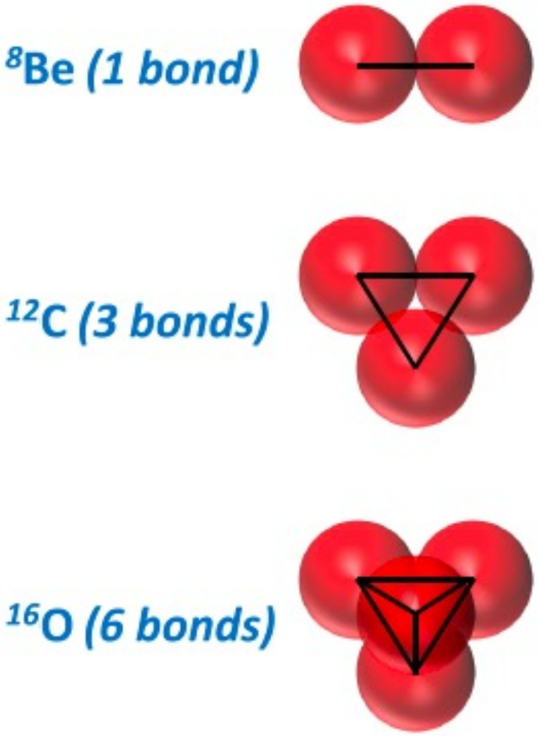
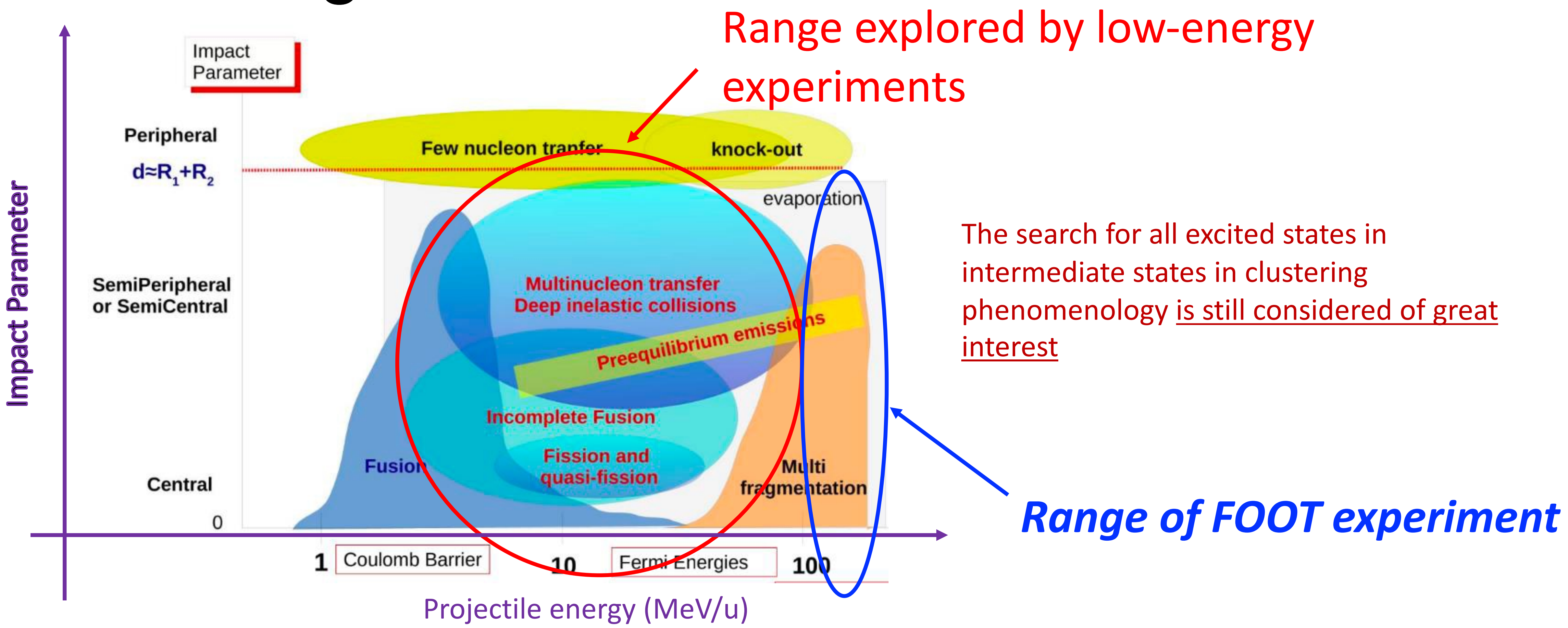
Alpha Clustering Fragmentation: Results at low energy from previous experiments and the status of modelling



Outline

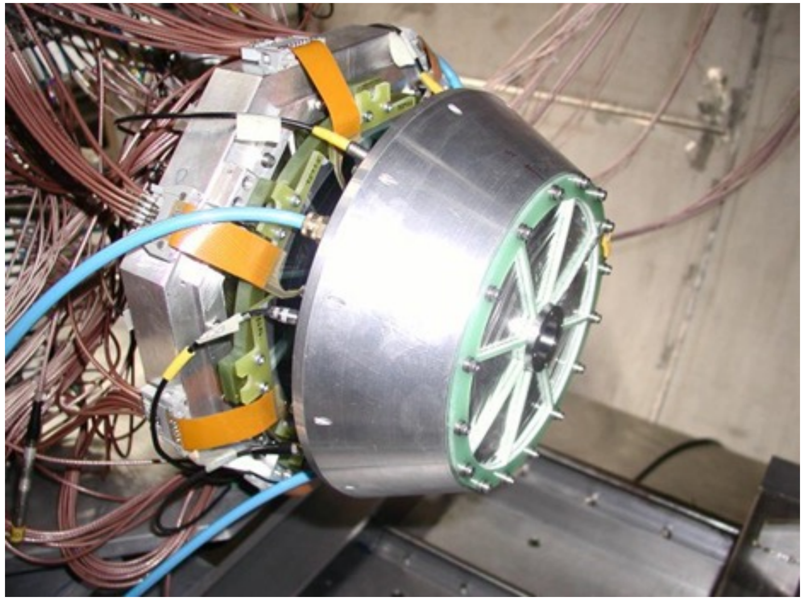
- Results from a few previous INFN experiments operating at Coulomb barrier and Fermi energies about α-conjugated nuclei reactions:
  - GARFIELD: $^{12}C+^{12}C \rightarrow \alpha$'s
  - CHIMERA: $^{40}Ca+^{12}C \rightarrow \alpha$'s
  - FAZIA (most recent analysis): $^{32}S+^{12}C$ and $^{20}Ne+^{12}C \rightarrow \alpha$'s
- Some infos about $^{12}C \rightarrow \alpha$'s fragmentation in Fluka models
- Some temptative conclusions

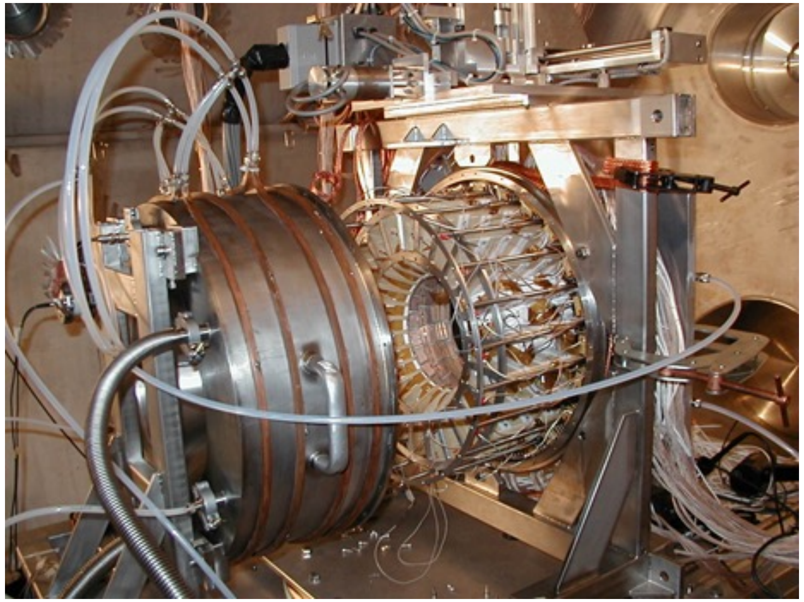
Experimental investigation of nuclear clustering



The search for all excited states in intermediate states in clustering phenomenology <u>is still considered of great interest</u>

GARFIELD at INFN LNL





ΔE-E telescopes made of gaseous microstrip drift chambers (low pressure CF_4)+ CsI(Tl) scintillators (30^o – 150^o in polar angle)

Plus Ring Counter ΔE-E telescopes made of ionization chambers, silicon microstrip and CsI(Tl) scintillators (7^o – 17^o in polar angle)

Operating at Coulomb barrier energies

GARFIELD: example of relevant work

PHYSICAL REVIEW C **87**, 054614 (2013)

~8 MeV/u

α-clustering effects in dissipative $^{12}C + ^{12}C$ reactions at 95 MeV

G. Baiocco,[1,2,*] L. Morelli,[1] F. Gulminelli,[2] M. D'Agostino,[1] M. Bruno,[1] U. Abbondanno,[3] S. Barlini,[4,5] M. Bini,[4,5] S. Carboni,[4,5] G. Casini,[5] M. Cinausero,[6] M. Degerlier,[7] F. Gramegna,[6] V. L. Kravchuk,[6,8] T. Marchi,[6,9] A. Olmi,[5] G. Pasquali,[4,5] S. Piantelli,[5] and Ad. R. Raduta[10]

- Energies close to Coulomb barrier: nuclear molecules showing up as resonances. Seen in $^{12}C+^{12}C$ reactions, where resonaces in $^{12}C+^{12}C \rightarrow ^{24}Mg$ seem to persist up tp ~50 MeV excitation energy
- Cluster correlations can be seen as searching for an excess of cluster production with respect to the prediction of a pure statistical model (phase space)
- Main result: abnormally high branching ratio toward the ($2\alpha,^{16}O^*$) channel with respect to the statistical expectation, which corresponds in part to the population of an intermediate (^{8}Be-$^{16}O^*$) channel

