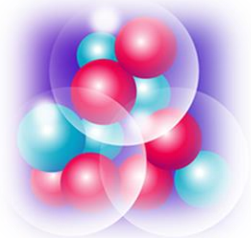
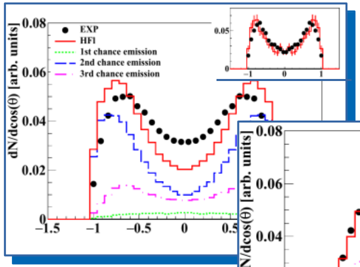
Experimental investigation of cluster production at Fermi energies in excited light systems

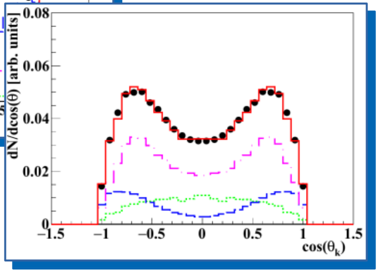


A. Camaiani
C. Frosin
S. Piantelli

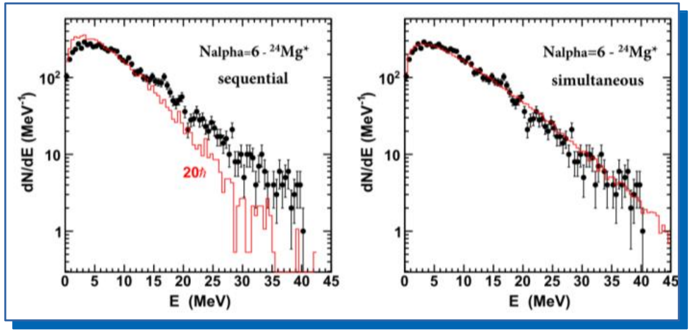
Z_{ER}	Channel	EXP [%]	HFℓ[%]
10	$^{21-x}$Ne $+ xn + \alpha$	29 ± 1	3.2–3.8
9	$^{20-x}F + xn + \mathrm{p} + \alpha$	86 ± 3	84–86
8	$^{17-x}$O $+ xn + 2\alpha$	69 ± 3	30–32
7	$^{15-x}$N $+ xn + p + 2\alpha$	83 ± 3	90–92
6	$^{13-x}$C $+ xn + 3\alpha$	97 ± 4	79–83

L. Morelli JPG. 41 (2014) 075108

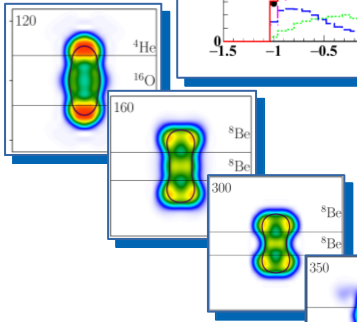


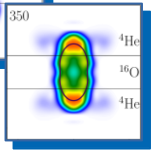


A. Camaiani PRC 97, 044607 (2018



B. Borderie Physics Letters B 755 (2016)





B. Schuetrumpf PRC 96, 064608 (2017)
and Private Comm.

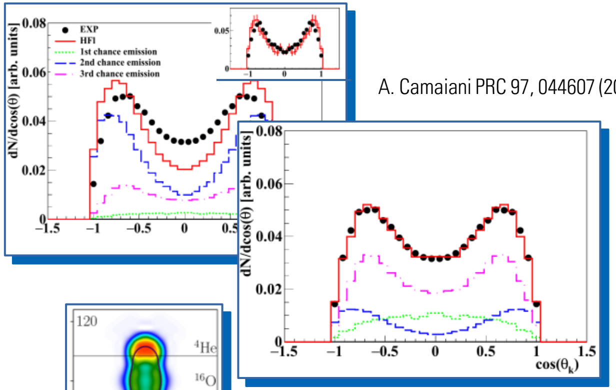
From tandem energies …

through Fermi regime…

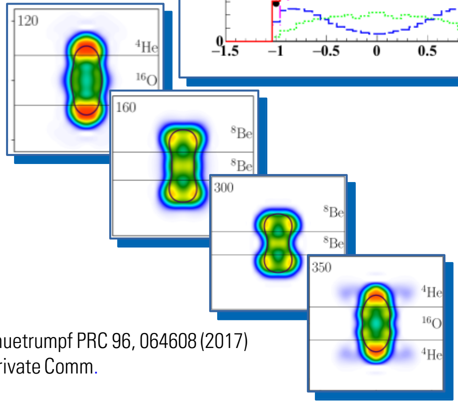
to intermediate energies

Z_{ER}	Channel	EXP [%]	HFℓ[%]
10	$^{21-x}Ne + xn + \alpha$	29 ± 1	3.2–3.8
9	$^{20-x}F + xn + p + \alpha$	86 ± 3	84–86
8	$^{17-x}O + xn + 2\alpha$	69 ± 3	30–32
7	$^{15-x}N + xn + p + 2\alpha$	83 ± 3	90–92
6	$^{13-x}C + xn + 3\alpha$	97 ± 4	79–83

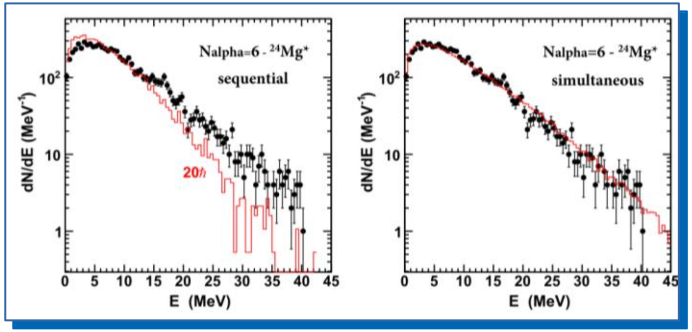
L. Morelli JPG. 41 (2014) 075108



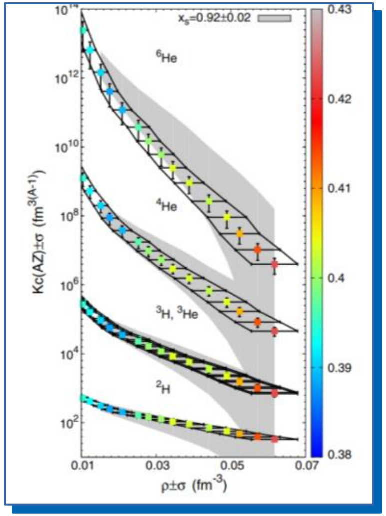
A. Camaiani PRC 97, 044607 (2018



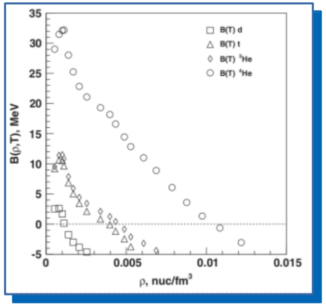
B. Schuetrumpf PRC 96, 064608 (2017)
and Private Comm.



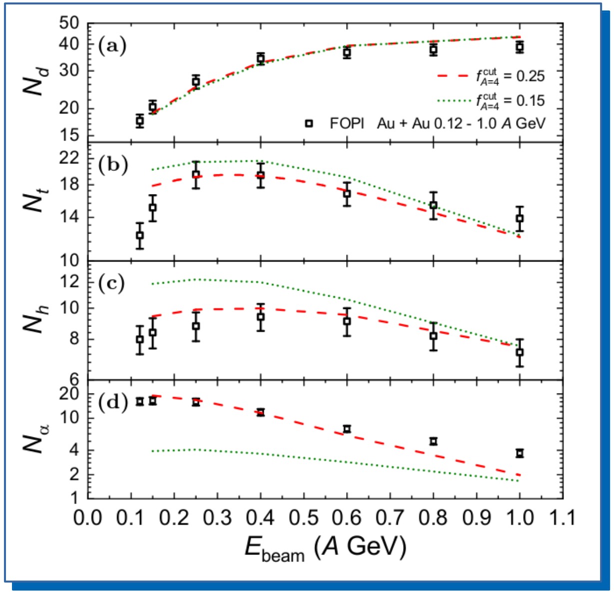
B. Borderie Physics Letters B 755 (2016)



