Nuclear Physics at intermediate energies and Monte Carlo models: the need for experimental data on double differential cross sections of nuclear fragmentation

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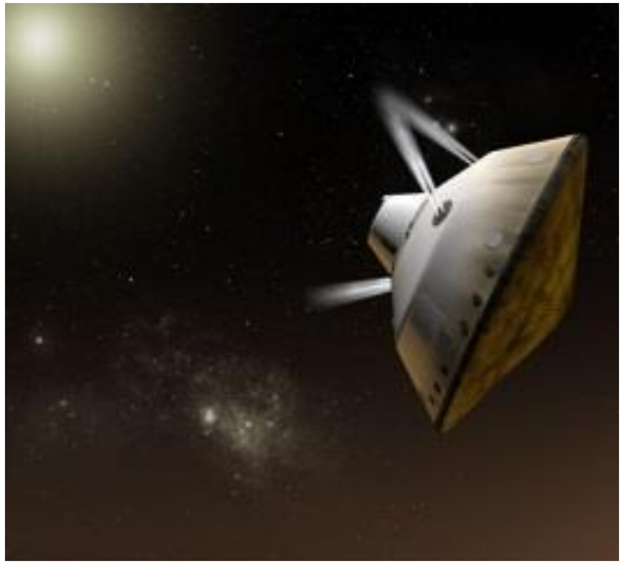
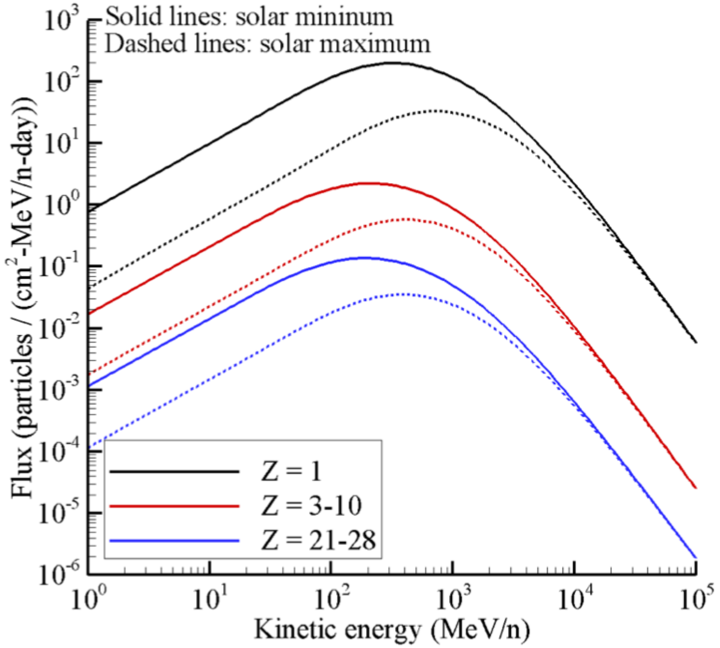
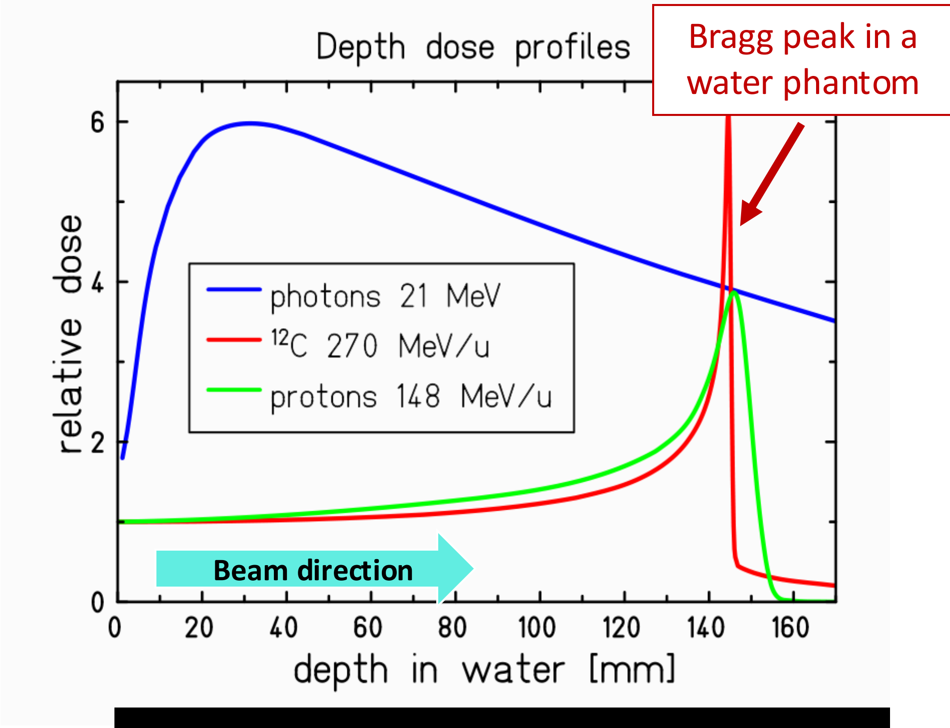
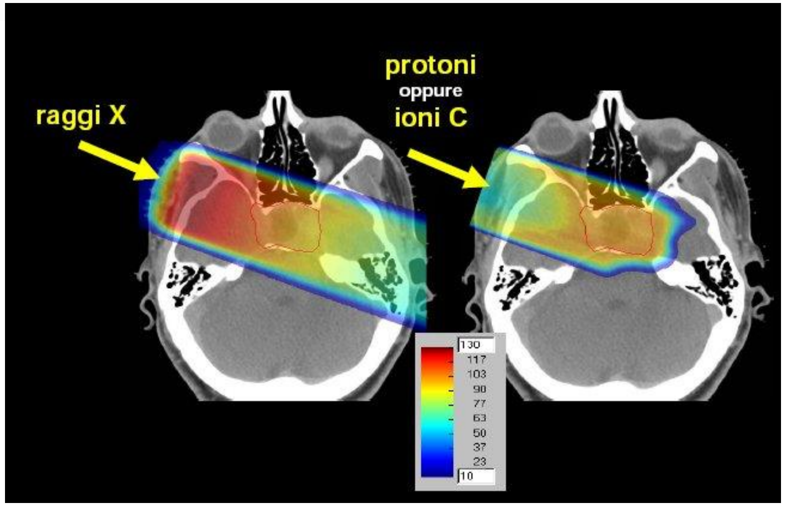
Introduction

The hadron-nucleus and nucleus-nucleus interactions for laboratory energy between 100 MeV/u and about 1 GeV/u play a key role in interesting application of nuclear physics: hadrontherapy and radioprotection on Earth and in space are probably the most important.



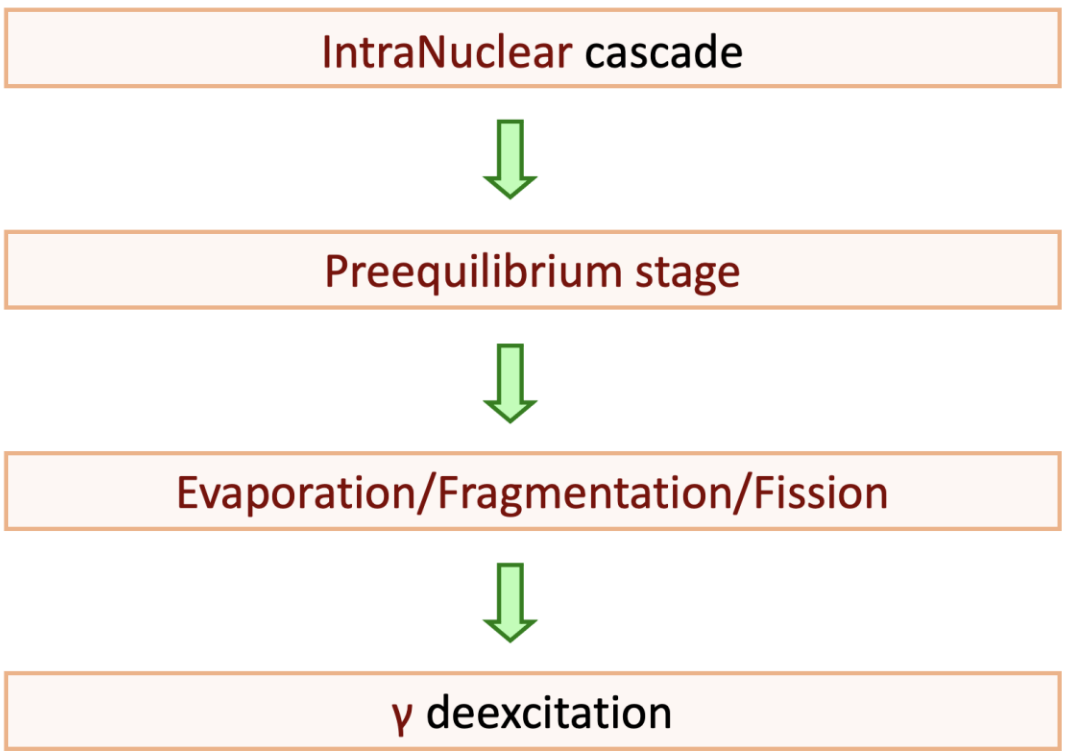


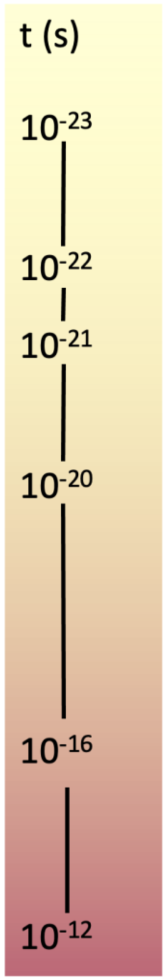




In all these areas, Monte Carlo codes have now gained a leading role.
However, the nuclear model are affected by significant uncertainties.

Qualitative time scale of different steps in nuclear interaction





The most critical phenomenon is the nuclei break-up, which at the energies of interest is dominated by nucleon-nucleon interaction.

In the non-perturbative regime, only phenomenological models are available.
The more reliable models, such as, for example, the AMD (Anti-symmetrized Molecular Dynamics) are too time consuming to be used in experimental environment.
More simplified models are used, built according to a “microscopic” approach, i.e. starting from the fundamental properties of the nucleus and of its constituents.

Two classes of simplified models are mostly used:
the primary fast interaction part: Intranuclear cascade & QMD (Quantum Molecular Dynamics)
+ **Thermalization: pre-equilibrium, evaporation, de-excitation**

PROBLEM: Is not always possible, within a given model, to achieve the same level of accuracy at all primary energies or in the whole accessible phase space.
Great care must be taken in order to ensure the proper continuity in the transition from one model to another.

The most useful data for model benchmarking are ***double differential cross sections for production of different secondaries at thin target***.

