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22-25 MAGGIO 2018
CATANIA

UNIVERSITÀ DEGLI STUDI DI PADOVA

INFN
Istituto Nazionale di Fisica Nucleare

A STUDY ON 4 REACTIONS FORMING THE ^{46}TI*

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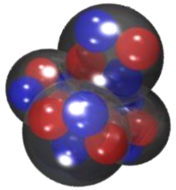
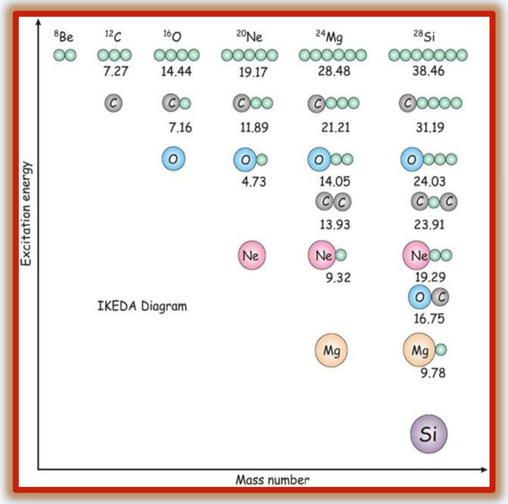
OUTLINE

- Clustering & Pre-equilibrium in Light Nuclei
- The Experiment
- The Simulation Codes: GEMINI++ and AMD
- Analysis Results

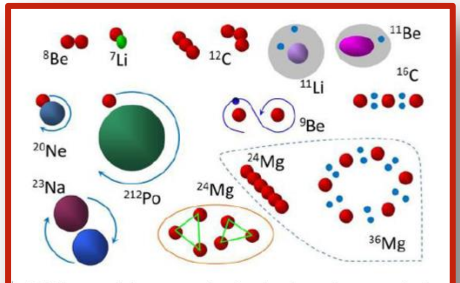


NUCLEAR CLUSTERING



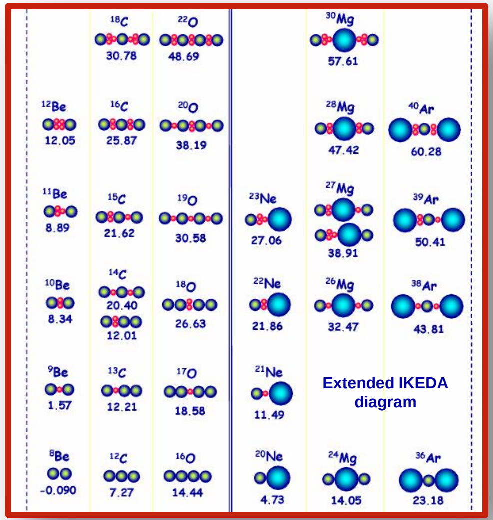
Ikeda Diagram

2N=2Z nuclei: α**-cluster structure** at **E*** close to the α**-decay threshold**



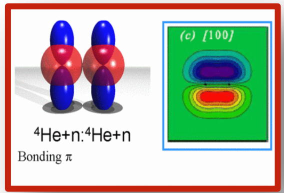
Different type of clustering in nuclei

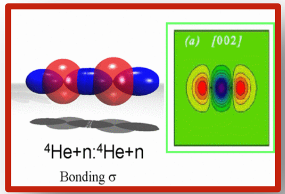
- W. Von Oertzen et al. Phys. Rep. 432 (2006) 43
- M. Freer et al. , Rep. Progr. Phys. 70 (2007) 2149
- J. P. Ebran et al. , Nature 487 (2012) 341
- W.N. Catford J. Phys. Conf. Series 436, 012095
- P.E. Hodgson, E. Běták, Phys. Rep. 374 (2003) 1-89

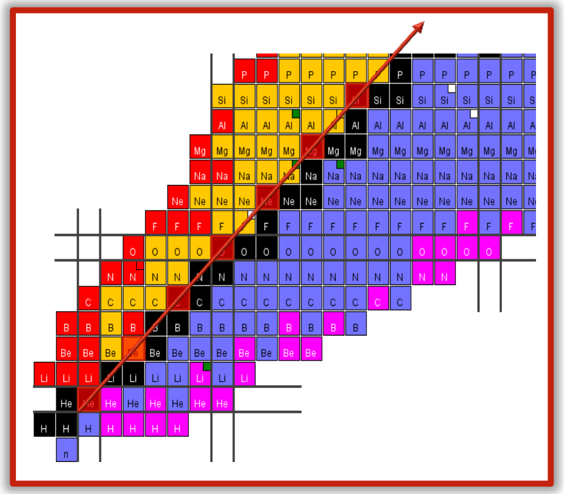


Extended Ikeda Diagram

Neutron-rich nuclei : **molecular structures of clusters** bound by valence neutrons

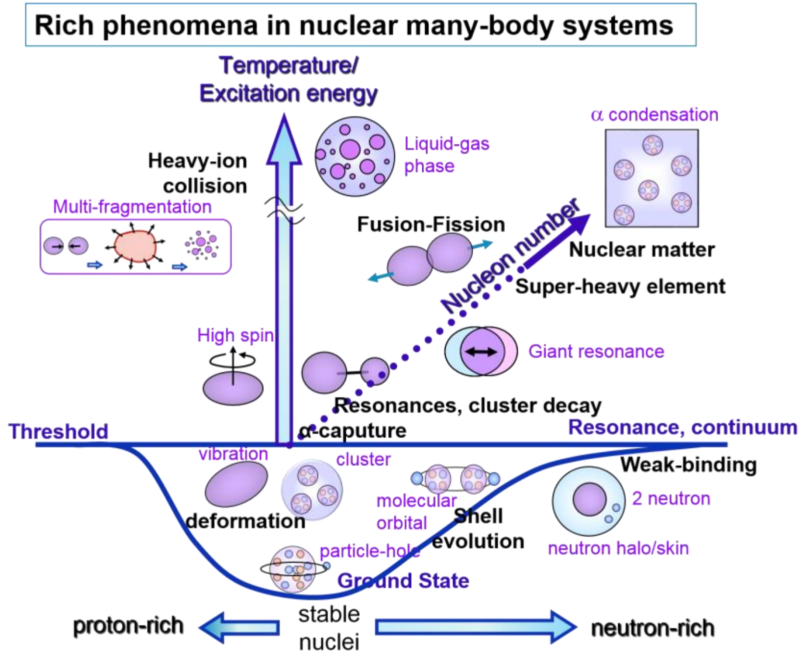






At <u>drip-lines:</u> clustering might be the preferred structural mode of the **light nuclei .**

STUDYING CLUSTER EFFECTS



Y. Kanada-En'yo, International School of Physics "Enrico Fermi", course 201 (Nuclear Physics with Stable and Radioactive Beams), 14-19 July 2017

- Y. Kanada-En'yo et al., Prog.Theo.Exp.Phys. 01A202 (2012).
- P.E. Hodgson, E. Běták, Phys. Rep. 374 (2003) 1-89.

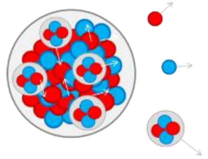
Light Nuclei

Coexistence of cluster and mean-fields aspects: connection between cluster emission and nuclear structure.

Medium Mass Nuclei

Clustering effects on reaction dynamics can be **related** either to their **preformation or** to their **dynamical formation**.

analize pre-equilibrium particles emission



Study the competition between evaporation (surface) and fast (volume) emission of LCP.

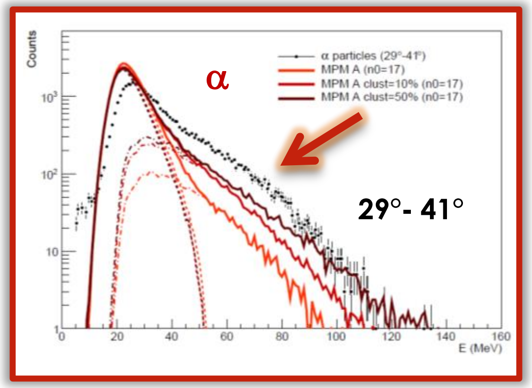
HOW TO STUDY THE CLUSTERING EFFECTS ON REACTION DYNAMICS?

Possible effects of **a-cluster structure in the projectile**

experimentally ↓

- Studying pre-equilibrium particles emission:

$^{16}O + {}^{116}Sn$ @ $8, 12, 16\ MeV/u$
Over-production of a-particles emitted during the non-equilibrium stage → a-cluster structure in the ^{16}O projectile nucleus.



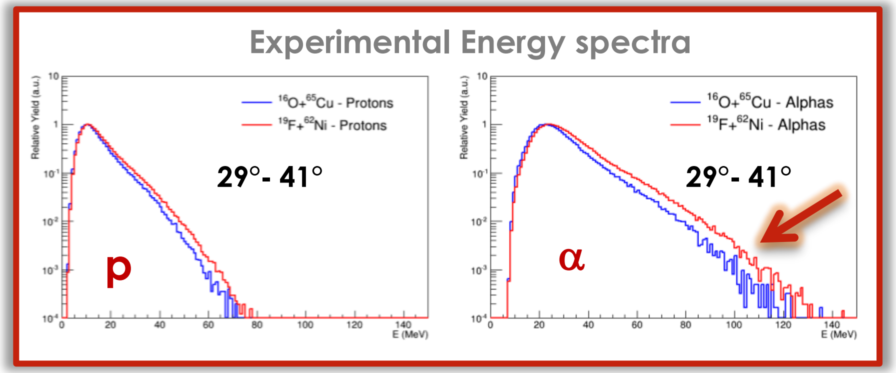
- A. Corsi et al., PLB 679 (2009) 197.