H. Pais PRL 125, 012701 (2020)



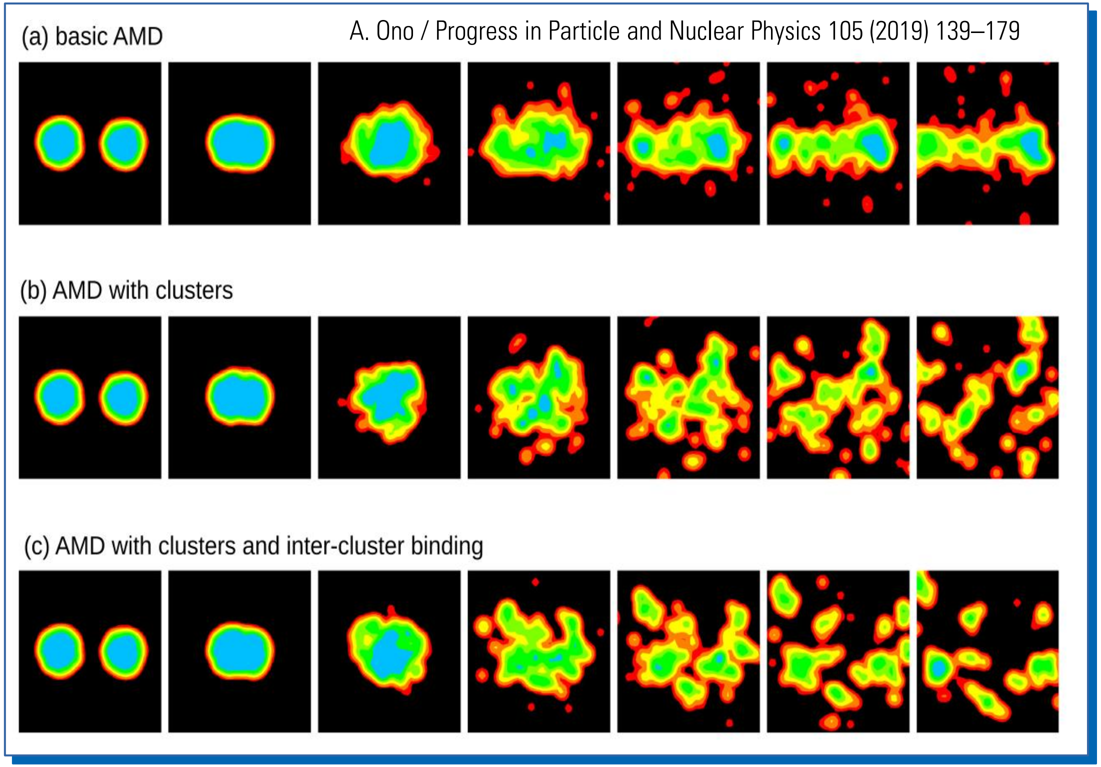
K. Hagel PRL 108, 062702 (2012)



R. Wang PRC, accepted

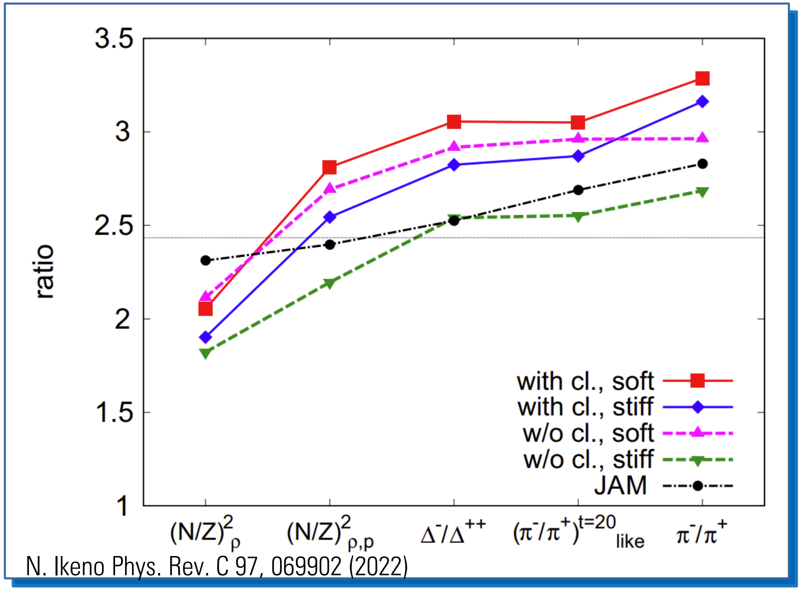
and see R. Wang talk

From tandem energies … through Fermi regime… to intermediate energies



How cluster can shape an heavy ion collision

How cluster can impact
the sensitivity of symmetry energy probe



From tandem energies … through Fermi regime… to intermediate energies

The G. Tian et al work on clusterization within AMD

AMD model by A. Ono

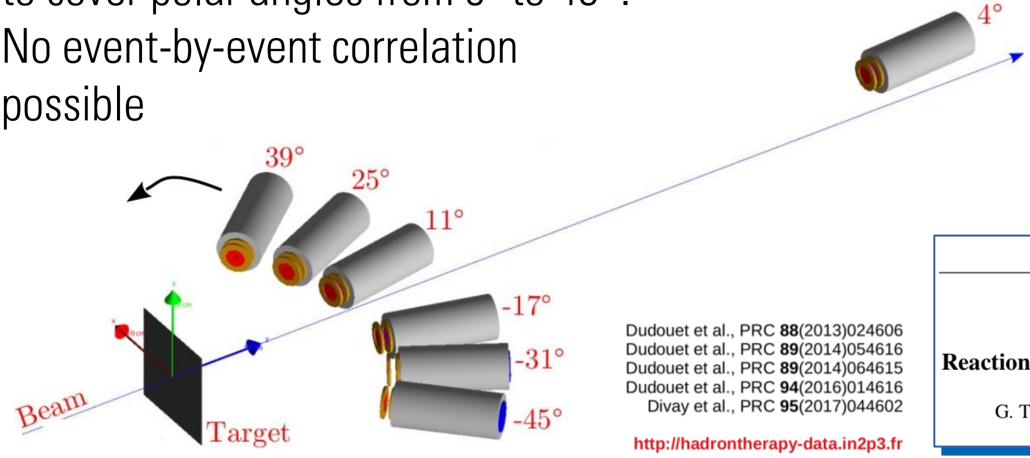
Prog. in Part. Nucl. Physics 105 (2019)139-179

$$v_i d\sigma(C_1, C_2, p_{\rm rel}, \Omega) = \frac{2\pi}{\hbar} \boxed{P_1(C_1, p_{\rm rel}, \Omega) P_2(C_2, p_{\rm rel}, \Omega)} |\mathcal{M}|^2 \delta\big(E_f(C_1, C_2, p_{\rm rel}, \Omega) - E_i\big) \frac{p_{\rm rel}^2 dp_{\rm rel} d\Omega}{(2\pi\hbar)^3}$$

$$N_1 + N_2 + B_1 + B_2 \rightarrow C_1 + C_2$$

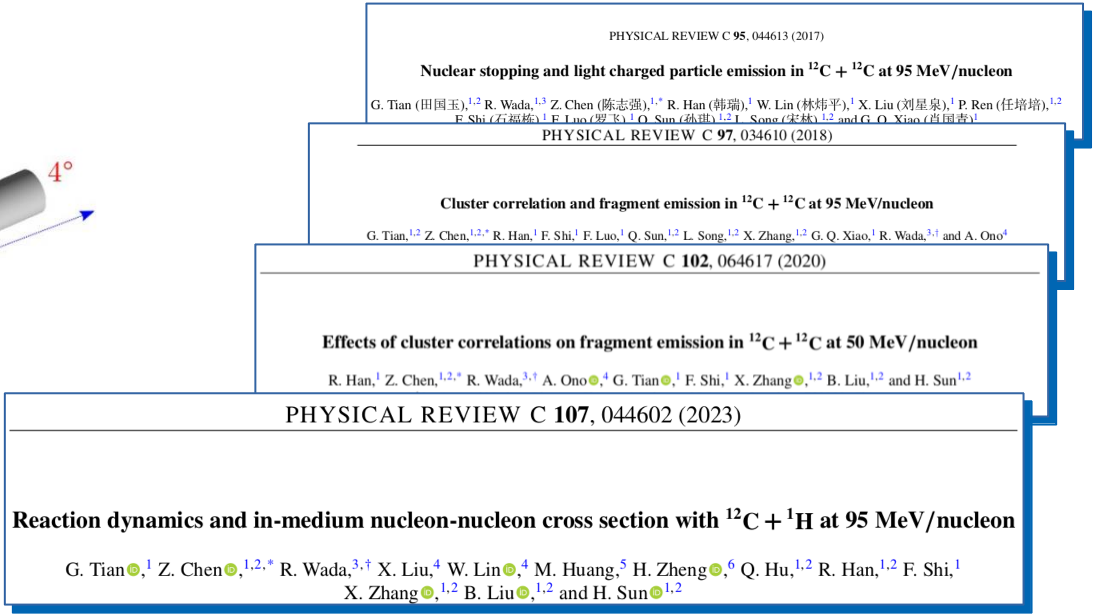
Inclusive measurements

Si-Si-CsI moving telescope
to cover polar angles from 0° to 45°.
No event-by-event correlation possible



Dudouet et al., PRC **88**(2013)024606
Dudouet et al., PRC **89**(2014)054616
Dudouet et al., PRC **89**(2014)064615
Dudouet et al., PRC **94**(2016)014616
Divay et al., PRC **95**(2017)044602

http://hadrontherapy-data.in2p3.fr


PHYSICAL REVIEW C **95**, 044613 (2017)

Nuclear stopping and light charged particle emission in $^{12}C + ^{12}C$ at 95 MeV/nucleon

G. Tian (田国玉),[1,2] R. Wada,[1,3] Z. Chen (陈志强),[1,*] R. Han (韩瑞),[1] W. Lin (林炜平),[1] X. Liu (刘星泉),[1] P. Ren (任培培),[1,2]

PHYSICAL REVIEW C **97**, 034610 (2018)

Cluster correlation and fragment emission in $^{12}C + ^{12}C$ at 95 MeV/nucleon

G. Tian,[1,2] Z. Chen,[1,2,*] R. Han,[1] F. Shi,[1] F. Luo,[1] Q. Sun,[1,2] L. Song,[1,2] X. Zhang,[1,2] G. Q. Xiao,[1] R. Wada,[3,†] and A. Ono[4]

