Experiment FIRST: Fragmentation of Carbon Beam at 400 MeV/u

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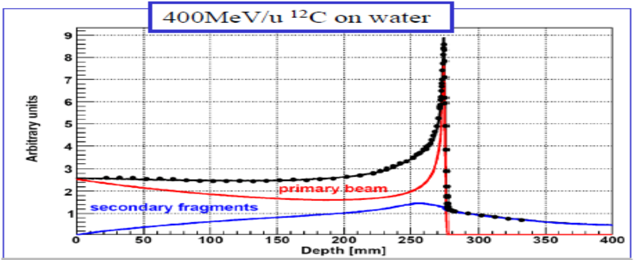
FIRST goals

- Experiment FIRST
  (Fragmentation of Ions Relevant for Space and Therapy)
  is focused on:
  - secondary effects of hadron-therapy ion beams on organic tissue
  - cosmic radiation (GCR) effects on humans and equipment on air/space-crafts
- Knowledge of nuclear fragmentation in this cases is limited
  - data of some mass and impulse distributions of fragments are lacking
- This experiment aims to measure the inclusive cross-section of fragments in ion - nuclear target reactions, $\frac{d^2\sigma}{d\theta dE}$
  - projectiles: $Z < 9$ ions
  - $100 - 1000\,\text{MeV/n}$ beam
  - targets: C, N, O, H, ...
- 1^{st} data taking @ GSI in 2011:
  - ^{12}C @ $400\,\text{MeV/n}$ on graphite and gold targets

fragmentation in Hadrontherapy



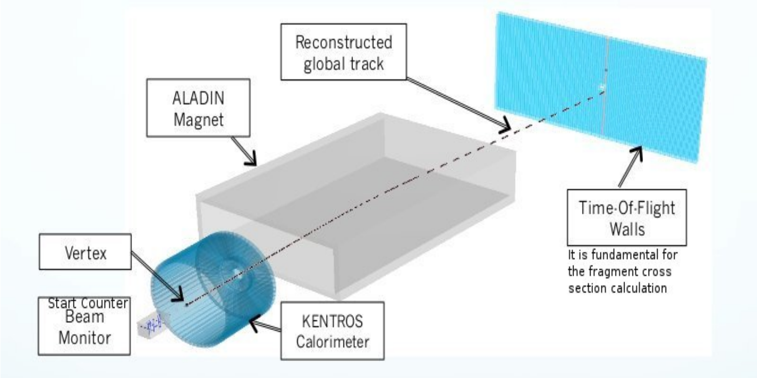
Exp. Data : Haettner et al, Rad. Prot. Dos. 2006
Simulation: A. Mairani PhD Thesis, 2007, Nuovo Cimento C, 31, 2008

- Red line: simulation of ^{12}C @ 400 MeV/n energy loss in water
- blue line: simulation of fragment energy loss in water
- black dots: corresponding experimental data

Fragmentation in radiation protection

- Fragmentation predictions of theoretical models vary over an order of magnitude for double-differential cross-section (in energy and angle)
- Most available measurements are limited to a small range of fragments and total fragmentation cross-sections.
- Codes used for radiation transport in shielding materials need more information on the fragmentation effects.
- Recently, NASA completed a large database of these measurements and observed that there are ion species and kinetic energy ranges not yet evaluated.

FIRST experiment layout



It is fundamental for the fragment cross section calculation

Features

- simultaneous tracking of several fragments
- particle identification based on energy deposition in ToF-Wall
- large angular acceptance of the whole detector assembly

