Reaction dynamics and exotic systems: a focus on fast processes

T. Marchi (IKS, KU Leuven) – XX Colloque GANIL, Amboise 15-20 October 2017

Motivation and outline

Fast processes in fusion reactions

1. **Competition between pre-equilibrium and evaporation processes in fusion reactions. [n,LCP,γ emission cross sections]**
2. **Influence of Nuclear Structure on the reaction dynamics.**
3. **Cluster pre-formation vs Dynamical formation (coalescence)**

Outline:

- ^{12}C and ^{16}O-induced reactions, inclusive cross sections with pre-equilibrium
- Pre-equilibrium and clustering
- The ACLUST campaigns
- Outlook with Stable beams and RIBs

Pre-equilibrium revival

PHYSICAL REVIEW C **91**, 014603 (2015)

Systematic study of pre-equilibrium emission at low energies in ^{12}C- and ^{16}O-induced reactions

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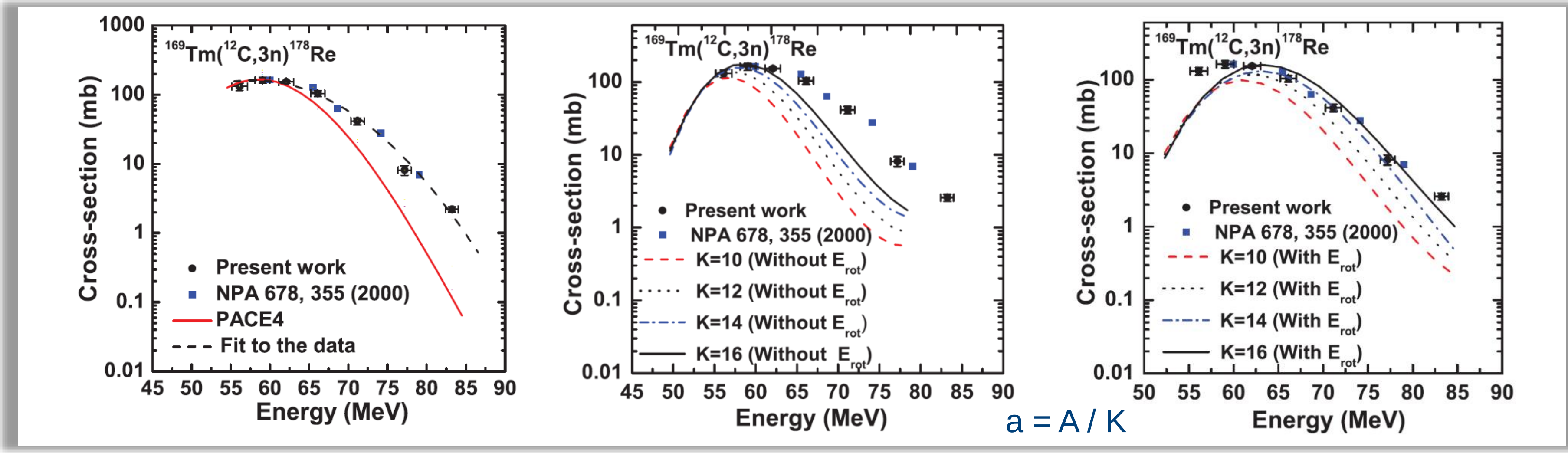
(Received 25 September 2014; revised manuscript received 22 October 2014; published 6 January 2015)

TABLE I. Details of the system studied, including measured thickness of the samples, Coulomb barrier, and energy of interest

Serial number	System studied	Measured thickness (mg/cm^2)	Coulomb barrier (MeV)	Energy studied (MeV)	Reaction channels	$T_{1/2}$	Energy (E_γ) (keV)	Branching ratio (%)
1	$^{12}C^{6+} + ^{128}Te$	0.92	42.2	≈42–80	$^{128}Te(^{12}C,3n)^{137}Ce$	13 h	254.29	11.0
2	$^{12}C^{6+} + ^{169}Tm$	0.50	51.5	≈55–85	$^{169}Tm(^{12}C,3n)^{178}Re$	13.2 m	106.0, 237.0	23.4, 44.5
							351.5	5.5
3	$^{16}O^{7+} + ^{159}Tb$	1.80	63.8	≈68–95	$^{159}Tb(^{16}O,3n)^{172}Ta$	38.8 m	214.0, 318.7	55.0, 49.0
							1109.2	14.9
4	$^{16}O^{7+} + ^{169}Tm$	0.50	67.2	≈70–95	$^{169}Tm(^{16}O,3n)^{182}Ir$	12 h	126.9 273.8	34.4, 43.0
5	$^{16}O^{7+} + ^{181}Ta$	1.72	70.5	≈75–100	$^{181}Ta(^{16}O,3n)^{194m}Tl$	32.8 m	636.1	99.0
					$^{181}Ta(^{16}O,3n)^{194g}Tl$	33.0 m	636.1	15.3

Pre-equilibrium revival – H.I. reactions



PACE 4

PACE 4 + ALICE91 (Hybrid model)

PACE 4 + ALICE91 + ROT energy

Pre-equilibrium signatures:

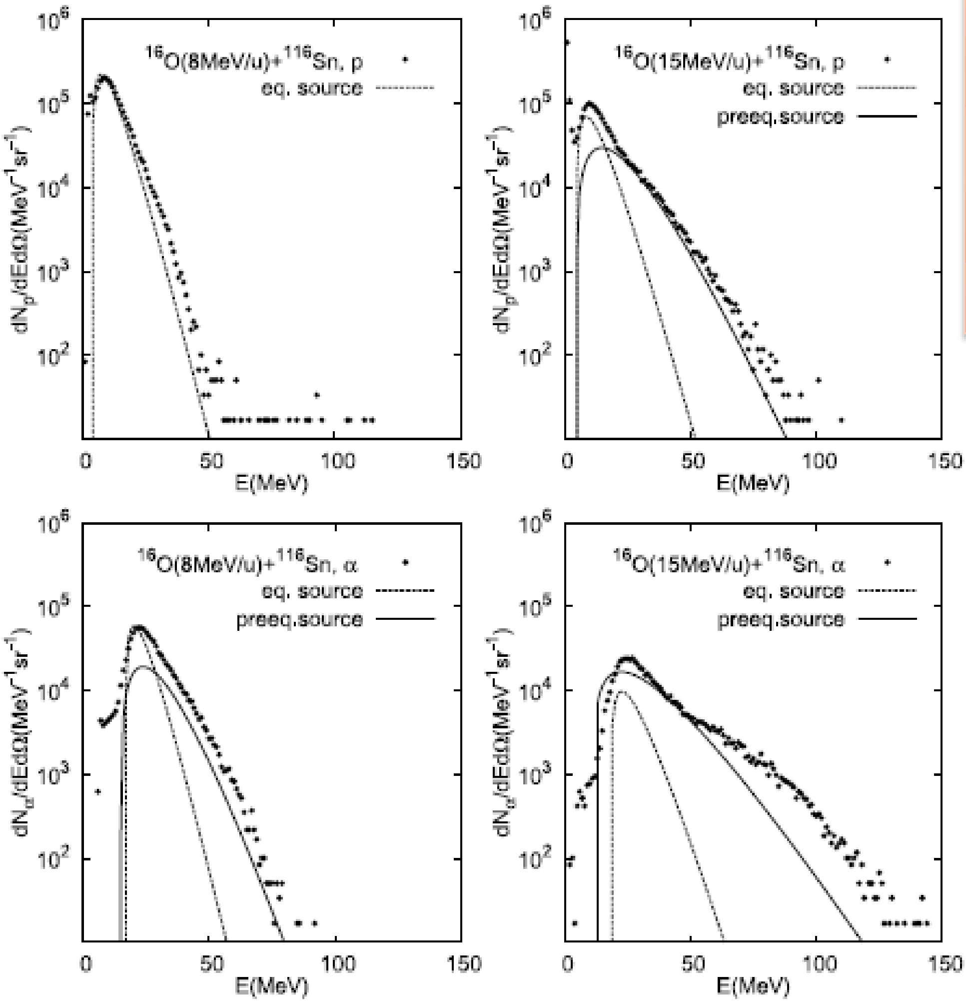
I. **Presence of a larger number of high-energy particles as compared to the spectrum predicted by the compound nucleus model (e.g. PACE4 calculations);**

II. **Forward –peaked angular distribution of emitted particles**

III. **Slowly decreasing tails of excitation functions**

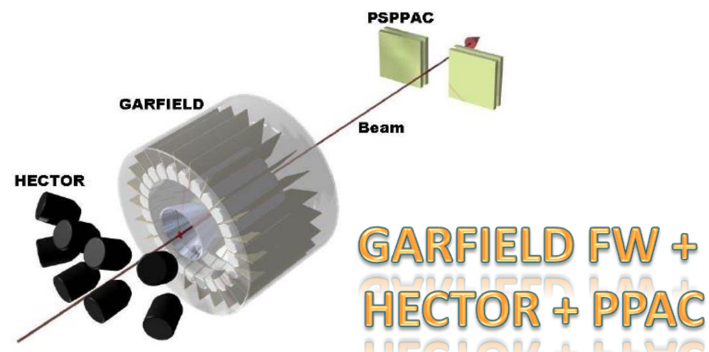
From our experience on pre-equilibrium emission