PHYSICAL REVIEW C **102**, 064617 (2020)

Effects of cluster correlations on fragment emission in $^{12}C + ^{12}C$ at 50 MeV/nucleon

R. Han,[1] Z. Chen,[1,2,*] R. Wada,[3,†] A. Ono,[4] G. Tian,[1] F. Shi,[1] X. Zhang,[1,2] B. Liu,[1,2] and H. Sun[1,2]

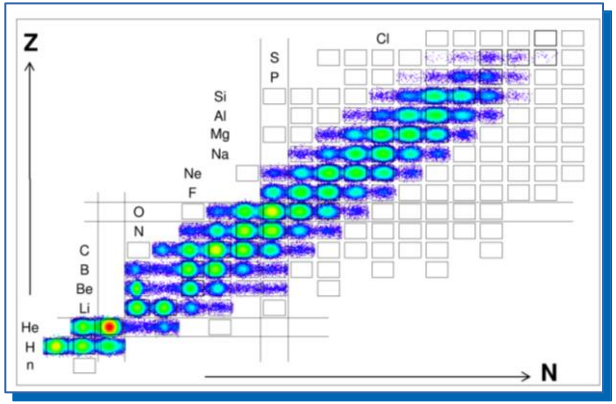
PHYSICAL REVIEW C **107**, 044602 (2023)

Reaction dynamics and in-medium nucleon-nucleon cross section with $^{12}C + ^{1}H$ at 95 MeV/nucleon

G. Tian,[1] Z. Chen,[1,2,*] R. Wada,[3,†] X. Liu,[4] W. Lin,[4] M. Huang,[5] H. Zheng,[6] Q. Hu,[1,2] R. Han,[1,2] F. Shi,[1] X. Zhang,[1,2] B. Liu,[1,2] and H. Sun[1,2]

The FaziaCOR Experiment

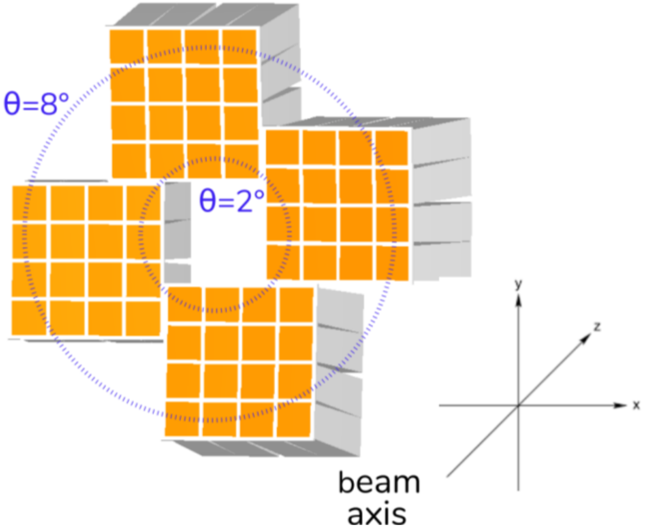
Examination of the cluster production in excited light system at Fermi energies



^{20}Ne + ^{12}C @ 25 MeV/u ^{20}Ne + ^{12}C @ 50 MeV/u

^{32}S + ^{12}C @ 25 MeV/u ^{32}S + ^{12}C @ 50 MeV/u

And comparison with transport model



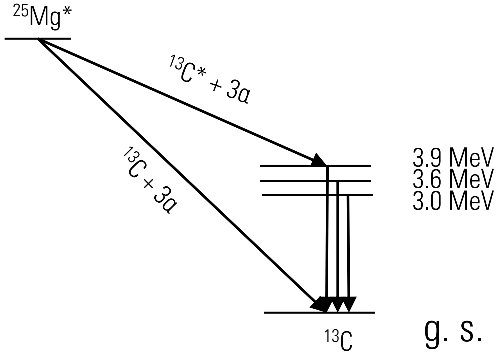
L. Morelli JPG 41 (2014) 075108

1- AMD + Hauser Feschbach light (HFl)

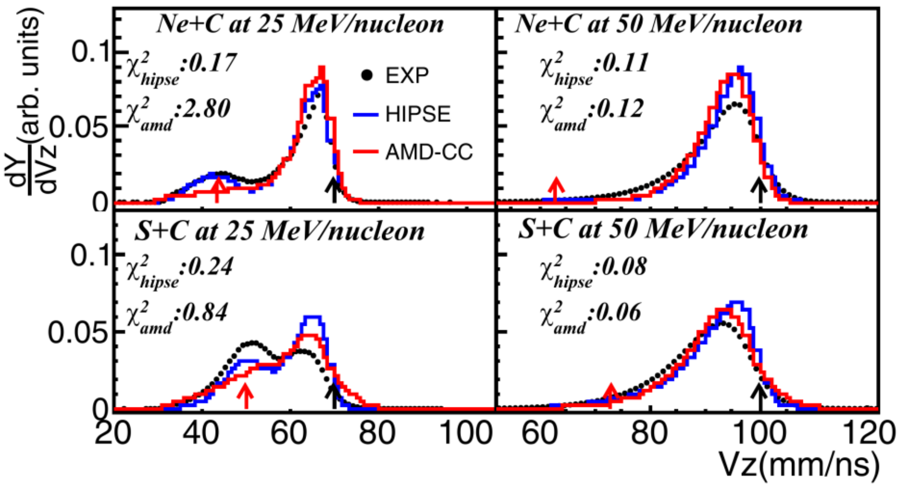
optimized for light nuclei

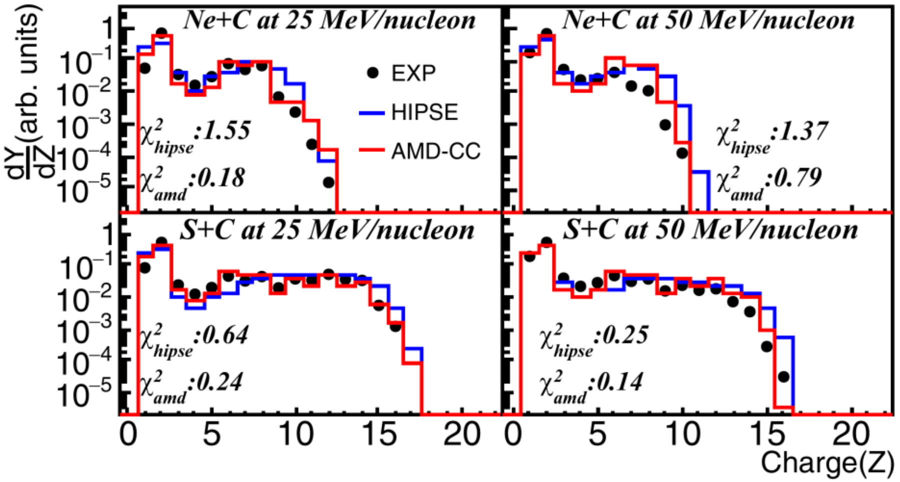
2- HISPE + SIMON

D. Lacroix PRC 69 (2014) 054604



A general panorama of the reactions





Accessed sources

- 25 AMeV: fusion-like + binary
  - 13%, 4% for S+C, Ne+C
- 50 AMeV: binary

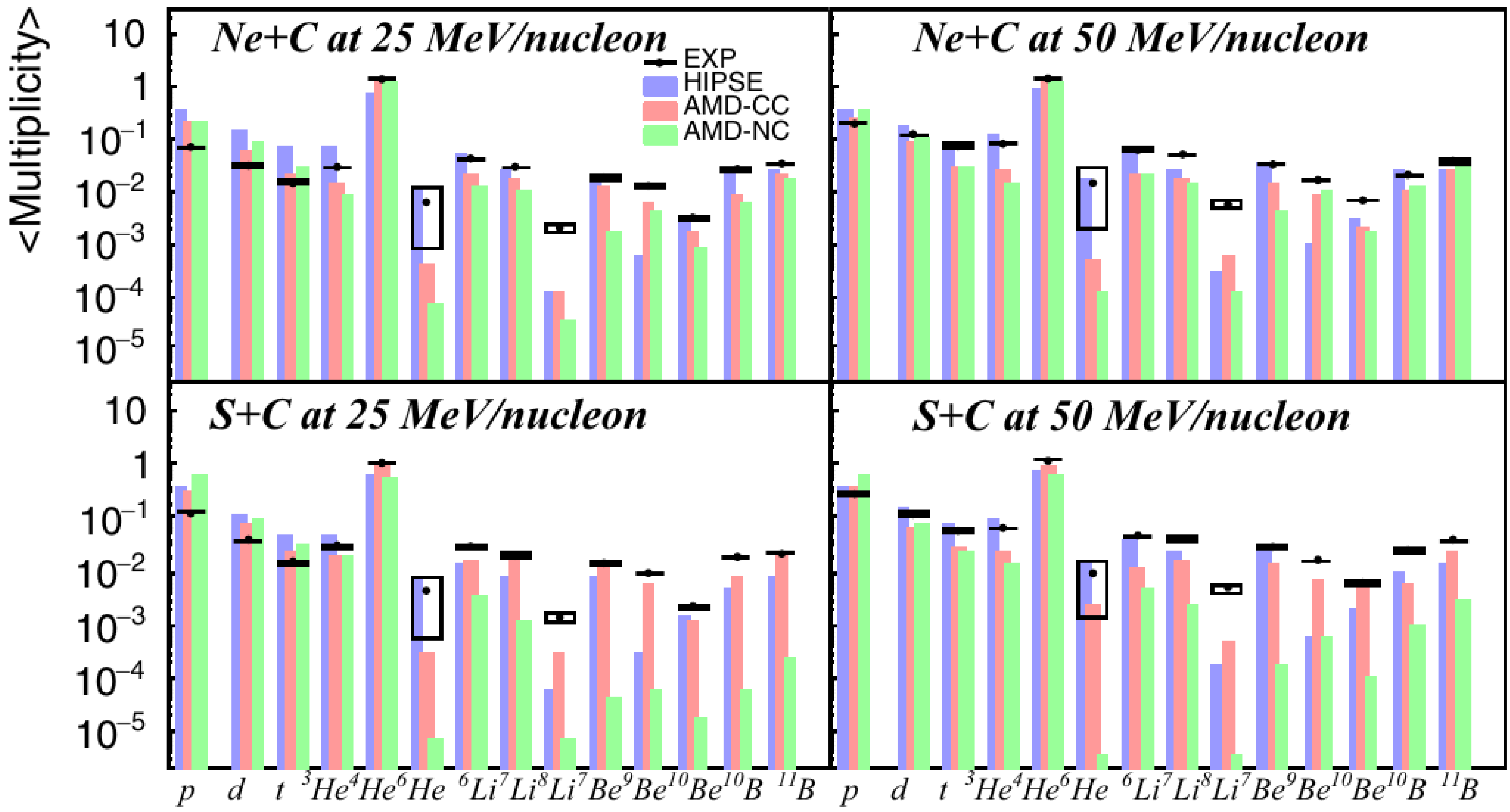
Production of light species favoured at 50 MeV/u

