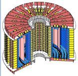
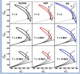




NUSPRASEN Workshop on Nuclear Reactions

^{12}C nuclear differential cross section measurements for hadrontherapy

(H, C, O, Al and ^{nat}Ti ($\sim$Ca) targets)

Marc Labalme

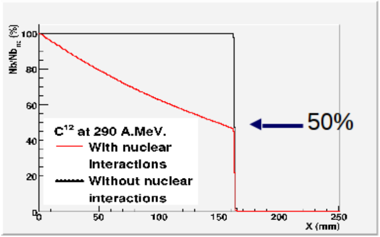
GDR Mi2B collaboration
LPC Caen

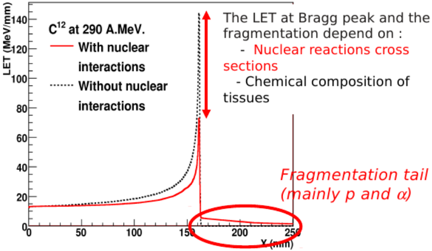
January 21-24, 2018

Fragmentation studies for hadrontherapy applications

Nuclear reactions impact in dose deposit

- Consumption of the incident ions ($N(x)=N_0.e^{(-\lambda x)}$)
- Creation of a mixed radiation field (H, He... C)
  - $\Rightarrow$ LET distribution $\rightarrow$ biological effectiveness modification (effect on the tumor)
  - $\Rightarrow$ Modification of the physical dose delivery (long term effects on healthy tissus)





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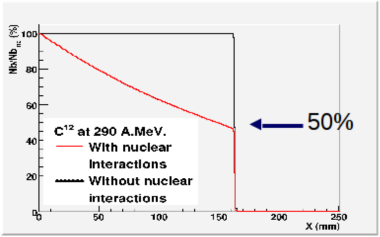
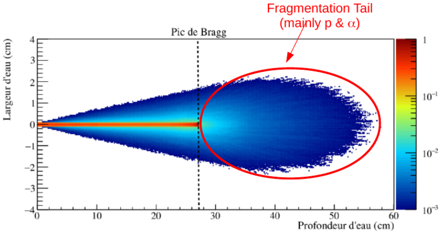




⇒ Nuclear reactions have to be considered for treatment planning

Fragmentation measurements at GANIL (France)

Codes are not able to reproduced the fragmentation

- Beam composition with depth
- Biological effects on healthy tissus
- Dose deposition imaging (prompt γ, β^+, p...)

$\Rightarrow$ Experimental data required in the full range of energies (400MeV/n)

Experiments on elemental targets

- Thin Targets ($\sim$50 mg$\cdot$cm^{-2}) : C, CH_2, Al, $Al_2 0_3$, ^{nat}Ti ($\sim$Ca)
- Projectile: 94.6 MeV/n ^{12}C (J. Dudouet PhD Thesis 2014)
  - E600 experiment $\rightarrow$ **cross sections from 4 to 43°**
  - France Hadron Beam Time $\rightarrow$ **cross sections at 0°**
- Projectile: 50 MeV/n ^{12}C (C. Divay PhD Thesis 2017)
  - France Hadron Beam Time $\rightarrow$ **cross sections from 3 to 39°**

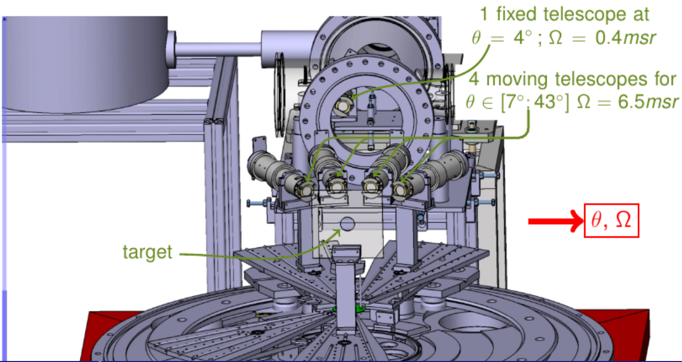
$\Rightarrow$ $\frac{\delta^2\sigma}{\delta E \cdot \delta\Omega}$ fragmentation measurements of ^{12}C on C, H, O, Ti (Z_{Ti}=22 $\sim$ Z_{Ca}=20)

$\approx$ 95% of a human body composition

Experimental Setup

- “Basic” experimental setup $\rightarrow$ 5 Si/Si/CsI telescopes (results a few months after the experiment)
- In vacuum measurements $\rightarrow$ ECLAN reaction chamber
- FASTER digital acquisition $\rightarrow$ **Δ**E/E analysis and pulse shape of CsI signal

$\rightarrow$ experimental estimation of systematics.