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



	E_beam		η	Comp	E*
$^{16}O + ^{116}Sn$	130 MeV 250 MeV	8 AMeV 15.8 AMeV	0.76	^{132}Ce	100 206
$^{16}O+^{116}Sn$	192 MeV	12 AMeV	0.76	^{132}Ce	155
$^{16}O+^{65}Cu$	256 MeV	16 AMeV	0.60	^{81}Rb	209
$^{19}F + ^{62}Ni$	304 MeV	16AMeV	0.53	^{81}Rb	240
$^{19}F + ^{63}Cu$	304 MeV	16 AMeV	0.52	^{82}Sr	243

Light charged particles
in coincidence with
Evaporation Residues



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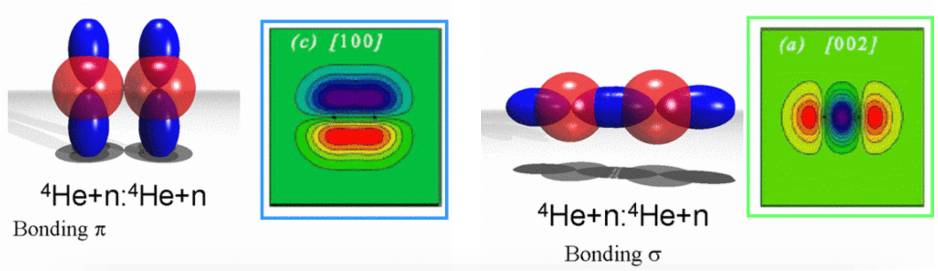
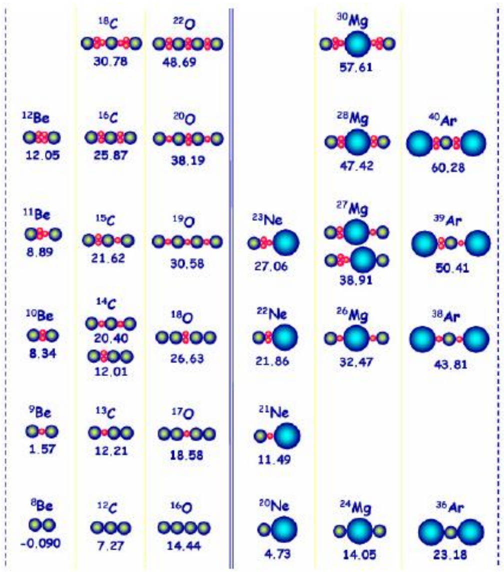
Pre-equilibrium emission and clustering

In 1968 Ikeda suggested that α-conjugate nuclei are observed as excited states close to decay threshold into clusters. The original idea was introduced by Hafstad and Teller in 1938.



Extended Ikeda diagram



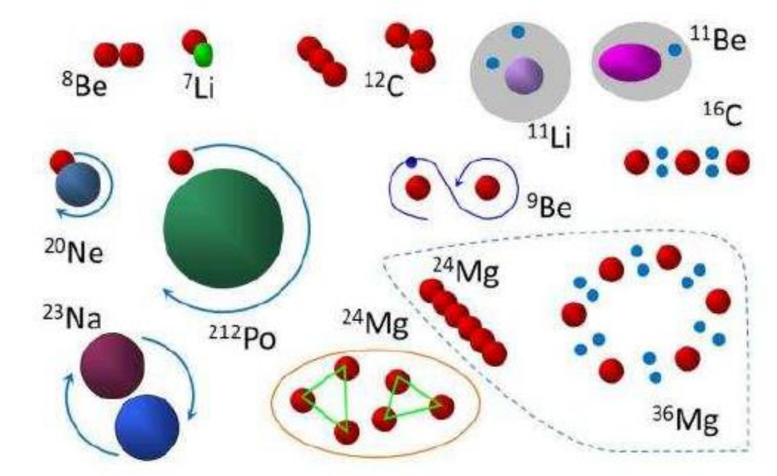

3rd International Workshop on "State of the Art in Nuclear Cluster Physics" IOP Publishing
Journal of Physics: Conference Series **569** (2014) 012002 doi:10.1088/1742-6596/569/1/012002

Figure 1. Different types of clustering in nuclei that have been discussed at this workshop. (Figure adapted from Ref.[1] courtesy from Catford).

1. **In light nuclei at the neutron drip-line, clustering might be the preferred structural mode**
2. **Nuclear states built on clusters bound by valence neutrons in their molecular configurations might appear.**
3. **These structures are mainly described by theory, but must be experimentally confirmed**

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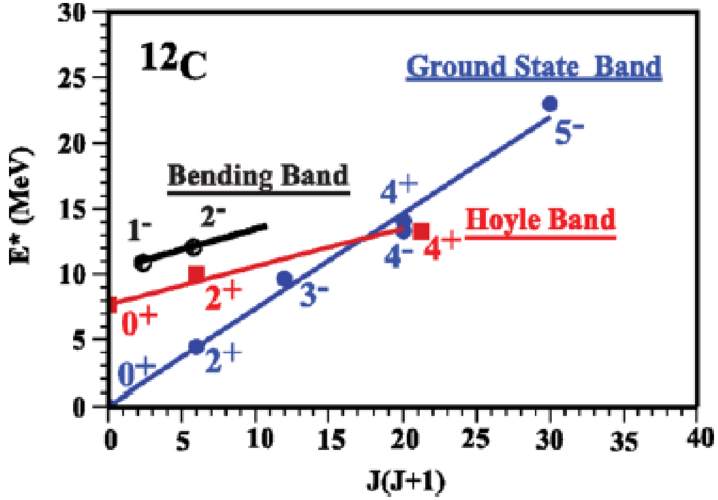
W. Von Oertzen et al., Phys. Rep. 432 (2006) 43 - M. Freer et al., Rep. Progr. Phys. 70 (2007) 2149
Ebran et al., Nature 487 (2012) 341 - C. Beck JoP: Conf. Ser. 569 (2014) 012002

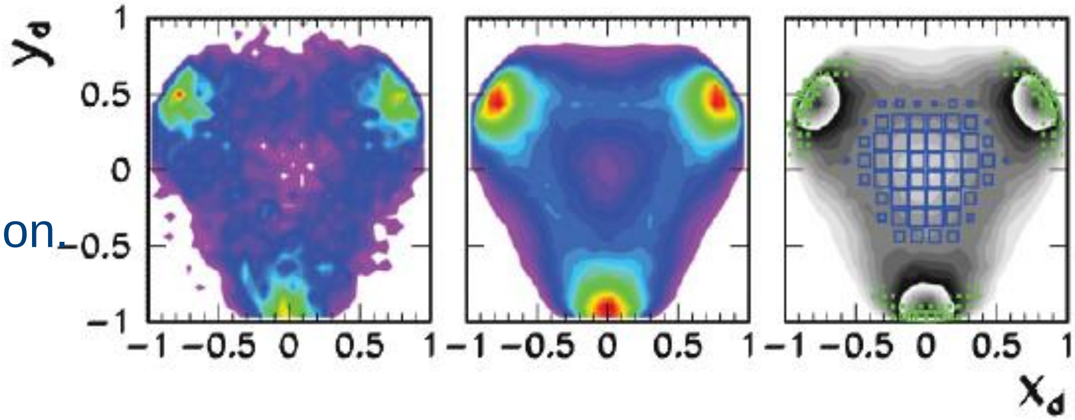
Clustering in Nuclear Structure and Dynamics



The different rotational band structures in ^{12}C. The smaller slope of the Hoyle band curve with respect to the ground state band indicates a more extended structure. [Marın-Lambarri et al, PRL 113 (2014) 1].