- More violent dynamics at early stage
- More E* in the in produced fragments and consequent longer decay chains

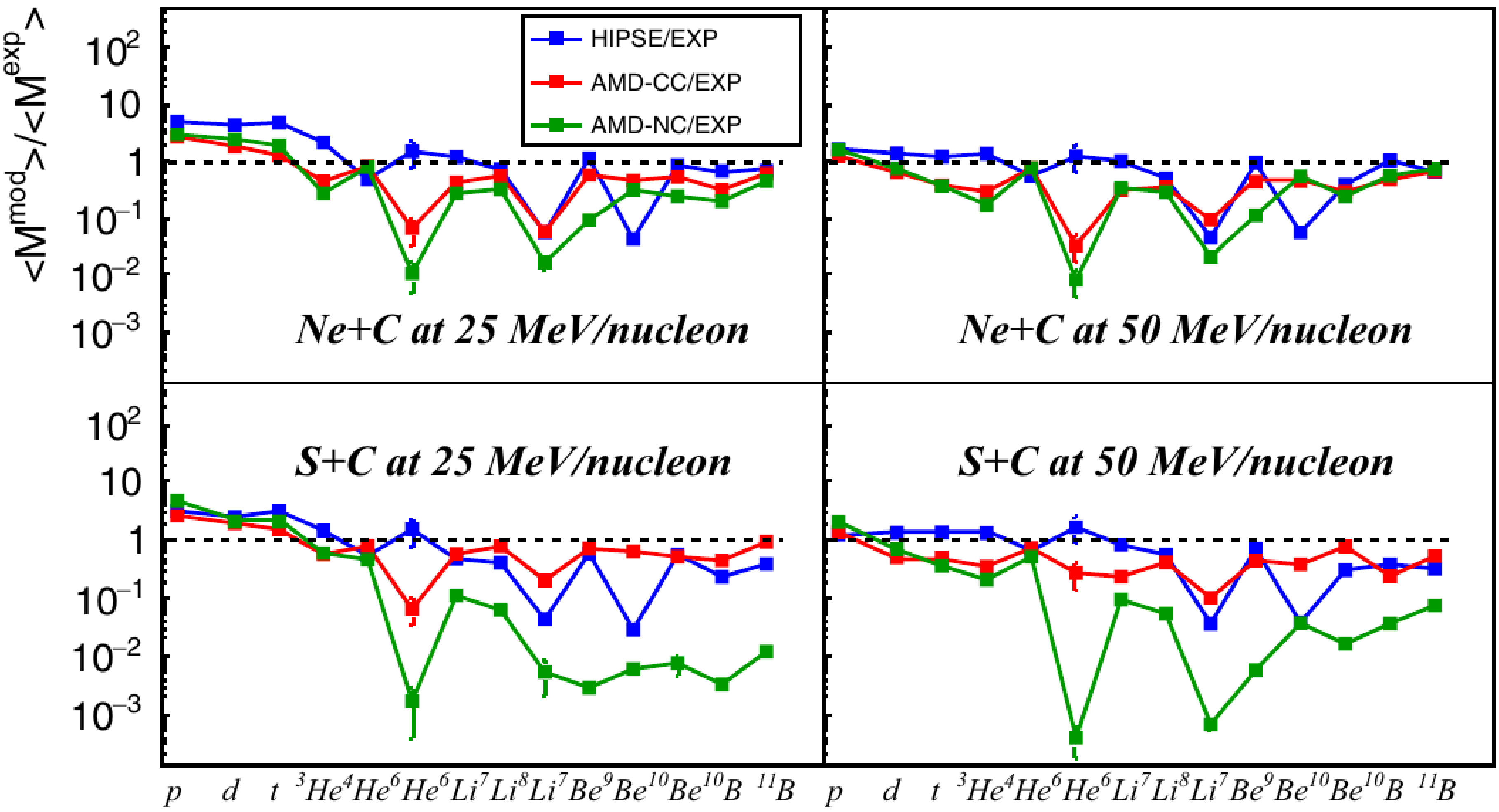
Models

- AMD – detailed Z but lacks fusion-like
- HIPSE – better mimic of cross sections