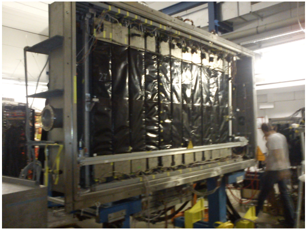
Description of detectors

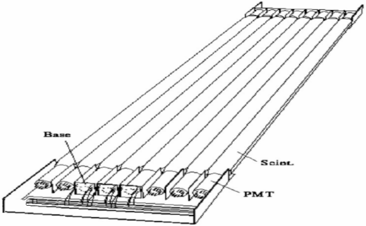
- Start Counter triggers all measurements
  - EJ-228 fast scintillator window (52 mm diameter, 250 μm thick)
  - 4 optical fiber bundles drive scintillation signals to 4 photomultipliers Hamamatsu H10721-201
- Beam Monitor tracks incoming ^{12}C ions (impact point position)
  - drift chamber (Ar-CO$_2$ $80\% - 20\%$ gas mixture)
  - 6 planes of 6 sensing wires hortogonal to the beam
- Vertex tracks charged particles emerging from the target
  - 4 planes of $\sim 2 \times 2\,\text{cm}^2$ area spaced by 3 mm (2 sensors per plane)
  - based on MIMOSA-26 silicon pixel sensors
    - 1152×576 pixels, $21.2 \times 10.6\,\text{mm}^2$ active area, 50 μm thick
- KENTROS detects fragments at polar angles from $\sim 5^o$ to 90^o
  - it measures time of flight and energy loss
  - EJ200 fast plastic scintillators read by AvanSiD photomultipliers
- ALaDiN-ToF-Wall: spectrometer for particles at polar angles $< 5^o$
  - ALaDiN is A Large Dipole magNet
  - ToF-Wall provides impinging point, time of flight and energy loss of charged particles for Z-identification and reconstruction

ToF-Wall layout and aims

ToF-Wall layout:

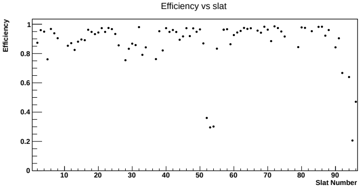
- 2 planes made of 12 modules (110 cm × 2400 cm active area)
- each module has 8 BC-408 scintillator slats
- slats are read by a PMT at each edge
    - PMT signals are split and read out by Fastbus ADCs and TDCs
- hit coordinates, arrival time and energy loss of particles are measured

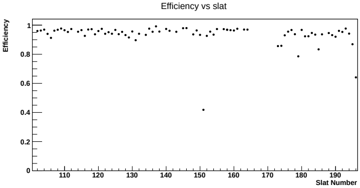




Overall efficiencies of front (left) and rear (right) wall slat

- a conditional frequency approach has been adopted
    - crossing PMT readings slat by slat
- efficiencies are generally above 80%





Calibrations of TDC based measurements

Time readings are made of more contributions

$$\begin{aligned} TDCt &= ToF + \tau_t + \Delta_t \\ TDCb &= ToF + \tau_b + \Delta_b \end{aligned}$$

- ToF, from target to ToF-Wall
- τ_t and τ_b taken by the scitillation pulse to reach top and bottom PMTs respectively
- Δ_t and Δ_b are the overall channel delays

- Y is related to τ_t and τ_b through v, the speed of light in slats
  $2 * Y = v * (\tau_b - \tau_t) = v * [(TDC_b - TDC_t) + (\Delta_t - \Delta_b)]$
- ToF is not affected by τ_t and τ_b: $(\tau_b + \tau_t) = L/v$ (L: slat length)
  $2 * ToF = (TDC_t + TDC_b - (\Delta_t + \Delta_b) - L/v)$
- delay corrections are found from TDC readings in known conditions:
  - sweepruns: ${}^{12}C$ @ 400 MeV/n, without target
    - ALaDiN magnetic field is varied and the beam sweeps horizontally
    - the sweep plane is taken as reference: $Y = 0$
    - simple reconstruction of ${}^{12}C$ path and momentum provides ToF

ADC Gain Calibration

- Be $E_0(E, Z, m, \alpha)$ energy lost by a particle (Bethe-Bloch formula)
- Pedestals are zero reference levels of ADCs (PMTs dark noise)
- ADC'_t and ADC'_b are related to energy loss in the slat
  - ϵ_t and ϵ_b are the gain/attenuation factors

$$\begin{aligned} ADC'_t &= ADC_t - Ped_t = \epsilon_t * E_0 * e^{-\mu(L/2-Y)} \\ ADC'_b &= ADC_b - Ped_b = \epsilon_b * E_0 * e^{-\mu(L/2+Y)} \end{aligned}$$