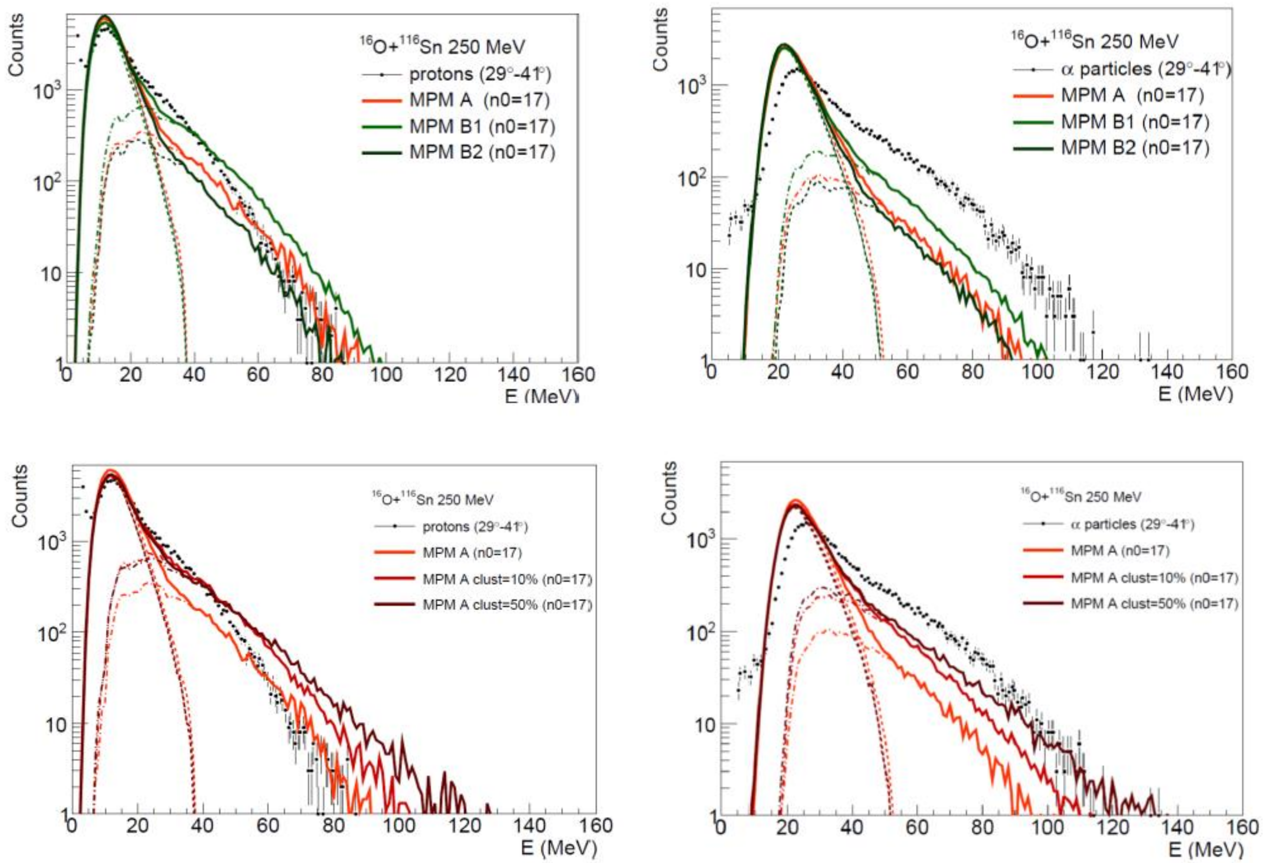
$^{12}C+^{12}C$ @ 95 MeV

Experimental and calculated energy Dalitz-plot obtained from a $^{12}C+^{12}C$ peripheral scattering reaction. [Morelli et al, JoP G 43 (2016) 4]



Pre-equilibrium and clustering?

Moscow Pre-equilibrium Model (MPM)



"Exciton Clusters"
MPM A:
- Griffin Exciton Model

MPM B:
- Hybrid Exciton Model

Cluster PRE-formation
"clustering add-on"
according to H.F. Zhang

MPM: O.V. Fotina, EPJ WoC 66 (2014) 03028 (and ref therein)
Cluster Pre-formation: H. F. Zhang *et al*, PRC 77 (2008) 054318; PRC 80 (2009) 057301

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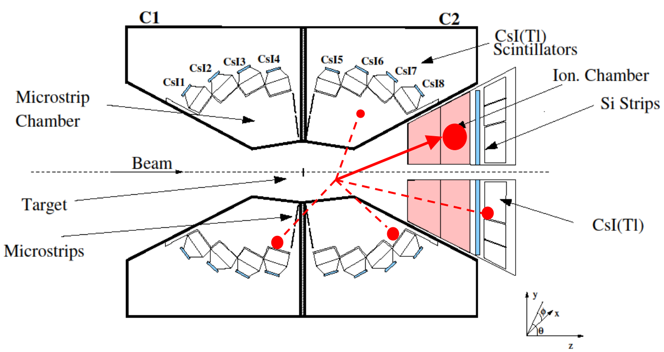
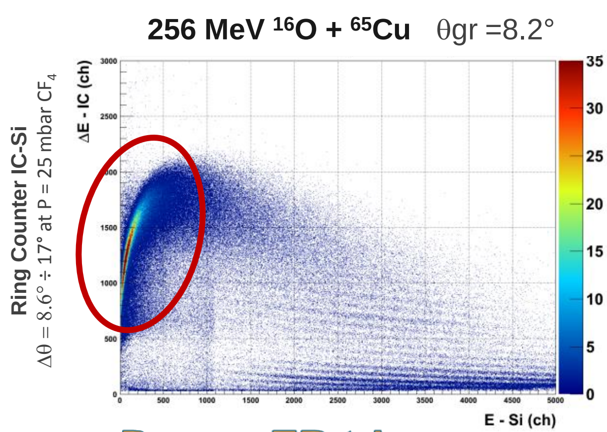
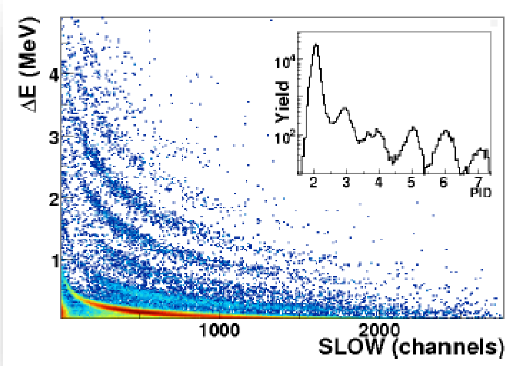
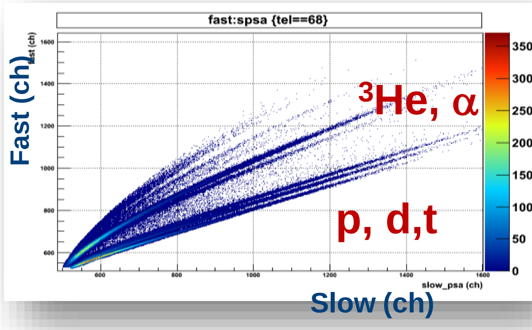
GARFIELD (full) + RCo





Proper ER trigger





Particle Identification

Neutrons: very important missing ingredient

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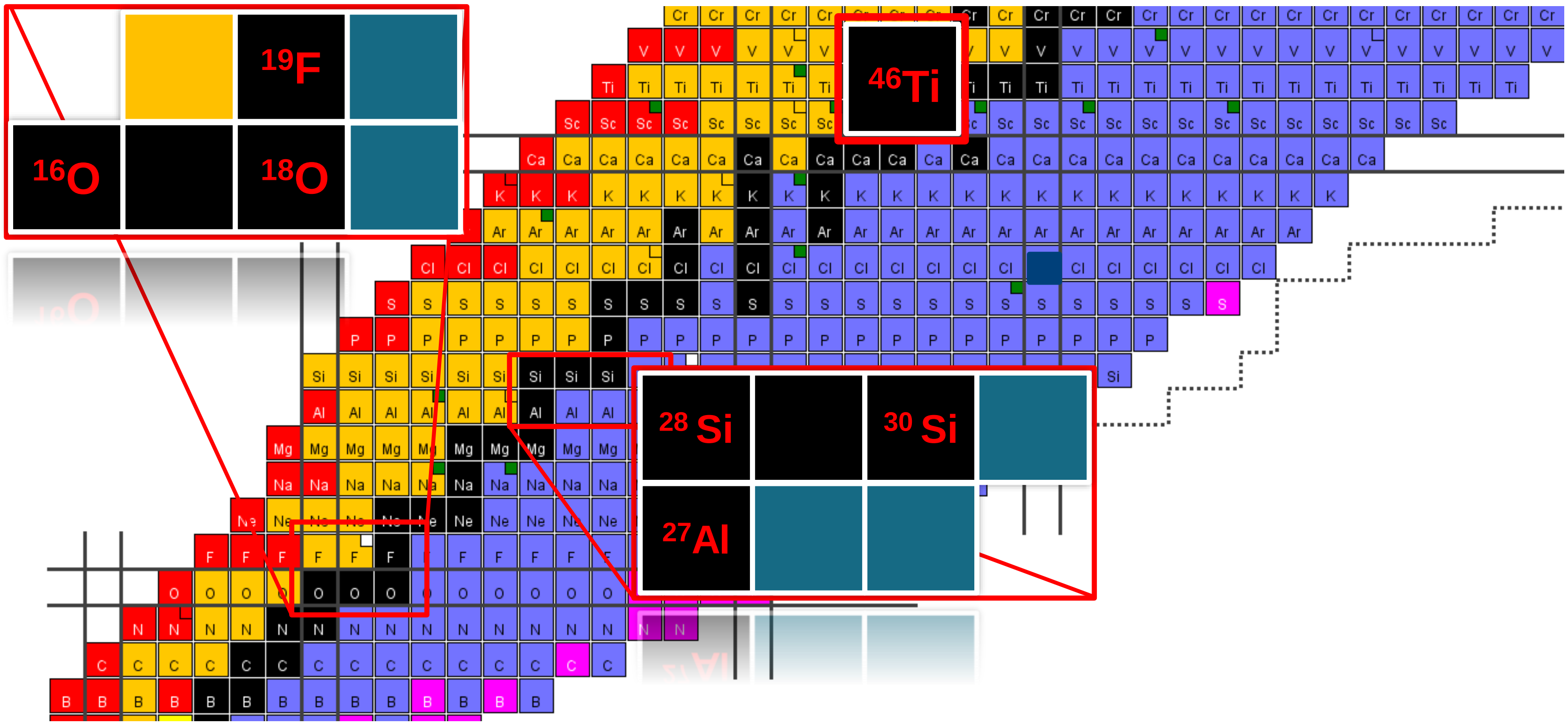
Experimental Campaigns