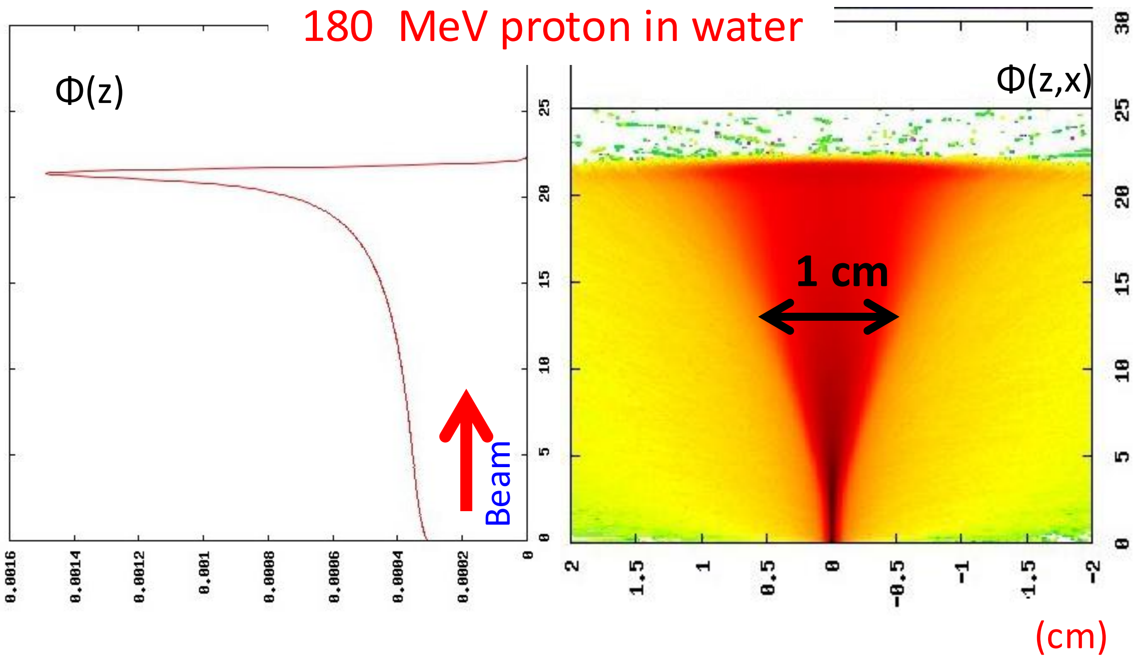
Why are they missing?
Traditionally this energy range is in a gap between the energy of interest for nuclear physics and high-energy physics

Uncertainties in MC models

All available Monte Carlo models of this kind are still affected by significant uncertainties and are constantly evolving.

Both elastic and inelastic nuclear reactions are relevant in particle therapy.

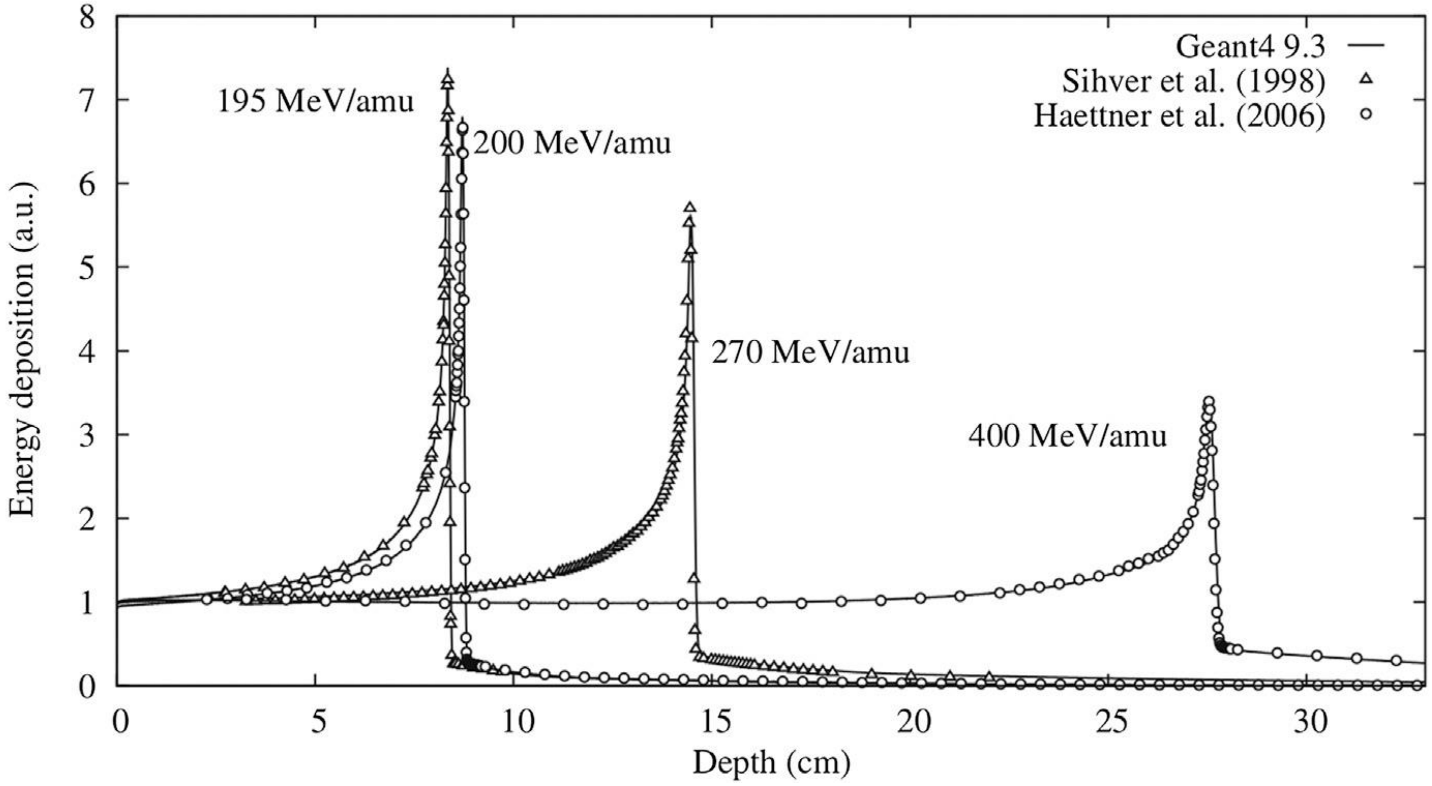
Elastic interactions contribute to the lateral broadening of the dose distribution and to lower the Bragg peak height.



In **inelastic nuclear collisions** the projectile may knock out secondary particles from the nucleus and break into fragments if the incoming projectile is an ion.

Strong impact on dose distribution, due to the build-up of secondary particles.

- *Beam attenuation*, because the primary particles disappear with penetration depth.
- The secondary particles *modify the build-up region of the Bragg curve* (mostly due to target fragmentation). In case of heavy ion projectiles: *dose deposition beyond the Bragg peak* (from projectile fragmentation).
- The production of low energetic secondary particles including neutrons, which are typically emitted at larger angles cause a relatively *wide low dose off-beam region*.



From *Lechner et al. [doi:10.1016/j.nimb.2010.04.008]:* an example of an excellent agreement between data and GEANT4 MC simulations in predicting the depth–dose profile of carbon ion beams.

Nice agreements in dose distributions: one may conclude that we have reached a satisfactory level of accuracy of the description of nuclear reactions in MC codes for physical dose calculations.
Partially true. Several important improvements in the context of dose calculations remain to be done.

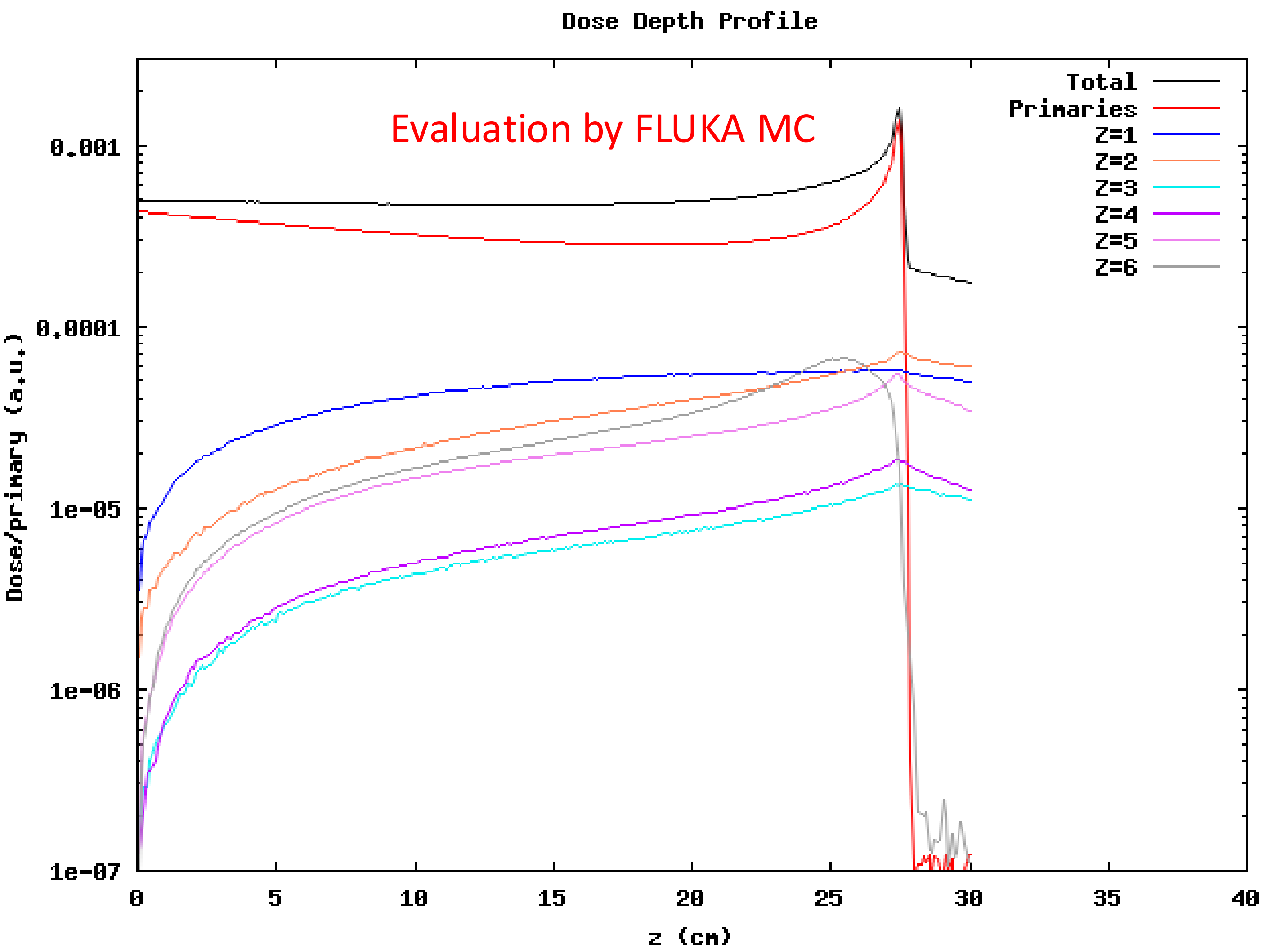
*The **biological effective dose** should be considered rather than the **physical dose**.*
Nuclear fragments of different charge (Z) and energy have a different biological effectiveness in the destruction of malignant cells ("Relative Biological Effectivess").
Therefore, it is of great importance to correctly model the production of secondary nuclear fragments.