- Comparing LCP emission from fusion reactions with different N/Z projectiles:

Analysis is still in progress

$^{16}O + {}^{65}Cu$ & $^{19}F + {}^{62}Ni$ @$16\ MeV/u$
^{19}F-reaction a-overproduction > ^{16}O one.
↓
$E_s(^{19}F \equiv \alpha + {}^{15}N) = 4{,}01\ MeV$ $E_s(^{16}O \equiv \alpha + {}^{12}C) = 7{,}2\ MeV$

- D. Fabris et al., Proceedings of the X LANSPA, Proc. of Science (2014).



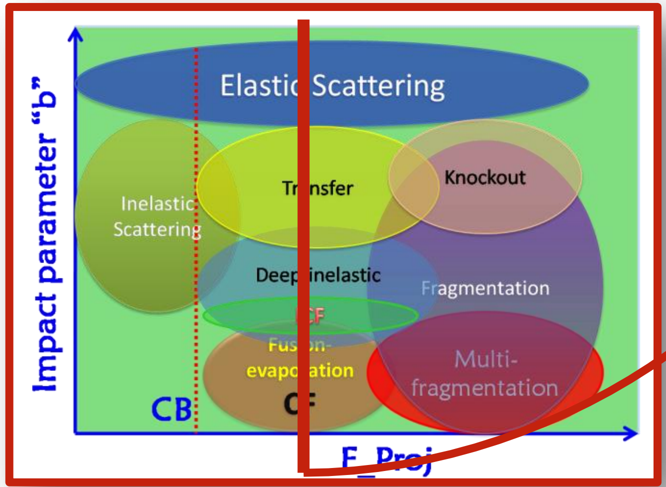
THE EXPERIMENT: REACTIONS MAIN CHARACTERISTICS

Entrance channel	$E_{beam,\ lab}$		$\theta_{grazing}$	CN	Mass Asymm	σ_{fus}	E*	Lab. Vel.	E.R. Distrib. θ_{lab}
Beam + Target	MeV	**MeV/u**	deg			mb	**MeV**	cm/ns	deg
$^{16}O + ^{30}Si$	128	**8**	8,8	**^{46}Ti**	0,30	1070	**98,4**	1,37	0 – 30
$^{16}O + ^{30}Si$	111	**7**	10,1	**^{46}Ti**	0,30	1081	**88,0**	1,28	0 – 30
$^{18}O + ^{28}Si$	126	**7**	9,0	**^{46}Ti**	0,22	1110	**98,5**	1,44	0 – 28
$^{19}F + ^{27}Al$	133	**7**	8,9	**^{46}Ti**	0,17	1100	**103,5**	1,52	0 – 28

same beam velocity ⇨ same pre-equilibrium component

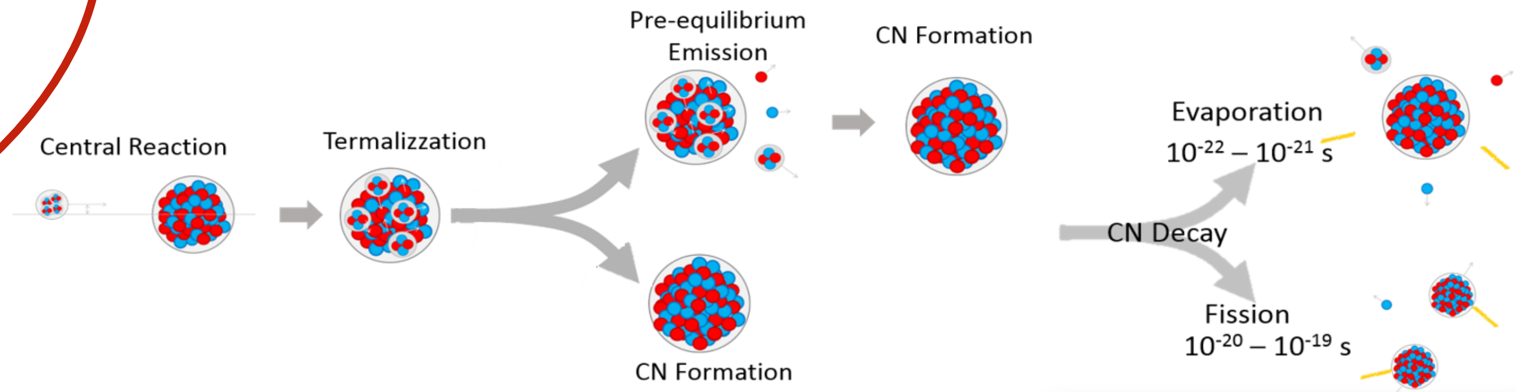
same CN Excitation Energy ⇨ same statistical component

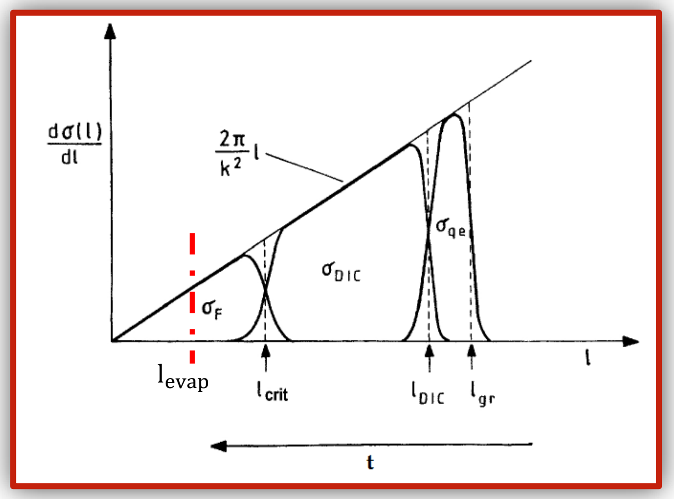
REACTION MECHANISMS



$$E_p > B_C \Rightarrow \sigma_{reaz} = \sum_{\ell} \sigma_{reaz}(\ell) = \frac{\pi}{k^2} \sum_{0}^{\infty} (2\ell + 1)\, T_\ell$$

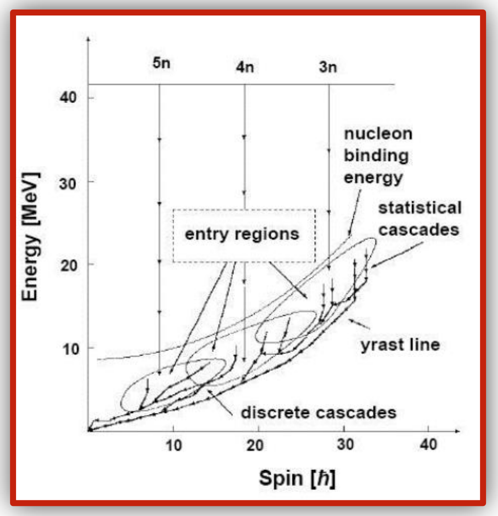
"Complete Fusion (CF) is the most dominating mode of reaction"



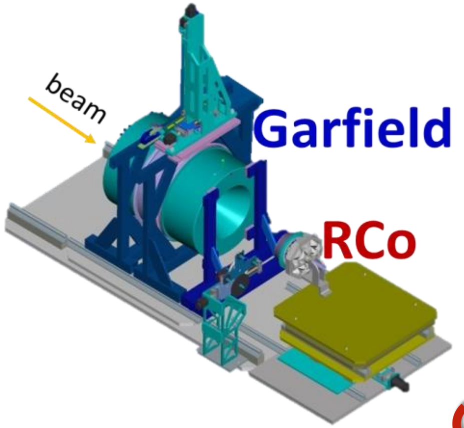


Process involving two heavy colliding ions that at end **form a CN** with LARGE EXCITATION ENERGY and ANGULAR MOMENTUM will DEEXCITE:

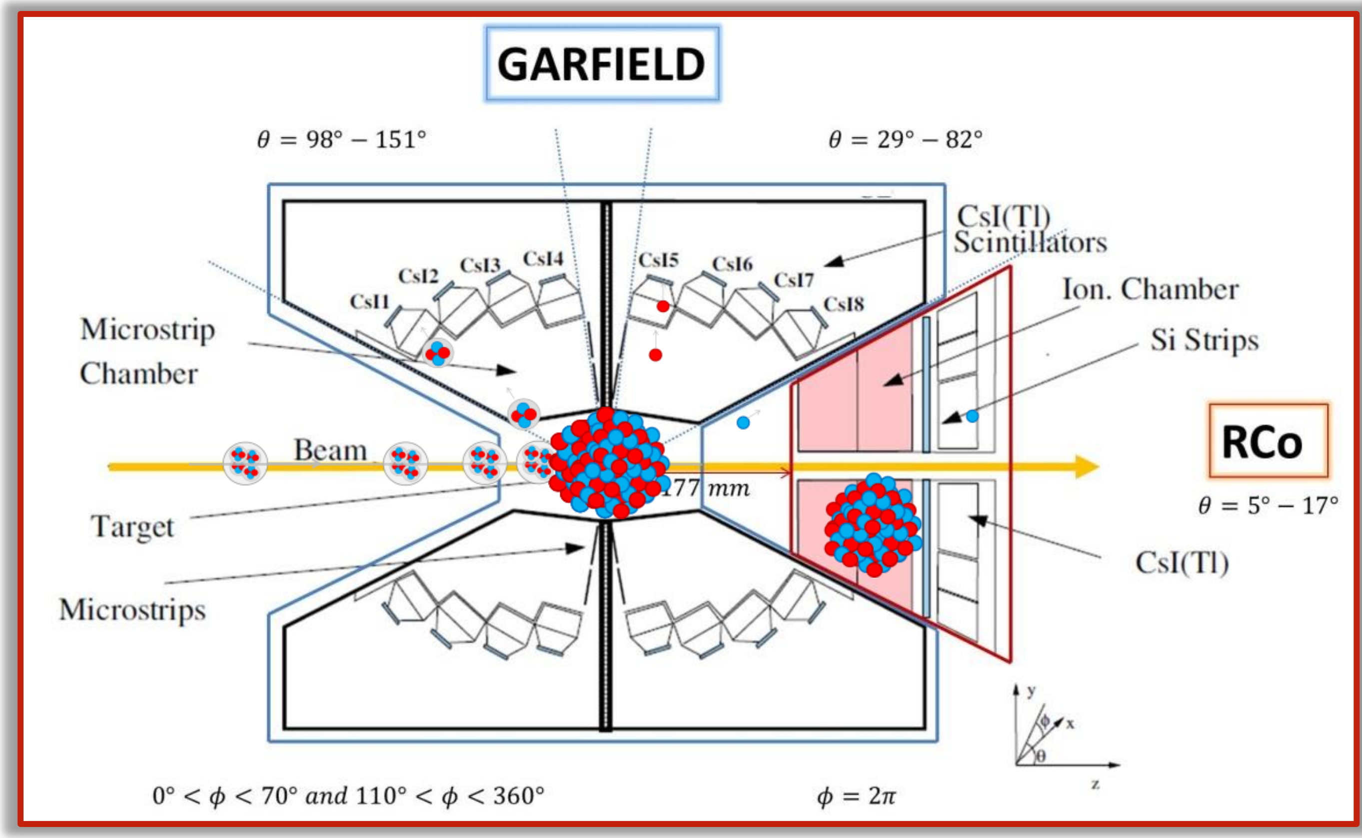
- emitting evaporation particles and residues
- fission