	E_beam (AMeV)	Comp	E* (MeV)
$^{16}O + ^{116}Sn$	8 15.8	^{132}Ce	100 206
$^{16}O+^{116}Sn$	12	^{132}Ce	155
$^{16}O+^{65}Cu$	16	^{81}Rb	209
$^{19}F + ^{62}Ni$	16	^{81}Rb	240
$^{19}F + ^{63}Cu$	16	^{82}Sr	243
$^{16}O+^{30}Si$	7	^{46}Ti	88
$^{16}O+^{30}Si$	8	^{46}Ti	98
$^{18}O+^{28}Si$	7	^{46}Ti	98
$^{19}F+^{27}Al$	7	^{46}Ti	103

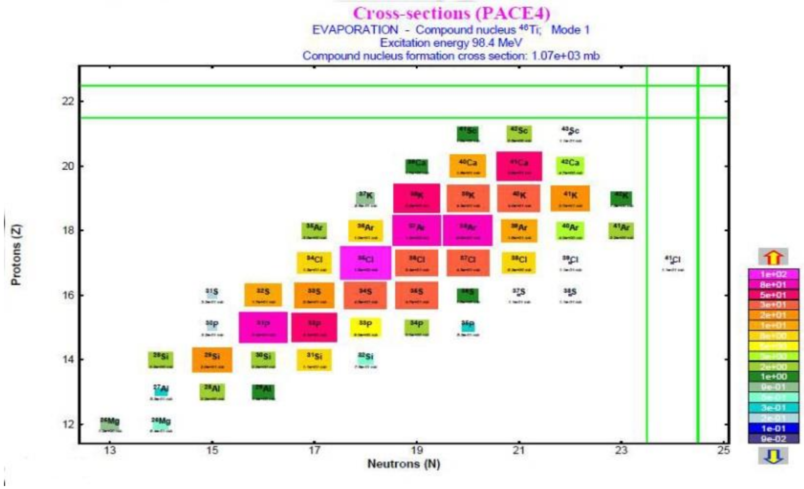
- Same compund nucleus with different entrance channles
- Same projectile at different energies
- At the onset of pre-equilibrium processes

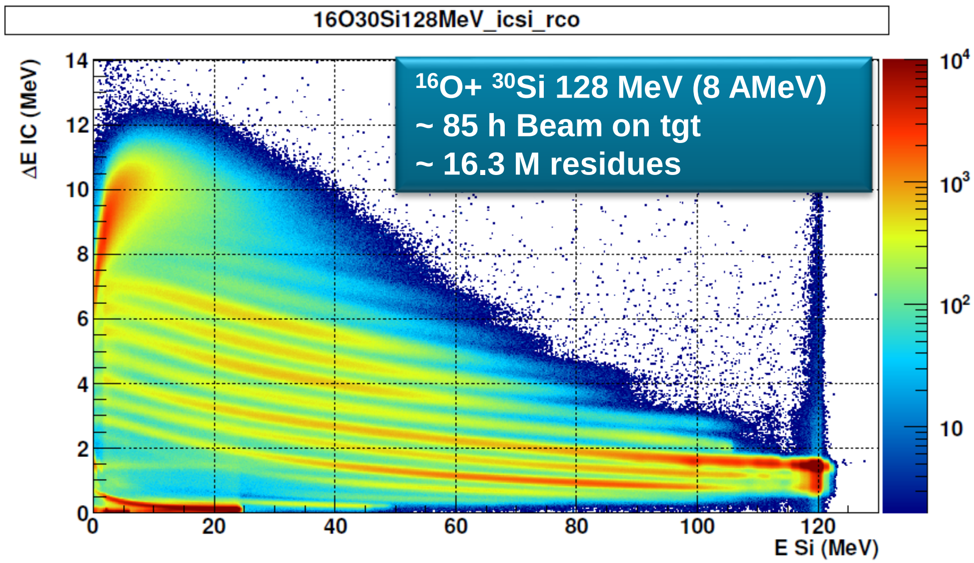
ACLUST2 experiment

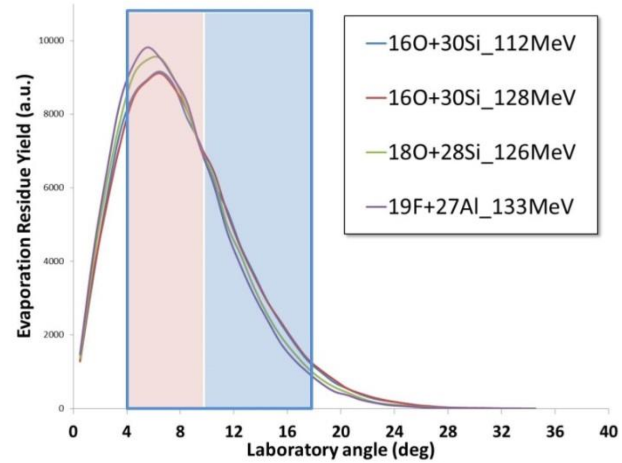


Projectile		Target	Grazing	Compound Nucleus					
Ion	E_{lab} (AMeV)	Isotope	θ_{lab} (deg)	Isotope	Mass Asymm.	σ_{fus} (mb)	E* (MeV)	Lab. Vel. (cm/ns)	E.R. Distrib. θ_{lab} (deg)
^{16}O	7.0	^{30}Si	10.1	^{46}Ti	0.30	1081	88.0	1.28	0 - 30
^{16}O	8.0	^{30}Si	8.8	^{46}Ti	0.30	1070	98.4	1.37	0 - 30
^{18}O	7.0	^{28}Si	9.0	^{46}Ti	0.22	1110	98.5	1.44	0 - 28
^{19}F	7.0	^{27}Al	8.9	^{46}Ti	0.17	1100	103.5	1.52	0 - 28

ACLUST2 experiment







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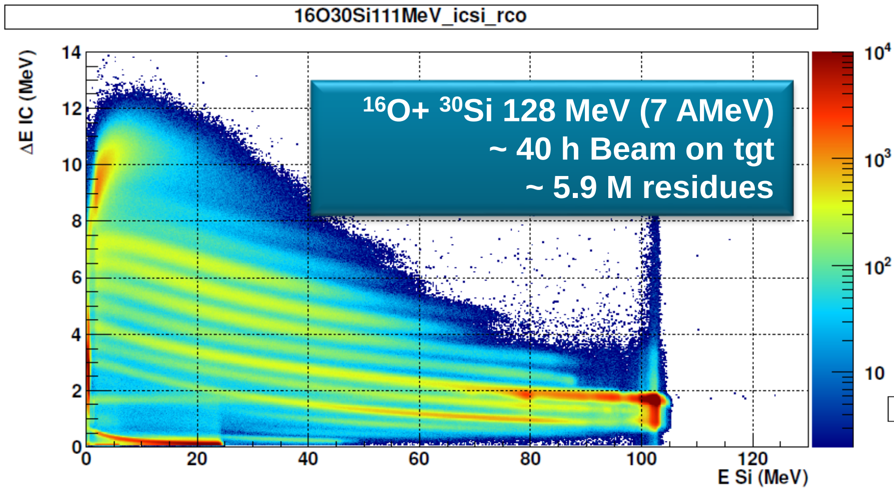
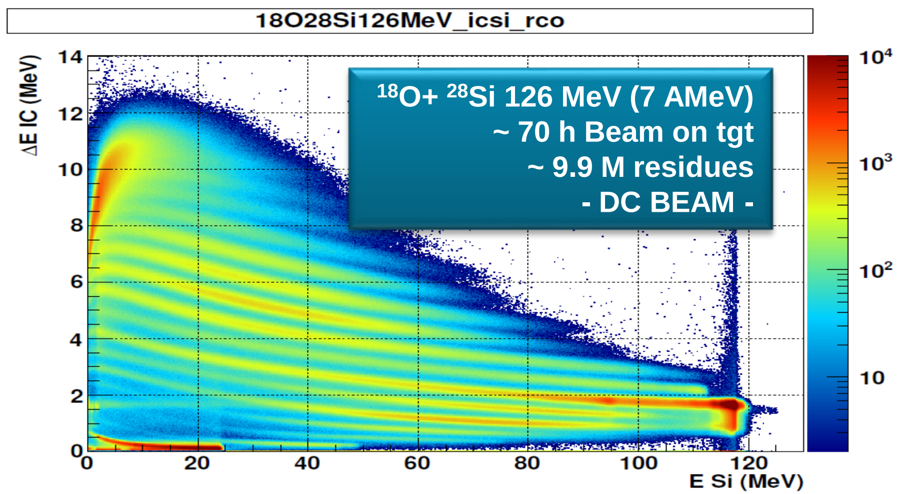
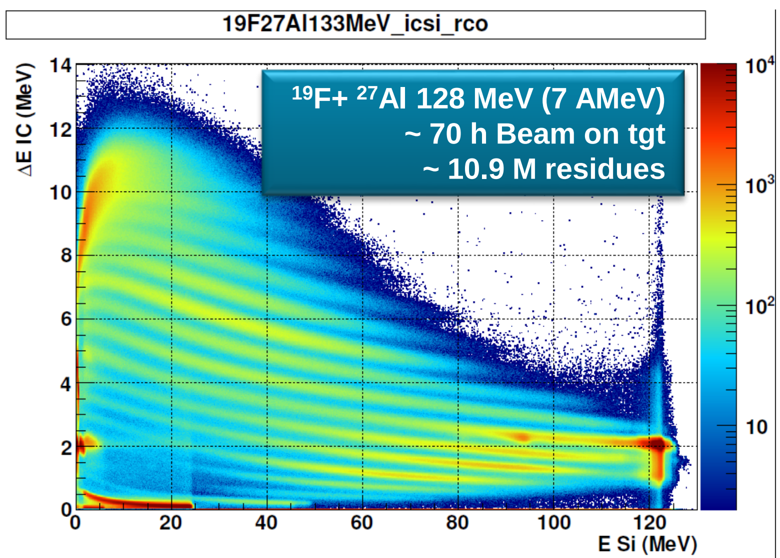
ACLUST2 experiment