Just to understand what sequential decay means, these are the most frequent channels with 6 α particles in the final state resulting in the statistical phase space approach for $^{12}C + ^{12}C \rightarrow ^{24}Mg^*$:

(i) $^{24}\mathrm{Mg}^* \rightarrow {}^{20}\mathrm{Ne}^* + \alpha \rightarrow {}^{16}\mathrm{O}^* + 2\alpha \rightarrow {}^{12}\mathrm{C}^* + 3\alpha \rightarrow {}^{8}\mathrm{Be} + 4\alpha$

(ii) $^{24}\mathrm{Mg}^* \rightarrow {}^{16}\mathrm{O}^* + {}^{8}\mathrm{Be} \rightarrow {}^{12}\mathrm{C}^* + {}^{8}\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C}^* + 3\alpha \rightarrow {}^{8}\mathrm{Be} + 4\alpha$

(iii) $^{24}\mathrm{Mg}^* \rightarrow {}^{20}\mathrm{Ne}^* + \alpha \rightarrow {}^{12}\mathrm{C}^* + {}^{8}\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C}^* + 3\alpha \rightarrow {}^{8}\mathrm{Be} + 4\alpha$

(iv) $^{24}\mathrm{Mg}^* \rightarrow {}^{20}\mathrm{Ne}^* + \alpha \rightarrow {}^{16}\mathrm{O}^* + 2\alpha \rightarrow {}^{8}\mathrm{Be}{*} + {}^{8}\mathrm{Be} + 2\alpha \rightarrow {}^{8}\mathrm{Be} + 4\alpha$

(v) $^{24}\mathrm{Mg}^* \rightarrow {}^{16}\mathrm{O}^* + {}^{8}\mathrm{Be} \rightarrow {}^{8}\mathrm{Be}{*} + {}^{8}\mathrm{Be} + 2\alpha \rightarrow {}^{8}\mathrm{Be} + 4\alpha$

Chains of 2-body break-ups are favoured by phase space probability

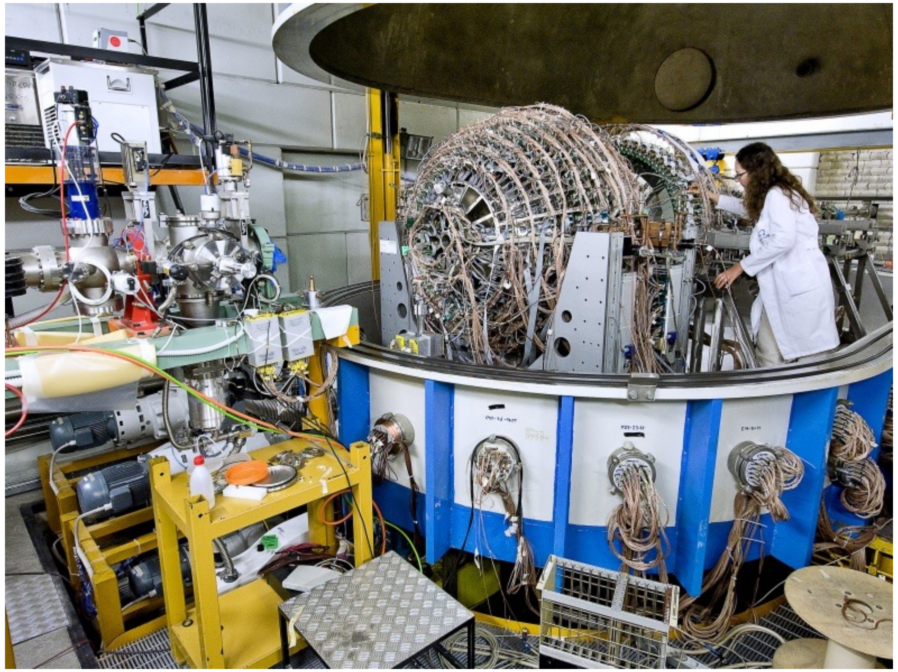
GARFIELD: example of relevant work - 2

PHYSICAL REVIEW C 99, 054610 (2019)

L. Morelli et al. **Full disassembly of excited ^{24}Mg into six α particles**

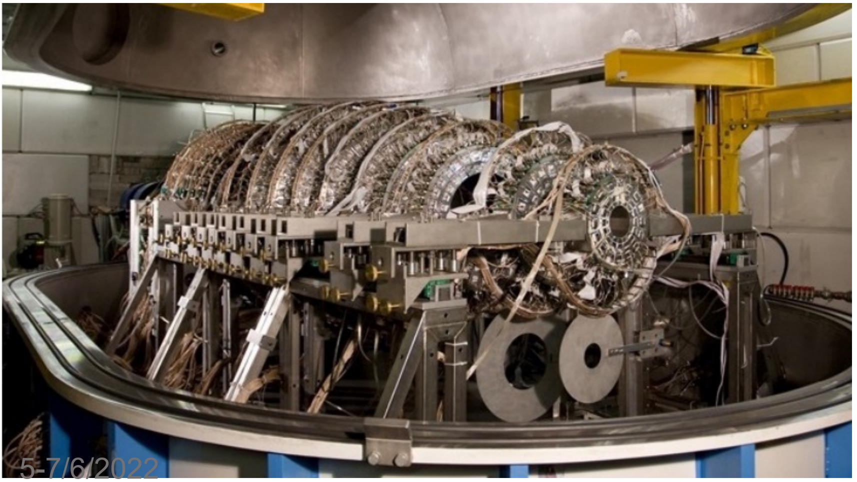
- Both the picture of pure sequential emission of uncorrelated α particles and of pure simultaneous breakup are clearly excluded by their data set.
- Different correlations are evident in the kinematic properties of the detected α particles, suggesting that disassembly occurs through different intermediate states involving $^{12}C*$ and $^{8}Be^{gs}/^{8}Be^{*}$.
- Results indicate that the decay can be decomposed into a first step, where the 3 dominant bodies are $^{12}C*$, $^{8}Be^{gs}/^{8}Be^{*}$, and α, followed by a successive deexcitation of C and Be into α particles.
- The grouping of 3 out of 6 α particles leads to the reconstruction of a $^{12}C*$ more populated at higher excitation energies with respect to the statistical model predictions
- A strong residual correlation is found in the remaining three α particles, showing that ^{8}Be emission also occurs, with ^{8}Be in either its ground or first excited state.

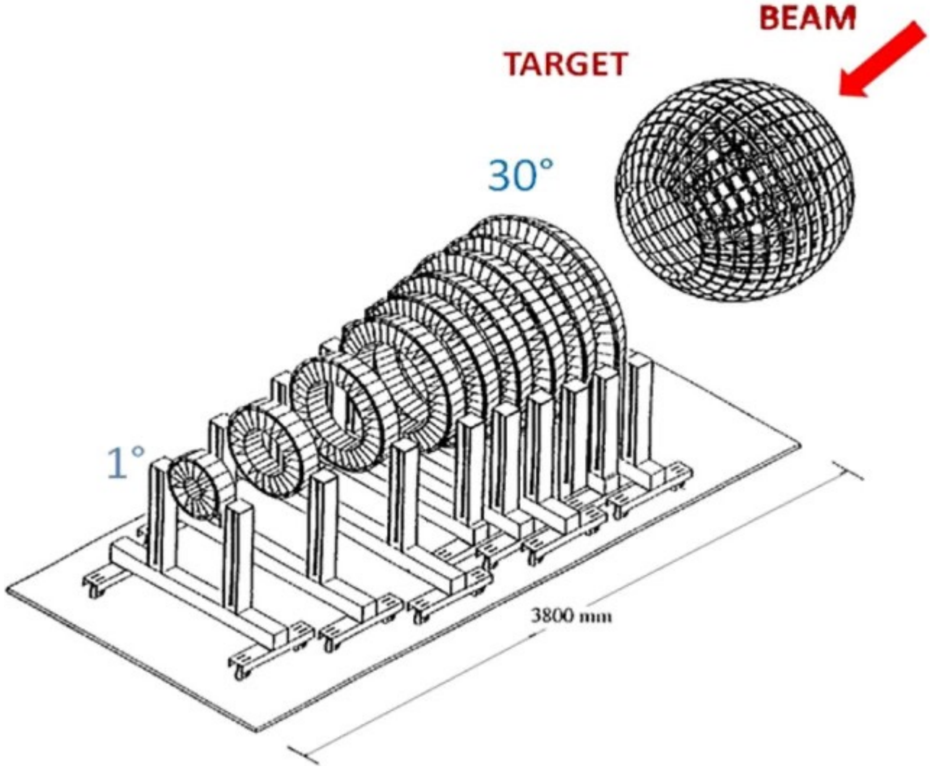
CHIMERA at INFN LNS



1192 telescopes made of ΔE silicon detectors 200–300 μm thick (depending on polar angle) and CsI(Tl) stopping detectors.

They are mounted on 35 rings covering 94% of the solid angle, with polar angle ranging from 1^{o} to 176^{o}.