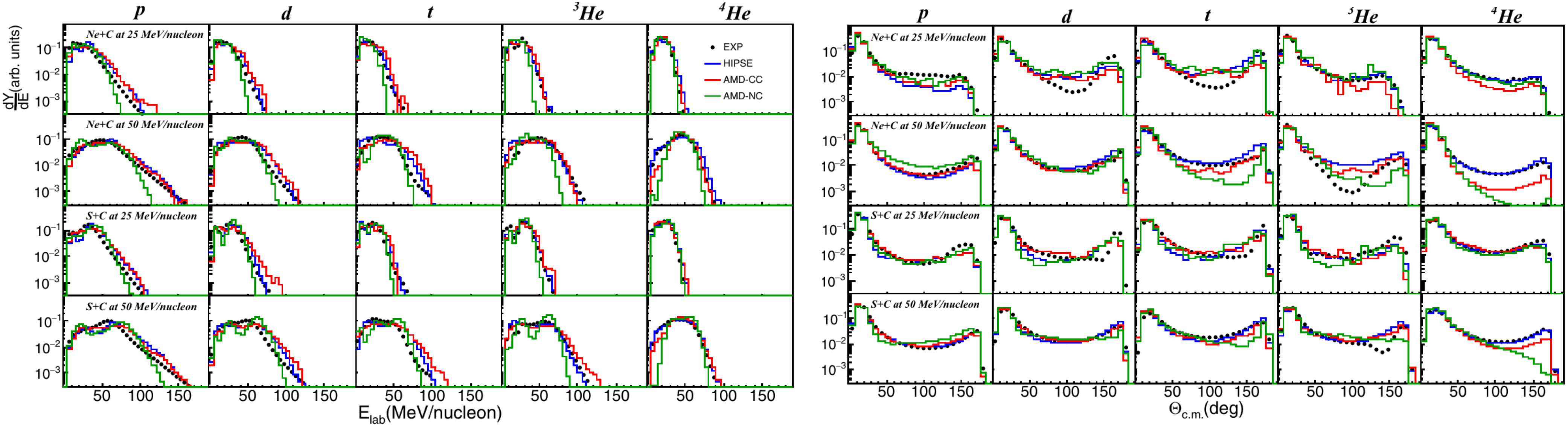
Cluster and IMF multiplicity



Cluster and IMF multiplicity

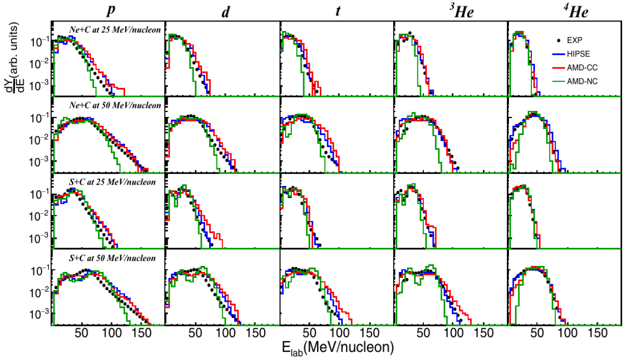


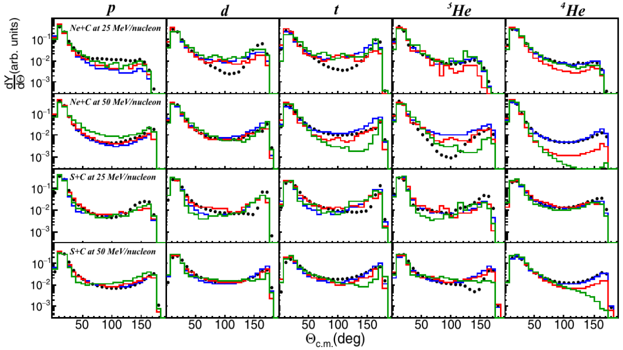
Cluster phase-space

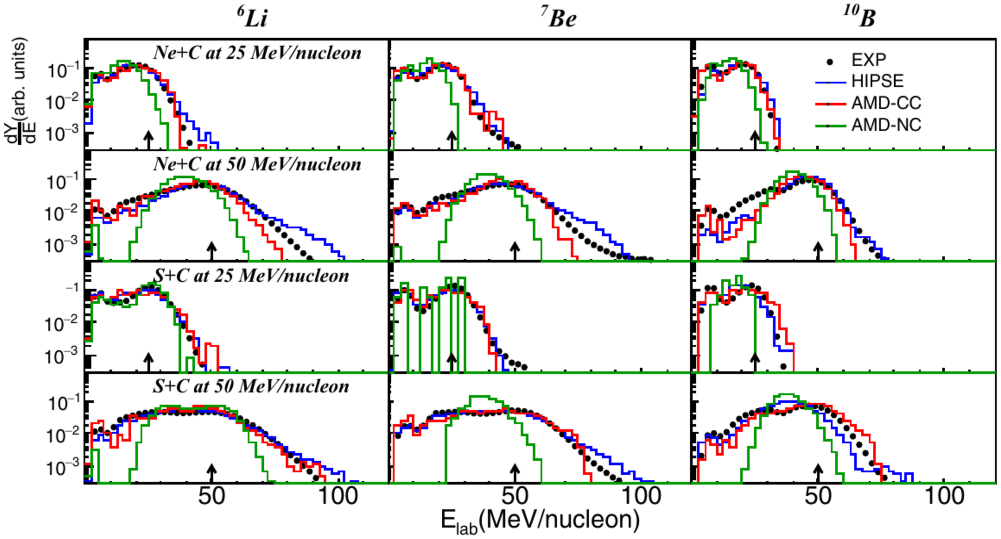


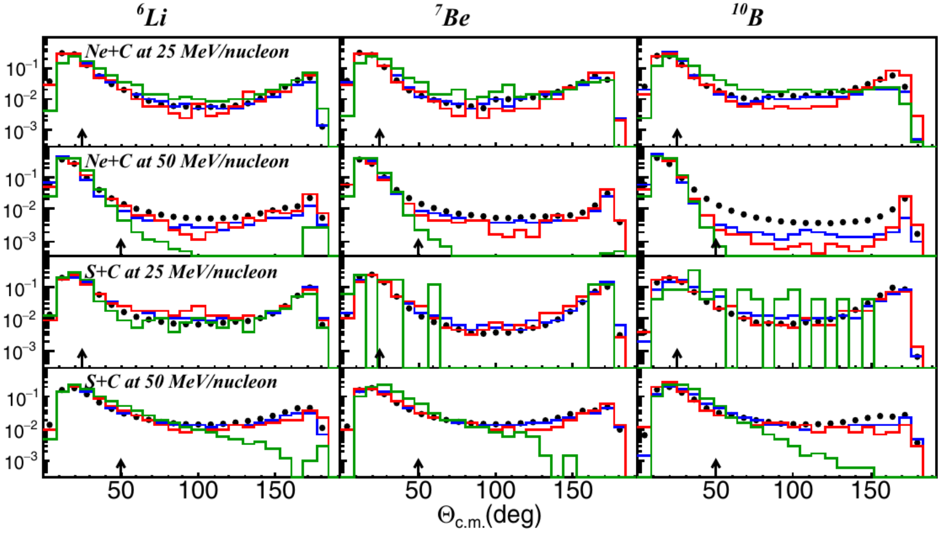
A reasonably good description of the cluster phase space when clusterization is allowed

Cluster and IMF phase-space









A reasonably good description of the cluster phase space when clusterization is allowed

Medium effects and clusterization

AMD model **by A. Ono**

$$f \sim \sigma_{NN}^{in}$$

$$v_i d\sigma(C_1, C_2, p_{\rm rel}, \Omega) = \frac{2\pi}{\hbar} P_1(C_1, p_{\rm rel}, \Omega) P_2(C_2, p_{\rm rel}, \Omega) |\mathcal{M}|^2 \delta(E_f(C_1, C_2, p_{\rm rel}, \Omega) - E_i) \frac{p_{\rm rel}^2 dp_{\rm rel} d\Omega}{(2\pi\hbar)^3}$$

$$N_1 + N_2 + B_1 + B_2 \to C_1 + C_2$$

Clusterization probability

In-medium NN cross-section

Medium effects and clusterization

AMD model **by A. Ono**

$$f \sim \sigma_{NN}^{in}$$

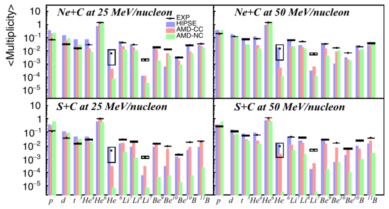
$$v_i d\sigma(C_1, C_2, p_{\mathrm{rel}}, \Omega) = \frac{2\pi}{\hbar} P_1(C_1, p_{\mathrm{rel}}, \Omega) P_2(C_2, p_{\mathrm{rel}}, \Omega) |\mathcal{M}|^2 \delta(E_f(C_1, C_2, p_{\mathrm{rel}}, \Omega) - E_i) \frac{p_{\mathrm{rel}}^2 dp_{\mathrm{rel}} d\Omega}{(2\pi\hbar)^3}$$

$$N_1 + N_2 + B_1 + B_2 \rightarrow C_1 + C_2$$

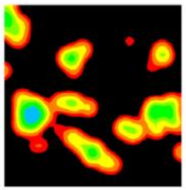
Clusterization probability

In-medium NN cross-section

Exp. cluster and IMF multiplicity



The MODEL
AMD+Gemini++



Medium effects and clusterization

AMD model by A. Ono

$$v_i d\sigma(C_1, C_2, p_{\rm rel}, \Omega) = \frac{2\pi}{\hbar} P_1(C_1, p_{\rm rel}, \Omega) P_2(C_2, p_{\rm rel}, \Omega) |\mathcal{M}|^2 \delta(E_f(C_1, C_2, p_{\rm rel}, \Omega) - E_i) \frac{p_{\rm rel}^2 dp_{\rm rel} d\Omega}{(2\pi\hbar)^3}$$

$f \sim \sigma_{NN}^{in}$

$N_1 + N_2 + B_1 + B_2 \rightarrow C_1 + C_2$

Clusterization probability

- from Max. (inf) to Minimum (1)

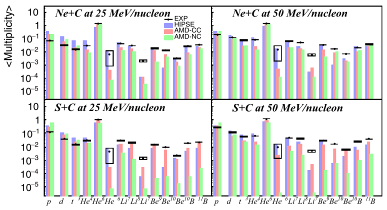
In-medium NN cross-section

- from y=0.15 to y=1.15

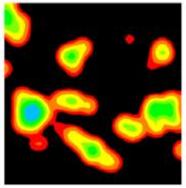
$$\sigma_{NN}^{in} = \sigma_0 \tanh\left(\frac{\sigma_{free}}{\sigma_0}\right)$$

$$\sigma_0 = y\rho^{-2/3}$$

Exp. cluster and IMF multiplicity



The MODEL
AMD+Gemini++



A reasonable prior

$$\mathcal{L} \approx e^{\frac{1}{2}\left(\frac{M_x^{exp} - M_x^{AMD}}{\sigma}\right)^2}$$

Bayesian inference

Medium effects and clusterization

AMD model by A. Ono

$$v_i d\sigma(C_1, C_2, p_{\rm rel}, \Omega) = \frac{2\pi}{\hbar} P_1(C_1, p_{\rm rel}, \Omega) P_2(C_2, p_{\rm rel}, \Omega) |\mathcal{M}|^2 \delta(E_f(C_1, C_2, p_{\rm rel}, \Omega) - E_i) \frac{p_{\rm rel}^2 dp_{\rm rel} d\Omega}{(2\pi\hbar)^3}$$

$f \sim \sigma_{NN}^{in}$

$N_1 + N_2 + B_1 + B_2 \to C_1 + C_2$

Clusterization probability

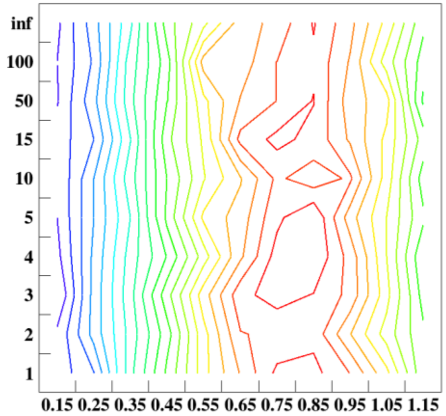
- from Max. (inf) to Minimum (1)