Contributions to the (physical) dose of the fragments of different atomic number

In the case of carbon ions, it was estimated with MC simulations that up to about 40% of the dose in the region between the entrance channel and the Bragg peak is delivered by fragments.
[Böhlen TT, et al. ;Phys Med Biol. (2010). 55:5833–47. doi:10.1088/0031-9155/55/19/014]

Wrongly modelled cross sections would clearly lead to <u>discrepancies in longitudinal and lateral dose distributions</u> between measurements and MC simulations.

Although the total contribution turns out to be satisfactory, there are still significant uncertainties on the contributions of the fragments of different atomic number Z.



Experimental data based on thin targets

Measurements performed with thin targets are the most appropriate for tuning MC models, because the energy of the beam doesn't decrease, and the model parameters can be isolated from transport issues.

Such measurements are particularly appropriate for determining:

- total cross sections ⇒ to predict primary beam attenuation
- partial cross sections
- single and double differential cross sections of specific processes

⇒ to predict yields, angles and energies of secondary particle

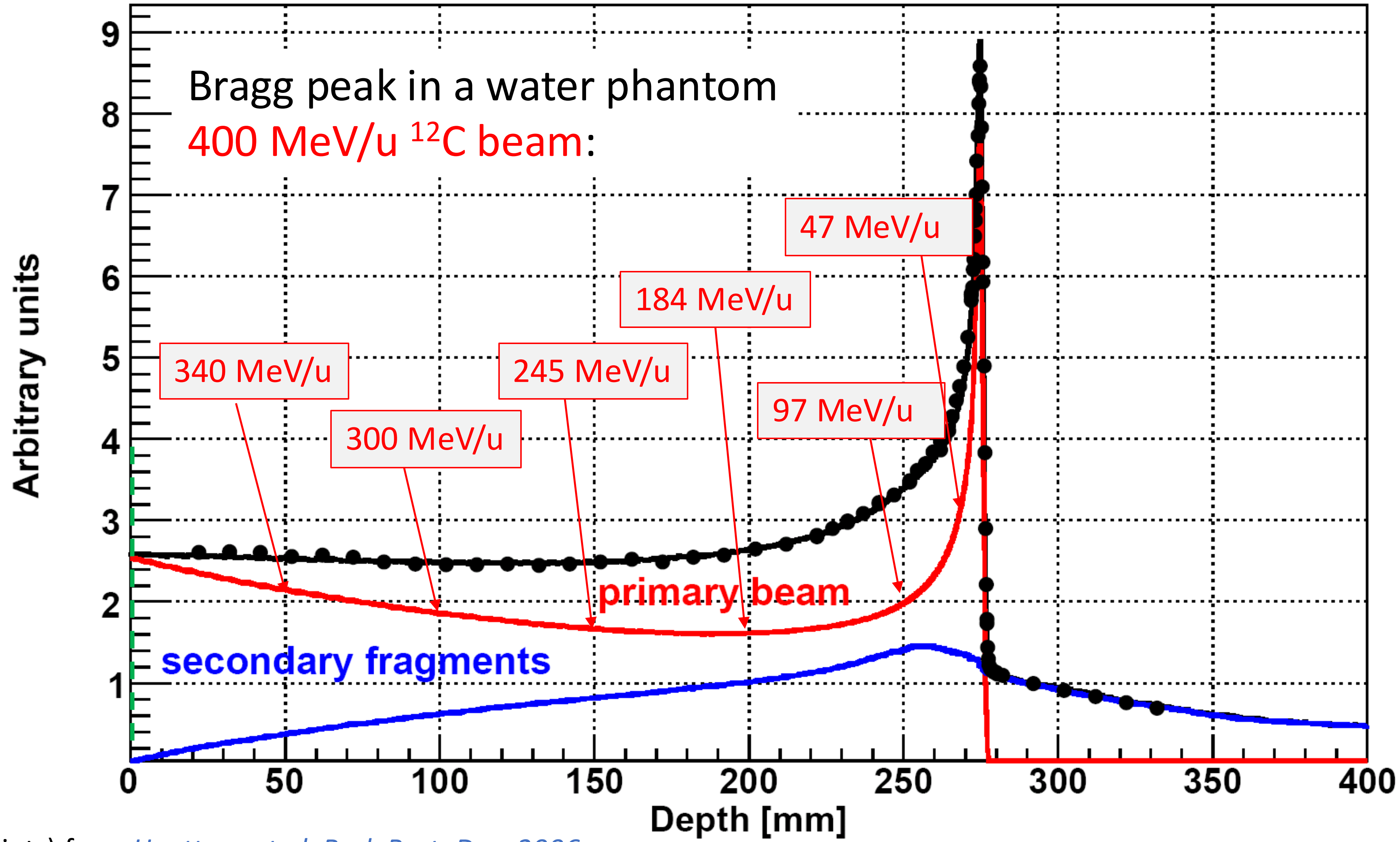
Incident beam	Energy [MeV/u]	Target	Measurement	Reference
^{4}He	70-220	H, C, O, Si	Charge and mass changing cross sections	Horst et al. [36, 35]
^{4}He, C	135, 290, 400	C, Li	Double differential cross section measurements of neutron production	Handbook [53], Chapter 3
^{12}C, ^{20}Ne	83, 200, 250, 300	C, Al, Ca, Fe, Zn, Y, Ag	Total cross section	Kox et al. [38, 39]
^{12}C	30 to 400	Be, C, Al	Total reaction cross section as function of projectile energy	Takechi et al. [76]
^{12}C	200 to 400	Water, polycarbonate	Total and partial charge changing cross sections for production of fragments up to $Z = 4$ at various energies	Toshito et al. [81]
^{12}C	62	C	Double differential cross sections and angular distributions of secondary charged fragments up to 25^o	De Napoli et al. [16]
^{12}C	95	C, CH_2, Al, Al_2O_3, Ti	Double differential cross section for secondary charged fragment production ranging from protons to carbon isotopes	Dudouet et al. [22]
^{12}C	50	C, CH_2, Al, Al_2O_3, Ti, PMMA	Double differential cross section for secondary charged fragment production ranging from protons to carbon isotopes	Divay et al. [20]
^{12}C	115, 153, 221, 281, 353	C, Plastic Scintillator, PMMA	Energy differential cross section at 60^o and 90^o of fragments with $Z = 1$	Mattei et al. [49]

S. Muraro, G. Battistoni, A.C. Kraan, "Challenges in Monte Carlo Simulations as Clinical and Research Tool in Particle Therapy: A Review" Front. Phys., Vol 8, 2020

A non-exhaustive selection of cross section measurements, that have frequently been used for tuning nuclear models in MC simulations in the particle therapy energy range.

The majority of data concern carbon projectiles

Ion therapy with ^{12}C: which energies are of interest?



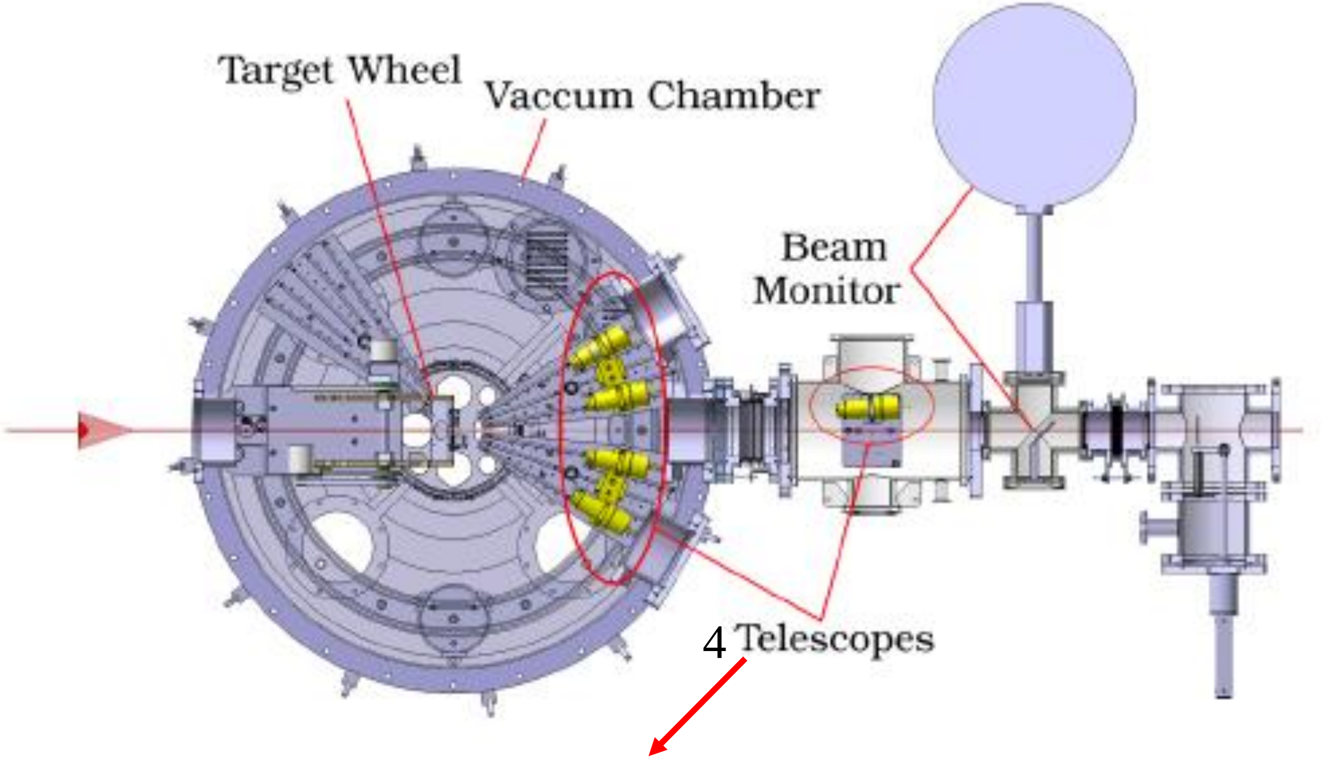
Exp. Data (points) from *Haettner et al, Rad. Prot. Dos. 2006*

Simulation (continuous lines): FLUKA MC

The E600 Experiment at GANIL (Caen)

At present, the most useful data for hadrontherapy on double differential fragmentation cross sections are those obtained at GANIL with a ^{12}C beam on various targets at 95 MeV/u and 50 MeV/u.