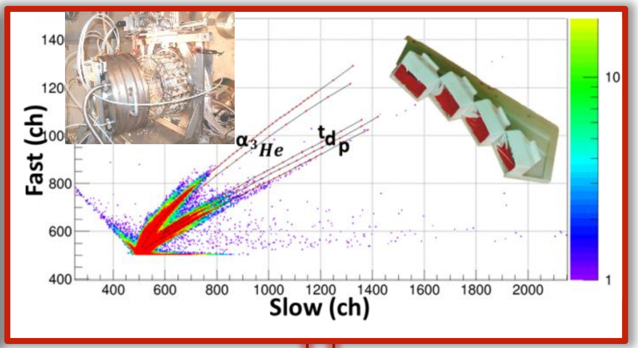
THE EXPERIMENTAL ARRAY



GARFIELD + RCo

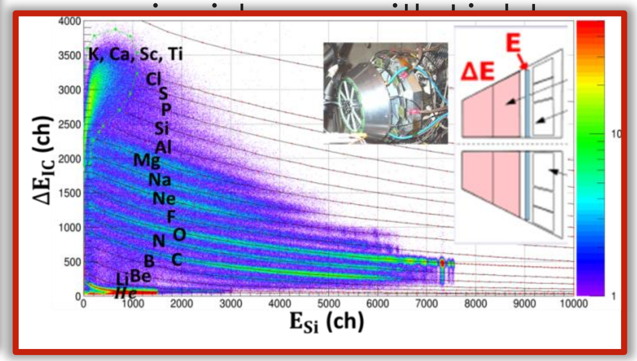


LCP identification



Evaporation Residue is

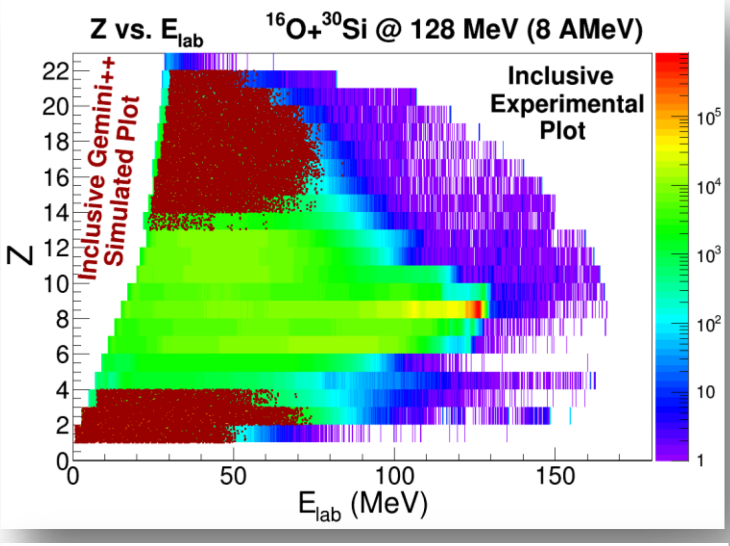
RESIDUE identification



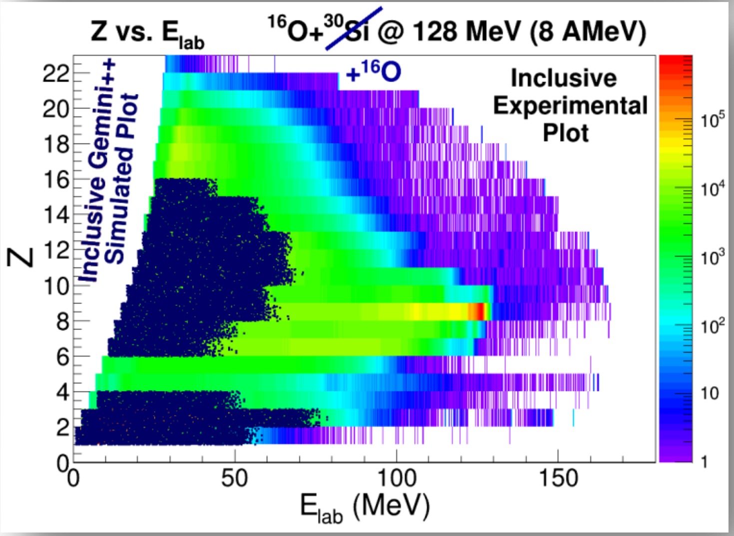
- F. Gramegna et al., Proc. of IEEE Nucl.Symp., 2004, Roma, Italy, 0-7803-8701-5/04/.
- M. Bruno et al. Eur. Phys. J. A (2013) 49: 128