- the product of both ADCs gives the deposited energy

$$E_0 = K * \sqrt{ADC'_t * ADC'_b}$$

- K is independent on the Y coordinate $1/K \equiv \sqrt{\epsilon_t * \epsilon_b \; e^{-\mu * L}}$
- K is found form ADC' readings in known conditions
  - sweepruns: ${}^{12}C$ @ 400 MeV/n, without target
    - ALaDiN magnetic field is varied and the beam sweeps horizontally
    - $E_0^C \approx 116$ MeV according to the Bethe-Bloch formula

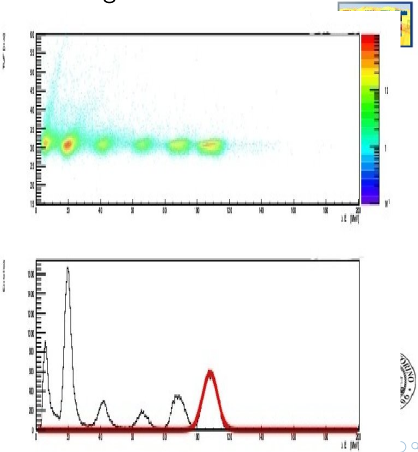
Z identification process

Fragments with different Z produce different energy loss in the slat

- Bethe-Bloch model
- fragments (H, He, Li, Be, B, C) can be recognized

Charge identification

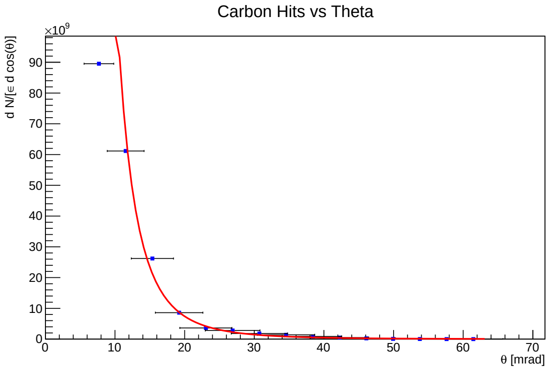
- ToF vs E_0 plots features six spots for Z from 1 to 6
- for each fragment ToF and E_0 are compared with those of the closest spot
- Z is guessed accordingly



^{12}C Scattering processes

Non-interacting and scattered ^{12}C statistics have been studied

- Single scattering: (external) interaction with the nucleus
- Multiple scattering: several interactions with the atomic electrons
- Nuclear scattering: strong interaction with the nucleus
    - Coulomb barrier is overcome, unlikely in our case



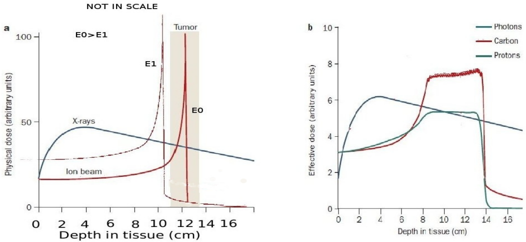
- a preliminary evaluation of scattered ^{12}C distribution was found in good agreement with the Rutherford model, $1/\sin^4(\theta/2)$
    - smaller cross-section
    - dominant at larger angles

THE END

Thanks for your attention

The importance of hadrontherapy

- Bethe-Block: $\frac{dE}{dx} = \frac{4\pi e^4 Z_t Z_p^2}{m_e v^2}[ln\frac{2m_e v^2}{<I>} - ln(1-\beta^2) - \beta^2 - \frac{C}{Z_t} - \frac{\delta}{2}]$
- Physical dose $D = d\epsilon / dm$
    - ϵ is the energy delivered to the mass unit m
- Effective dose $ED = \Sigma_T w_T * \Sigma_R w_R * D_{T,R}$
    - w_T weights different radiation types
    - w_R takes into account effects on different body tissues and organs