Data are available at:
http://hadrontherapy-data.in2p3.fr/index.php



$\Delta E_{thin}/\Delta E_{thick}/E$: 150 µm Si/1000 µm Si/10 cm CsI

Accuracy on angles ~ 1°

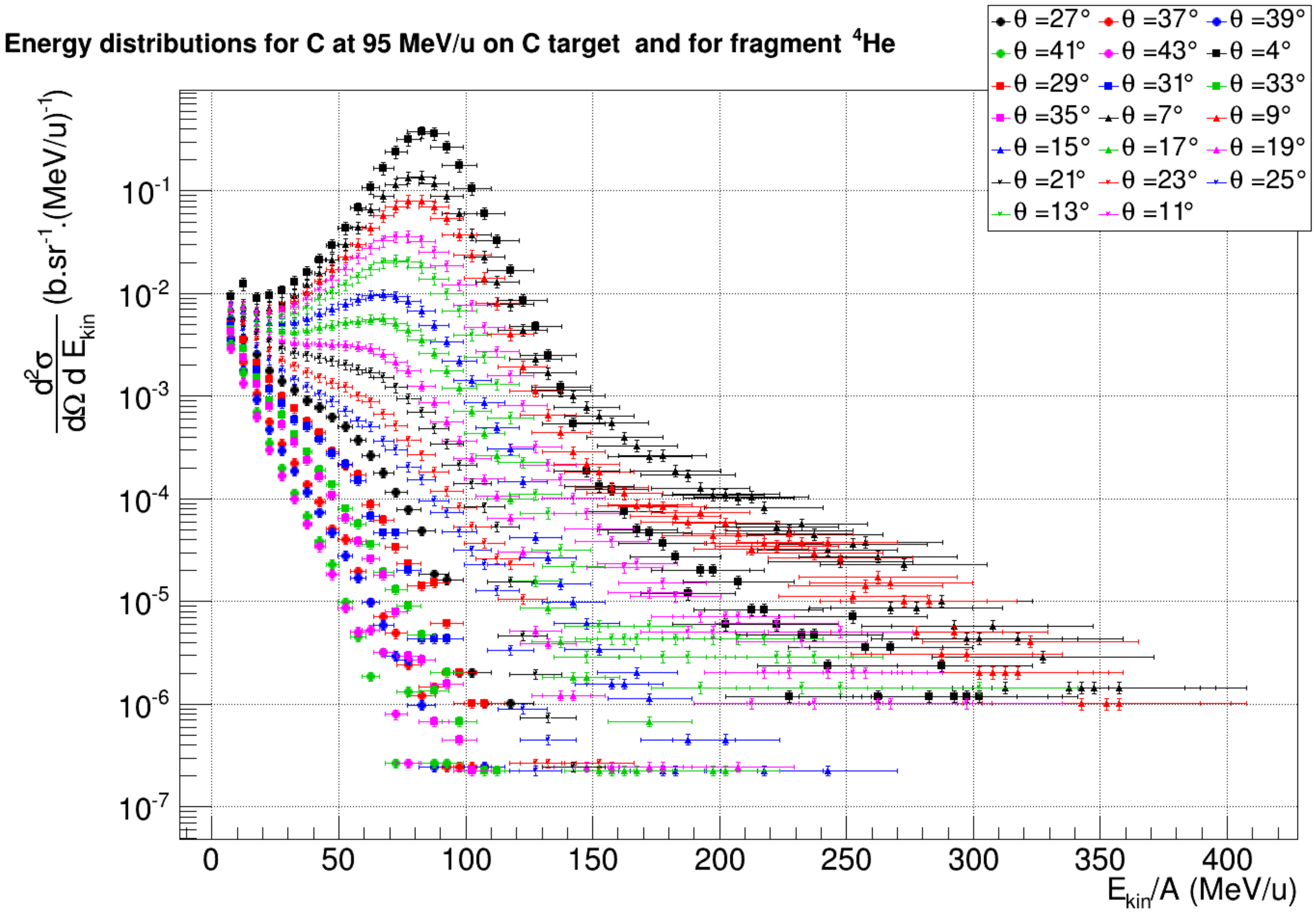
The error on the beam intensity ~5%

Energy resolution ion dependent: from ~20% for protons to 4-5% for C ions

J.Dudouet et al. Phys Rev C 88, 024606 (2013)

C. Divay et al., Phys Rev C 95, 044602 (2017)

An example of E600 data



^{4}He production

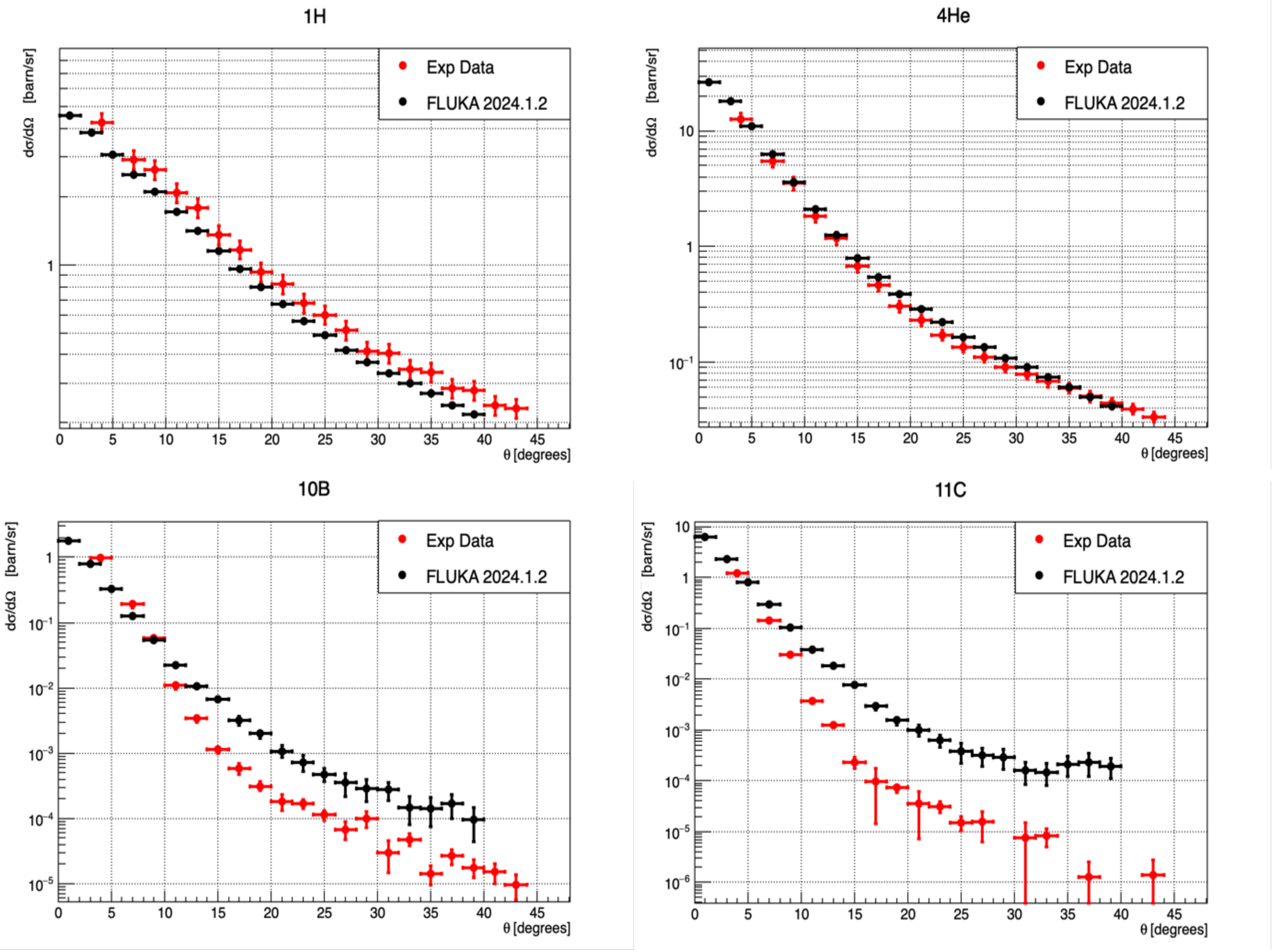
Double differential distribution for ^{12}C @ 95 MeV/u + C

Some comparisons of E600 data at 95 MeV/u with FLUKA MC

At these energies (< 150 MeV/u) the FLUKA MC code implements the BME model of *M. Cavinato, E. Fabrici, E. Gadioli, E. Gadioli-Erba, E. Risi, Boltzmann Master Equation theory of angular distributions in heavy-ion reactions, Nucl. Phys. A 643, 15 (1998)*