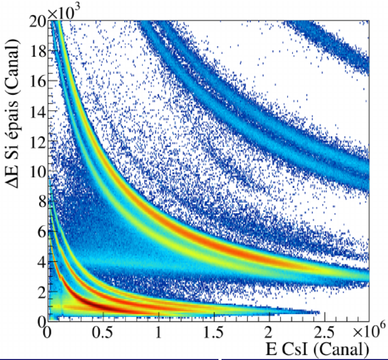
Analysis

$\Delta E/E$ (Si/Si or Si/CsI) and PSA of the CsI
$\rightarrow$ Experimental Systematic errors estimation

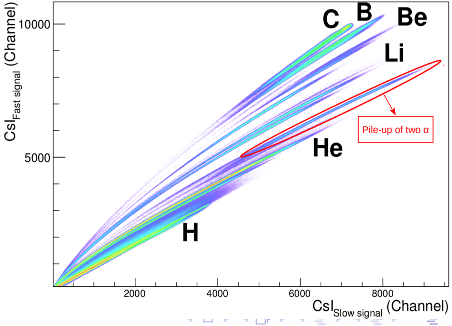
- Two main sources of systematic errors:
  - ^{4}He Fragmentation in the CsI $\rightarrow$ ^{3}He
  - 2α pile-up $\rightarrow$ ^{6}He, ^{6}Li and ^{7}Li distributions

Digital acquisition with BLR $\rightarrow$ Experimental estimation (CsI pulse shape analysis)

ΔE/E map



PSA (CsI)



Analysis

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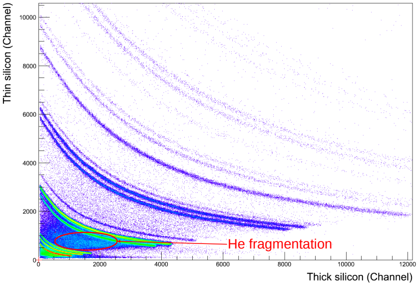
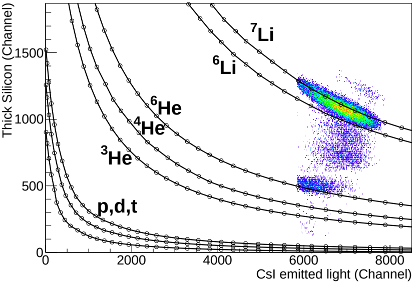
ΔE/E map

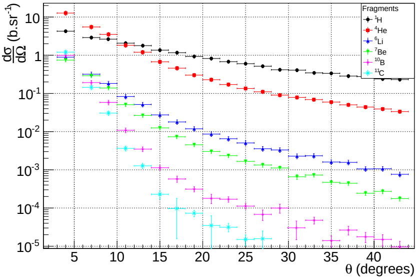


PSA (CsI)

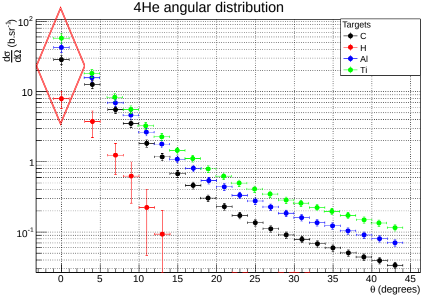


95 MeV/n experiment (~50 mg·cm^{-2}): $\frac{\delta\sigma}{\delta\Omega}$

Carbon target



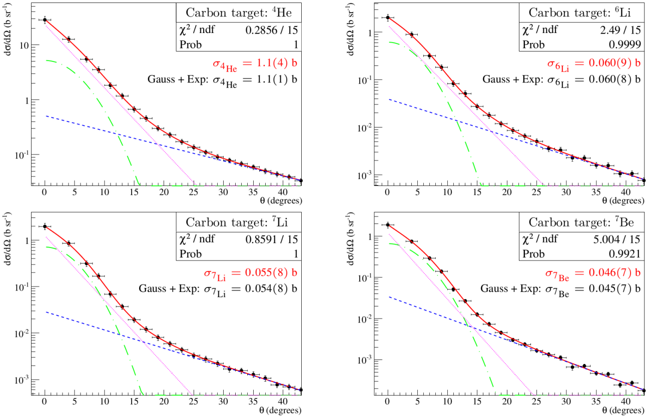
All targets



J. Dudouet et al., PRC 88 (2013) & J. Dudouet et al., PRC 89 (2014)

- Predominance of Z=1 and Z=2 production (^{4}He domination $\lesssim 10°$)
- Heavy fragments are more forward focused
- $\frac{d\sigma}{d\Omega}$ increase with the mass of the target.
- Angular distribution broadening with the mass of the target.
- No emission at large angle with the Hydrogen target (A>3) (no mid rapidity emission)