Comparison of the depth-dose for X-rays, protons and ^{12}C ions at different energies and in a wide range (used for extended ill regions)

worldwide treated patients (up to 2012):

- p beam: 93895
- C-ion beam: 10756

(http://ptcog.web.psi.ch)

Channel Efficiency

A conditional frequency approach is used
Efficiencies are defined per each channel of each slat

- $n_{tb}(sl)$ is the number of events with both TDCs fired (good entries)
- $n_t(sl)$ is the number of events with only top TDC fired (bad bottom entries)
- $n_b(sl)$ is the number of events with only bottom TDC fired (bad top entries)

$$\eta_t(sl) = \frac{n_{tb}(sl)}{n_{tb}(sl) \ + \ n_b(sl)} \qquad \eta_b(sl) = \frac{n_{tb}(sl)}{n_{tb}(sl) \ + \ n_t(sl)}$$

The FIRST collaboration

The acronym FIRST means: Fragmentation of Ions Relevant for Space and Therapy.
The experiment is performed by an international collaboration which includes organizations from:

- Italy: INFN: Cagliari,LNF,LNS,Milano,Roma2,Torino;
- France: DSM/IRFU/SPhN CEA Saclay, IN2P3 Caen, Strasbourg, Lyon;
- Germany: GSI

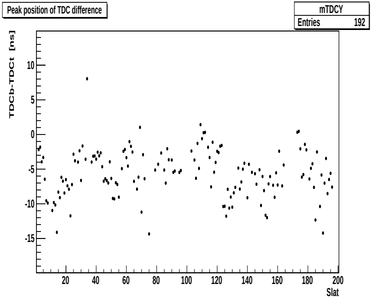
The first data taking has been performed in August 2011 @ GSI.

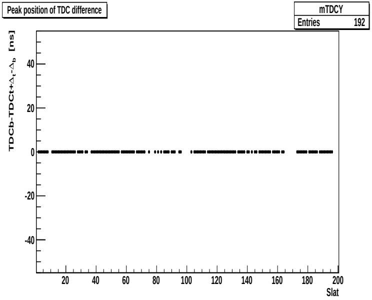
Y calibration: TDC-difference delay correction

For sweep-runs:

- Y coordinate is known: Y=0;
    - therefore it is possible to evaluate $(\Delta_t - \Delta_b)$ from: $(TDC_b - TDC_t + \Delta_t - \Delta_b)$=0.
- $\Delta Y \leq 3\,\text{cm}$ (depending on the spot of ^{12}C beam in sweep-runs).

The plot of TDC-difference peak centers vs slat before and after calibration is shown in the next figures:





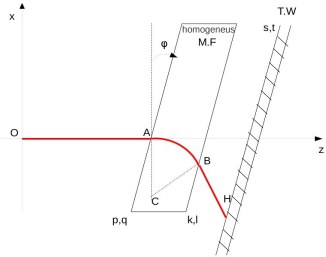
ToF calibration: TDC-sum delay correction

To determine the delay sum $(\Delta_t + \Delta_b) + (\tau_b + \tau_t)$:

- we need to know the particle ToF and then its trajectory and speed
- we use sweep-runs in which:
  - no target,
  - the energy of the carbon projectiles is known: 400 MeV/n.