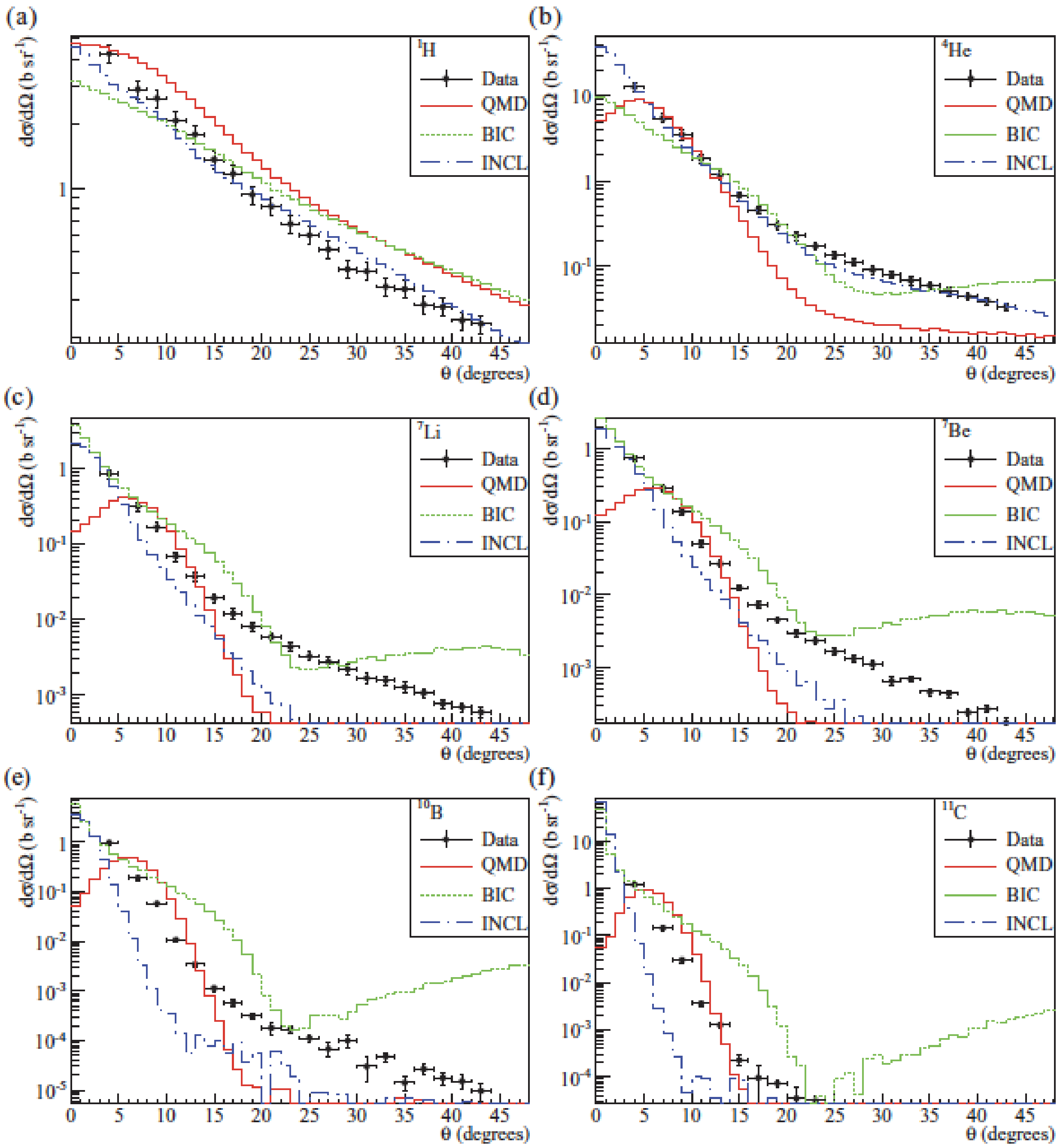
It describes the thermalization of a composite nucleus, created in the complete or incomplete fusion of two ions.

dσ/dΩ with C target



Benchmarking GEANT4 nuclear models for hadron therapy with 95 MeV/nucleon carbon ions

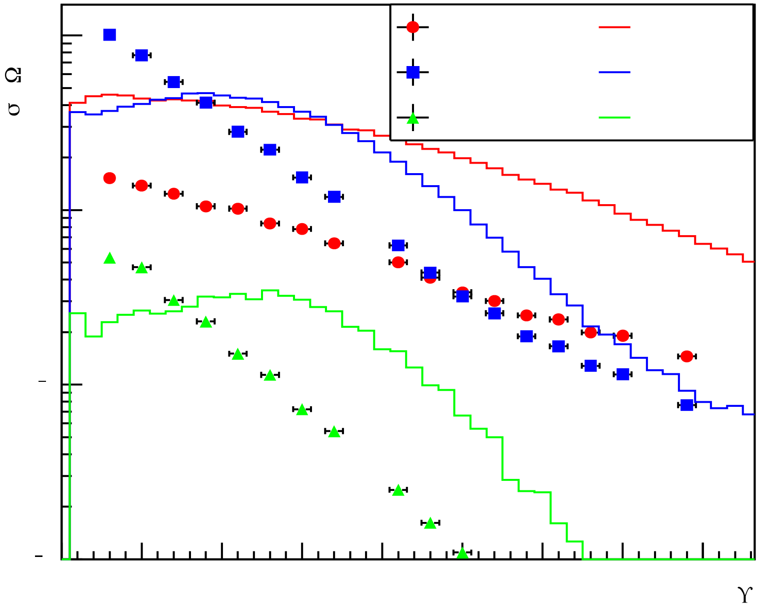
J.Dudouet et al, Phys. Rev C 89, 054616 (2014)



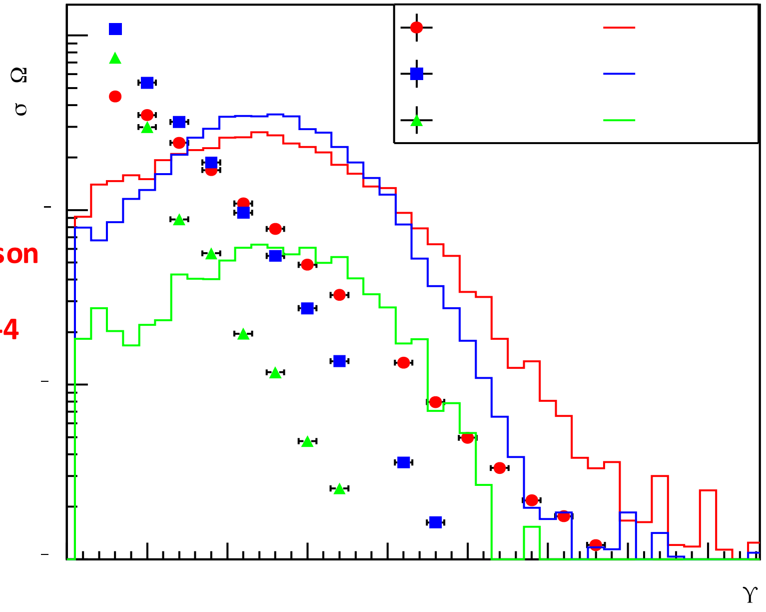
Absolute differential angular cross sections of protons, 4He, 6Li, 7Be, 10B, and 11C for the carbon target.

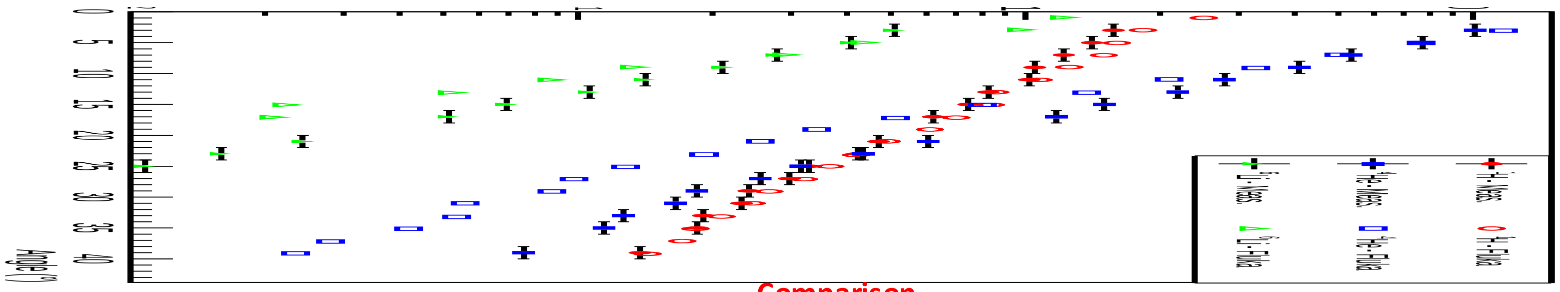
Experimental data: black points.
Histograms: GEANT4 simulations with QMD, BIC, and INCL models coupled to the FBU de-excitation model as indicated in the insets.

dσ/dΩ with C target

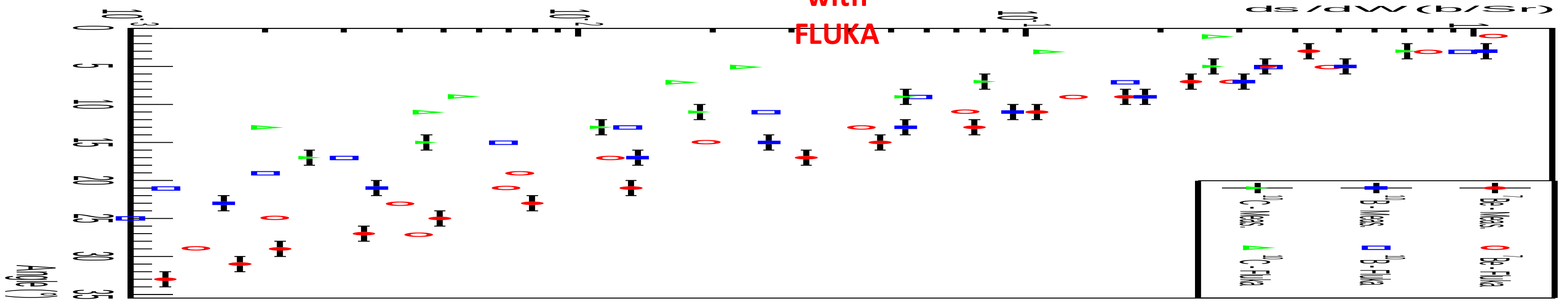


Comparison with GEANT-4





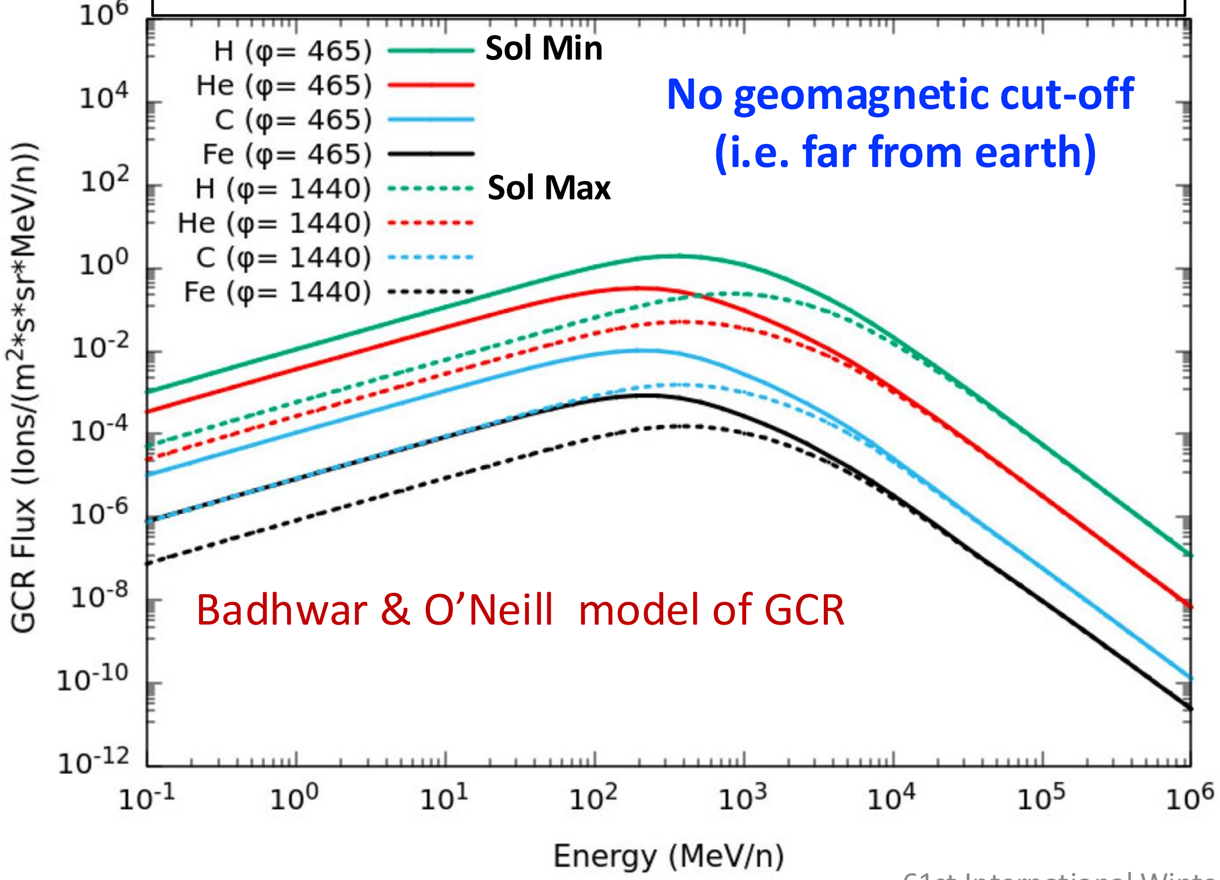
Comparison with FLUKA



Some comparisons of E600 data at 50 MeV/u with FLUKA and GEANT-4 MC

The ions and energies of relevance for space radioprotection

Galactic Cosmic Ray Spectra.
A few Z species for 2 values of solar modulation potential representing typical solar max and solar min conditions