Operating at Fermi energies

CHIMERA: example of relevant work

Physics Letters B 755 (2016) 475–480

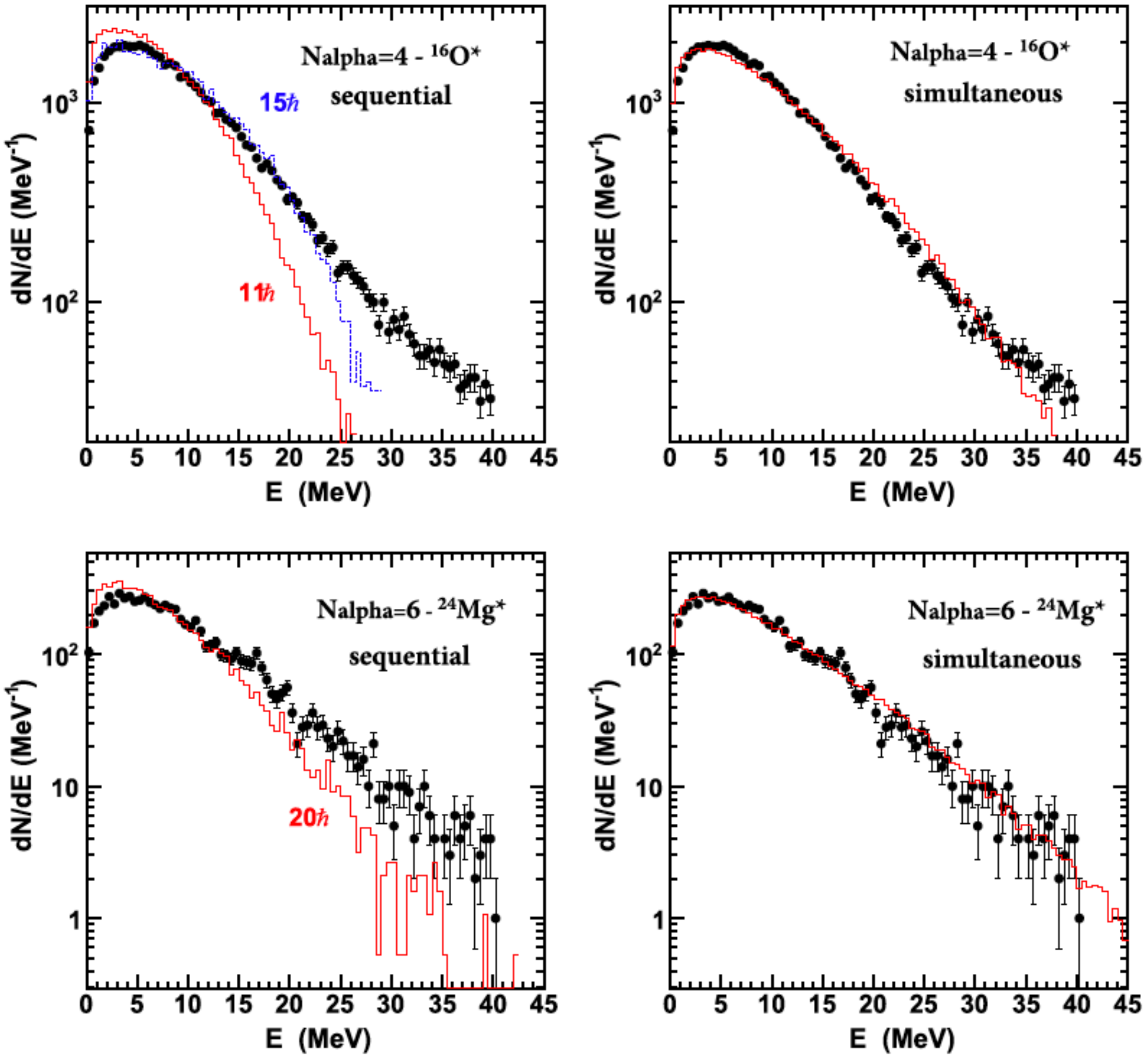
Probing clustering in excited alpha-conjugate nuclei

B. Borderie[a,*], Ad.R. Raduta[a,b], G. Ademard[a], M.F. Rivet[a,1], E. De Filippo[c], E. Geraci[c,d,e], N. Le Neindre[a,f], R. Alba[g], F. Amorini[g], G. Cardella[c], M. Chatterjee[h], D. Guinet[i], P. Lautesse[i], E. La Guidara[c,j], G. Lanzalone[g,k], G. Lanzano[c,1], I. Lombardo[g,l], O. Lopez[f], C. Maiolino[g], A. Pagano[c], M. Papa[c], S. Pirrone[c], G. Politi[c,d], F. Porto[g,d], F. Rizzo[g,d], P. Russotto[g,d], J.P. Wieleczko[m]

Study of α-emission sources in the fragmentation of quasi-projectiles from the nuclear reaction ^{40}Ca+^{12}C at 25 MeV/u

Comparisons with models of sequential (i.e. statistical = phase space) and simultaneous decays (i.e. clustering)

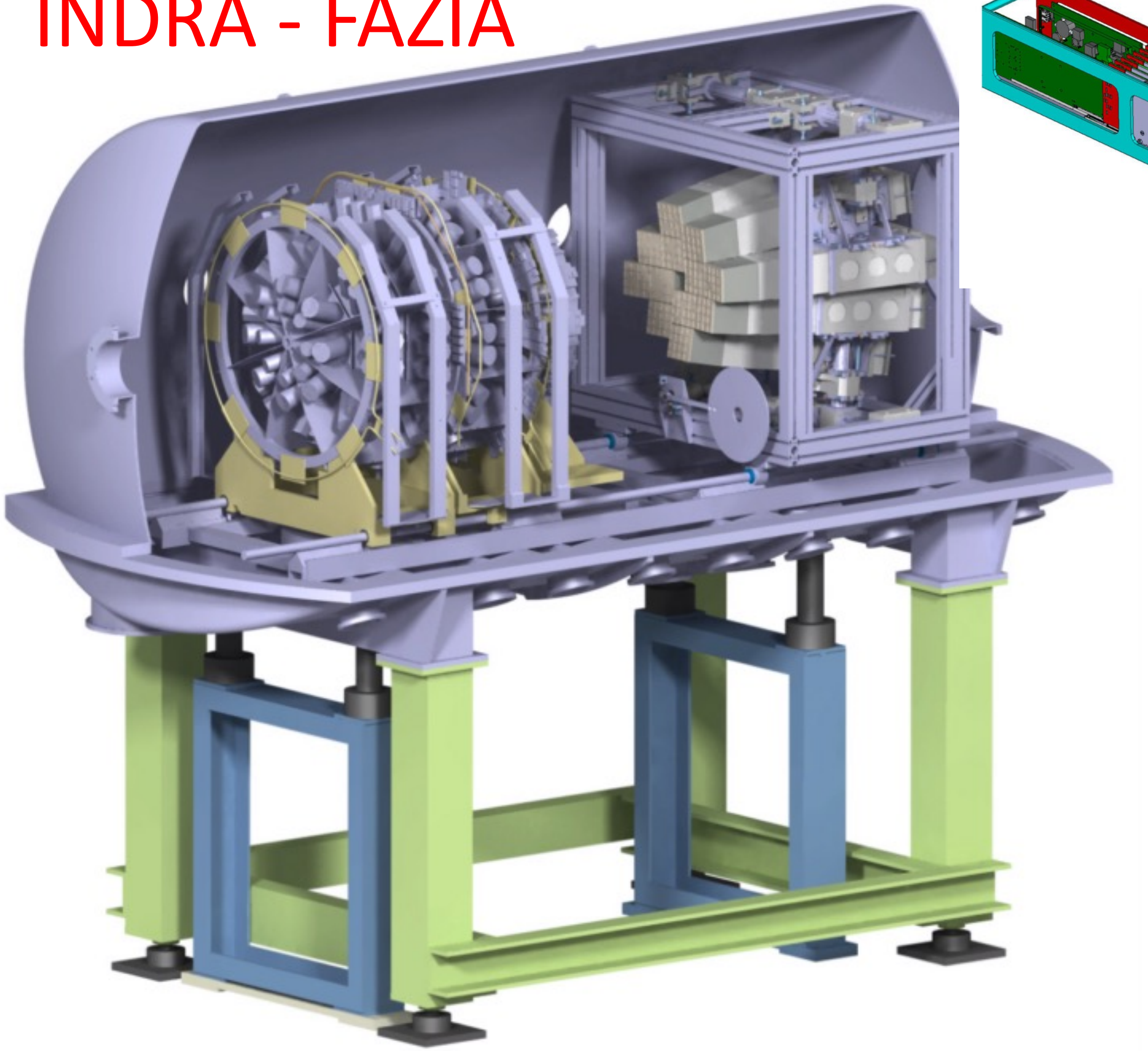
Evidence in favour of α-particle clustering from excited ^{16}O, ^{20}Ne and ^{24}Mg

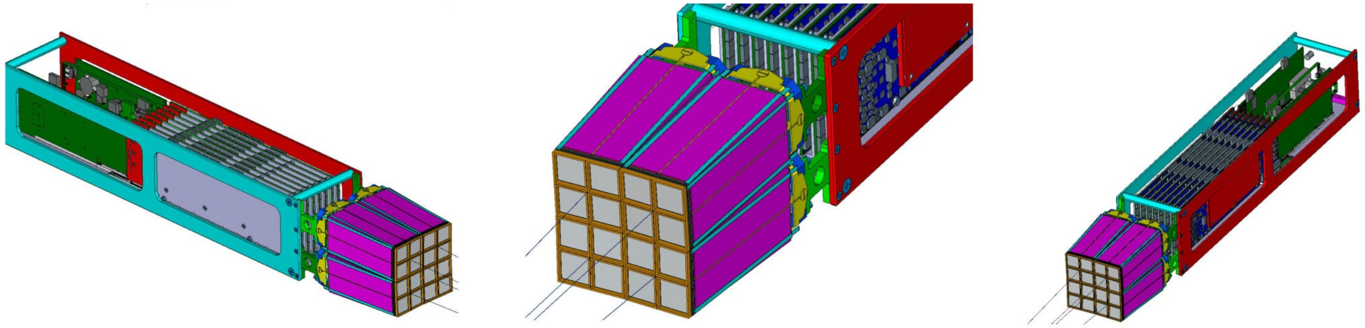


Particle spectra from $N\alpha$ sources: $^{16}O^*$, top and $^{24}Mg^*$, bottom;

FAZIA

INDRA - FAZIA





4 blocks 80 cm from target

Each block has 16 3-layers Si-Si-CsI(Tl) ΔE-E telescopes (and pulse shape analysis)