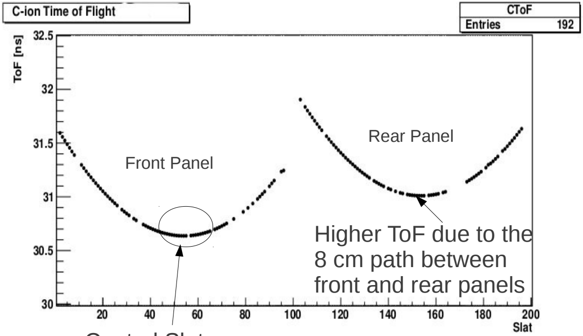
ToF Calibration

We made a geometrical reconstruction to calculate the theoretical ToF:



- from the reconstructed trajectory we have the path length (LoF) of the ^{12}C (on each slat);
- from the particle energy we can deduce its speed $v_p = \beta c$;
- $ToF = \frac{LoF}{\beta c}$ therefore:
  - $(TDC_t + TDC_b) - (\Delta_t + \Delta_b) - (\tau_b + \tau_t) = 2 * ToF$ is determined;
- $\Delta ToF \leq 0.5\,\mathrm{ns}$ (depending on the spot of ^{12}C beam in sweep-runs).

ToF Calibration: TDC-sum delay correction



Higher ToF due to the 8 cm path between front and rear panels

Central Slats: path length is minimum → small ToF

ADC-pedestal subtraction

- PMTt and PMTb energies are converted into channel values (ADC_t and ADC_b)
- these ADC raw values must be subtracted by pedestals
  - Ped_t and Ped_b, assumed as zero energy
  - ADCs are assumed linear from pedestal to full scale, i.e. the lost energy is proportional to ADC' defined as:

$$ADC'_t \equiv ADC_t - Ped_t \tag{1}$$

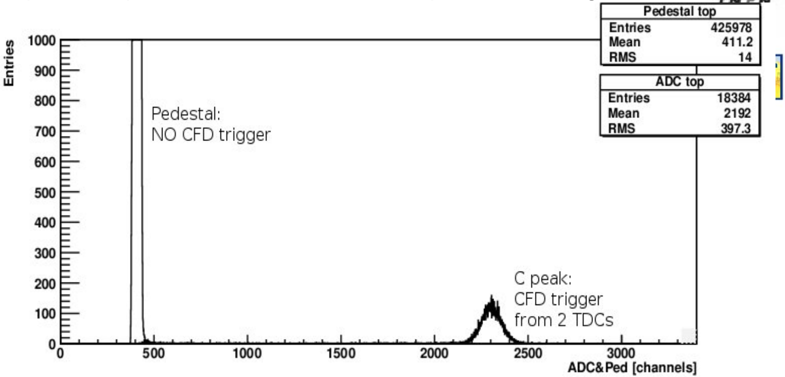
$$ADC'_b \equiv ADC_b - Ped_b \tag{2}$$

Pedestal Calibration

- Calibration has been based on sweep-runs
- Ped_t and Ped_b have been found (for every slat and for each channel)
    - **dark noise and MIPs** (i.e. ADCs without TDC responses) have been distinguished from hits
    - each **pedestal** has been found as the MIPs distribution starting energy
    - a **gaussian fit** of the peak has been built in an asymmetrical way on the left side – the fit mean value is taken as pedestal.

An example of ADC reading is shown in the following figure produced on top channel of slat 38 during sweep-runs

- the pedestal peak on the left and the C peak on the right are visible


Pedestal:
NO CFD trigger

C peak:
CFD trigger
from 2 TDCs

- Calibration has been based on sweep-runs
- Ped_t and Ped_b have been found (for all the slats and for each channel)

- in sweep-runs the ion energy is known and the energy released E_0 inside the slat can be evaluated
- E_0^C in eq. **??** gives K

$$K = \frac{E_0^C}{\sqrt{ADC_t' * ADC_b'}} \qquad (3)$$

$E_0^C \approx 116$ MeV and $\sqrt{ADC_t' * ADC_b'}$ is obtained by a gaussian fit on its distribution and taking the mean value.

- $\Delta E_{loss} \leq 3.5\,\mathrm{MeV}$ (depending on the spot of ^{12}C beam in sweep-runs)
- eq. 3 allows to evaluate the proportionality factors for all slats
- ADC channels must be used as in eq. **??** in order to get the energy deposit of every track passing through ToF-Wall

The plot of the E_{loss} peak centers vs slat is shown for sweep-runs, before and after calibration, in the following figures