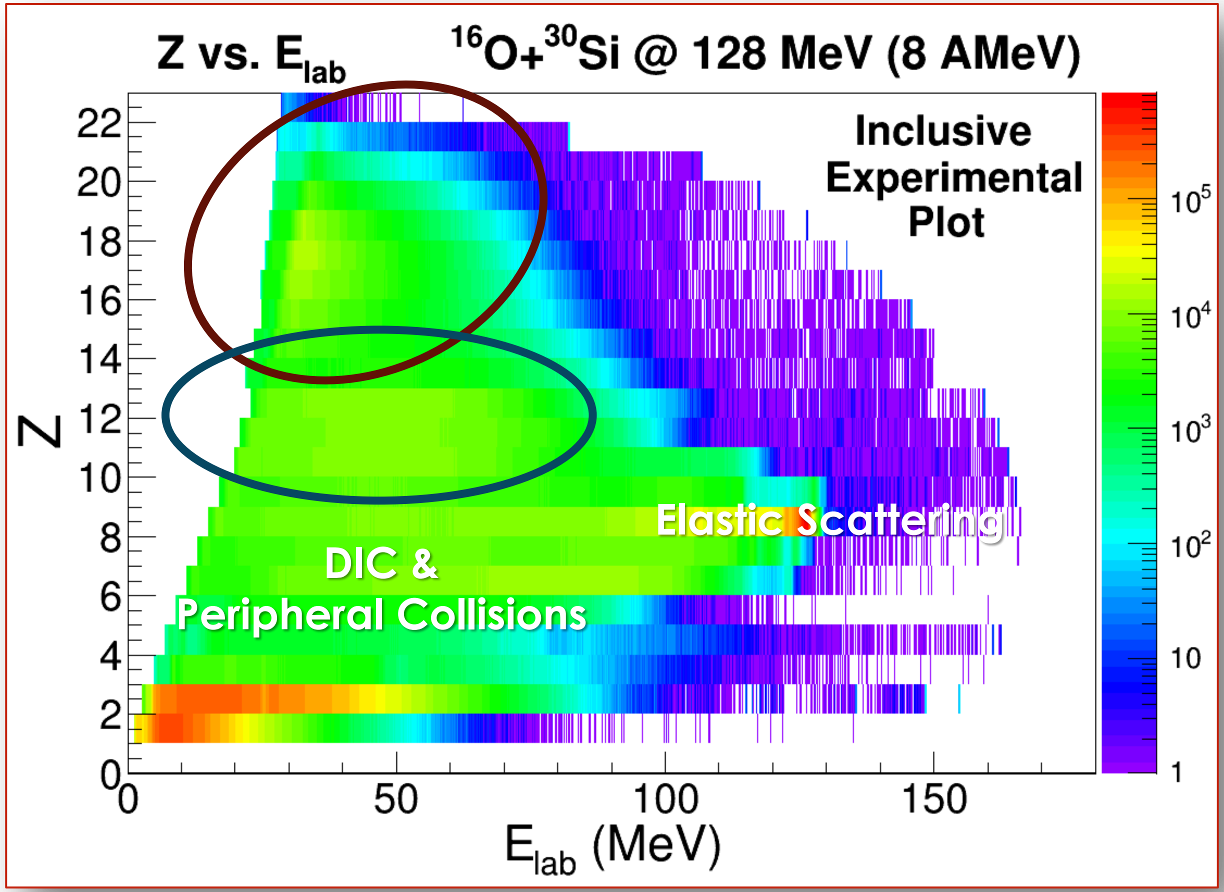
TARGET CONTAMINATION

Gemini Simulation Plot: ^{30}Si target



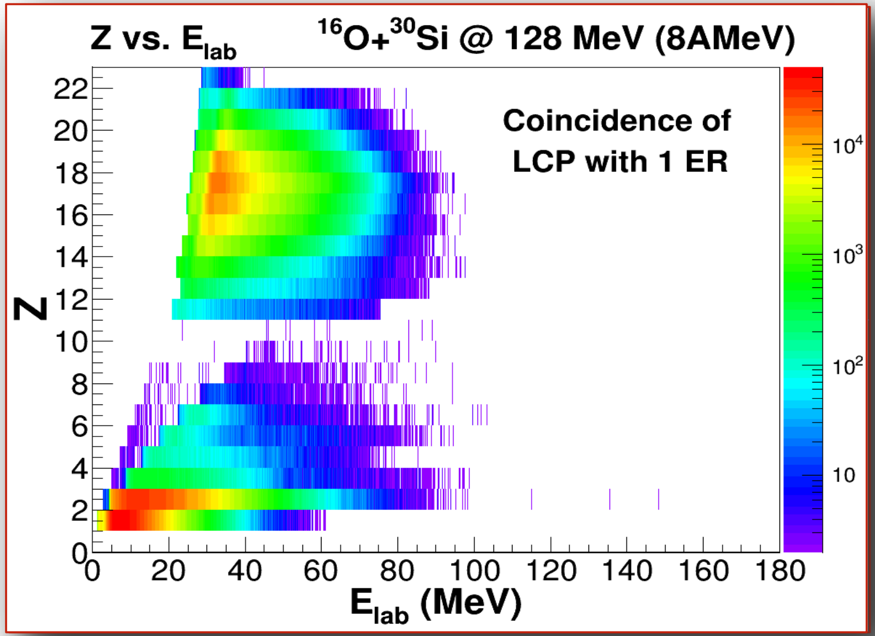
Gemini Simulation Plot: ^{16}O target



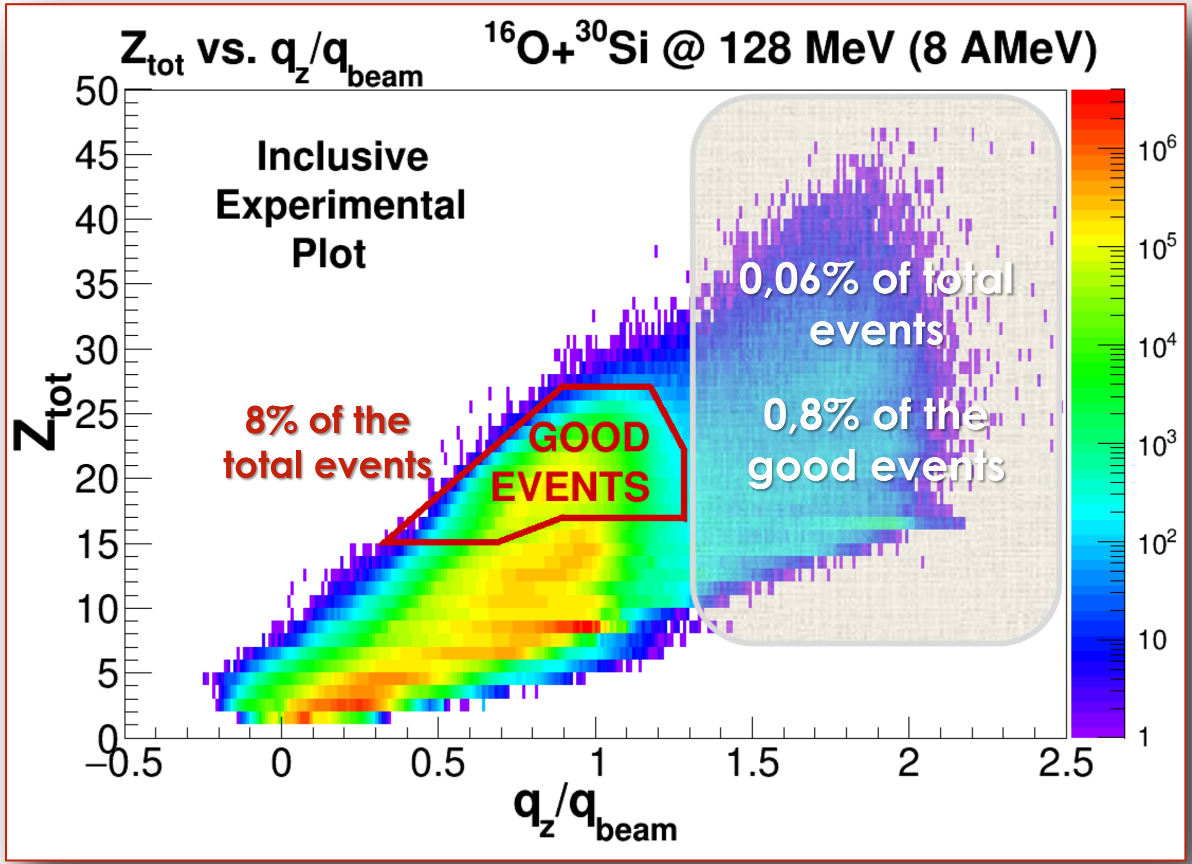


GOOD EVENTS SELECTION

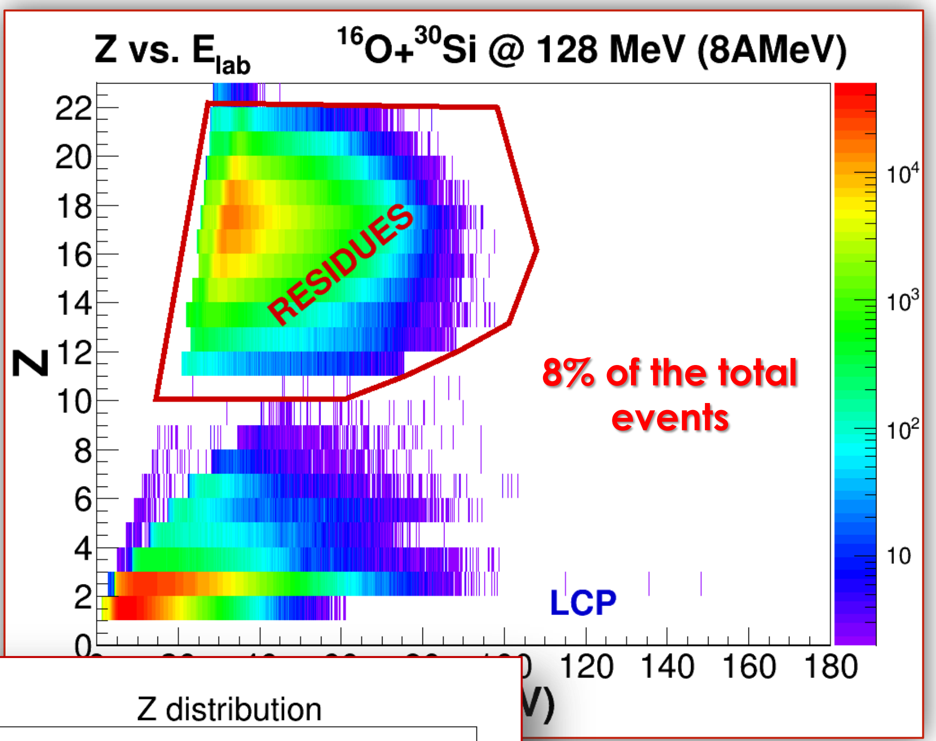
Correlation between the laboratory energy and charge



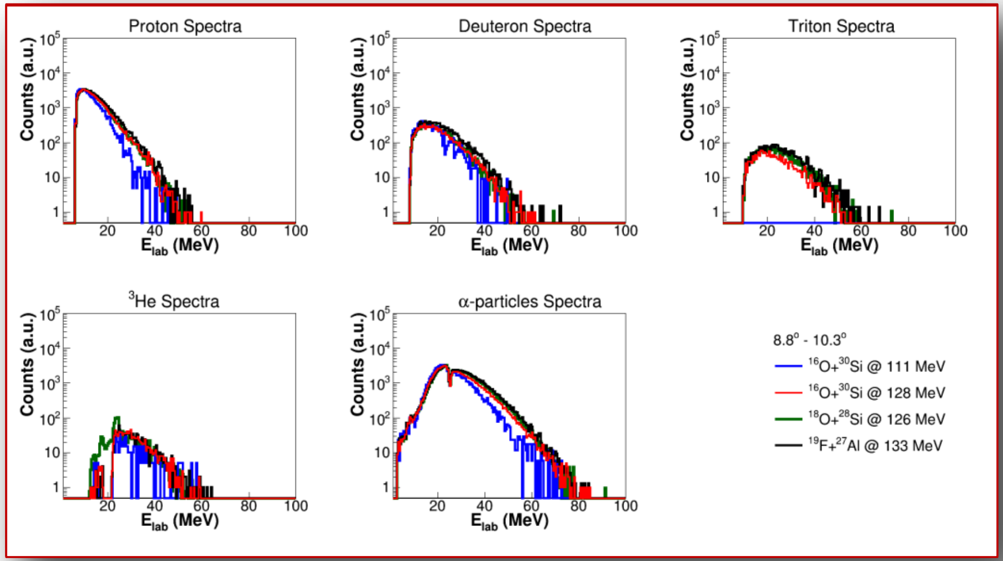
Correlation between the longitudinal momentum and total charge