Angular distribution Fits (Gaussian + Exponential)

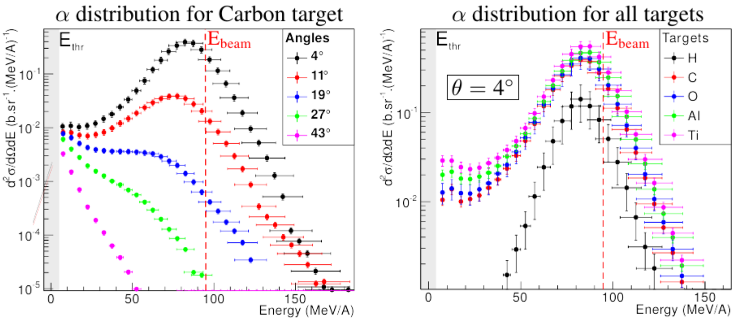


$\rightarrow$ Fragment production cross sections

6 parameters to reproduce the angular distributions

$\rightarrow$ phenomenological codes

95 MeV/n experiment (∼50 mg·cm^{-2}): $\frac{\delta^2\sigma}{\delta E \delta\Omega}$

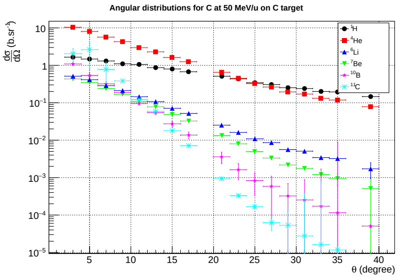


J. Dudouet et al., PRC 88 (2013)

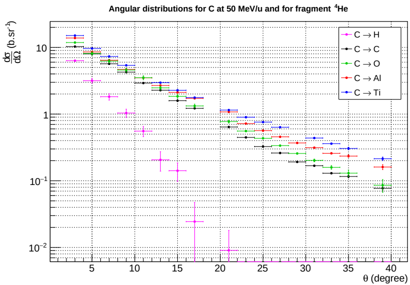
- E close to the beam energy at forward angles → Distributions dominated by the quasi-projectile contribution
- Cross sections increase with the mass of the target
- Hydrogen target: no low E emission → only quasi projectile contribution (for A>3)

50 MeV/n experiment (∼50 mg·cm^{-2}): $\frac{\delta\sigma}{\delta\Omega}$

Carbon target



All targets (^{4}He)

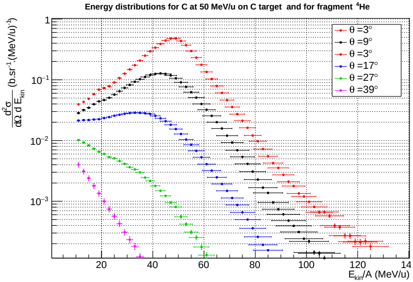


C. Divay et al., PRC 95 (2017)

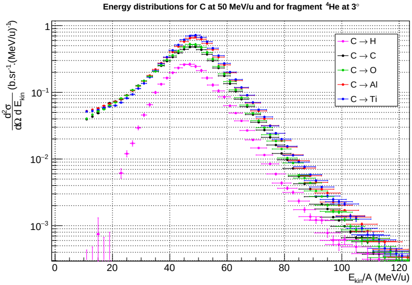
- Predominance of Z=1 and Z=2 production (^{4}He domination $\lesssim$20°)
- Heavy fragments ⟶ more forward focused
- $\frac{d\sigma}{d\Omega}$ increase with the mass of the target.
- No emission at large angle with the Hydrogen target (A>3) (no mid rapidity emission)
- Angular distribution broadening when incident energy decreases.