Each telescope has 2x2 cm^2 area

Preprint March 2023

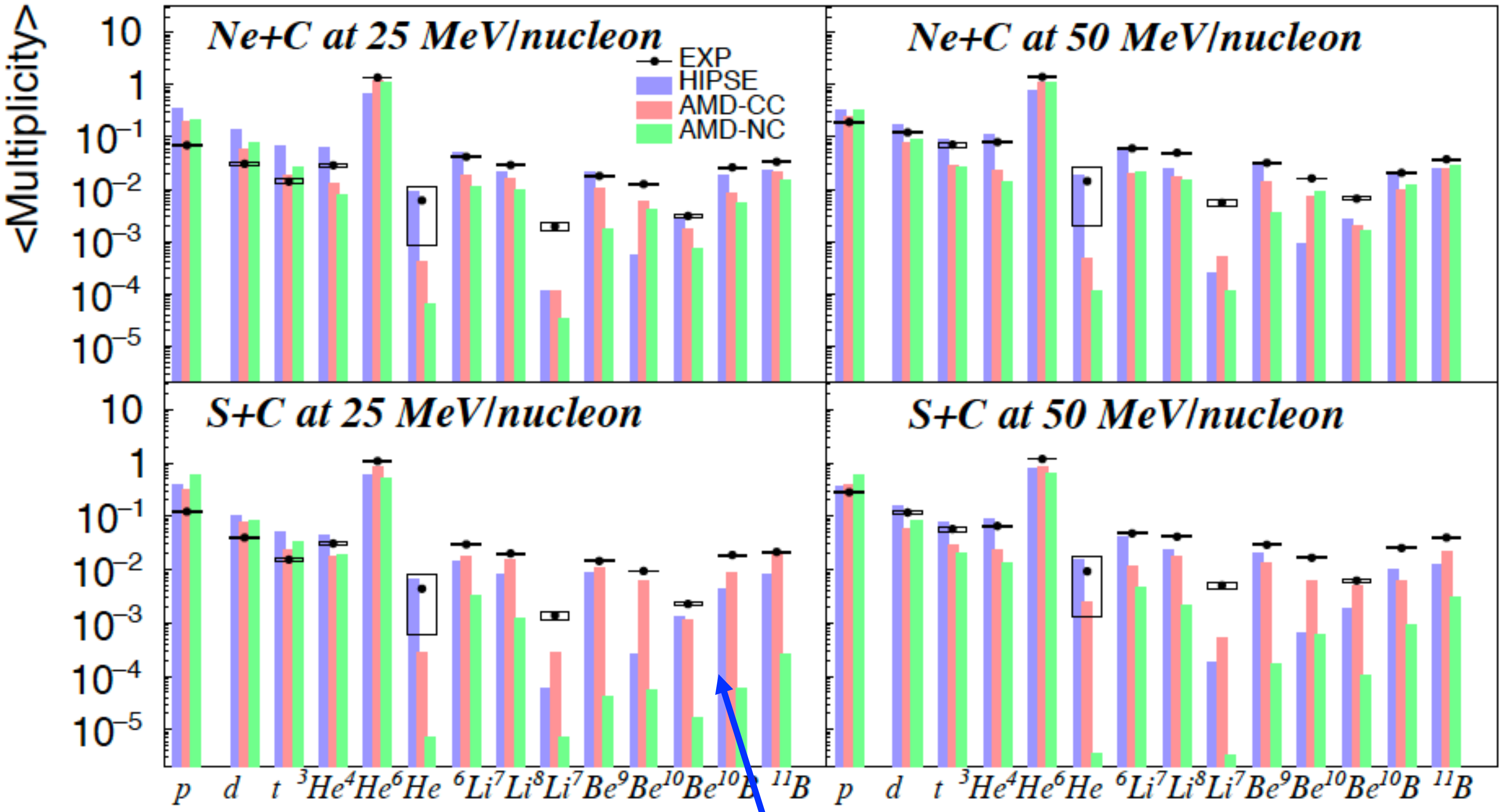
C. Frosin et. al. **"Examination of cluster production in excited light systems at Fermi energies from new experimental data and comparison with transport model calculations"** (arXiv:2303.17390v1 [nucl-ex] 30 Mar 2023)

$^{32}S+^{12}C$ and $^{20}Ne+^{12}C$ at 25 and 50 MeV/u: exploring Fermi Energy region up to the onset of the regime explored by FOOT

Comparison with statistical (phase space) model and AMD(*) model with or without clustering inclusion

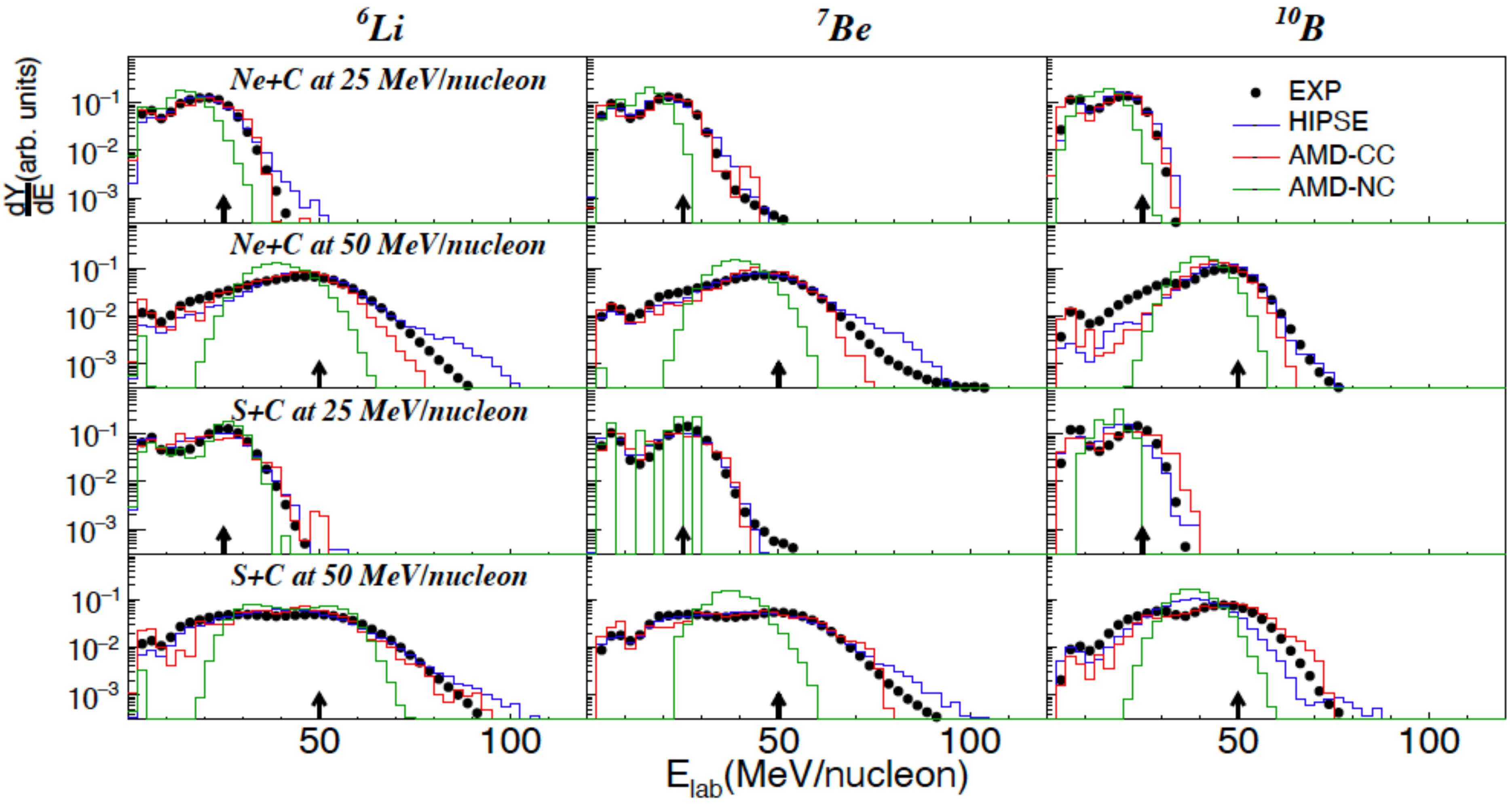
Quoting from the paper: *"The interest in light ion reactions at Fermi energy and beyond has also been renewed due to hadrontherapy, where the physical dose deposition is significantly affected by the inelastic interactions and fragmentation of ions along the penetration path in human tissues. In these cases, the ability of appropriate Monte Carlo codes to reproduce the differential yield of charged fragments is fundamental for treatment planning"*

(*) AMD = Antisymmetrized Molecular Dynamics, see G.B.'s talk at Strasbourg meeting

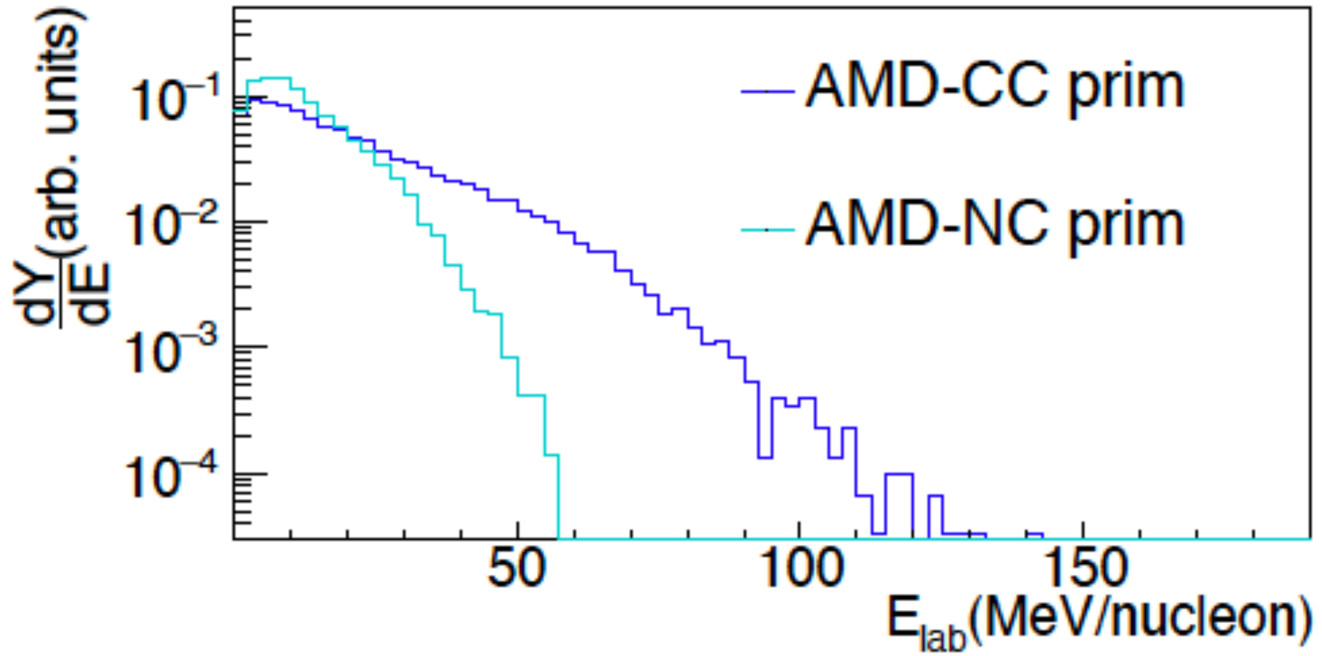


Proton and cluster multiplicities (Z<6), after the secondary decay, in ^{20}Ne+^{12}C (upper panels) and ^{32}S+^{12}C (bottom panels) reactions.