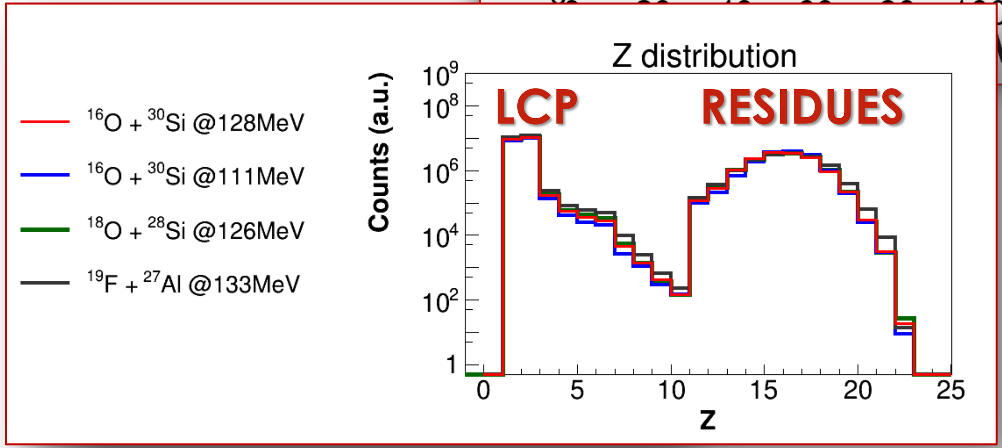


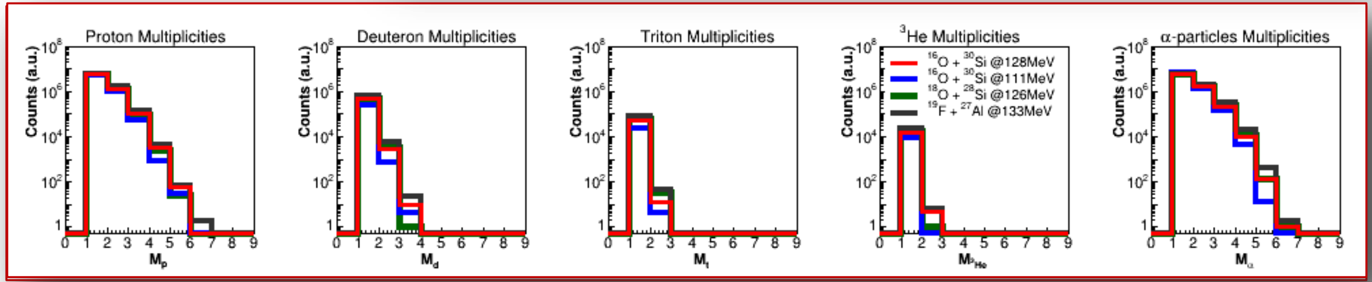
QUASI-COMPLETE EVENTS



LCP







THEORETICAL SIMULATIONS

$^{16}O(8AMeV)+^{30}Si$
$^{16}O(7AMeV)+^{30}Si$
$^{18}O(7AMeV)+^{28}Si$
$^{19}F(7AMeV)+^{27}Al$

→ $^{46}Ti^*$ → **DEFORMED NUCLEUS**

$^{46}Ti^*$ → DECAY

Interacting Nuclei Structure & Reaction Dynamics

AMD code

- describes the cluster structure of the interacting particles.
- takes into account the particle-particle correlations.

{A. Ono, Phys. Rev. C59, 853 (1999)}

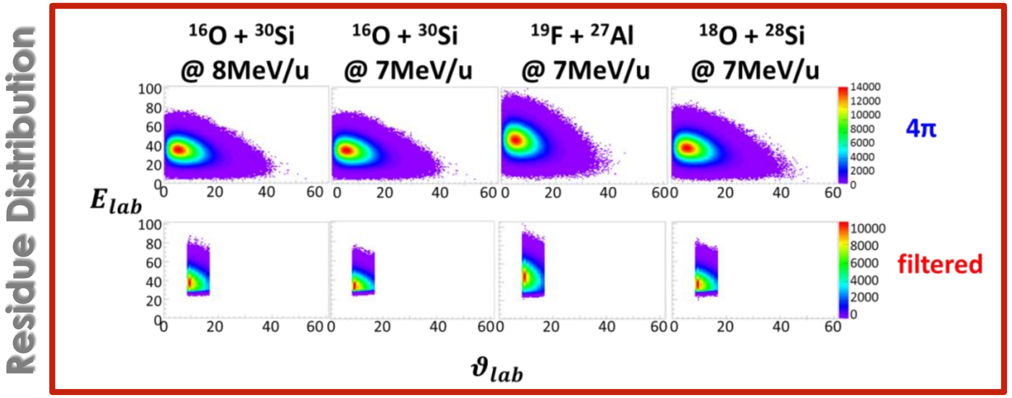
GEMINI++ code

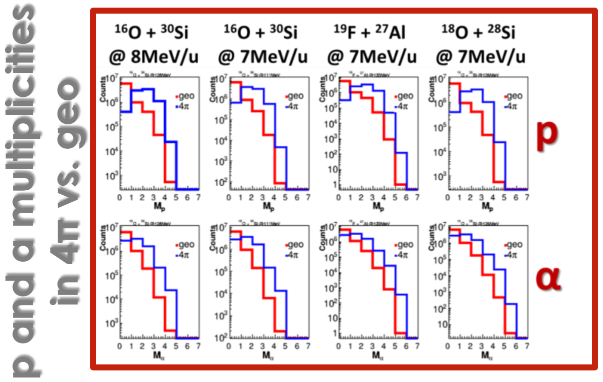
Simulate the decay of hot nuclei formed in fusion/quasi-fusion reaction.

- **Standalone** when a good selection of central events can be performed;
- **Afterburner** (after a dynamical code) to produce secondary particles distributions from primary fragments -> to be compared with exp data.

{R. J. Charity, Phys Rev C 82 (2010) 014610.}

Effect of the Experimental filter (software) applied on GEMINI++ simulation of the 4 studied systems





^{46}Ti: A DEFORMED NUCLEUS

{A. Maj et al., Eur.Phys.J. A 20 (2004) 165-166}

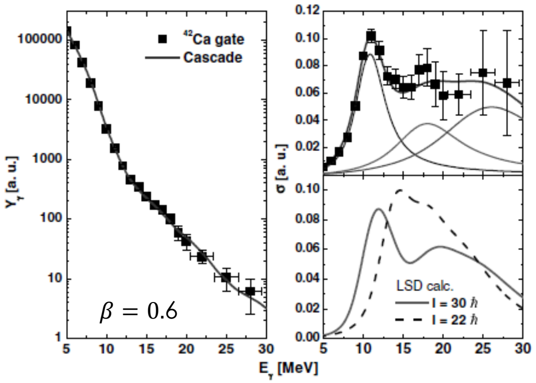


Fig. 2. Left: spectrum of the γ-rays from the decay of the GDR built in hot ^{46}Ti in coincidence with the discrete transitions in the residual nucleus ^{42}Ca, together with the Cascade calculations assuming 3-Lorentzian GDR strength function with E_{GDR} = 10.8, 18 and 26 MeV. Upper right: experimentally obtained GDR absorption cross-section and the GDR strength function used in Cascade calculations. Bottom right: thermal shape fluctuation predictions based on potential energies from the LSD model calculations for $I = 22\hbar$ and $I = 30\hbar$.

{M. Brekiesz et al., Nucl.Phys A 788 (2007) 224c-230c}

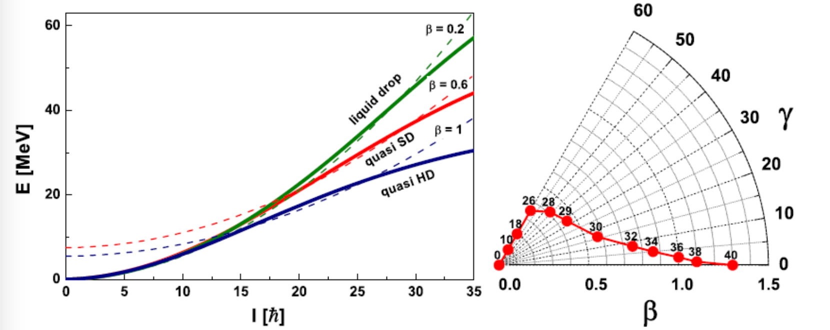
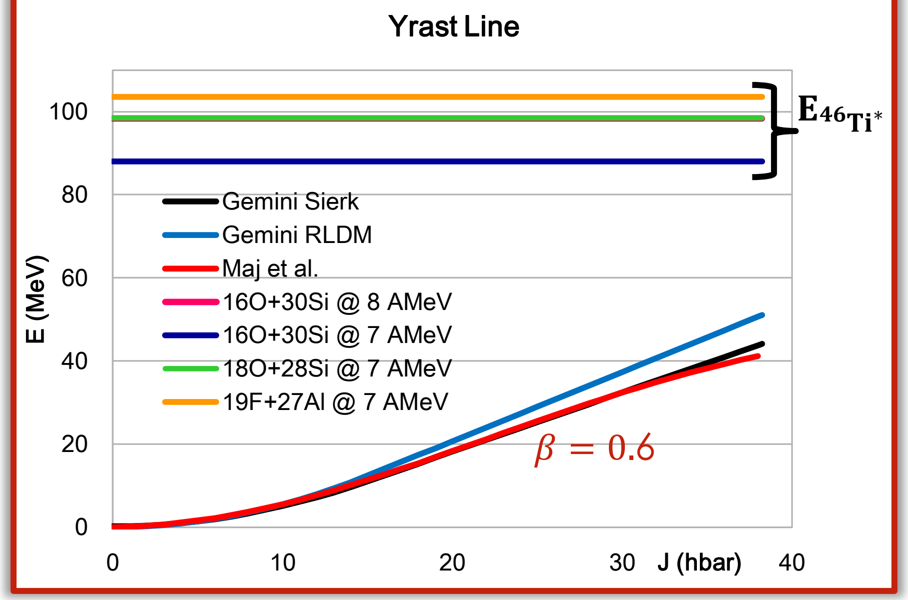


Figure 2. Left: the yrast lines used in the calculations (solid lines) and the rigid body yrast lines with different deformation parameters (dotted lines). Right: the evolution of the equilibrium shape of ^{46}Ti as a function of spin predicted by the LSD model.