50 MeV/n experiment (∼50 mg·cm^{-2}): $\frac{\delta^2\sigma}{\delta E \delta\Omega}$

Carbon target (^{4}He)



All targets (^{4}He at 3°)

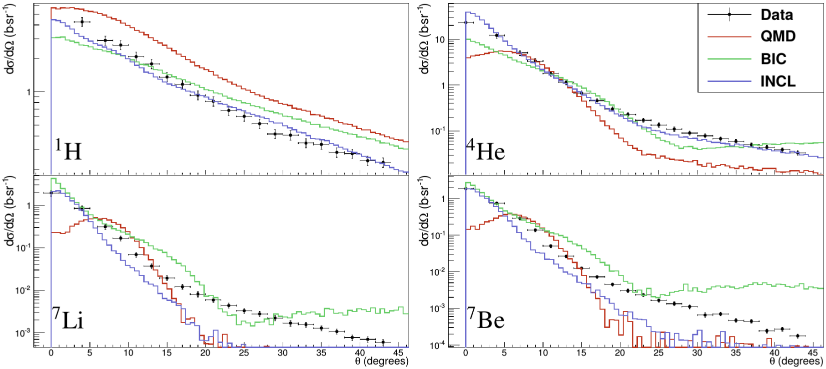


C. Divay et al., PRC 95 (2017)

- E close to the beam energy → Distributions dominated by the quasi-projectile fragmentation
- Cross sections increase with the mass of the target
- Hydrogen target: no low E emission → only quasi projectile contribution (for A>3)

GEANT4(v9.6) angular distributions (BIC, QMD, INCL++)

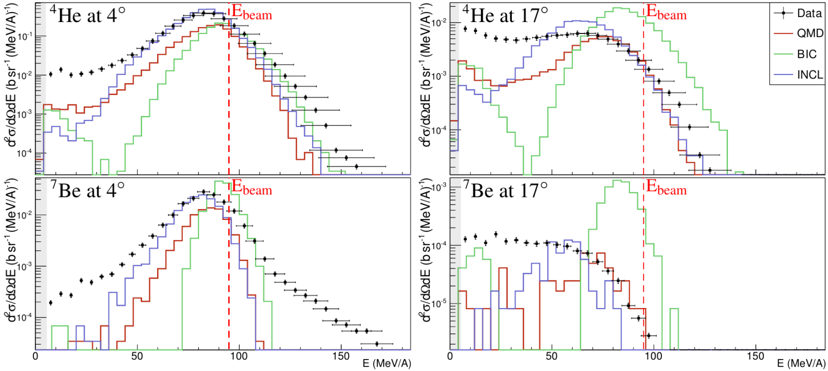
Carbon target at 95MeV/n



J. Dudouet et al., PRC 89 (2014), p054616

- None of the models included in G4 is able to accurately reproduce the experimental and angular distributions
- INCL: Best results at forward angles for A<18 (quasi projectile emission); not @50MeV/n
- Problem to take into account the "mid-rapidity" emission (large angles)
- jQMD: Decrease of the production at forward angles.

GEANT4(v9.6) energy distributions (BIC, jQMD, INCL++)

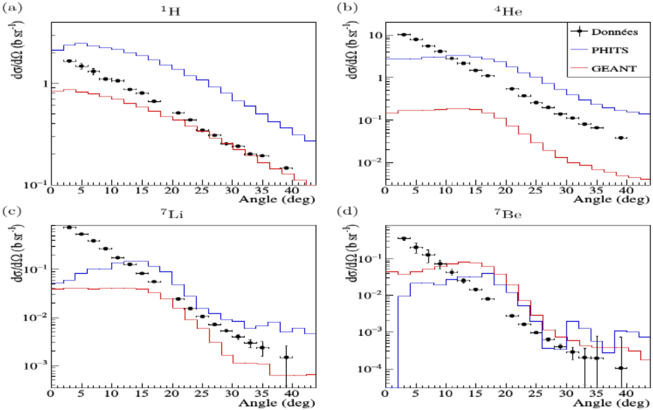


J. Dudouet et al., PRC 89 (2014), p054616

- None of the models is able to accurately reproduce the energy distributions
- BIC : Width too small, E mean too high, no mid-rapidity emission
- INCL: Best results (not @ 50MeV/n) at forward angles for A<18 (QP well reproduced), mid-rapidity shape not reproduced
- jQMD: Best shape; Low energies still underestimated.