Notice the strong difference in predictions between AMD-NC and AMD-CC



2<Z≤5 energy distribution for $^{20}Ne+^{12}C$ and $^{32}S+^{12}C$. Spectra are normalized to the integral for a better shape comparison.



AMD calculations. Proton energy distribution for
$^{20}Ne+^{12}C$ at 25 MeV/nucleon in 4π with cluster and no cluster

Main conclusions from INDRA-FAZIA

1) Charge and velocity distributions of all measured reaction products are rather well described by both Phase Space and AMD models and the evolution of these observables with the system mass and beam energy is nicely reproduced.

2) At 50 MeV/nucleon the inclusion of the cluster option in AMD produces a variation of up to around a factor 100 in the yield of Be and B isotopes.

3) Accordingly, the use of the cluster option depletes the reservoir of free nucleons and tends on average to produce less excited sources: part of the initial energy is carried out as the kinetic energy of emitted nucleons and clusters.

4) On average, one observes more energetic protons/light clusters in the presence of clustering than without, due to energy and momentum conservation in the N-N and N-cluster collisions.

5) As observed also for the C+C reaction the inclusion of the clustering improves the model

Points 2, 3 and 4 could have relevance from the RBE point of view

How does FLUKA introduce clustering?

Target nucleus description (density, Fermi motion, etc)

↓

Glauber-Gribov cascade with formation zone

↓

(Generalized) IntraNuclear cascade

↓

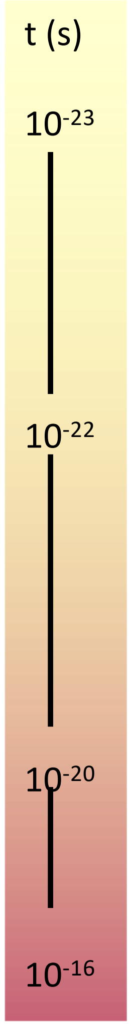
Preequilibrium stage with current exciton configuration and excitation energy
(all non-nucleons emitted/decayed + all nucleons below 30-100 MeV)

↓

Here → **Evaporation/Fragmentation/Fission model**

↓

γ deexcitation



For nuclei with A<18 a Fermi Break-up model is used

Clustering in FLUKA MC - 1

- Break-up is activated in the nuclear environment as one of the last stages of the nuclear interaction, at the end of pre-equilibrium.

- **Fermi break-up (*)** is activated for all nuclei (both primary and residual) with A<18. It provides for ~50000 combinations and a maximum of 6 final products. It is triggered in FLUKA regardless of the model that handled the direct interaction, be it BME or rQMD.

- Instead, for A>17, a statistical evaporation model is triggered that does not explicitly predict α correlations due to clustering. This implies that *the simulation with FLUKA of interactions with α-conjugated heavy nuclei probably does not correctly match what happens in reality from the clustering point of view* *(for example, we have considered the case of ^{40}Ca for the TOFpRad PRIN project)*

(*) Originally conceived for "high energy" proton-proton collisions, E. Fermi, Prog. Theor. Phys. Vol. 5, no.4 (1950), p. 570

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Clustering in FLUKA MC - 2

- The clustering mechanism implemented in FLUKA's Fermi break-up considers the creation of intermediate states (e.g., ^{8}Be) with a number of energy levels known from nuclear databases.

- The probability of passing through intermediate states depends on the excitation energy available in the reaction. For example, fragmentation of ^{12}C into 3 α's can also occur directly for very high excitation energies. Thus there is an energy dependence, but not directly related to the energy of the projectile: the excitation energy depends, for example, on the impact parameter, the number of nucleons involved, etc.

- Peripheral interactions (high value of the impact parameter) are the most frequent, resulting in low values of the excitation energy. In this case, the 2-step process is favoured, for example: $^{12}\mathrm{C} \rightarrow {}^{8}\mathrm{Be} + \alpha \rightarrow 3\ \alpha$

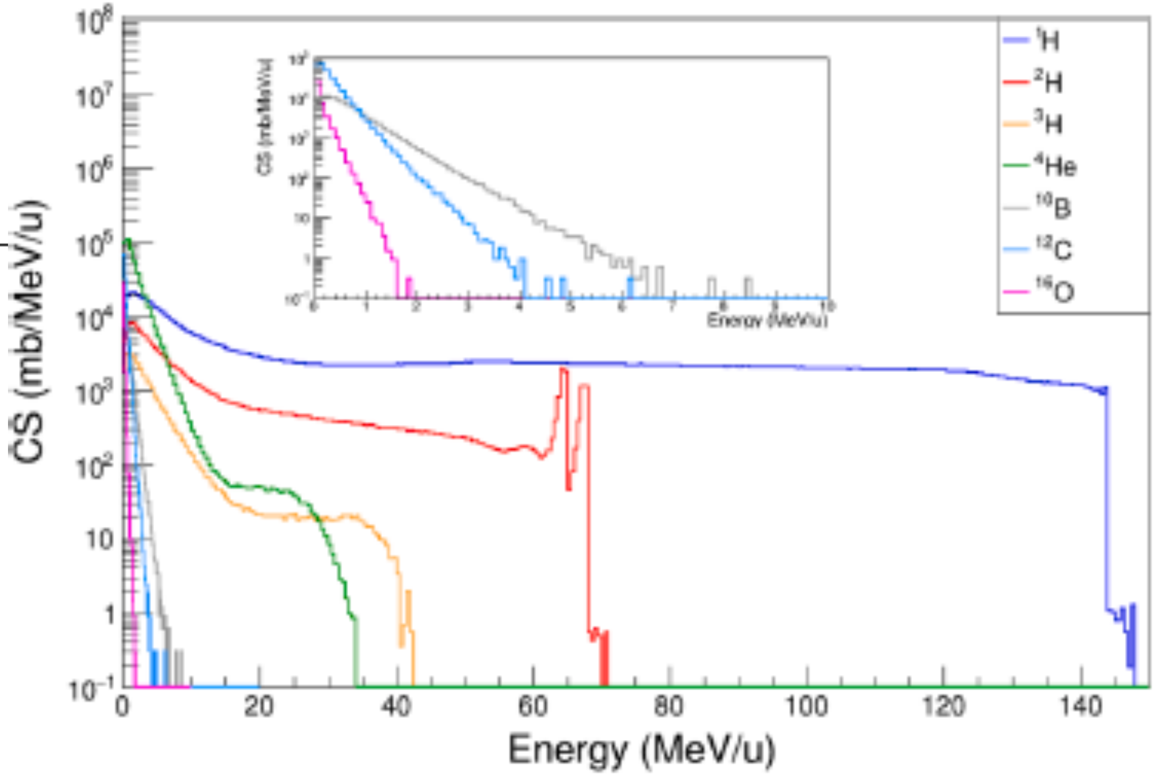
The weight of α's in biological-effective dose

Physica Medica 80 (2020) 342–346

FLUKA simulation of target fragmentation in proton therapy

A. Embriaco [a,*], A. Attili [b], E.V. Bellinzona [c,d], Y. Dong [a,e], L. Grzanka [f], I. Mattei [a], S. Muraro [a], E. Scifoni [d], F. Tommasino [c,d], S.M. Valle [a], G. Battistoni [a,d]

[a] Istituto Nazionale di Fisica Nucleare, Sezione di Milano, Italy
[b] Istituto Nazionale di Fisica Nucleare, Sezione di Roma Tre, Italy
[c] Universitá degli studi di Trento, Italy
[d] TIFPA Trento Institute for Fundamental Physics and Application, Italy
[e] Universitá degli studi di Milano, Italy
[f] Institute of Nuclear Physics, Kraków, Poland



The weight of α's in biological-effective dose

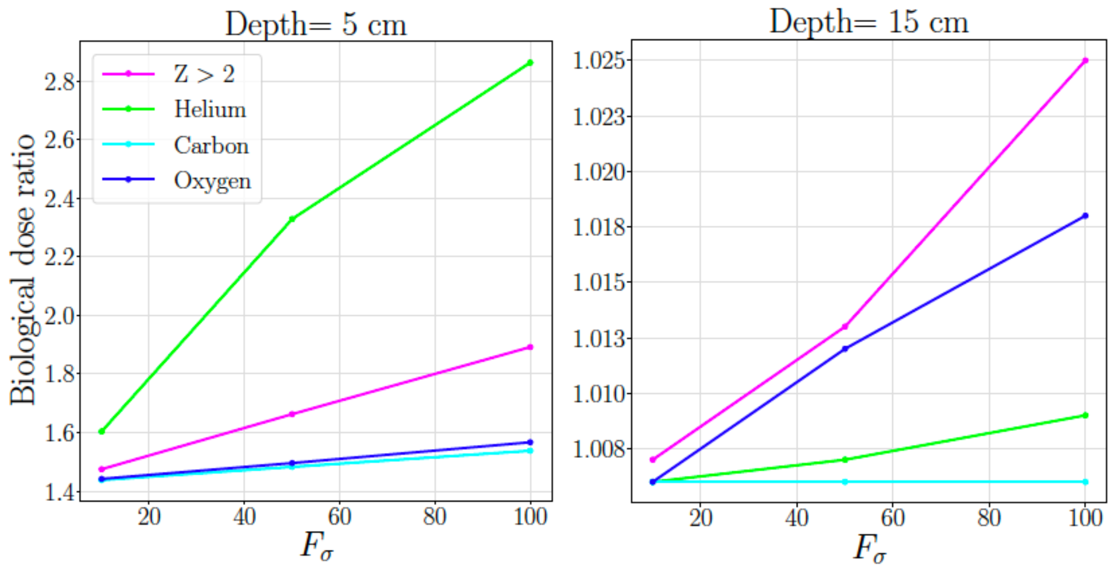
Cancers **2021**, *13*, 4768. https://doi.org/10.3390/cancers13194768