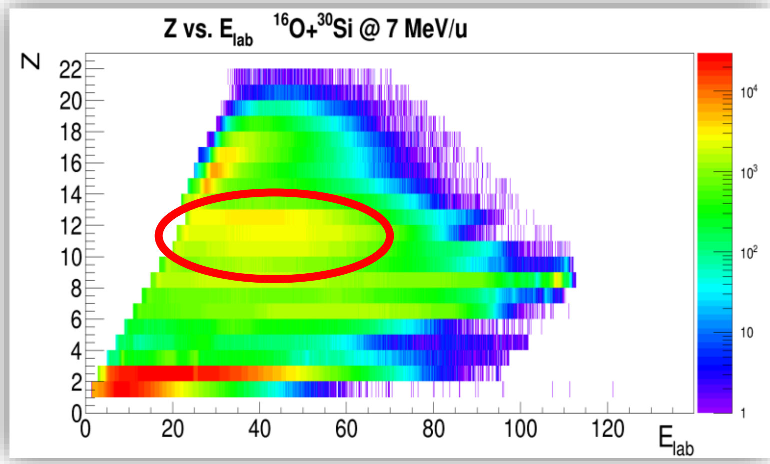




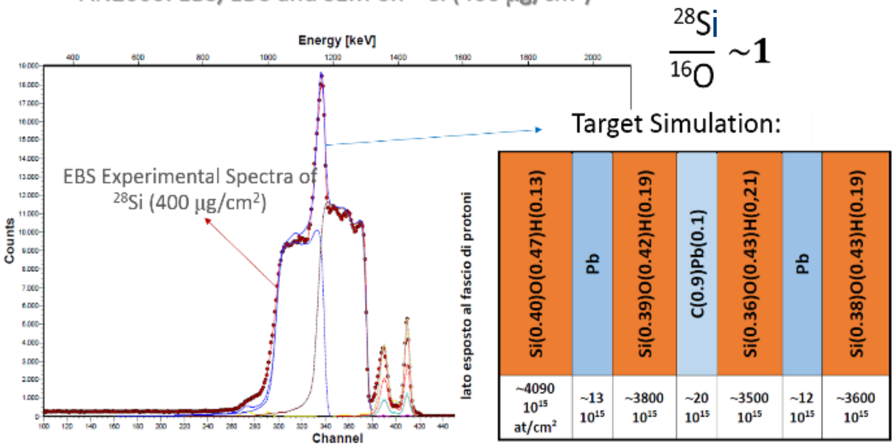


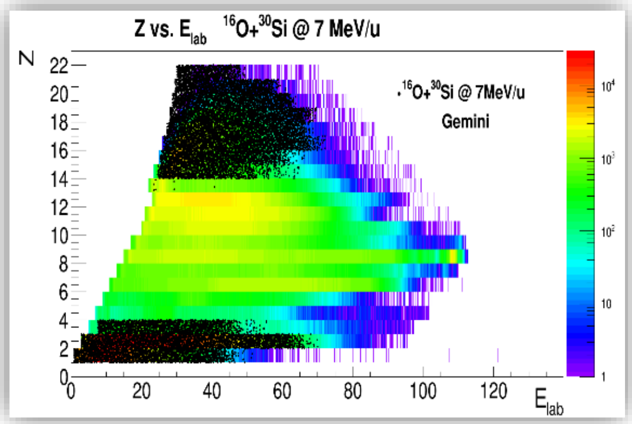
ACLUST2 experiment – ER selection and target contamination

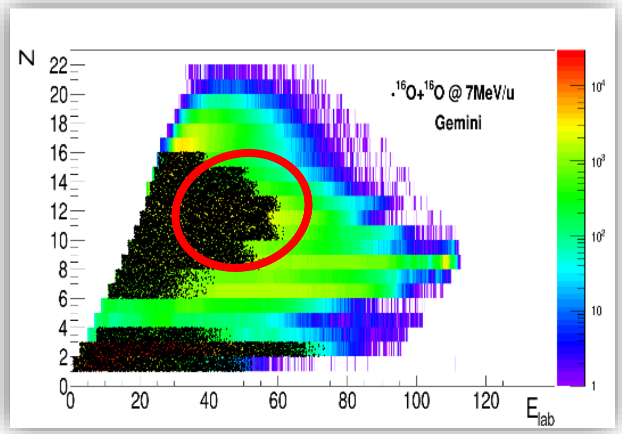
Z vs E : inclusive - EXP



AN2000: EBS, EDS and SEM on ^{28}Si (400 μg/cm²)







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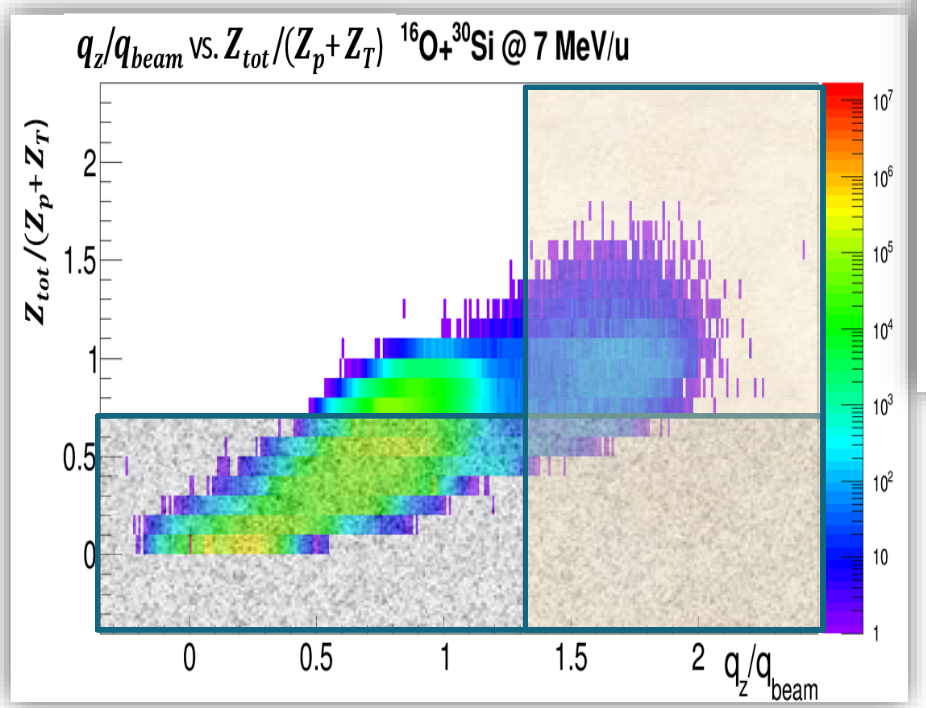
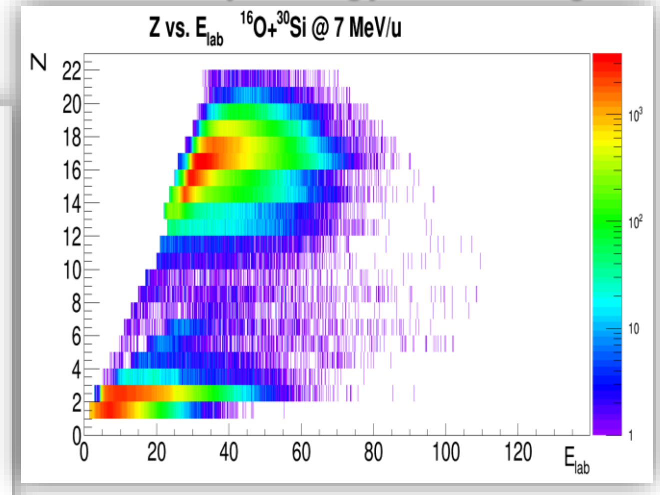
ACLUST2 experiment – ER selection