In-medium NN cross-section

- from y=0.15 to y=1.15

$$\sigma_{NN}^{in} = \sigma_0 \tanh\left(\frac{\sigma_{free}}{\sigma_0}\right)$$

$$\sigma_0 = y\rho^{-2/3}$$



A reasonable prior

Medium effects and clusterization

AMD model by A. Ono

$$v_i d\sigma(C_1, C_2, p_{\mathrm{rel}}, \Omega) = \frac{2\pi}{\hbar} P_1(C_1, p_{\mathrm{rel}}, \Omega) P_2(C_2, p_{\mathrm{rel}}, \Omega) |\mathcal{M}|^2 \delta(E_f(C_1, C_2, p_{\mathrm{rel}}, \Omega) - E_i) \frac{p_{\mathrm{rel}}^2 dp_{\mathrm{rel}} d\Omega}{(2\pi\hbar)^3}$$

$f \sim \sigma_{NN}^{in}$

$N_1 + N_2 + B_1 + B_2 \to C_1 + C_2$

Clusterization probability

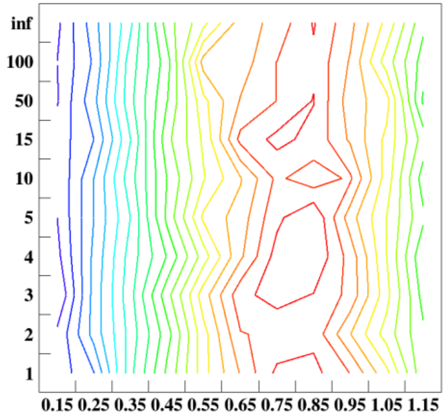
- from Max. (inf) to Minimum (1)

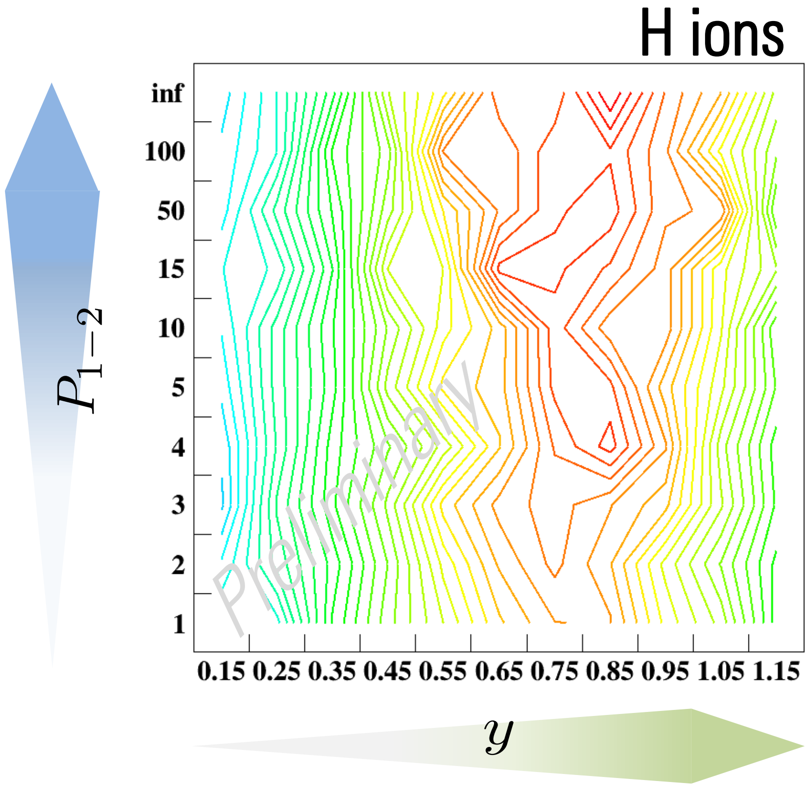
In-medium NN cross-section

- from y=0.15 to y=1.15

$$\sigma_{NN}^{in} = \sigma_0 \tanh\left(\frac{\sigma_{free}}{\sigma_0}\right)$$

$$\sigma_0 = y\rho^{-2/3}$$





Medium effects and clusterization

AMD model by A. Ono

$$f \sim \sigma_{NN}^{in}$$

$$v_i d\sigma(C_1, C_2, p_{\rm rel}, \Omega) = \frac{2\pi}{\hbar} P_1(C_1, p_{\rm rel}, \Omega) P_2(C_2, p_{\rm rel}, \Omega) |\mathcal{M}|^2 \delta(E_f(C_1, C_2, p_{\rm rel}, \Omega) - E_i) \frac{p_{\rm rel}^2 dp_{\rm rel} d\Omega}{(2\pi\hbar)^3}$$

$$N_1 + N_2 + B_1 + B_2 \rightarrow C_1 + C_2$$

Clusterization probability

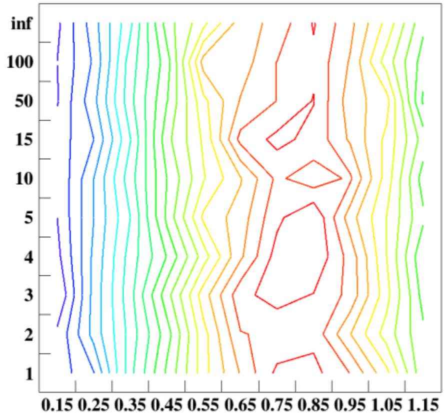
- from Max. (inf) to Minimum (1)

In-medium NN cross-section

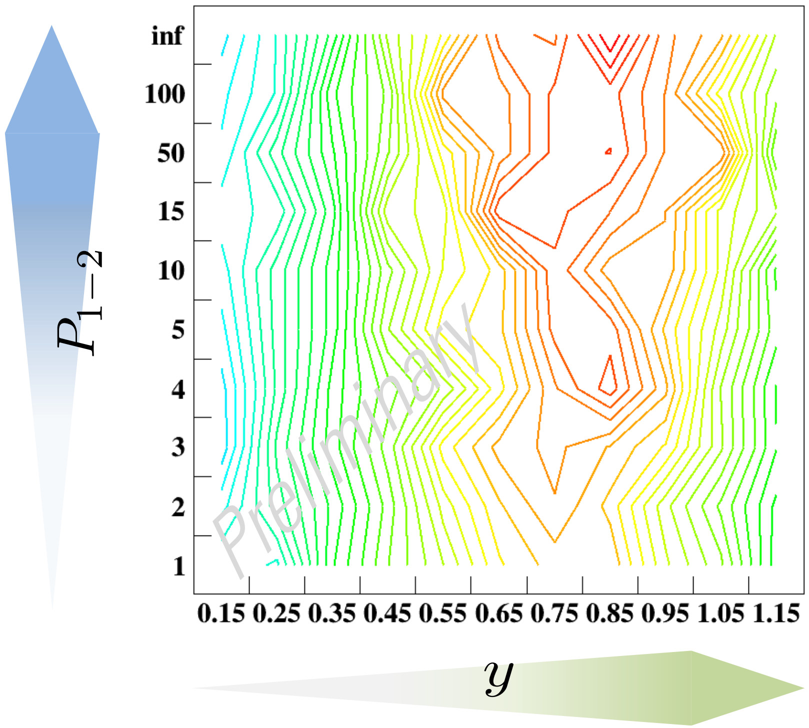
- from y=0.15 to y=1.15

$$\sigma_{NN}^{in} = \sigma_0 \tanh(\frac{\sigma_{free}}{\sigma_0})$$

$$\sigma_0 = y\rho^{-2/3}$$



H+He ions



Medium effects and clusterization

AMD model by A. Ono

$$v_i d\sigma(C_1, C_2, p_{\rm rel}, \Omega) = \frac{2\pi}{\hbar} P_1(C_1, p_{\rm rel}, \Omega) P_2(C_2, p_{\rm rel}, \Omega) |\mathcal{M}|^2 \delta(E_f(C_1, C_2, p_{\rm rel}, \Omega) - E_i) \frac{p_{\rm rel}^2 dp_{\rm rel} d\Omega}{(2\pi\hbar)^3}$$

$$f \sim \sigma_{NN}^{in}$$

$$N_1 + N_2 + B_1 + B_2 \rightarrow C_1 + C_2$$

Clusterization probability

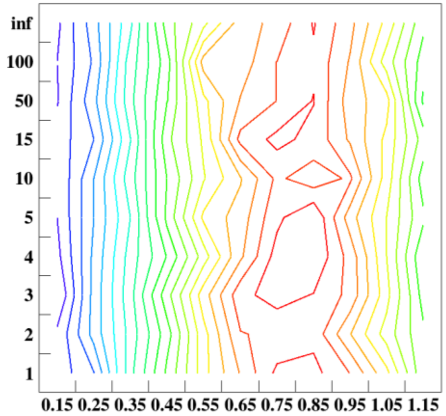
- from Max. (inf) to Minimum (1)