TOPAS (G4) together with TRiP calculations

Article

Biological Impact of Target Fragments on Proton Treatment Plans: An Analysis Based on the Current Cross-Section Data and a Full Mixed Field Approach

Elettra Valentina Bellinzona [1,2], Leszek Grzanka [3], Andrea Attili [4], Francesco Tommasino [1,2], Thomas Friedrich [5], Michael Krämer [5], Michael Scholz [5], Giuseppe Battistoni [2], Alessia Embriaco [6], Davide Chiappara [7,†], Giuseppe A. P. Cirrone [7], Giada Petringa [7,‡], Marco Durante [5,8] and Er



(A) **(B)**

Figure A2. Ratio between the biological dose obtained by considering a modified cross-section for (separately) Helium, Carbon, Oxygen, $Z > 2$ and the biological dose of primary protons, at 50 mm depth (A), 150 mm (B) as a function of cross-section scaling factor $F_\sigma = 10, 50$ and $F_\sigma = 100$ as a limit calculation to give an idea of the asymptotic behaviour. The legend stands for both panels.

These works conffirmed the relevant role of Z=2 in biological effectiveness

My only bit of criticism with respsect to the this work (which I signed):

TRiP considers production of secondaries in an inclusive way. There is no distinction between $^{12}C \rightarrow \alpha + X$ and exclusive channels like $^{12}C \rightarrow 3\alpha$

The weight of α's in biological-effective dose

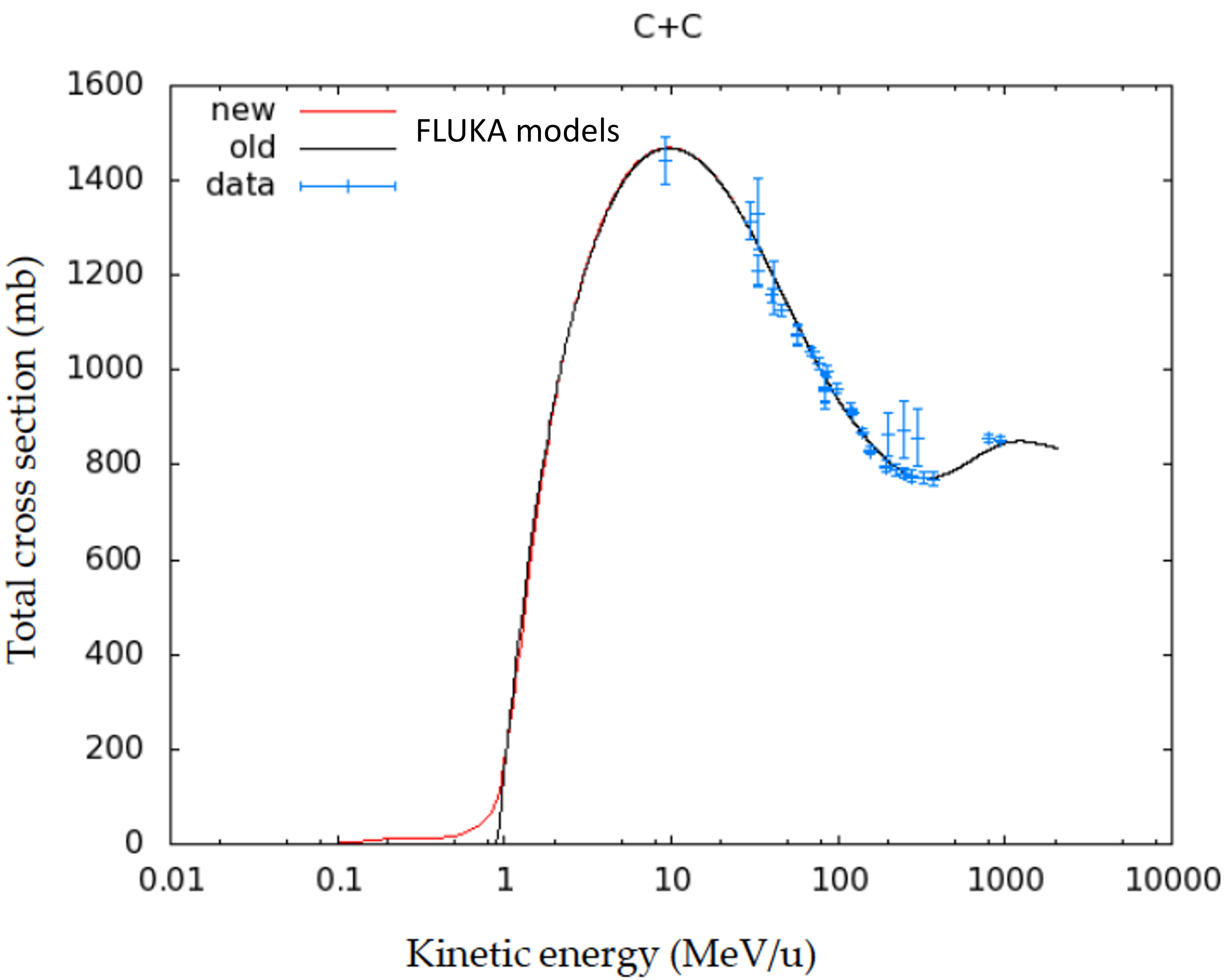
To be discussed:
consider the correct evaluation of multiple- α production in the same collision in the dose calculation models in place of simple inclusive production

Could multiple α production could be more effective (Z=2) with respect to the case of multple Z=1 fragmentation?