In GCR you can find all nuclei from H to Fe (and also something beyond Fe).
Above a few GeV/nucleon all energy spectra exhibit a power law behaviour ~$E^{-\gamma}$, where γ~2.7 (somewhat depending on nuclear species)

The peak energy for He, C moves from ~200 MeV/u at solar min to ~400 MeV/u at solar max.

From the point of view of radiation protection, solar max is a safer condition with respect to solar min as far as GCR are concerned

Space Weather (2014) 12, 217–224, doi:10.1002/2013SW001025.

Dose contribution from GCR

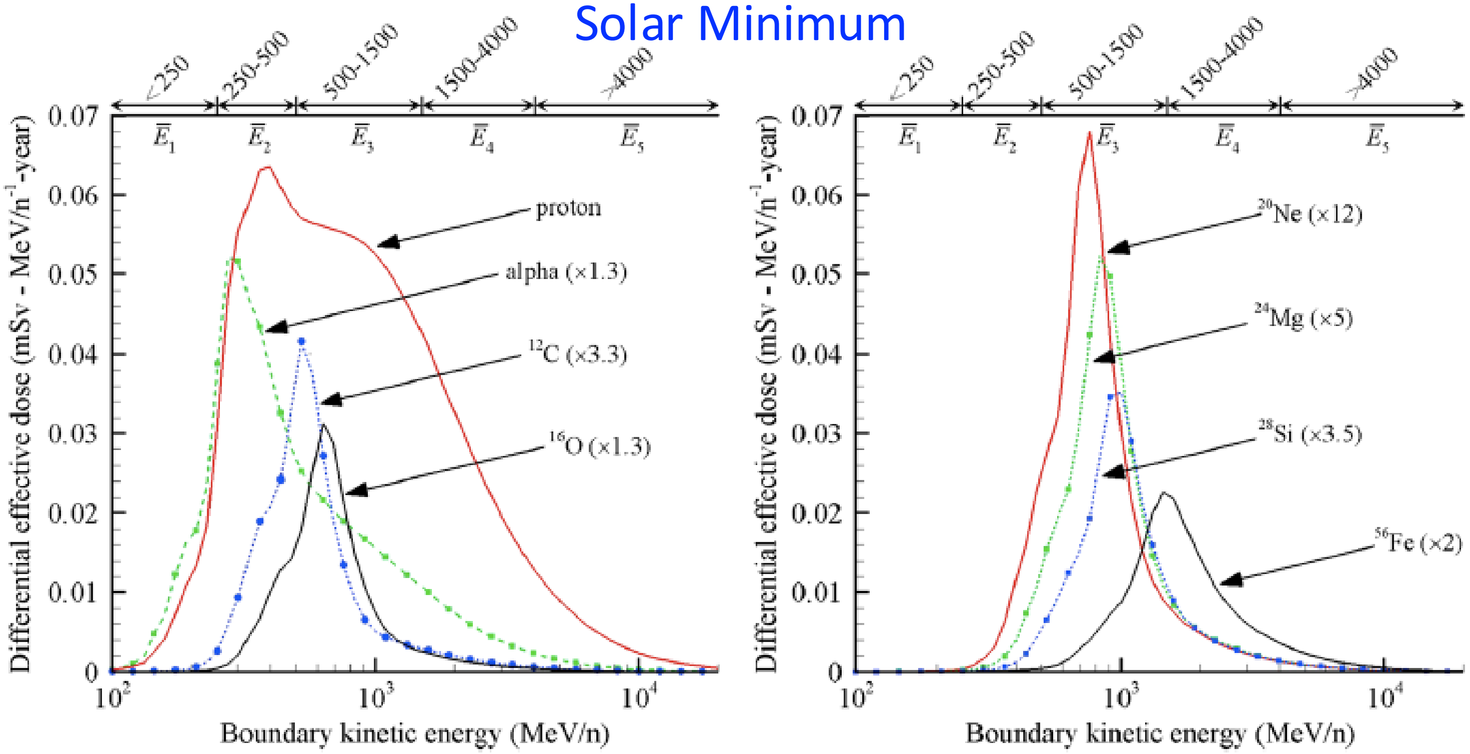
on the basis of BON spectra (2010 update)

GCR environmental models I: Sensitivity analysis for GCR environments

Tony C. Slaba[1] and Steve R. Blattnig[1]

[1]NASA Langley Research Center, Hampton, Virginia, USA

Solar Minimum



Differential effective dose rate as a function of incident kinetic energy behind 20 g/cm^2 of Aluminium exposed to solar minimum conditions described by BON2010 model. Results for specific ions have been scaled to improve plot clarity.

GCR spectrum 90% effective dose > 500 MeV/n

Z=1 and 2 are the most effective

GCR environmental models I: Sensitivity analysis for GCR environments

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Space Weather (2014) 12, 217–224, doi:10.1002/2013SW001025.

E_1: < 250 MeV/n

E_2: 250-500 MeV/n

E_3: 500-1500 MeV/n

E_4: 1500-4000 MeV/n

E_5: > 4000MeV/n

$E_3 + E_4 + E_5 = 86\%$

$E_4 + E_5 = 49\%$

Solar Minimum	$\bar{E}_1$	$\bar{E}_2$	$\bar{E}_3$	$\bar{E}_4$	$\bar{E}_5$	Total
$Z = 1$	1.2	5.4	18.2	18.4	14.8	58.1
$Z = 2$	1.2	2.2	4.1	2.9	1.7	12.2
$Z = 3\text{-}10$	0.0	3.3	3.8	1.3	0.8	9.1
$Z = 11\text{-}20$	0.0	0.2	6.6	2.0	1.1	10.0
$Z = 21\text{-}28$	0.0	0.0	4.7	3.8	2.1	10.6
Totals	2.5	11.1	37.4	28.4	20.5	100.0

Relative contribution (×100) of GCR boundary energy and charge groups to effective dose with **<u>20 g/cm²</u>** aluminium shielding. A value of 0.0 indicates that the relative contribution is less than 0.1%.

For **<u>40 g/cm²</u>**: $E_3 + E_4 + E_5 = 91\%$ $E_4 + E_5 = 57\%$

The 2020 paper by J. Norbury (NASA) et al.
Main remarks and suggestions

Are Further Cross Section Measurements Necessary for Space Radiation Protection or Ion Therapy Applications? Helium Projectiles

John W. Norbury[1], Giuseppe Battistoni[2], Judith Besuglow[3,4], Luca Bocchini[5], Daria Boscolo[6], Alexander Botvina[7], Martha Clowdsley[1], Wouter de Wet[8], Marco Durante[6,9], Martina Giraudo[5], Thomas Haberer[10], Lawrence Heilbronn[11], Felix Horst[6], Michael Krämer[6], Chiara La Tessa[12,13], Francesca Luoni[6,9], Andrea Mairani[10], Silvia Muraro[2], Ryan B. Norman[1], Vincenzo Patera[14], Giovanni Santin[15,16], Christoph Schuy[6], Lembit Sihver[17,18], Tony C. Slaba[1], Nikolai Sobolevsky[7], Albana Topi[6], Uli Weber[6], Charles M. Werneth[1] and Cary Zeitlin[19]*

Front. Phys. 8:565954. doi: 10.3389/fphy.2020.565954

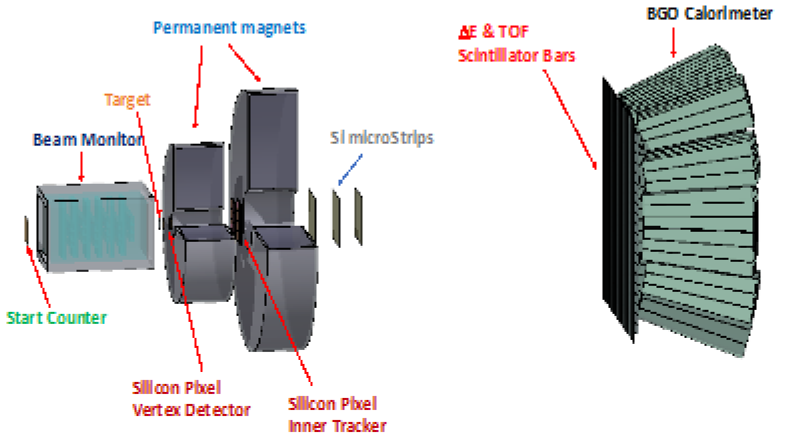
- He data below 3 GeV/n reveals significant problems and defects:

  almost no high-quality double differential data for helium projectiles over the entire energy region

- No double differential cross section data exist for light ion fragment production from O projectiles above the pion threshold (>280 MeV/n).
- Energies > 500 MeV/u have to be considered in any case, better if up to 1500 MeV/u.
- Most important **targets**: H, C, O, Ca, Al, [Fe] (secondary production in shielding is important)
- Priority has to be given to the double differential cross sections for the production of **light fragments**

The FOOT Experiment of INFN

https://indico.mitp.uni-mainz.de/event/380/contributions/4769/attachments/3477/4436/Bormio24Muraro.pdf