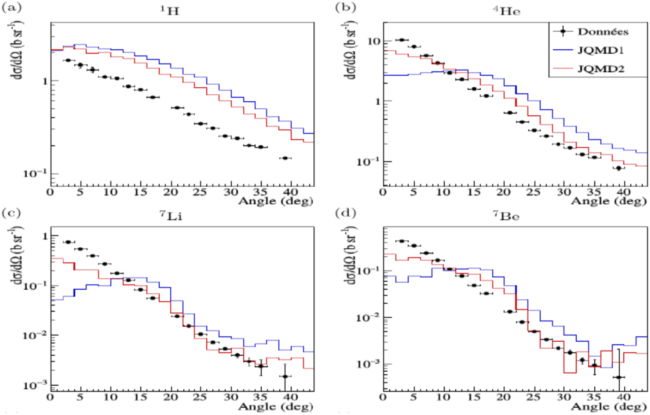
jQMD: GEANT4(v10.02) vs PHITS(v2.82)

Carbon target at 50MeV/n



- jQMD @ 50MeV/n & 95MeV/n
- None of the codes is able to accurately reproduce the experimental distributions (angle and energy)
- Importance of the transport simulation code: the same entrance model gives different results in GEANT and PHITS

PHITS:jQMD "old" vs jQMD 2.0 Carbon target at 50MeV/n



C. Divay et al., EPJ146 (2017), ND2016

- New version of jQMD seems more acurate → no more production fall of at forward angles
- jQMD old: Innacurate treatment of peripheral collisions → instability of the reaction products *(T. Ogawa et al., EPJ117 (2016), NN2015)*

Summary

- Fragmentation of 50 and 95 MeV/n ^{12}C ions on thin targets of medical interest on H, C, O, Al, Ti targets has been measured.
  - double differential cross sections $\frac{\delta^2}{\delta E \delta \Omega}$
  - angular differential cross sections from 0° to ∼40° (10-15% -sys+stat)
  - Integration of the angular distributions → production cross sections

- Composite targets (PMMA) can be deduced from the cross sections of elemental targets (→ organic tissues)

- GEANT4 hadronic models (BIC, jQMD, INCL) do not accurately reproduced the data.
- PHITS (jQMD) do not accurately reproduced the data; jQMD 2.0 > jQMD old

Data and experimental setup details available with free access :
http://hadrontherapy-data.in2p3.fr

Outlooks

Long term program of systematic measurements of nuclear reactions for hadrontherapy from 50 to 400 MeV/n

- **Production measurements of β^+ emitters for hadrontherapy**

  $\rightarrow$ measurement at GANIL in 2016 (S. Salvador et al. PRC 95 (2017)) + measurements at LNS in 2018

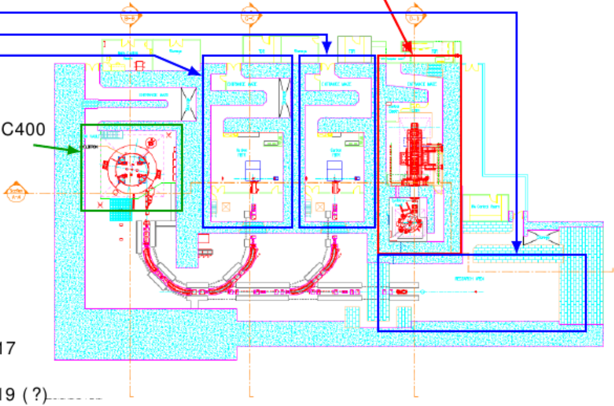
- **ARCHADE** (t_0 = December 2014)
  - New resource center for hadrontherapy in Caen (first proton treatment in july 2018)
  - First carbon beam in 2021-2022

  $\Rightarrow \sim 6 \times 15$ m^2 experimental room

  $\Rightarrow \frac{\delta^2 \sigma}{\delta E \delta \Omega}$ measurements with α to ^{12}C (^{20}Ne) beams from 100 to 400 MeV/n.

ARCHADE

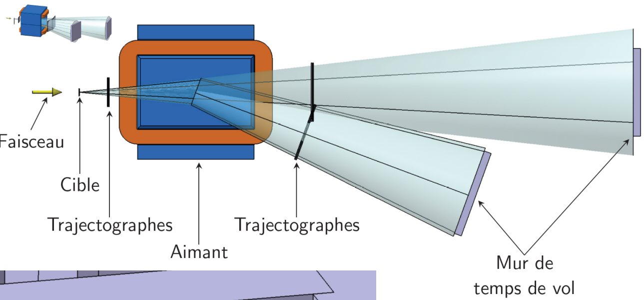
- Hadrontherapy center :
  - Protontherapy treatments
    Proteus One (S2C2)
    Protons at 250 MeV
  - Research in carbon-therapy
    - Physics
    - Biology
    - Clinical testing



- Supraconducting Cyclotron C400
  ^{12}C at 400 MeV/u
  Protons at 250 MeV
  All light nuclei with A/Z=2

- Planned timeline
  Contract signatures
  in march 2014
  Buildings : 2015 → 2017
  Proteus One : 2015 → 2017
  Proton treatments in 2018
  Carbon beams in 2018-2019 (?)