β	δ_1	δ_2	Shape
0.2		*RLDM* parameters	
0.6	$\mathbf{4.6 \times 10^{-4}}$	$\mathbf{1.0 \times 10^{-7}}$	***Quasi − SUPERDEFORMED***
1.0	1.1×10^{-3}	1.0×10^{-7}	*Quasi − HYPERDEFORMED*



<u>CACARIZO code</u>:

$$E(J) = \frac{\hbar^2 J(J+1)}{\Im_{sphere}(1+\delta_1 L^2+\delta_2 L^4)},\ with\ \delta_1 and\ \delta_2 \text{ deformation parameters}$$

<u>the equivalent in **GEMINI++ code**</u>:

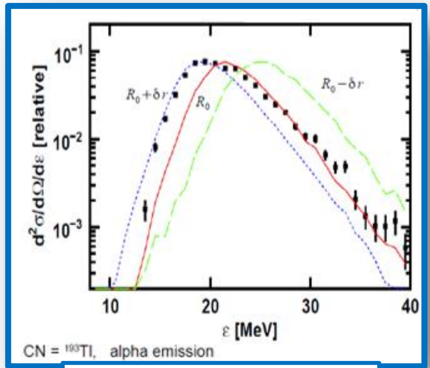
$$E_{Yrast}(J) = \begin{cases} E_{Sierk}(J)\ if\ J < J^* \\ E_{Sierk}(J) + (J - J^*)E_{Sierk}(J^*)\ if\ J > J^* \end{cases},\ with\ J^* = 0.319A$$

THE STATISTICAL CODE: GEMINI++

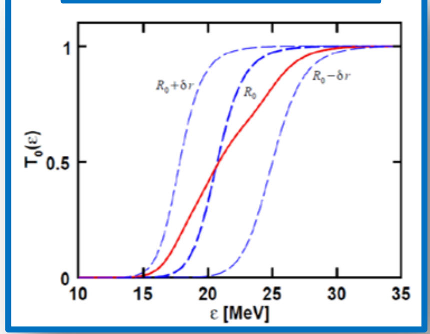
Hauser-Feshbach Model → Weisskopf Evaporative Theory; Quantum Description of Angular Momentum

$$W_\beta \propto \iint \tilde{\ell}\, T_\ell \rho_B(E^*{}_B, J_B)\, d\varepsilon_b\, d\phi$$

$$\tilde{\ell} = 2\ell + 1$$



{R. J. Charity, Phys Rev C 82 (2010) 014610}



3 ingredients in the statistical model:

1. Transmission coefficients

$$T_l(\epsilon) = \frac{T_l^{R_0-\delta r}(\epsilon) + T_l^{R_0}(\epsilon) + T_l^{R_0+\delta r}(\epsilon)}{3}, \delta r = w\sqrt{T}$$

2. Level density parameter

$$\rho_B(E_B^*) \propto 2\sqrt{aE_B^*}$$

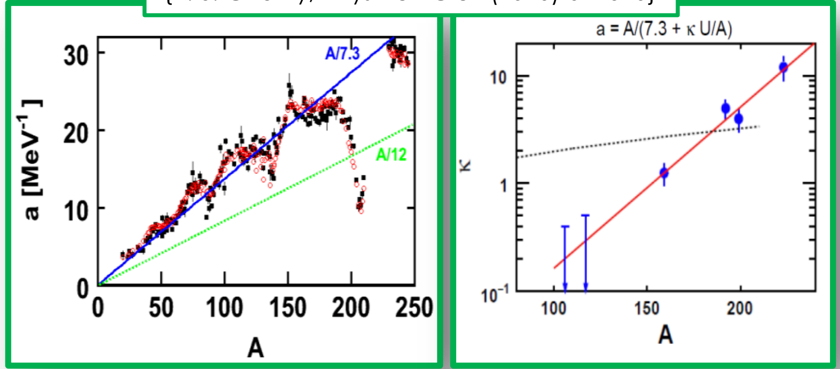
$$a = \frac{A}{k_\infty - (k_\infty - k_0)exp\left(-\frac{\kappa}{k_\infty - k_0}\frac{U}{A}\right)}$$

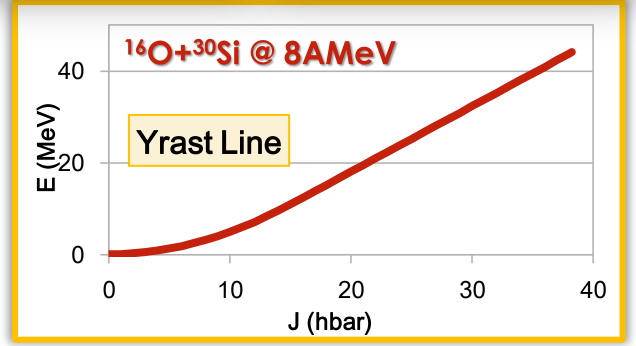
$$\kappa(A) = 0.000517exp(0.0345A)$$

3. Macroscopic rotational energy of the nucleus

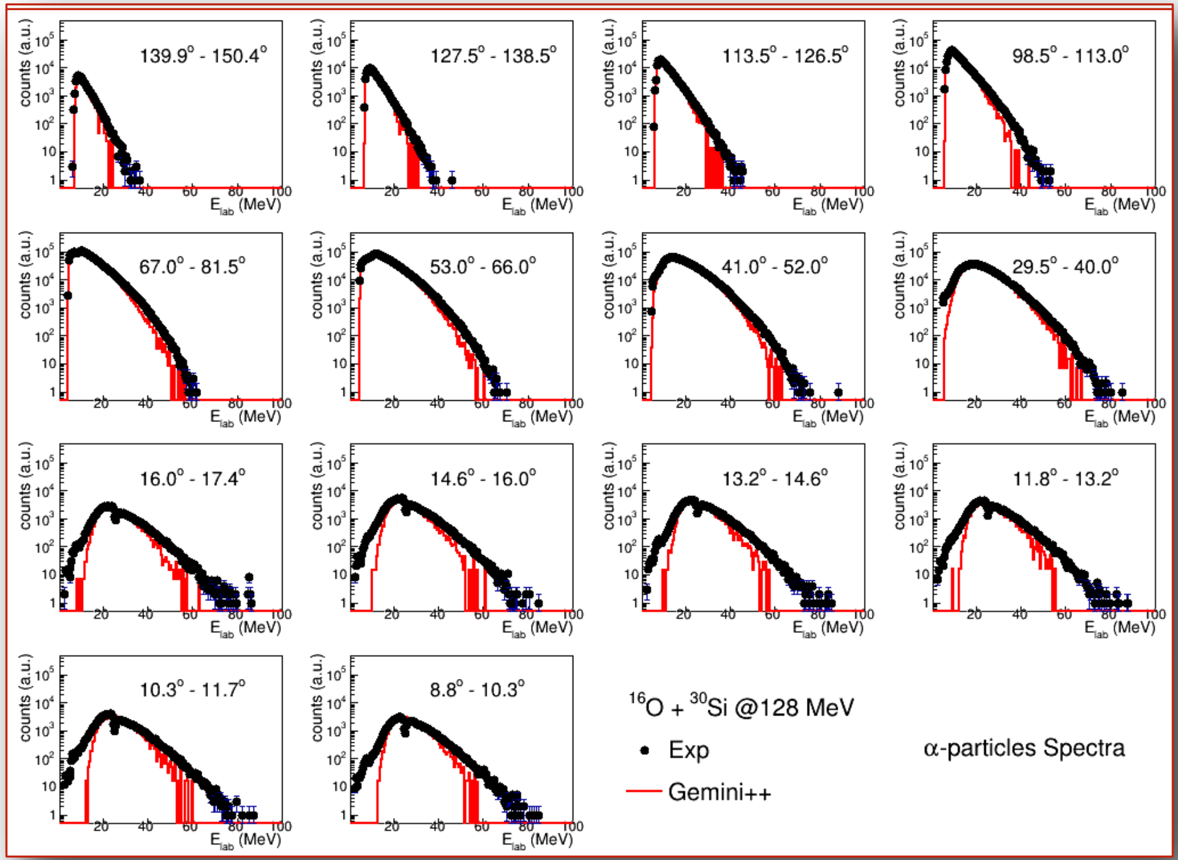
$$E_{Yrast}(J) = \begin{cases} E_{Sierk}(J)\ if\ J < J^* \\ E_{Sierk}(J) + (J - J^*)E_{Sierk}(J^*)\ if\ J > J^* \end{cases}, J^* = 0.319A$$