Correlation between the longitudinal momentum and total collected charge



Correlation between the laboratory energy and charge



$$\frac{q_z}{q_{beam}} < 1.3$$

$$Z_{tot} > 70\%\ Z_p + Z_T$$

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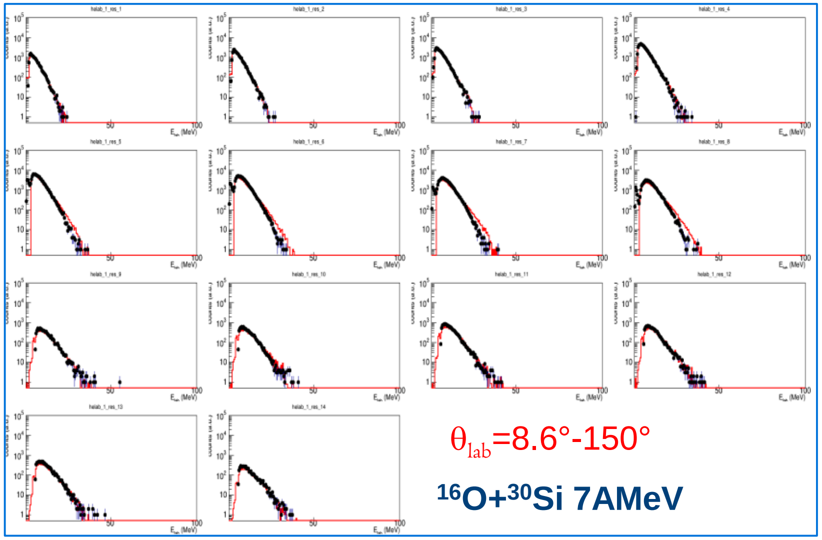
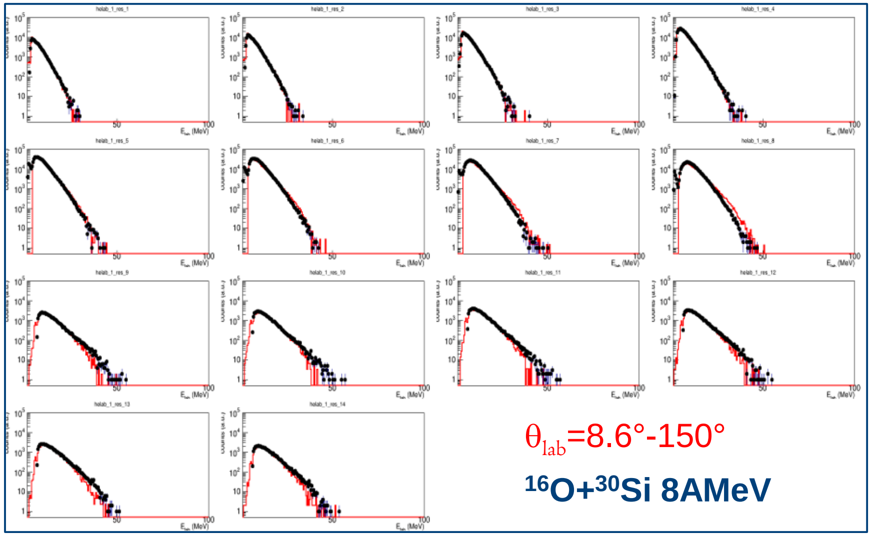
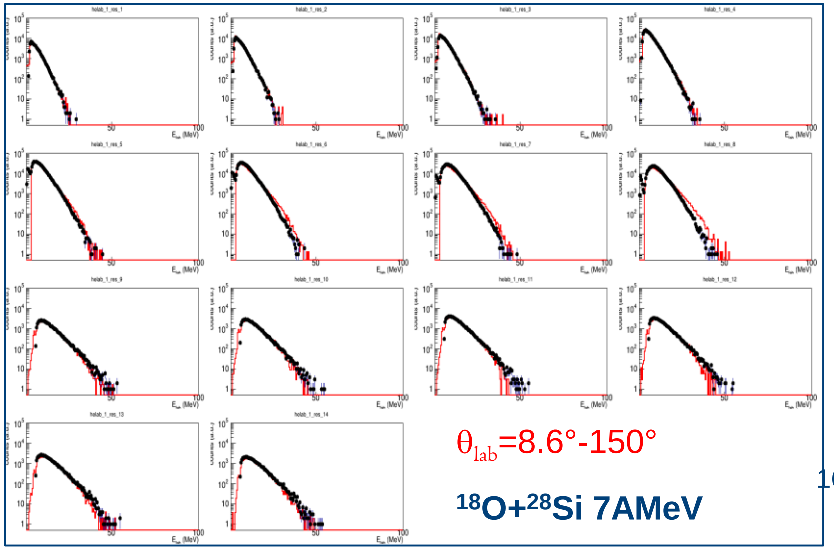
Experimental data and GEMINI

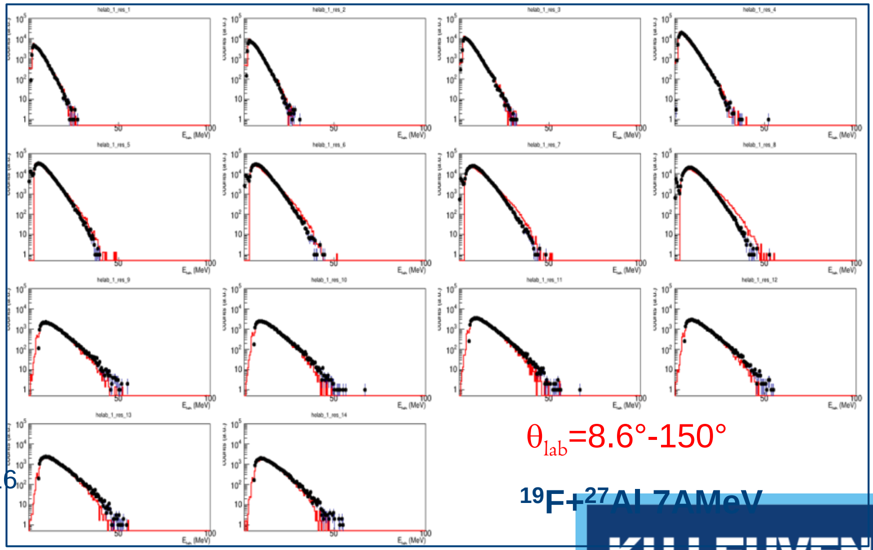
P in coincidence with ER – almost complete events **(Ztot > 0.70 Zp+Zt)**: comparing the experimental energy distributions with Statistical calculation predictions