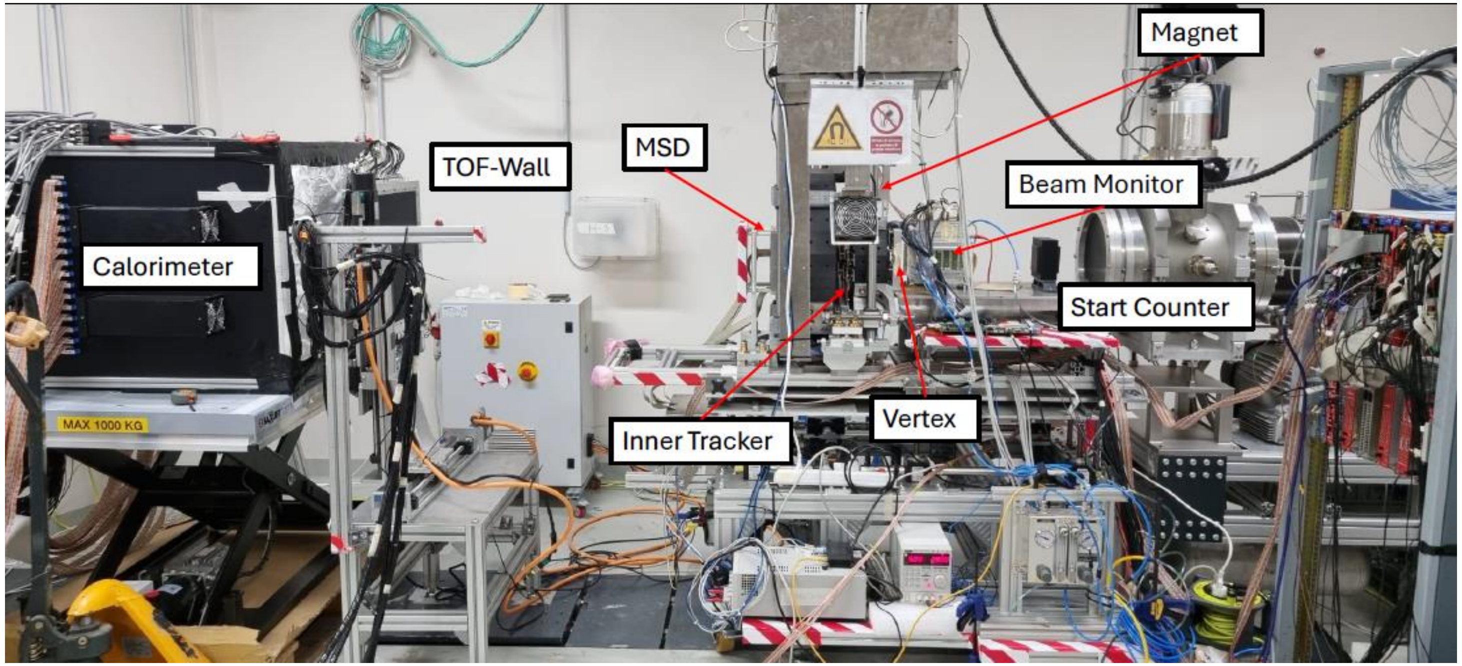


p +
C +
He +
O +

C, O, H, (Si, Al)

$$\frac{d^2\sigma}{d\Omega\, dE_{\mathrm{kin}}}$$

Goal accuracy <5%



"Portable" experiment

Taking data at:

Hadrontherapy

CNAO (C @ 200 – 400 MeV/u)

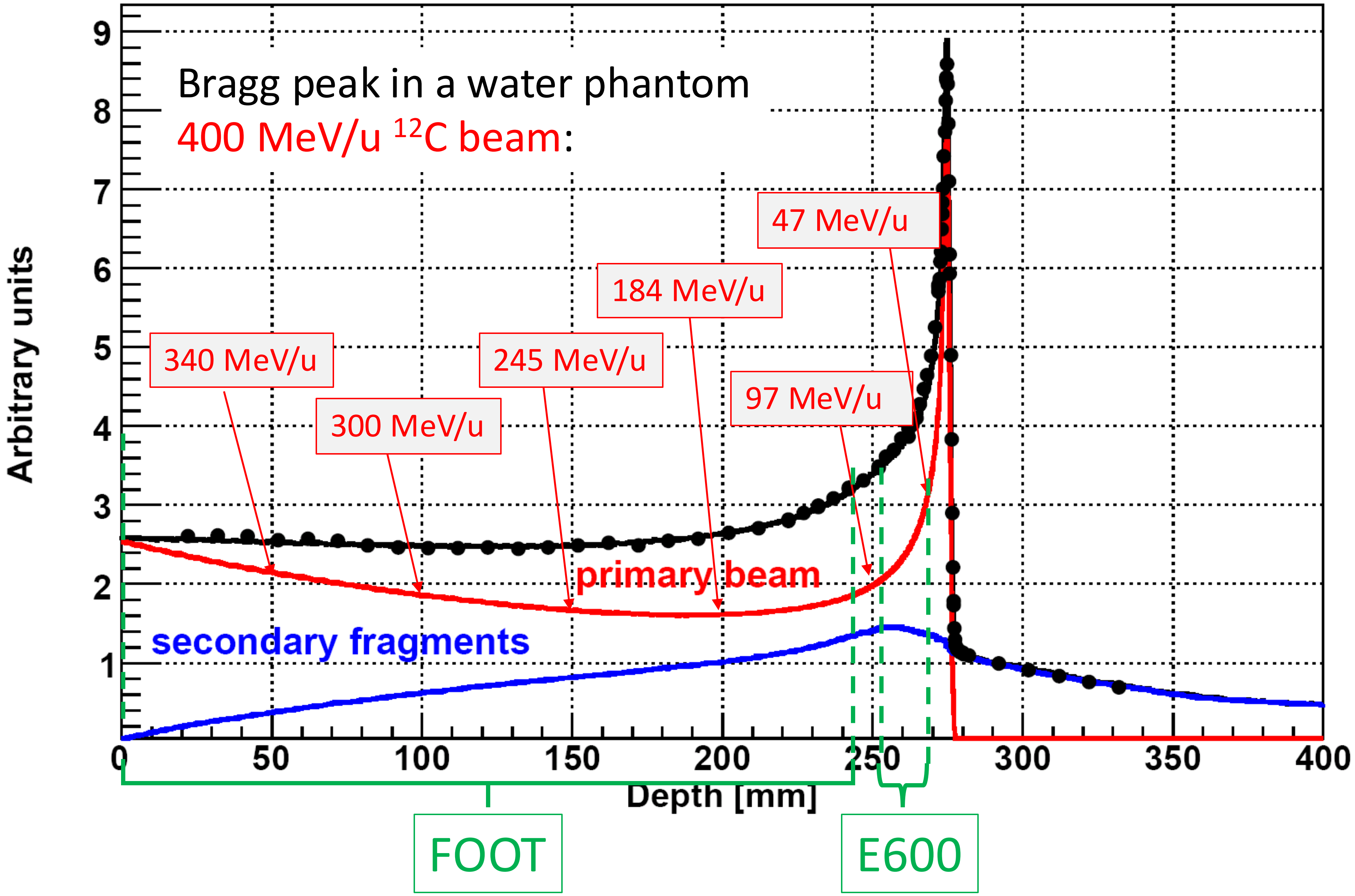
GSI (C, O @ 200 MeV/u)

HIT (He @ 100 – 220 MeV/u)

Space radioprotection

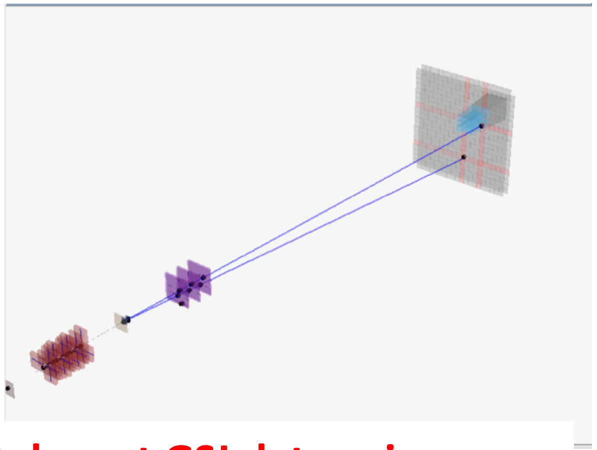
GSI (O @ 700/800 MeV/u)

The contributions of FOOT and E600



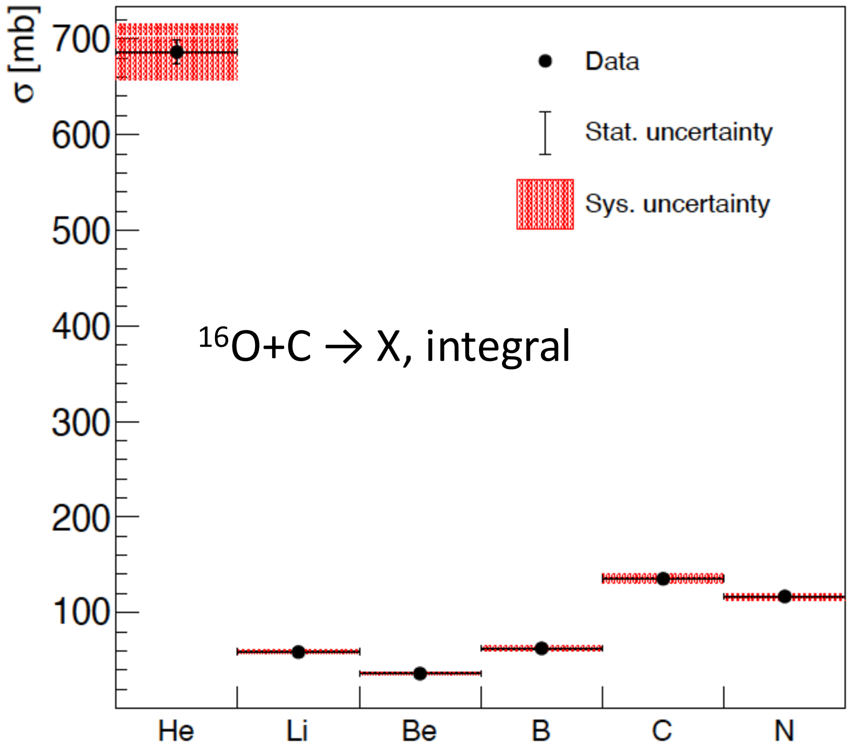
Angular differential and elemental fragmentation cross sections of a 400 MeV/nucleon ^{16}O beam on a graphite target with the FOOT experiment