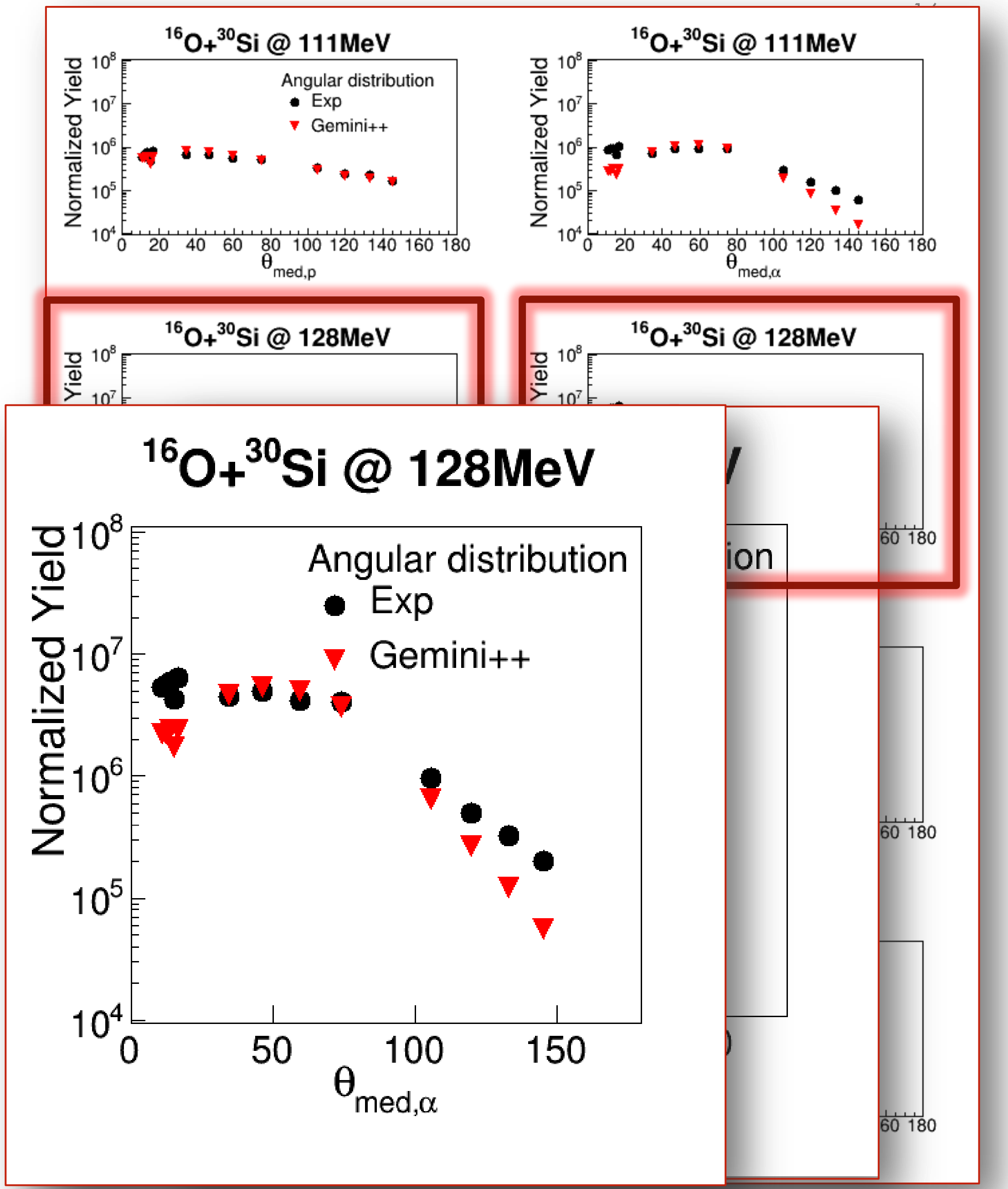
{R. J. Charity, Phys Rev C 82 (2010) 014610}