protons





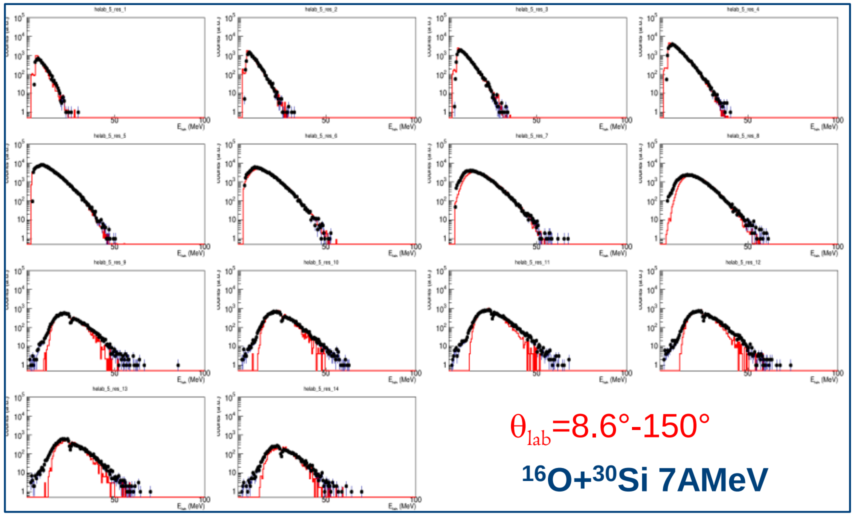


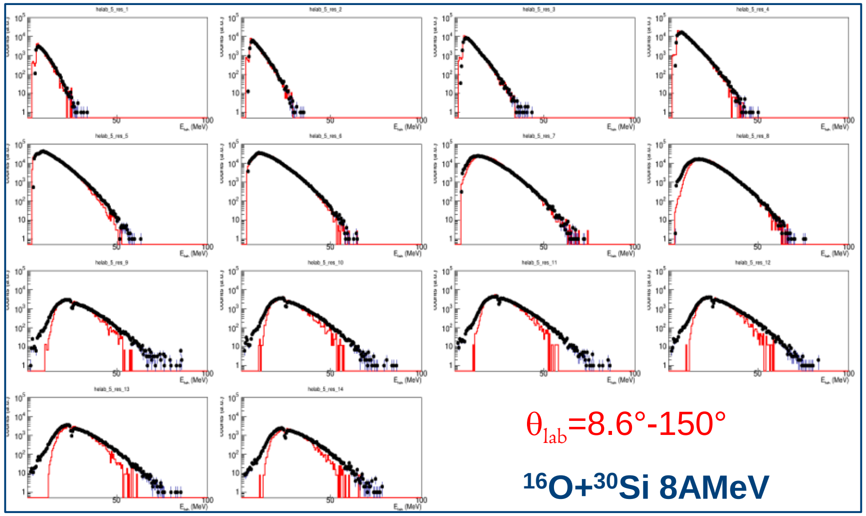


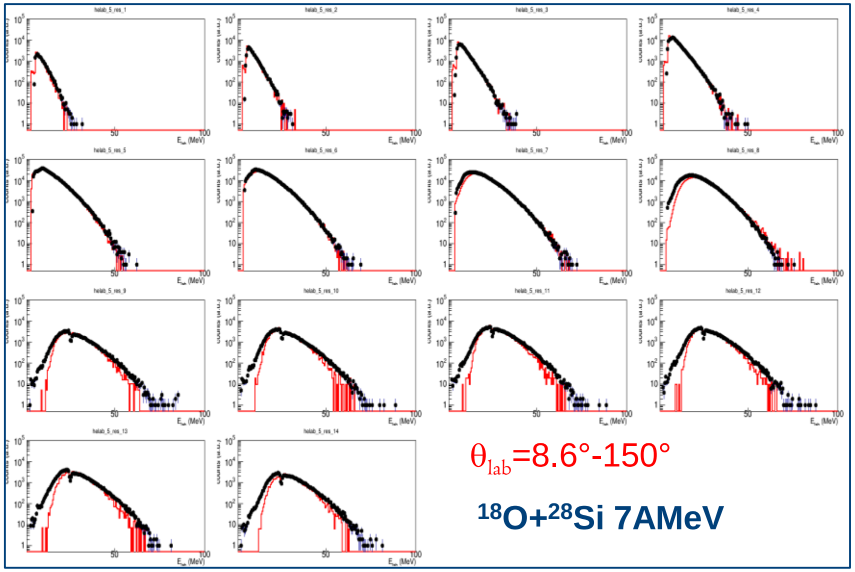
Experimental data and GEMINI

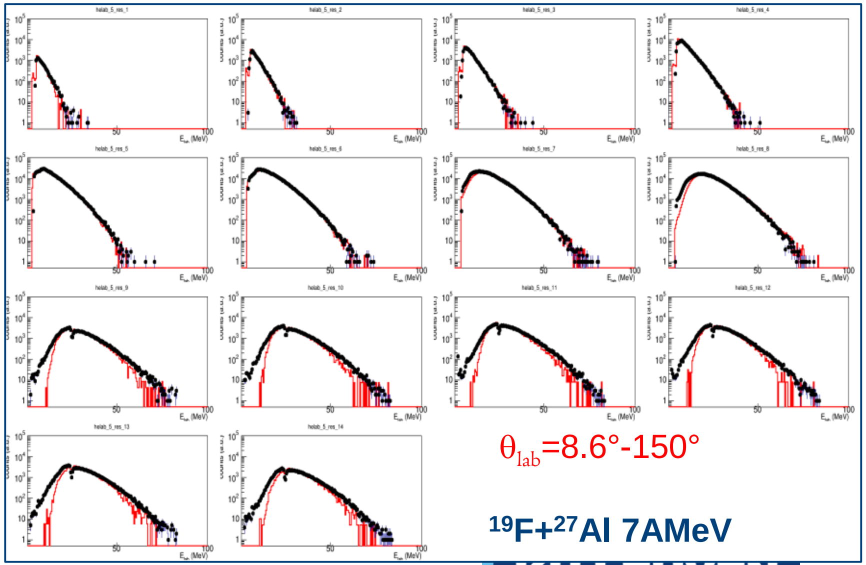
α- particles in coincidence with ER – almost complete events **(Ztot > 0.70 Zp+Zt)**:
comparing the experimental energy distributions with Statistical calculation predictions

a l p h a



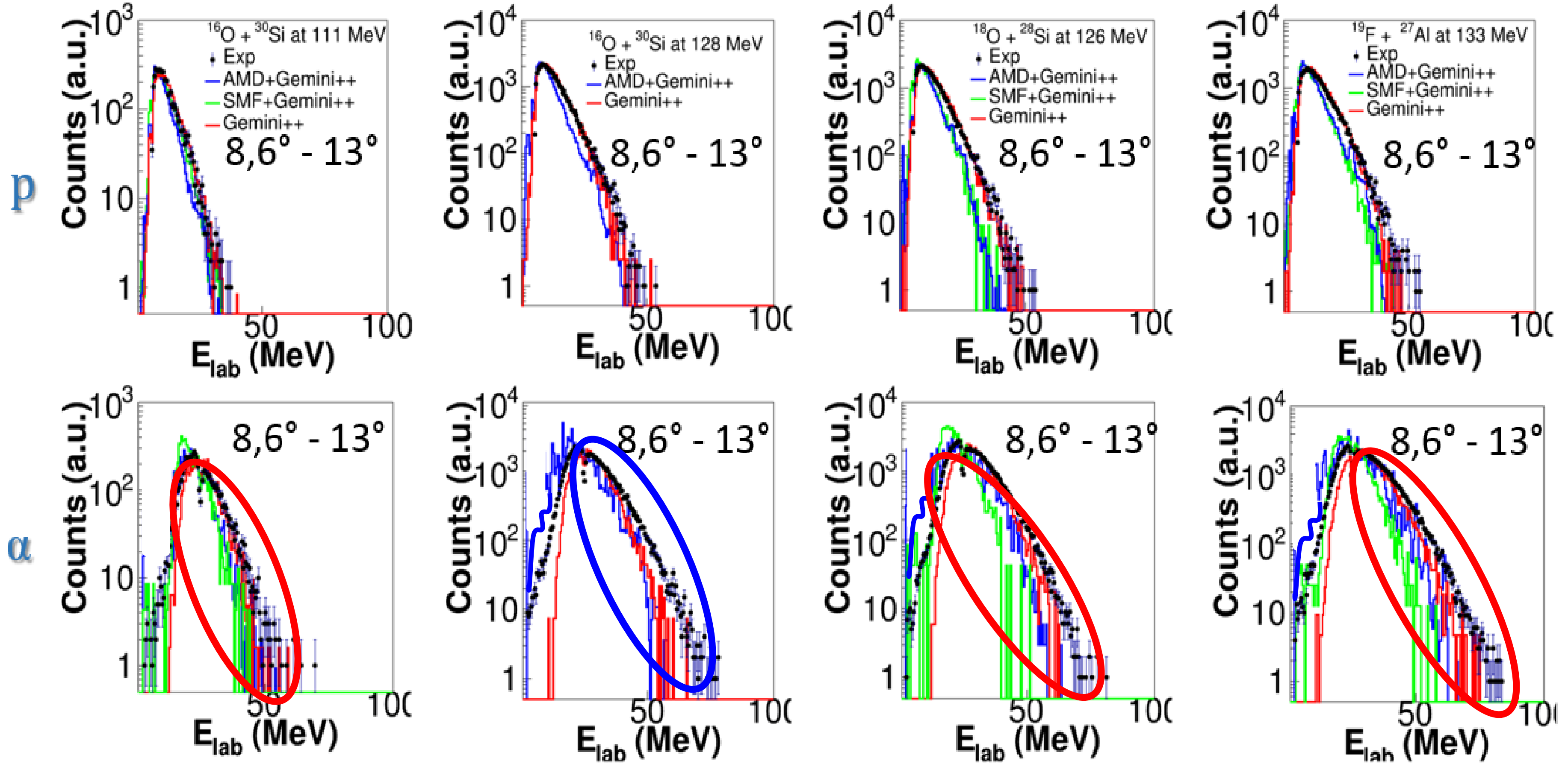






Experimental data and preliminary results

$^{16}O+^{30}Si$ @ 111 MeV $^{16}O+^{30}Si$ @ 128 MeV $^{18}O+^{28}Si$ @ 126 MeV $^{19}F+^{27}Al$ @ 133 MeV