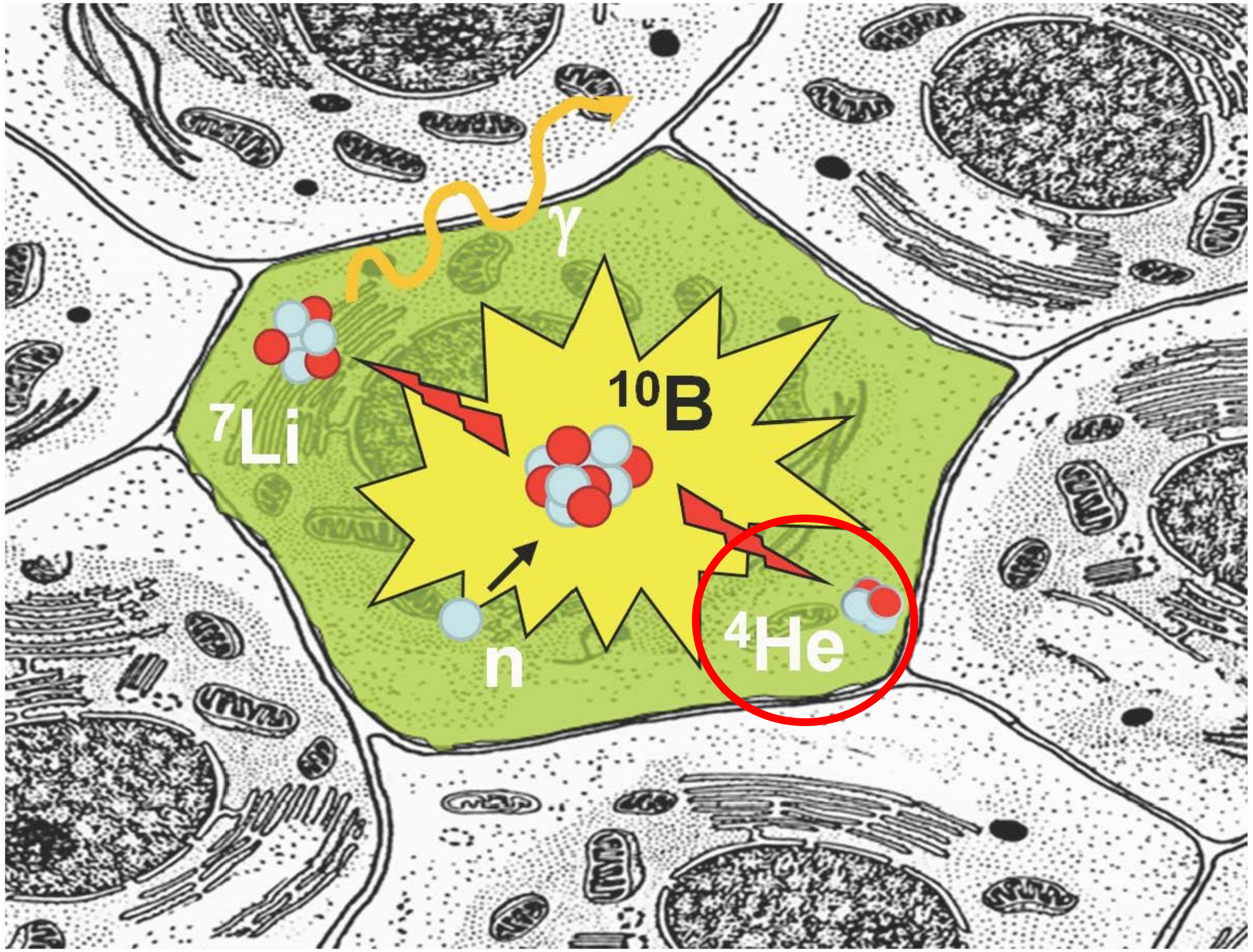
A temptative summary

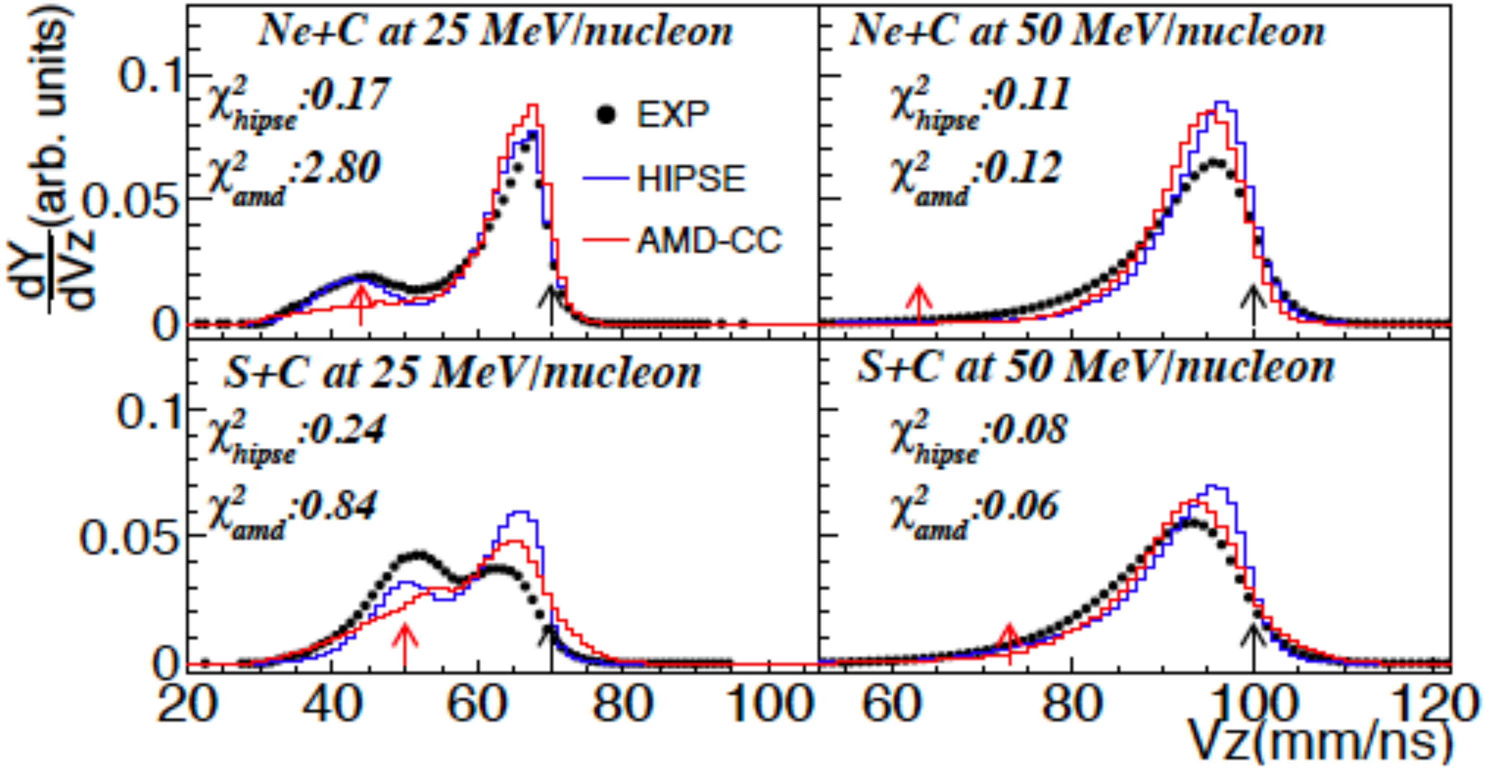
- The presence and importance of clustering is confirmed by pre-FOOT experiments which have operated at Coulomb barrier and Fermi energies
- Although at energies lower than the range of FOOT, these indications are precious for model building *(and this is important for applications!)*
- Apparently, the inclusion of clustering has also important consequences for the multiplicity and energy distribution of nucleons and light fragments: this could be relevant for a correct RBE evaluation in target fragmentation
- At present, it is not clear at all if the clustering phenomenology included in FLUKA, or other general purpose codes, is fully adequate to describe real data
- Maybe FOOT should look for a collaboration with theoreticians managing the use of specialized codes, like for instance AMD

Backup Slides


C+C
new
old
data
FLUKA models
Total cross section (mb)
Kinetic energy (MeV/u)
1600
1400
1200
1000
800
600
400
200
0
0.01
0.1
1
10
100
1000
10000

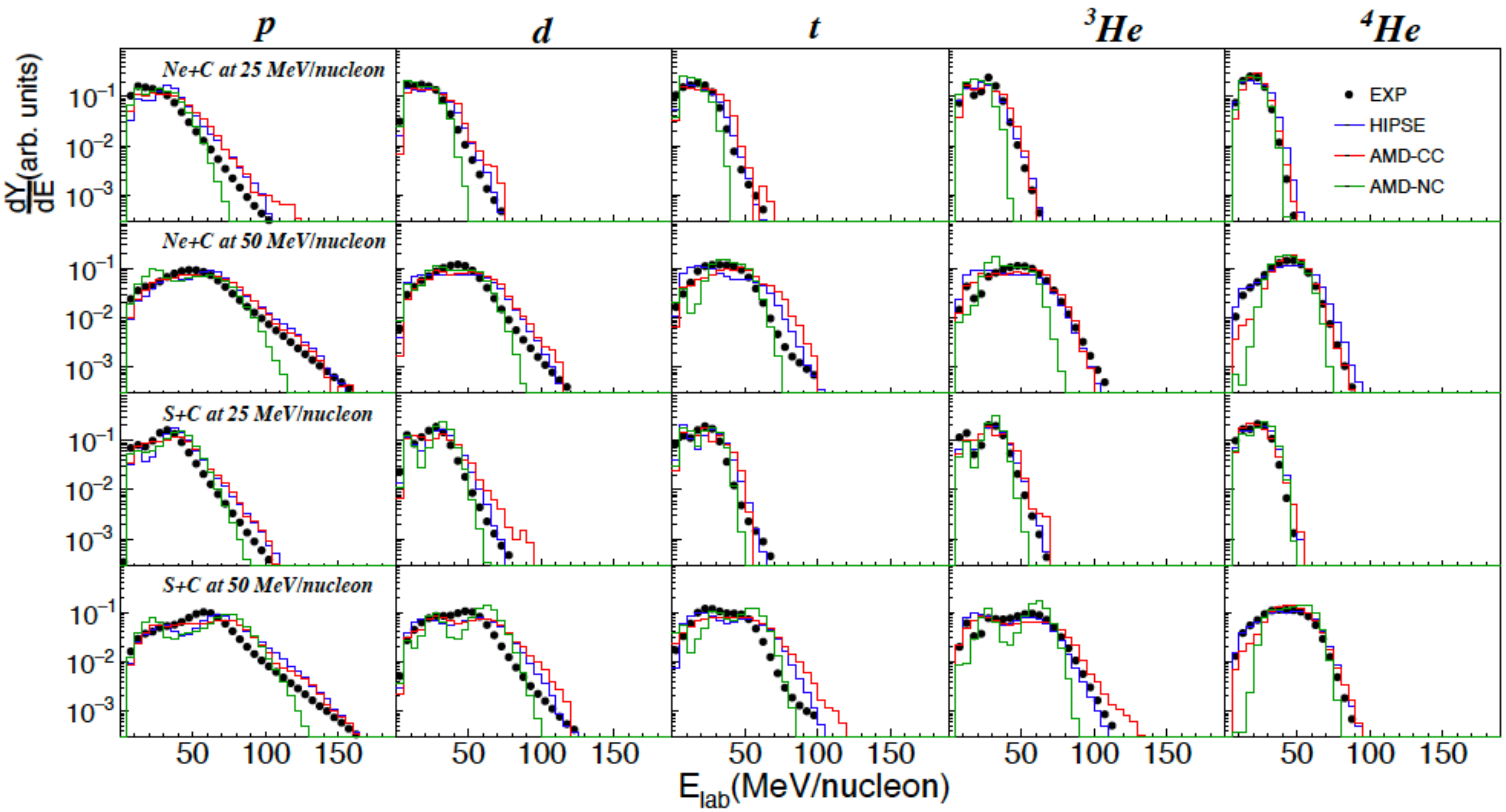
Example of target fragmentation with Z>1 products: BNCT