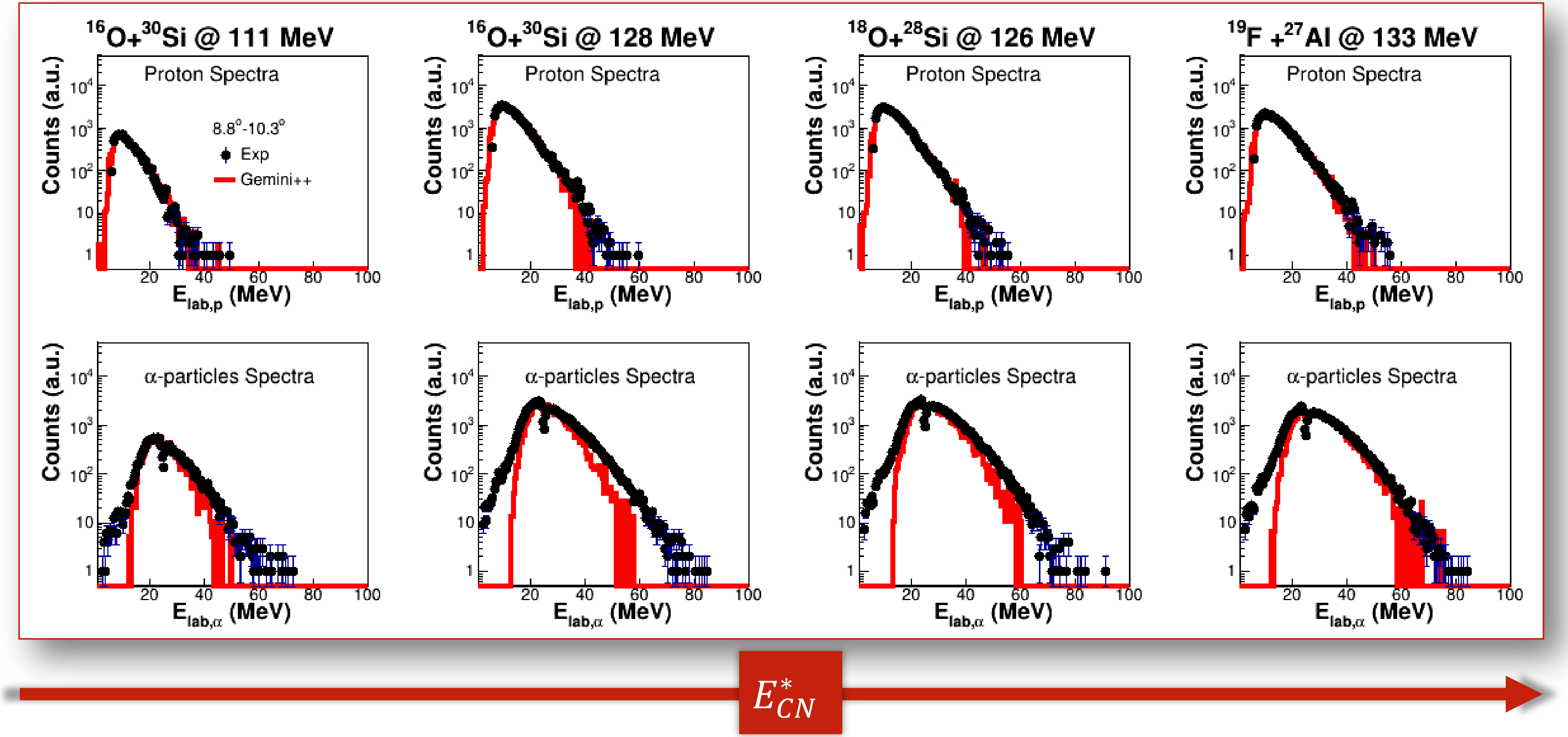


ANALYSIS RESULTS: ANGULAR DISTRIBUTION

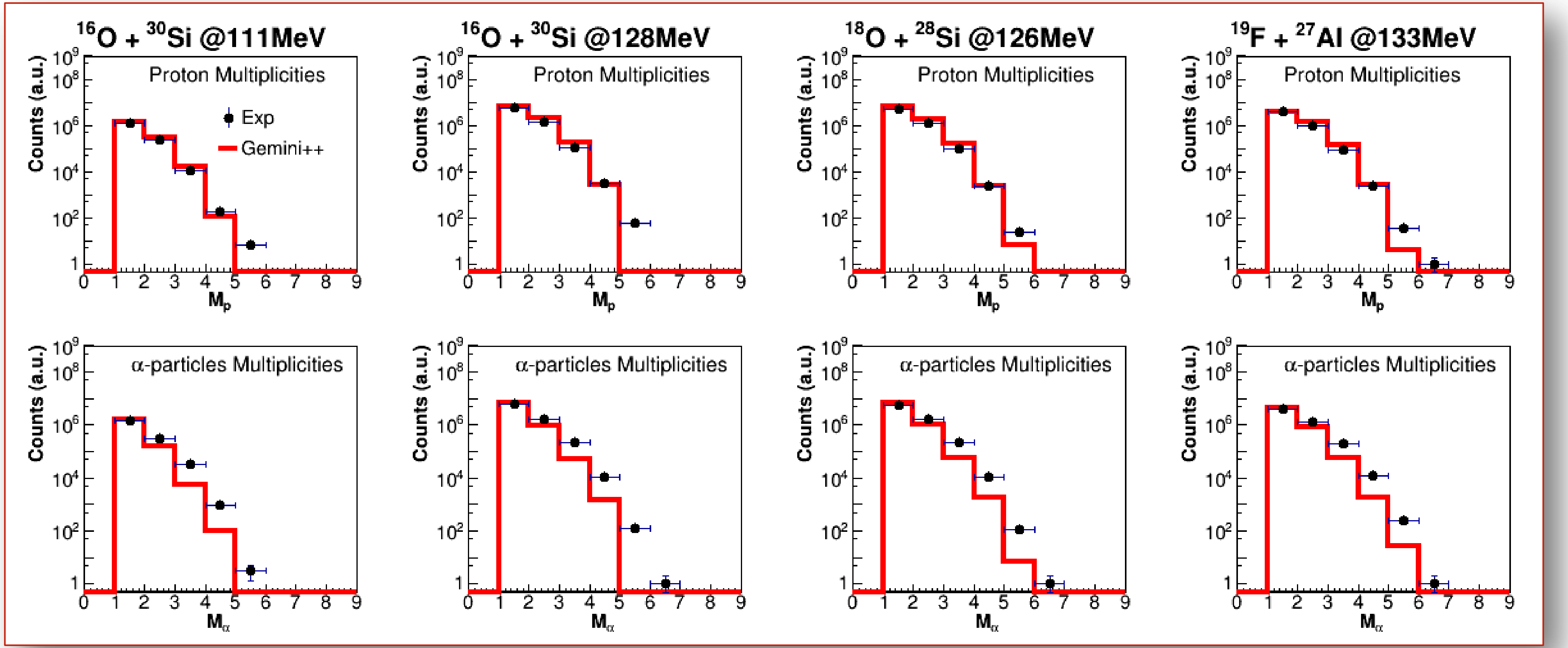




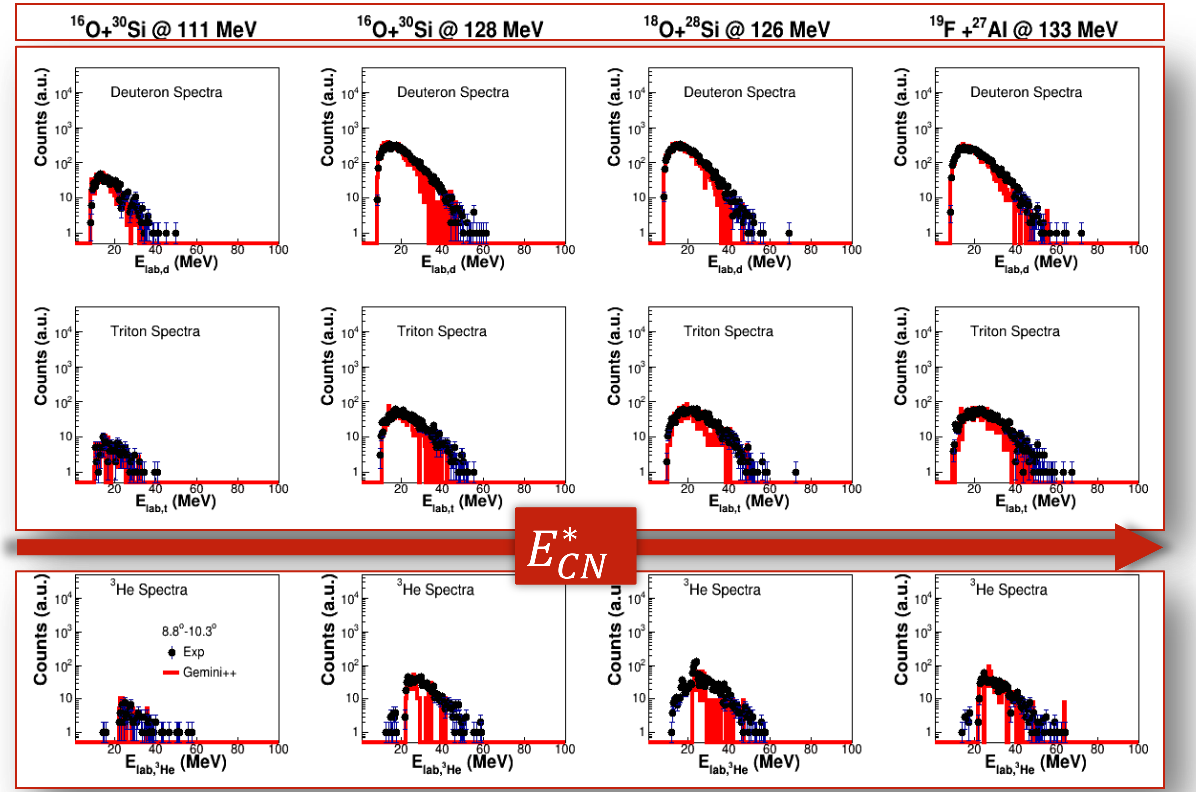
ANALYSIS RESULTS: PROTON & α-PARTICLE SPECTRA

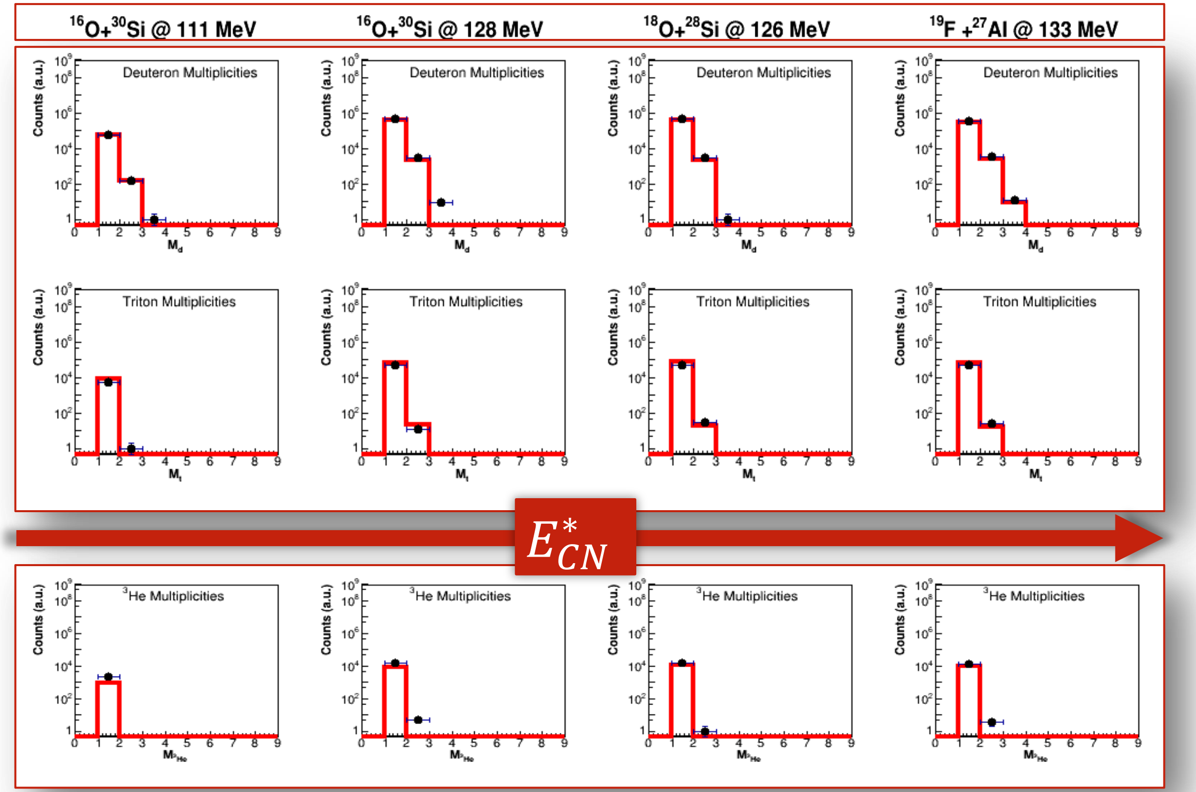


ANALYSIS RESULTS: PROTON & α-PARTICLE MULTIPLICITY



ANALYSIS RESULTS: DEUTERON, TRITON AND ^{3}HE



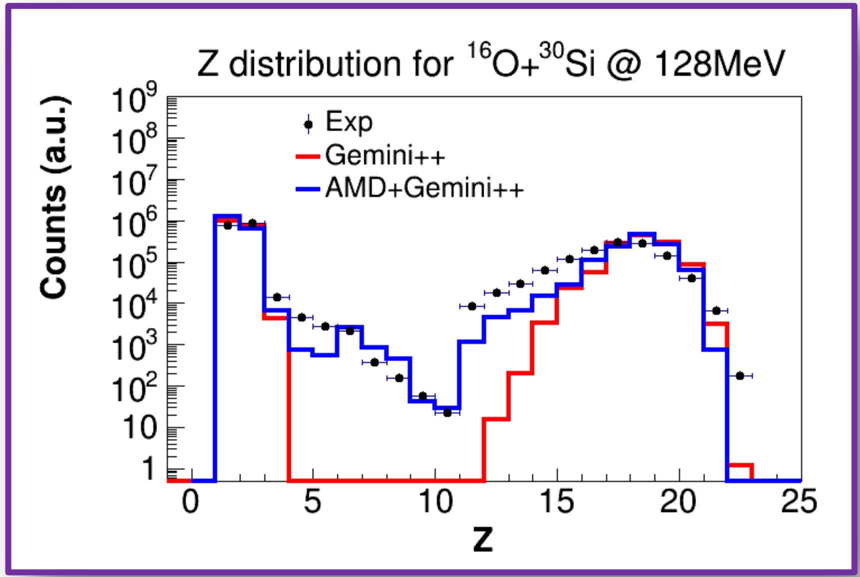


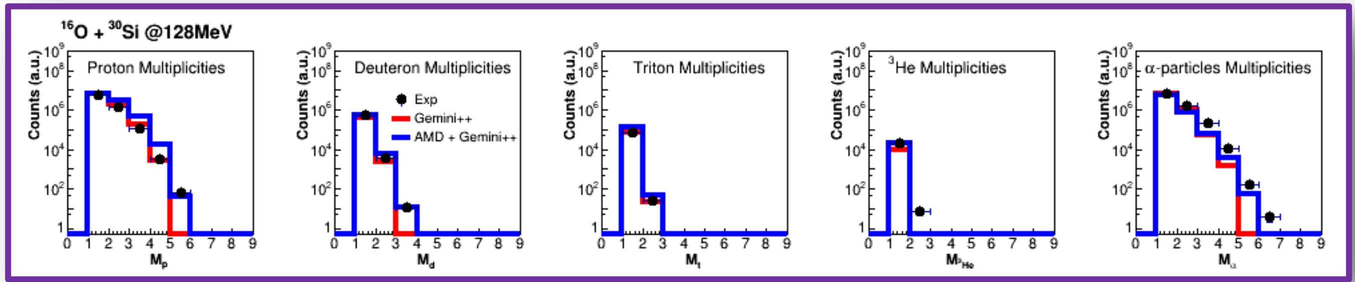
SUMMARY

Studying the **decay of ^{46}Ti***, the theoretical **GEMINI++ simulations reasonably reproduce the major part of global variables** for all the reactions; nevertheless, the **slight differences** observed are crucial for analyzing the **interplay between the two different reaction mechanisms**. In particular, the overproduction of alpha-particles of forward angles represents a signature of the onset of fast emission.

… AND PERSPECTIVE

- Study on **particle-particle correlations** will be performed, **selecting specific decay channels** (1a, 2a, 3a …) to get a better insight on the reaction interplay;
- The **AMD calculations are in progress**: AMD events are available for only one system. Further calculations are ongoing for all systems for a number of events necessary to compare with exclusive experimental data.





THANK YOU FOR YOUR ATTENTION!

NUCL-EX COLLABORATION

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