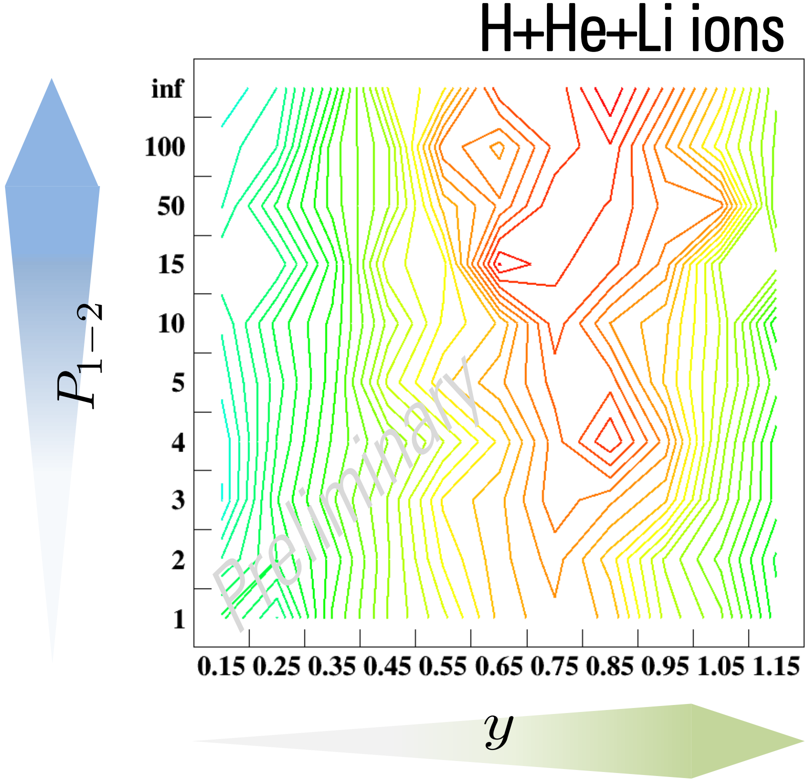
In-medium NN cross-section

- from y=0.15 to y=1.15

$$\sigma_{NN}^{in} = \sigma_0 \tanh\left(\frac{\sigma_{free}}{\sigma_0}\right)$$

$$\sigma_0 = y\rho^{-2/3}$$





Medium effects and clusterization

AMD model by A. Ono

$$f \sim \sigma_{NN}^{in}$$

$$v_i d\sigma(C_1, C_2, p_{\text{rel}}, \Omega) = \frac{2\pi}{\hbar} P_1(C_1, p_{\text{rel}}, \Omega) P_2(C_2, p_{\text{rel}}, \Omega) |\mathcal{M}|^2 \delta(E_f(C_1, C_2, p_{\text{rel}}, \Omega) - E_i) \frac{p_{\text{rel}}^2 dp_{\text{rel}} d\Omega}{(2\pi\hbar)^3}$$

$$N_1 + N_2 + B_1 + B_2 \to C_1 + C_2$$

Clusterization probability

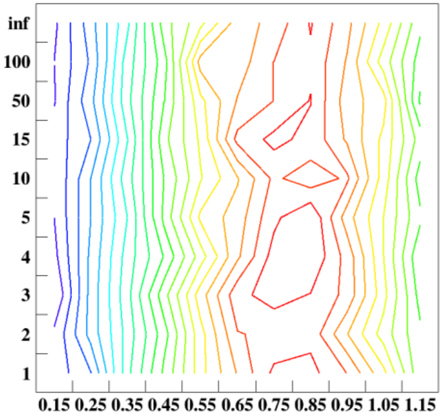
- from Max. (inf) to Minimum (1)

In-medium NN cross-section

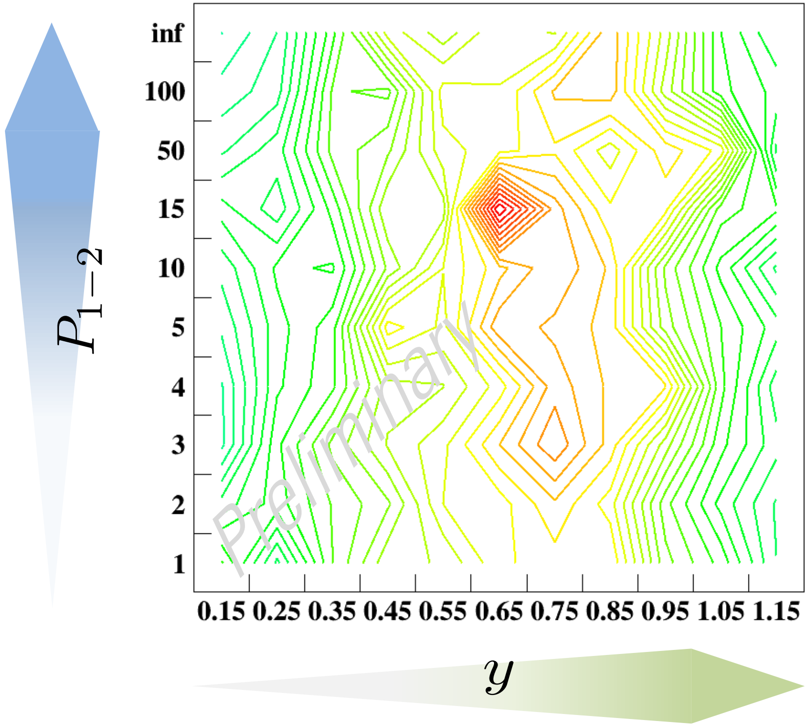
- from y=0.15 to y=1.15

$$\sigma_{NN}^{in} = \sigma_0 \tanh\left(\frac{\sigma_{free}}{\sigma_0}\right)$$

$$\sigma_0 = y\rho^{-2/3}$$



H+He+Li+Be ions



Medium effects and clusterization

AMD model by A. Ono

$$f \sim \sigma_{NN}^{in}$$

$$v_i d\sigma(C_1, C_2, p_{\rm rel}, \Omega) = \frac{2\pi}{\hbar} P_1(C_1, p_{\rm rel}, \Omega) P_2(C_2, p_{\rm rel}, \Omega) |\mathcal{M}|^2 \delta(E_f(C_1, C_2, p_{\rm rel}, \Omega) - E_i) \frac{p_{\rm rel}^2 dp_{\rm rel} d\Omega}{(2\pi\hbar)^3}$$

$$N_1 + N_2 + B_1 + B_2 \to C_1 + C_2$$

Clusterization probability

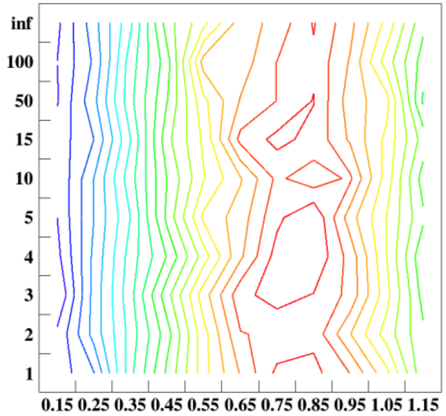
- from Max. (inf) to Minimum (1)