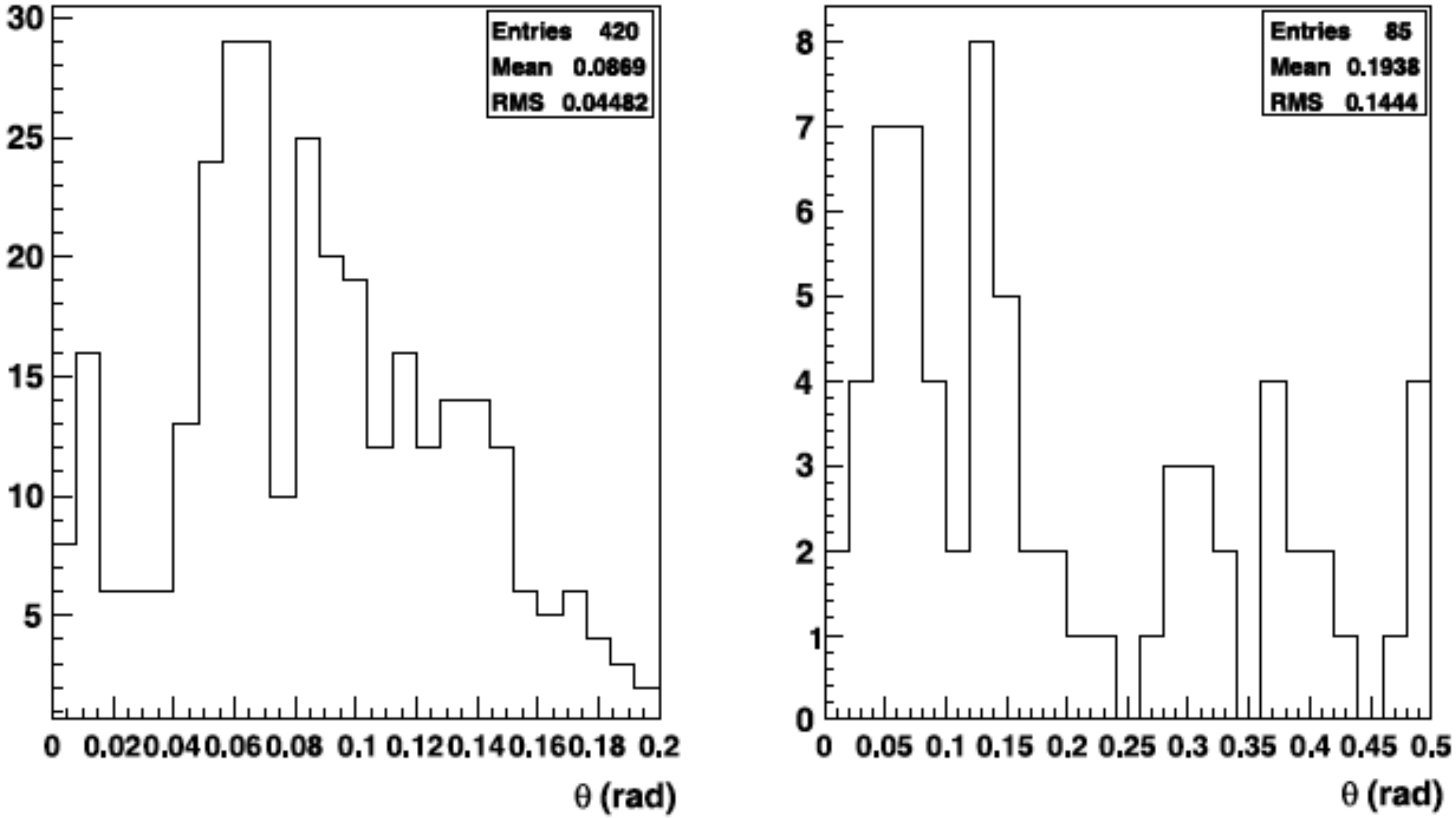
Velocity probability distributions of Z>5 fragments along the beam axis in the lab reference frame for the four reactions.

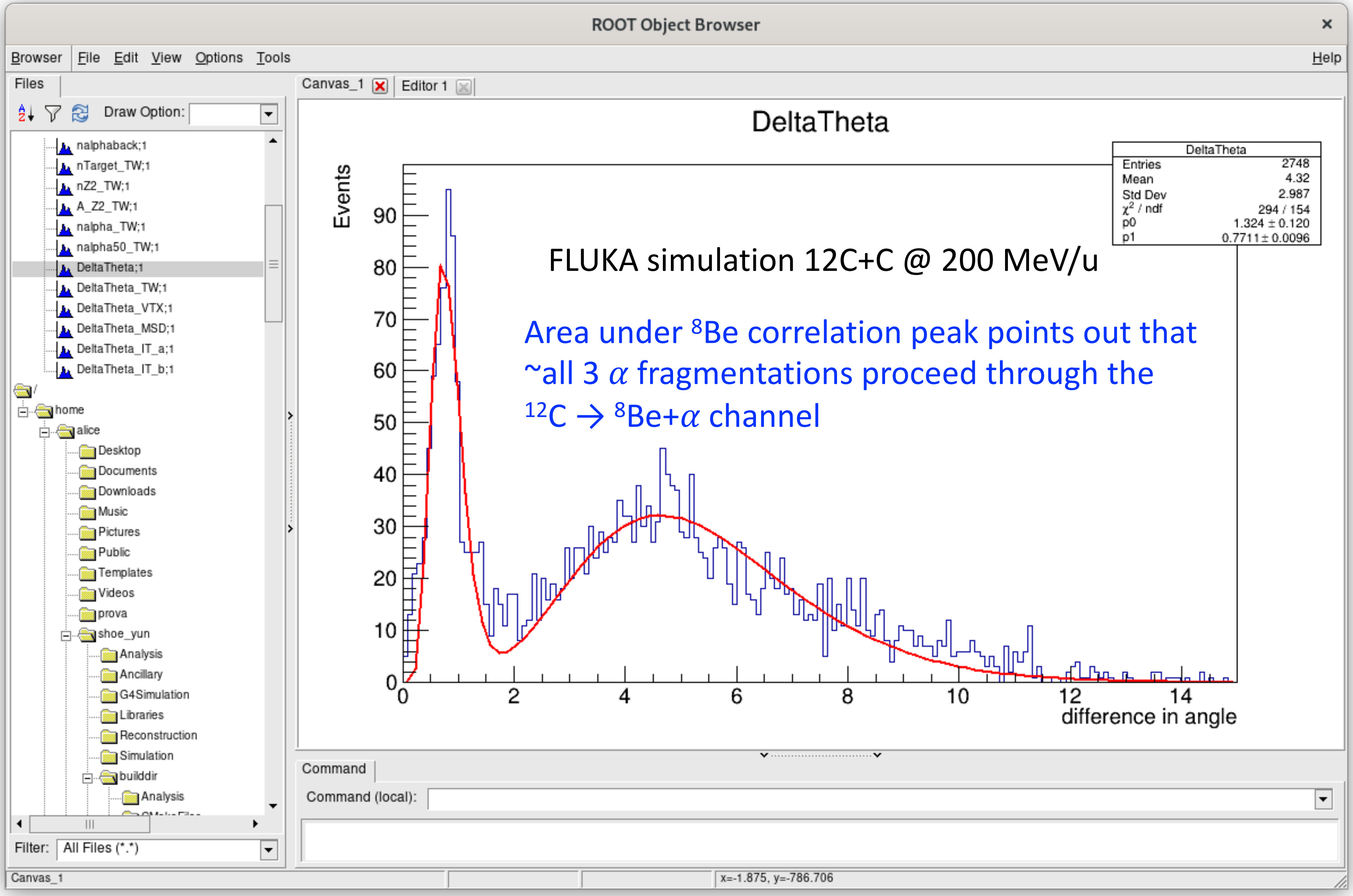
Black points show the experimental data while continuous lines represent the AMD-CC model and HIPSE (statistical) calculations, respectively. Arrows indicate the center of mass velocity (red) and beam velocity (black).



Z≤2 energy distribution for $^{20}Ne+^{12}C$ and $^{32}S+^{12}C$. Spectra are normalized to the integral for a better shape comparison.

G. De Lellis et al. / Nuclear Physics A 853 (2011) 124–134





FLUKA simulation 12C+C @ 200 MeV/u

Area under ^{8}Be correlation peak points out that ~all 3 α fragmentations proceed through the ^{12}C → ^{8}Be+α channel

Appendix: AMD (Antisymmetrized Molecular Dynamics) models - 1

In spite of the many successes of QMD models, a more fundamental quantum mechanical foundation was needed. In AMD models a system of A nucleons is described by an antysimmetrized wave function, using a Slater determinant. Pauli exclusion is naturally taken into account:

$$|\Phi\rangle = \frac{1}{\sqrt{A!}} \det[\varphi_i(j)]$$

$$\varphi_i = \phi_{Z_i} \chi_{\alpha_i} (\alpha_i = p\uparrow, p\downarrow, n\uparrow, n\downarrow)$$

χ_{α_i} is the spin-isospin wave function

ϕ_{Z_i} is the spatial wave function of the i-th single particle state.

$|\phi_Z\rangle$ is the coherent state of harmonic oscillator

$$\boldsymbol{a}|\phi_Z\rangle = \boldsymbol{Z}|\phi_Z\rangle,$$

ν is a parameter representing the width of the gaussian wave packet

$$\boldsymbol{a} \equiv \sqrt{\nu}\boldsymbol{r} + \frac{i}{2\hbar\sqrt{\nu}}\boldsymbol{p}$$

$$\boldsymbol{Z} = \sqrt{\nu}\boldsymbol{D} + \frac{i}{2\hbar\sqrt{\nu}}\boldsymbol{K}$$

where

$$\frac{\langle\phi_Z|\boldsymbol{r}|\phi_Z\rangle}{\langle\phi_Z|\phi_Z\rangle} = \boldsymbol{D}, \quad \frac{\langle\phi_Z|\boldsymbol{p}|\phi_Z\rangle}{\langle\phi_Z|\phi_Z\rangle} = \boldsymbol{K}$$

Main reference: *A. Ono, H. Horiuchi, T. Maruyama, A. Onishi, Progress of Theoretical Physics, Vol. 87, No.5, (1992) 1185*

Appendix: AMD (Antisymmetrized Molecular Dynamics) models - 2

- A nuclear force model (potential) is needed to build the Hamiltonian for the time evolution of the system. The choice of nuclear force is one of the main ingredients which differentiates the various implementation of AMD.

- The matter is quite complicated. Typically authors make use of the Skyrme *[T.H.R. Skyrme, Nuclear Phys. 9 (4) (1959) 615]* or Gogny interaction potential *[J. Decharge and D. Gogny, Phys. Rev. C 21 no. 4 (1980) 1568]*. They contain all possible admixtures of spin, isospin, and space exchange operators, spin-orbit interactions, etc.

- The A-body wave function is then evolved in time according a time-dependent variational

$$\delta \int_{t_1}^{t_2} dt \frac{\langle \Phi(Z) | \left(i\hbar \frac{d}{dt} - H \right) | \Phi(Z) \rangle}{\langle \Phi(Z) | \Phi(Z) \rangle} = 0$$

- Nucleon-nucleon interaction in collisions between nuclei are then incorporated in a second stage: two nucleons interact stochastically when their mutual distance is sufficiently low.