FRACAS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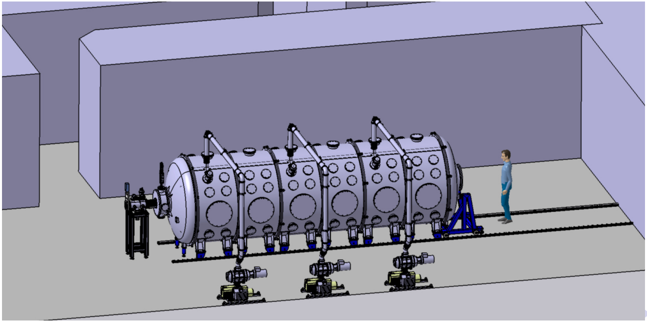
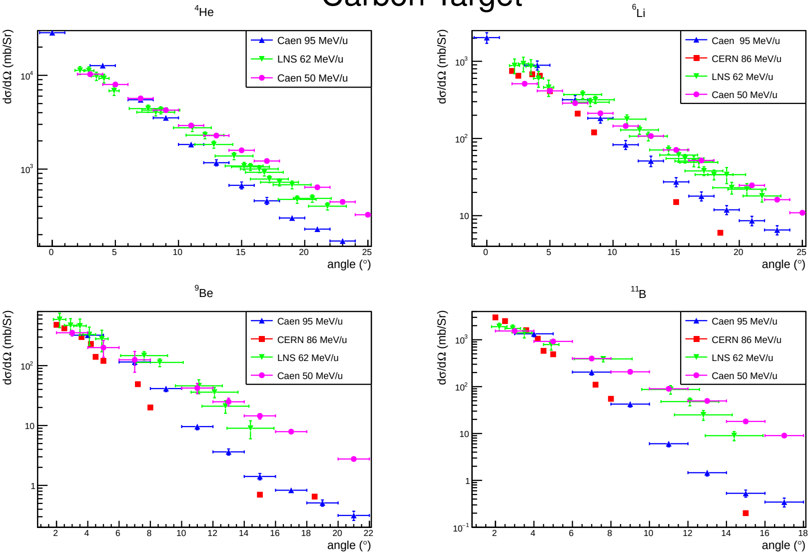
temps de vol



Back Up Slides

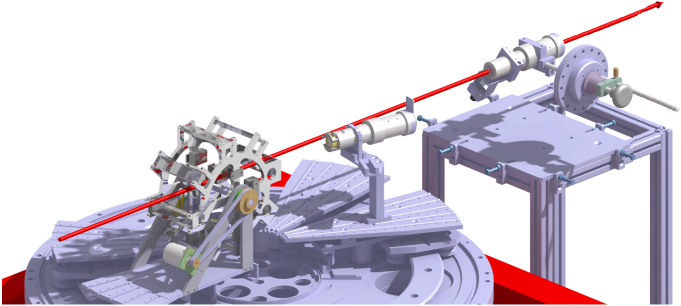
Comparisons with CERN (86 MeV/n) and LNS (62 MeV/n) data

Carbon Target



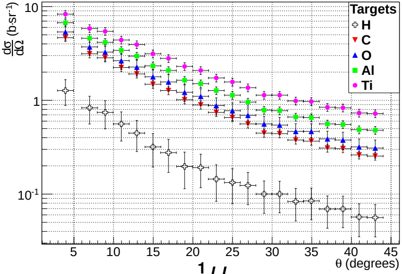
CERN data: Mougey et al., Nucl. Phys. A 387 (1982); LNS data: De Napoli et al., Phys. Med. Biol. 57 (2012).

Experimental Set-Up : 0° experiment (2013)

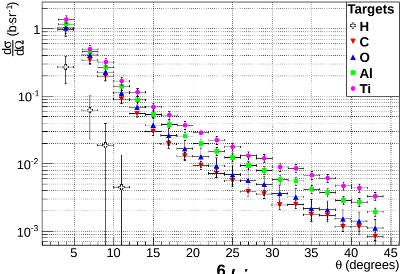


- 9° detector → cross check with previous experiment (agreement within 3%)

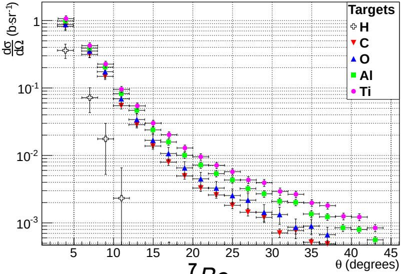
95 MeV/n experiment: $\frac{\delta\sigma}{\delta\Omega}$ all targets