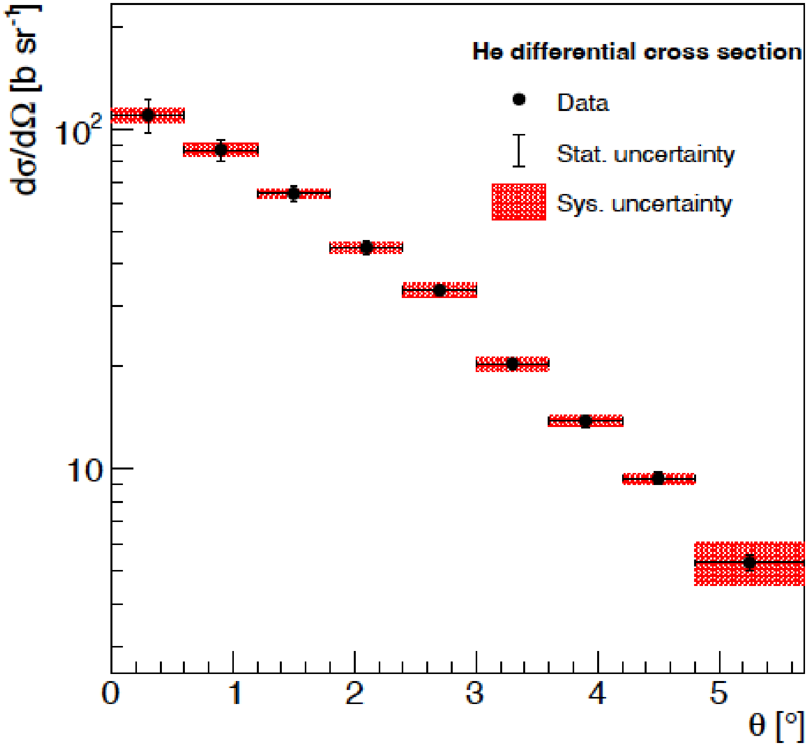
arXiv:2501.00553v1 [nucl-ex] 31 Dec 2024

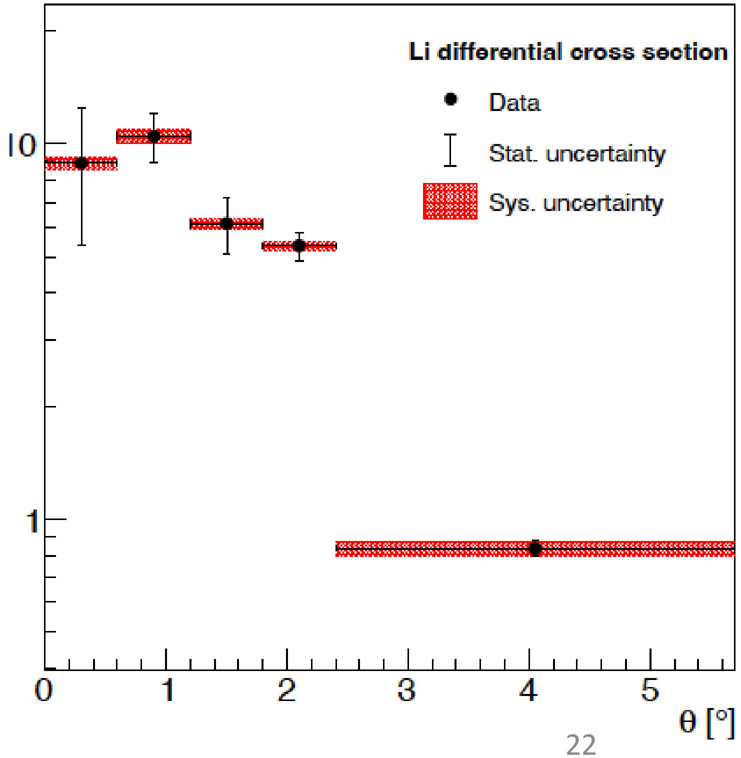


Submitted to Phys. Rev. C

Data taken at GSI data using a reduced set-up in 2021







Cross Section Measurements of Large Angle Fragments Production in the Interaction of Carbon Ion Beams with Thin Targets

arXiv:2501.04392v1 [nucl-ex] 8 Jan 2025

Submitted to Phys. Rev. C

Data taken at CNAO in 2017

^{12}C + C, C9H10, PMMA;

energy: 115-351 MeV/n

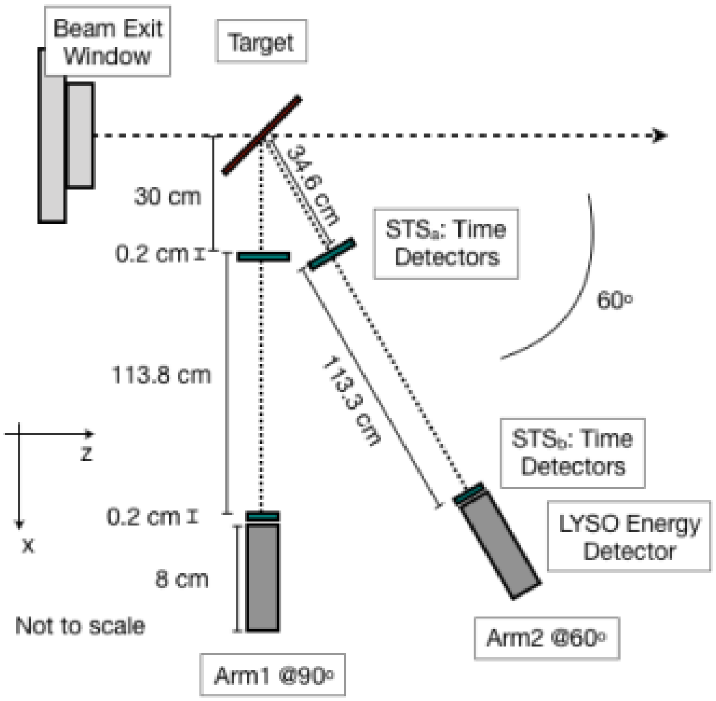
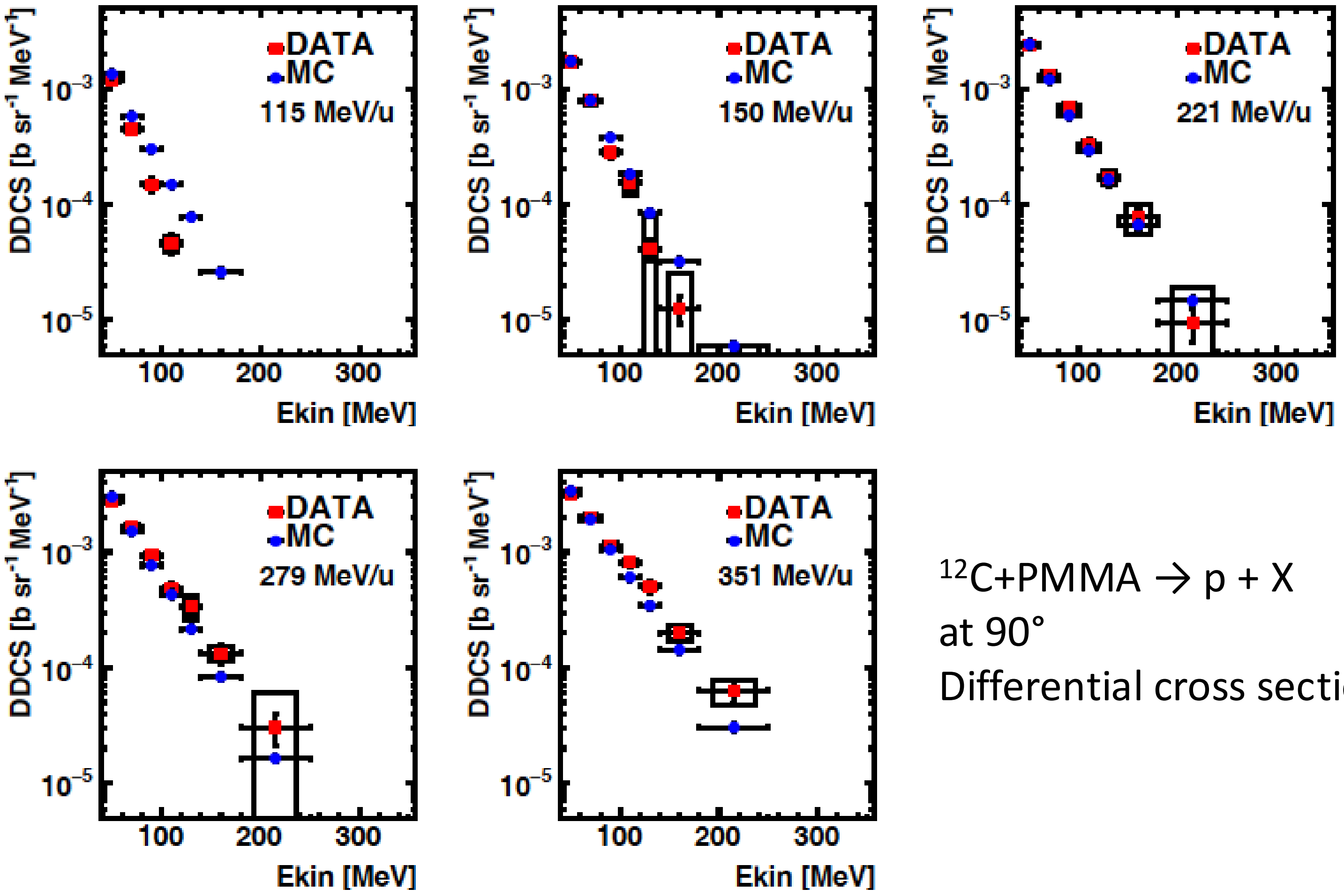


FIG. 1. Sketch of the experimental setup (not to scale)[1].



^{12}C+PMMA → p + X
at 90°
Differential cross sections

Conclusions

The hadron-nucleus and nucleus-nucleus interactions for laboratory energy between 100 MeV/u and about 1 GeV/u play a key role in application of nuclear physics: hadrontherapy and radioprotection on Earth and in space

Inelastic nuclear interactions have a strong impact on dose distribution, due to the build-up of secondary particles. Contributions to the (physical) dose of the various fragments is not satisfactory.

Uncertainties in the MC hadronic models are still very important.
Data are still urgently needed to improve models.

The most useful data for model benchmarking are *double differential cross sections for production of different secondaries on thin targets.*

LACK OF DATA ➔ dedicated experiments are necesssary:

Hadrontherapy:

New experiments are in progress, since most of the existing data are only for C projectiles and at energies < 100 MeV/u

Space radioprotection:

- Energies > 500 MeV/u have to be considered
- Important **Projectiles**: He, C, N, O, Fe. Important **Targets**: H, C, O, Ca, Al, [Fe]

S. Muraro, G. Battistoni, A.C. Kraan,
"Challenges in Monte Carlo Simulations as Clinical and Research Tool in Particle Therapy: A Review"
Front. Phys., Vol 8, 2020

G. Battistoni, A.C. Kraan, S. Muraro,
"Experimental data of nuclear fragmentation for validating Monte Carlo codes: Present availability and lacks"
Chapter 6 of "Monte Carlo in Heavy Charged Particle Therapy",
P. Cirrone and G. Petringa editors, CRC press, 2024

Thank you for the attention

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