In-medium NN cross-section

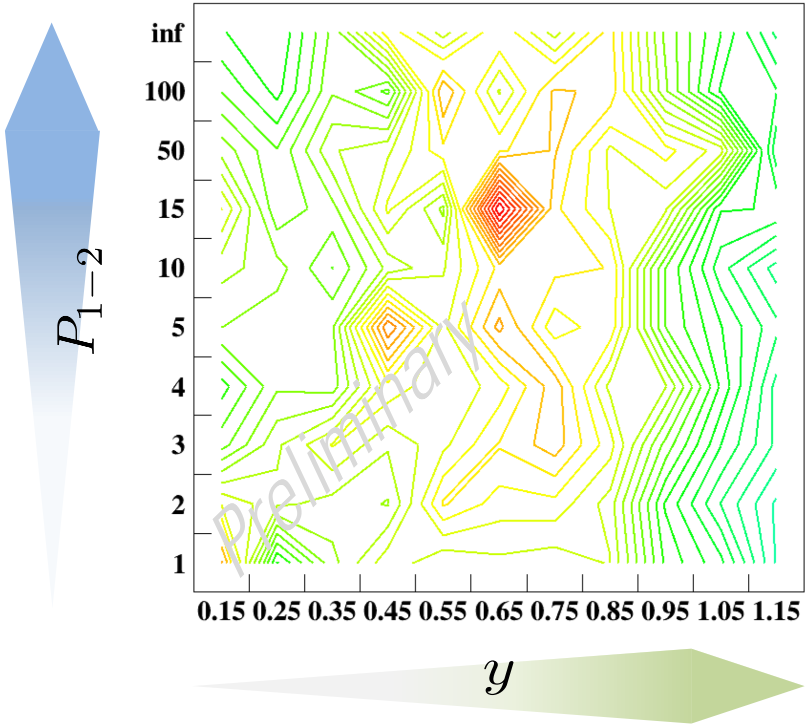
- from y=0.15 to y=1.15

$$\sigma_{NN}^{in} = \sigma_0 \tanh\left(\frac{\sigma_{free}}{\sigma_0}\right)$$

$$\sigma_0 = y\rho^{-2/3}$$



H+He+Li+Be+B ions



Medium effects and clusterization

AMD model by A. Ono

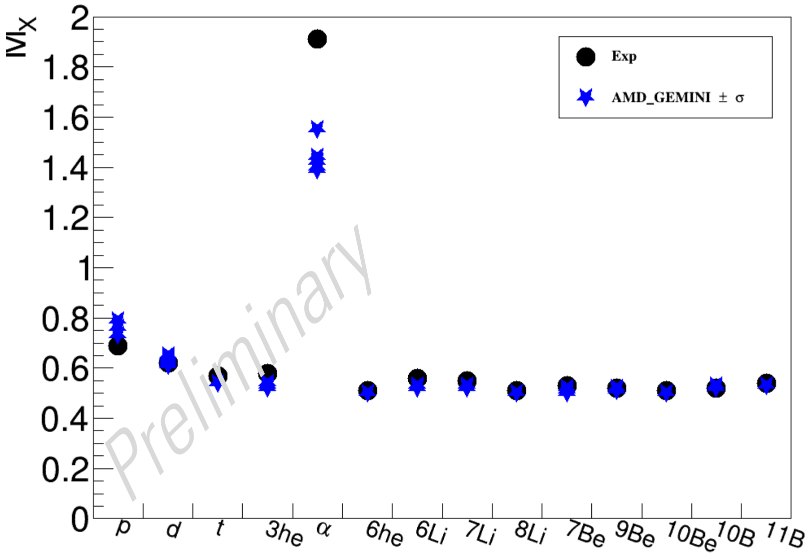
$$f \sim \sigma_{NN}^{in}$$

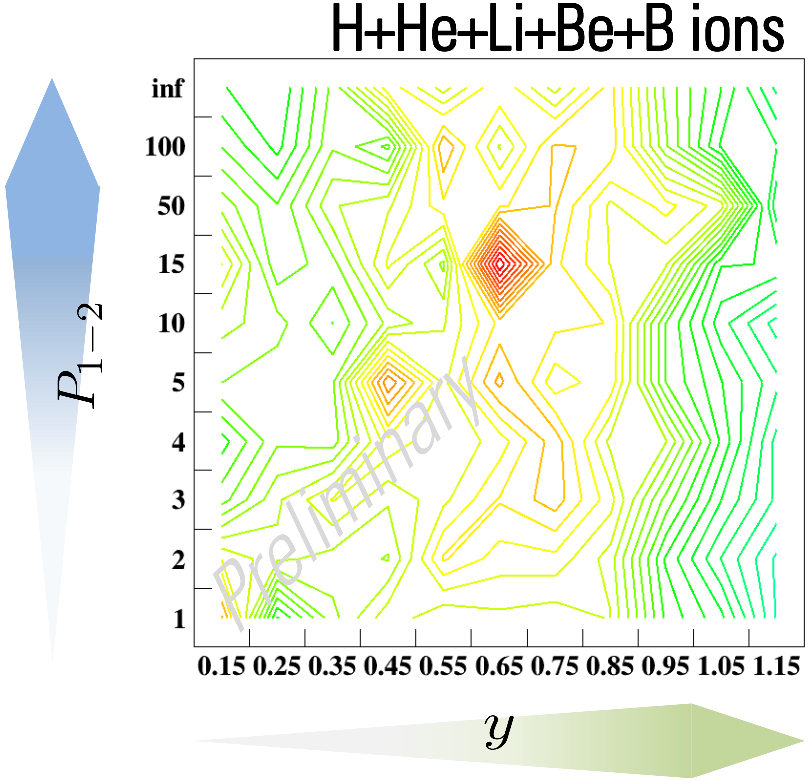
$$v_i d\sigma(C_1, C_2, p_{\rm rel}, \Omega) = \frac{2\pi}{\hbar} P_1(C_1, p_{\rm rel}, \Omega) P_2(C_2, p_{\rm rel}, \Omega) |\mathcal{M}|^2 \delta(E_f(C_1, C_2, p_{\rm rel}, \Omega) - E_i) \frac{p_{\rm rel}^2 dp_{\rm rel} d\Omega}{(2\pi\hbar)^3}$$

$$N_1 + N_2 + B_1 + B_2 \to C_1 + C_2$$

Clusterization probability: $P_{1\text{-}2} = 15$

In-medium NN cross-section: y=0.65

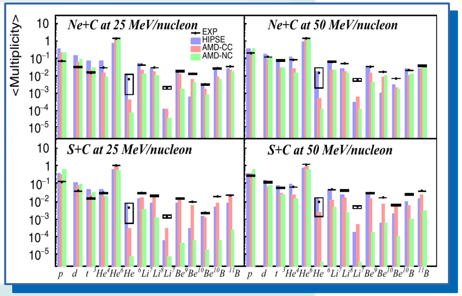




Conclusions

Examination of the cluster production in excited light system at Fermi energies

Cluster production is essential to have a proper reproduction of a collision

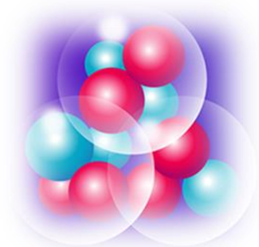


Featured in Physics

Examination of cluster production in excited light systems at Fermi energies from new experimental data and comparison with transport model calculations

C. Frosin *et al.* (INDRA-FAZIA Collaboration)
Phys. Rev. C **107**, 044614 – Published 28 April 2023

Physics See synopsis: Characterizing Clusters in Nuclear Collisions

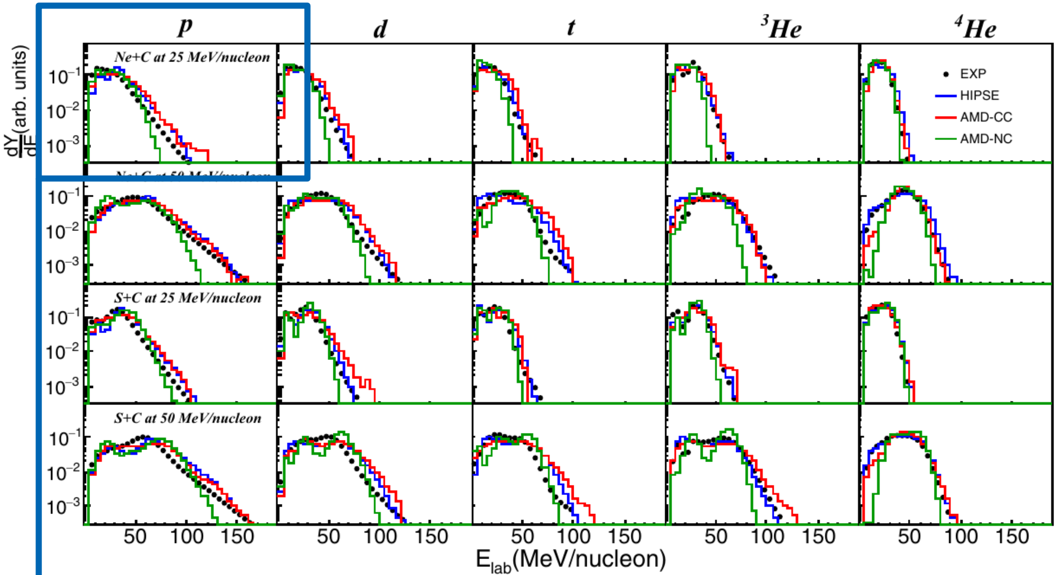


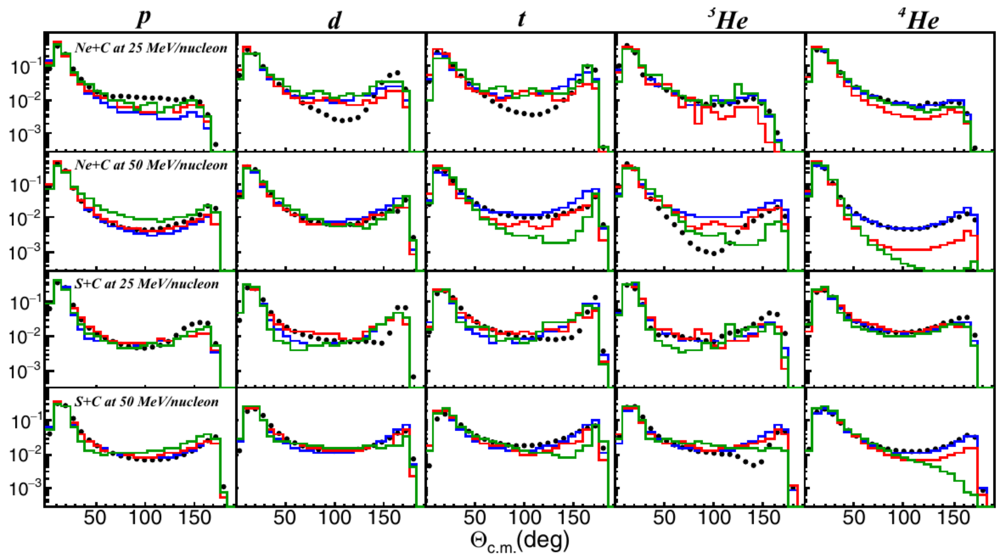
But to what extent?

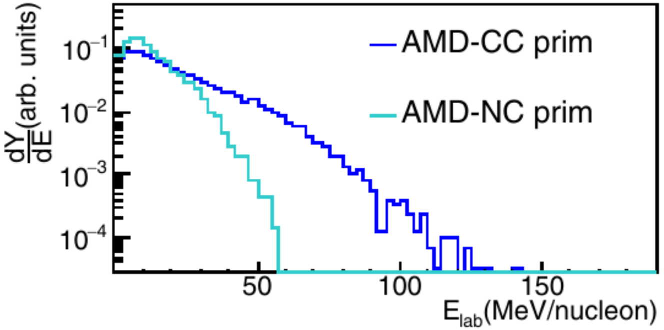
We started a a preliminary Bayesian Inference through AMD+statistical model acting on $(P_{1\text{-}2}, \sigma_{NN})$.

What signals the lack/overproduction of alpha particles?

Cluster phase-space







Pure AMD model: high energy proton reflects the clusterization property during and heavy ion collision