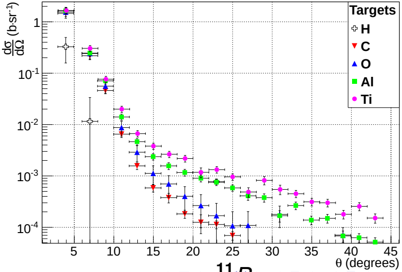
^{1}H



^{6}Li

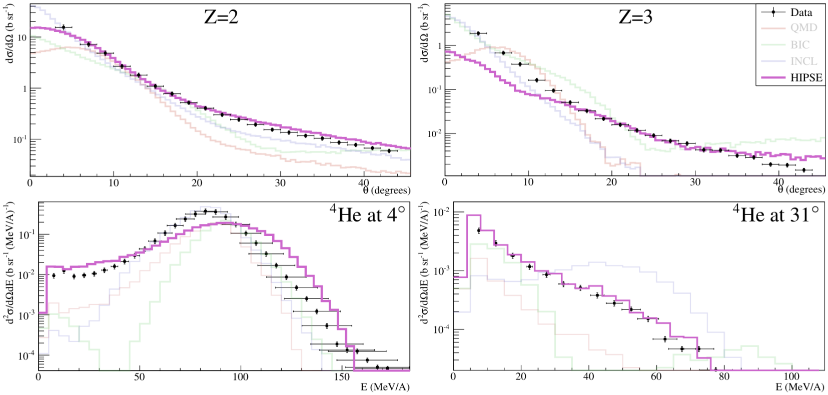


^{7}Be



^{11}B

HIPSE simulations (developed for INDRA)



- Phenomenological model developed for heavy systems close to Fermy energies
- Partition inside the overlap region built following coalescence rules in momentum and position spaces (participant-spectator)
- Do not reproduce the QP
- Better reproduction of the “mid-rapidity” emission (medium E) than G4 models

Composite target cross sections reconstruction from cross sections of elemental targets

Experimental PMMA target

$$\frac{d\sigma}{d\Omega}(C_5H_8O_2)$$

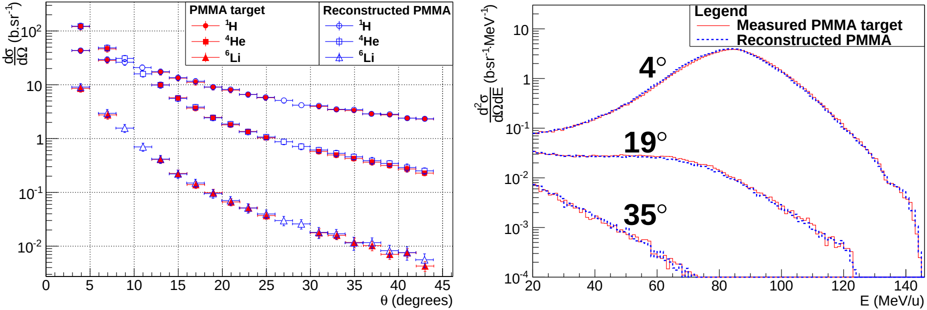
$$\stackrel{?}{=}$$

Calculated PMMA target

$$5 \times \frac{d\sigma}{d\Omega}(C) + 8 \times \frac{d\sigma}{d\Omega}(H) + 2 \times \frac{d\sigma}{d\Omega}(O)$$

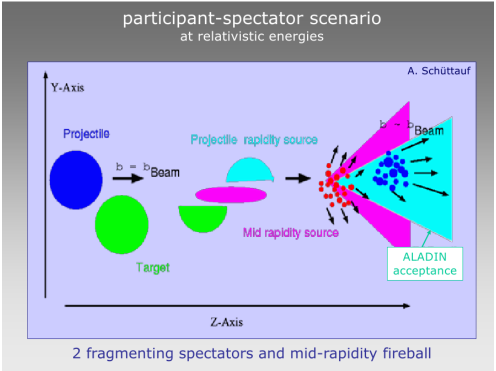
Distributions for a 1 mm thick PMMA target

Angular and Energy distributions comparison between experimental measurements and calculations from cross sections of elemental targets



⇒ Reproduction of composit material cross sections

Nuclear reactions



W. Trautmann; NUFRA 2013

- Processes: break-up, projectile or target fragmentation, neck emission, fission, multifragmentation...
- $<$ 100 MeV/n all these processes can coexist in a complex way (function of the incident beam energy) due to the competition between mean field dynamics and two body in medium interactions .
- $>$ 100-150 MeV/n $\sim$ two body (nucleons-nucleons) interactions.

