial resolution is of the order of 100 μm. The BM detector,

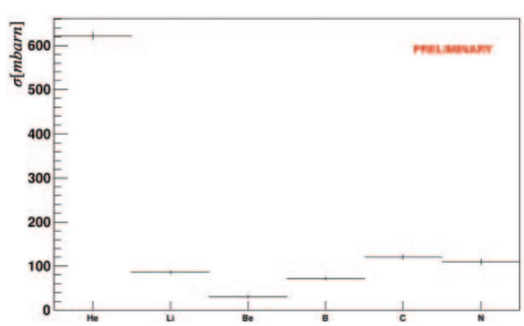

Fig. 2. – Fragmentation total cross section for different fragment charges.

placed between the SC and the target, is used to measure the direction and impinging point of the ion beam on the target. Its readout time ($\leq 1\,\mu$s) is fast enough to ensure that tracks belonging to different events cannot be mixed [1].

2·3. *Tof Wall*. – The Tof Wall detector is composed of two layers of 20 plastic scintillator bars arranged orthogonally, each 0.3 cm thick, 2 cm wide and 44 cm long. The two orthogonal layers provide measurements of energy deposited ΔE, the needed information to compute the TOF (using t_0 from SC as the input), and the hit position [2]. Each of the two edges of the TW bars is coupled to 4 SiPMs and the signals of each channel are digitized at rates of 3–4 G samples/s by the WaveDAQ system, the same readout shared also with the SC detector. The thickness of the bars and the selected readout chain have been chosen to meet the FOOT requirements of the TOF resolution better than 100 ps and energy loss resolution $\sigma(\Delta E/E) \sim 5\%$, for the heavier fragments. Finally, the high precision time measurement provides a hit position reconstruction along the bar with a precision $\sigma_{pos} \leq 8$ mm, better than the bars crossing of 2 cm.

3. – Analysis strategy

The fragmentation cross sections have been computed for each Z population using the following equation:

$$\sigma(Z) = \int_{E_{min}}^{E_{max}} \int_{0}^{\Delta\theta} \left(\frac{\partial^2 \sigma}{\partial\theta \partial E_{kin}} \right) \mathrm{d}\theta \mathrm{d}E_{kin} = \frac{N_{frag}(Z)}{N_{prim} \cdot N_{TG} \cdot \epsilon(Z)}, \tag{1}$$

where $\Delta\theta$ is the maximum TW detector acceptance angle (5.7°), E_{min} and E_{max} are the minimum and the maximum kinetic energy for integration, $N_{frag}(Z)$ is the number of fragments of a specific charge measured by the TW, N_{prim} is the number of initial ^{16}O ions impinging on the target, $\epsilon(Z)$ is the elemental reconstruction efficiency in the TW acceptance and N_{TG} the number of target scattering centers per unit surface obtained as

$$N_{TG} = \frac{\rho \cdot \Delta x \cdot N_A}{A}, \tag{2}$$

in which $\rho = 1.83\,\mathrm{g/cm}^3$ is the target density; $\Delta x = 0.5$ cm is the target thickness; N_A is the Avogadro number and $A = 12.0107$ is the graphite mass number. The fragment reconstruction is performed using reconstruction and identification algorithms exploiting the information available from the active detectors.

3·1. *Fragments reconstruction algorithms*. – The fragments charge is calculated from the information about the energy loss, ΔE and the time of flight (TOF), measured by TW and ST. The Z identification (ZID) algorithm correlates the measurement of ΔE and the TOF for each track that hits the TW to Z of the track, through a parametrization of the Bethe Bloch formula as a function of time of flight [3]. The tracks are plotted on a ΔE *vs.* TOF plane and the algorithm assigns to each TW hit the Z corresponding to the closest Bethe Block curve.

In order to reconstruct a fragment track impinging on the detector, the hits arriving on the two layers of the TW have to be clusterized. The clustering algorithm has the aim of joining pairs of hits corresponding to the same fragment in a unique TW point: the reconstruction is done dynamically, starting from the hits corresponding to the layer with the higher occupancy, in a given event, in order to resolve the cases in which multiple hits occur on the two layers.

3˙2. *Reconstruction efficiencies.* – To obtain a cross section measurement the detector efficiency is needed. This is given by

$$\epsilon(Z) = \frac{N_{TW}(Z)}{N_{prod}(Z)}, \tag{3}$$

where $N_{TW}(Z)$ is the number of fragments with charge Z reconstructed by the TW and $N_{prod}(Z)$ are the fragments with charge Z produced in the interaction between the primary beam and TG. Efficiencies have been evaluated using a Monte Carlo simulation reproducing the setup used at GSI. To extract $N_{TW}(Z)$, the TW reconstructed points, which satisfy the same conditions required for $N_{prod}(Z)$, have been counted, for each Z. The number of fragments detected by the TW ($N_{TW}(Z)$) has been computed using the charge reconstructed by the ZID algorithm.

3˙3. *Yields extraction and background subtraction.* – During data taking the adopted trigger was a minimum bias trigger based on SC good signals. The fragments yields extracted by the TW detector mix primary fragmentation produced in the TG, corresponding to the signal in the measurements, and primary fragmentation out of target that results in a source of background. From the study of the ΔE distributions extracted from the MC simulations, it can be seen that the fragmentation out of target has a great impact on the selected yields. For this reason, calibration runs without carbon target have been used to evaluate the background due to the fragmentation out of target.

4. – Results

Finally, fig. 2 reports the preliminary values obtained for the cross sections of an ^{16}O beam at 400 MeV/u on a C target for the production of He, Li, Be, B, C and N integrated in the angle $0 \leq \theta \leq 5.7$Å and in the energy interval [200, 600] MeV/u.

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