Hydrogen and Oxygen Angular distributions

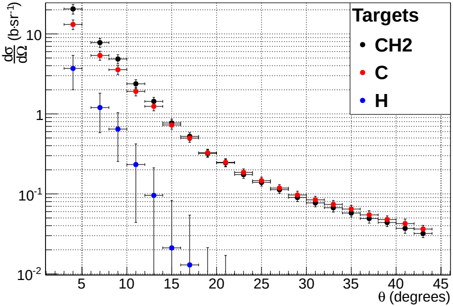
Oxygen and Hydrogen cross sections have been obtained from composit targets

$$CH_2 \rightarrow \frac{d\sigma}{d\Omega}(H) = \frac{1}{2} \times \left(\frac{d\sigma}{d\Omega}(CH_2) - \frac{d\sigma}{d\Omega}(C) \right)$$

$$Al_2O_3 \rightarrow \frac{d\sigma}{d\Omega}(O) = \frac{1}{3} \times \left(\frac{d\sigma}{d\Omega}(Al_2O_3) - 2 \times \frac{d\sigma}{d\Omega}(Al) \right)$$

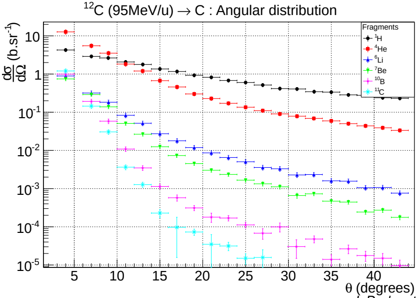
Hydrogen exemple

1. CH_2 & C cross sections measurements
2. C cross section subtraction
3. Obtained value divided by 2

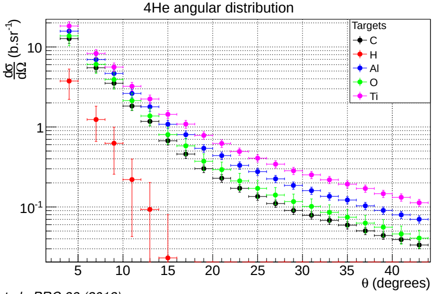


95 MeV/n experiment (∼50 mg·cm^{-2}): $\frac{\delta\sigma}{\delta\Omega}$

Carbon target



All targets



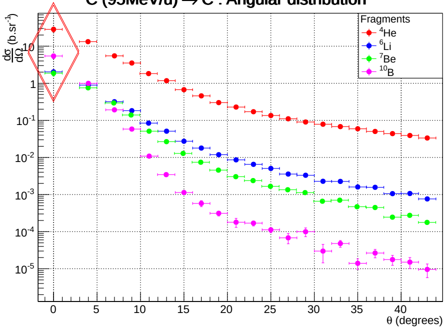
J. Dudouet et al., PRC 88 (2013)

- Predominance of Z=1 and Z=2 production (^{4}He domination $\lesssim 10°$)
- Heavy fragments are more forward focused
- $\frac{d\sigma}{d\Omega}$ increase with the mass of the target.
- Angular distribution broadening with the mass of the target.
- No emission at large angle with the Hydrogen target (A>3) (no mid rapidity emission)

95 MeV/n at 0° experiment (∼250 mg·cm^{-2}): $\frac{\delta\sigma}{\delta\Omega}$

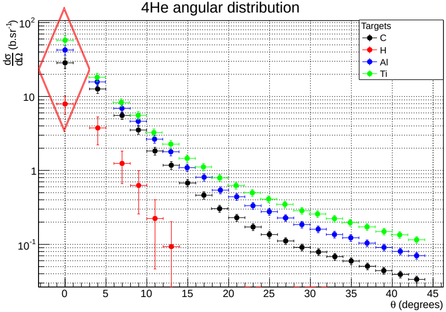
Carbon target

^{12}C (95MeV/u) → C : Angular distribution



^{4}He distributions; all targets

4He angular distribution



J. Dudouet et al., PRC 89 (2014), p 064615

- Important to constraint the distribution at forward angle (most of the production)
- 0° data for H, C, Al and Ti targets (not enough beam time for $Al_2 0_3$ (and PMMA) targets)
- $\frac{d\sigma}{d\Omega}$ for $2 \leq Z \leq 5$ (only most produced fragments in mass)