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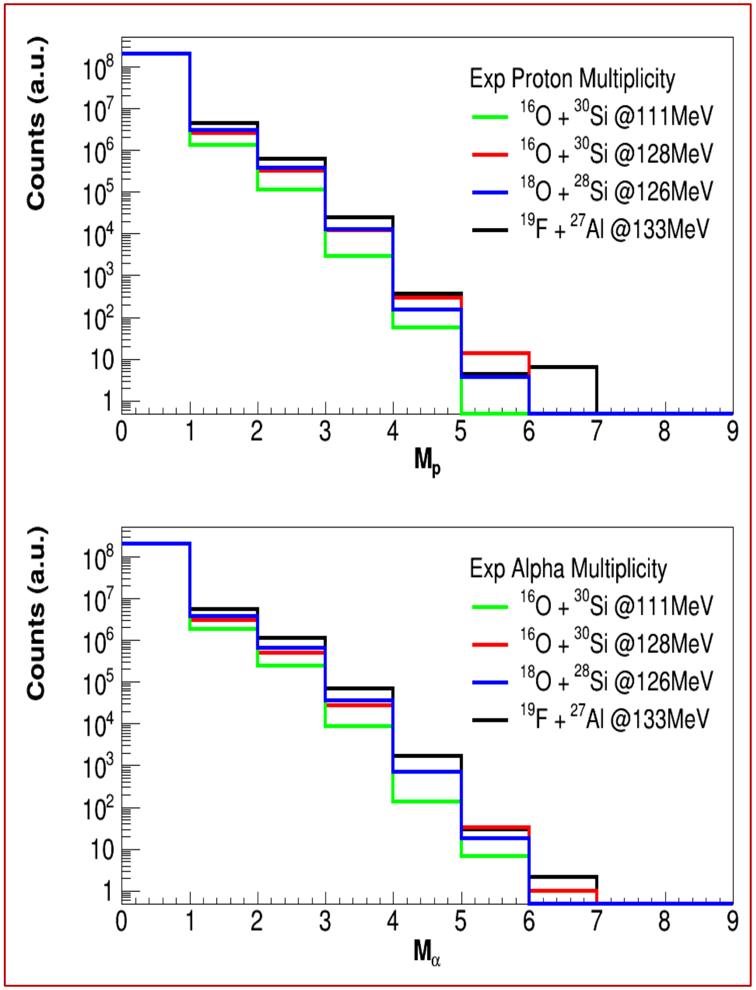
Multiplicity spectra

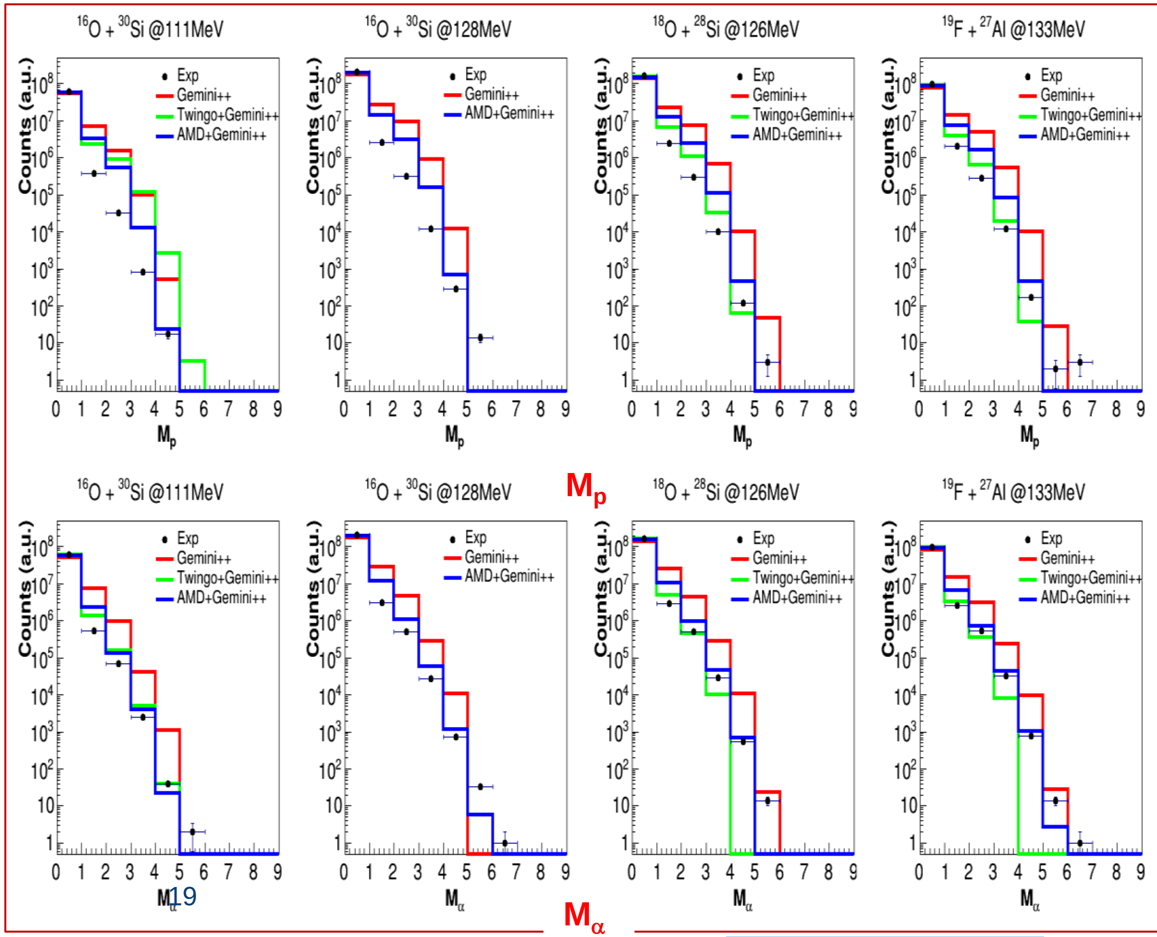
EXP MULTIPLICITY – comparison between the different reactions



COINCIDENCE with ER

FILTERED MULTIPLICITY – comparison to EXP DATA

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



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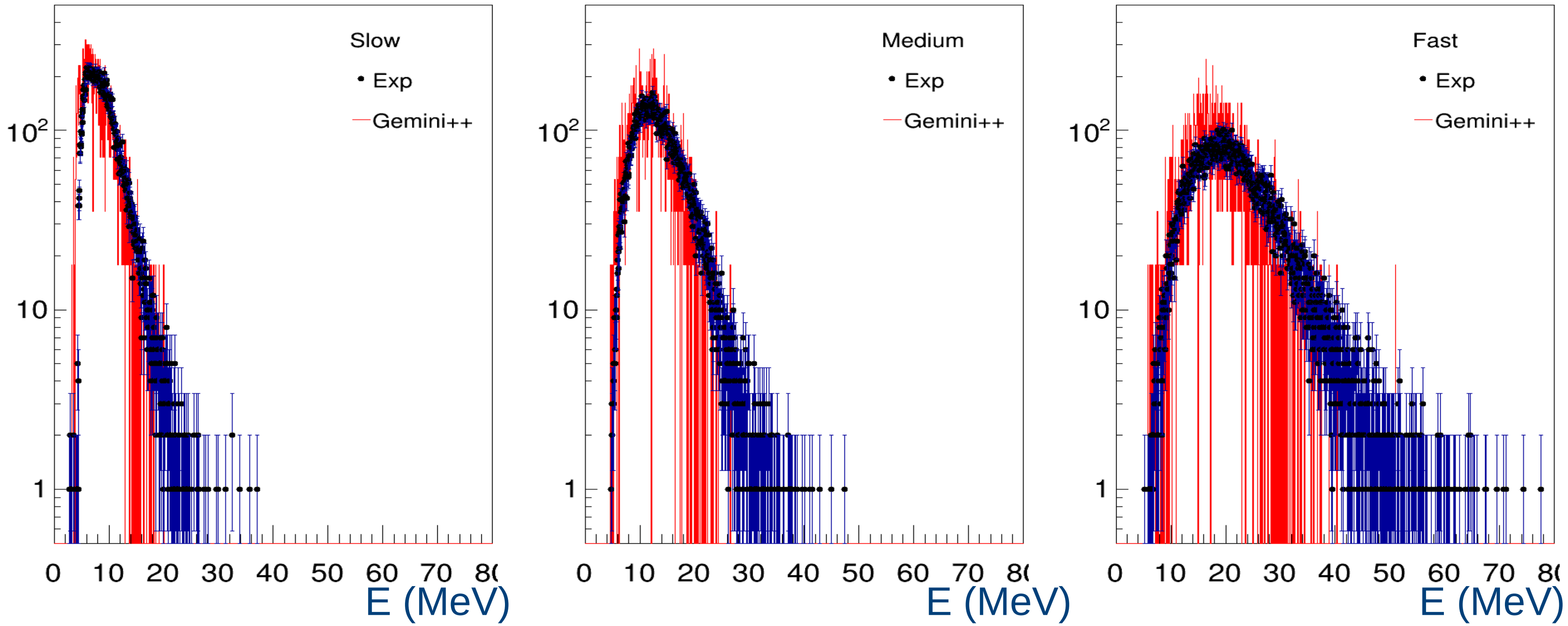
Exclusive observables - preliminary

$^{16}O+^{30}Si$ 8AMeV

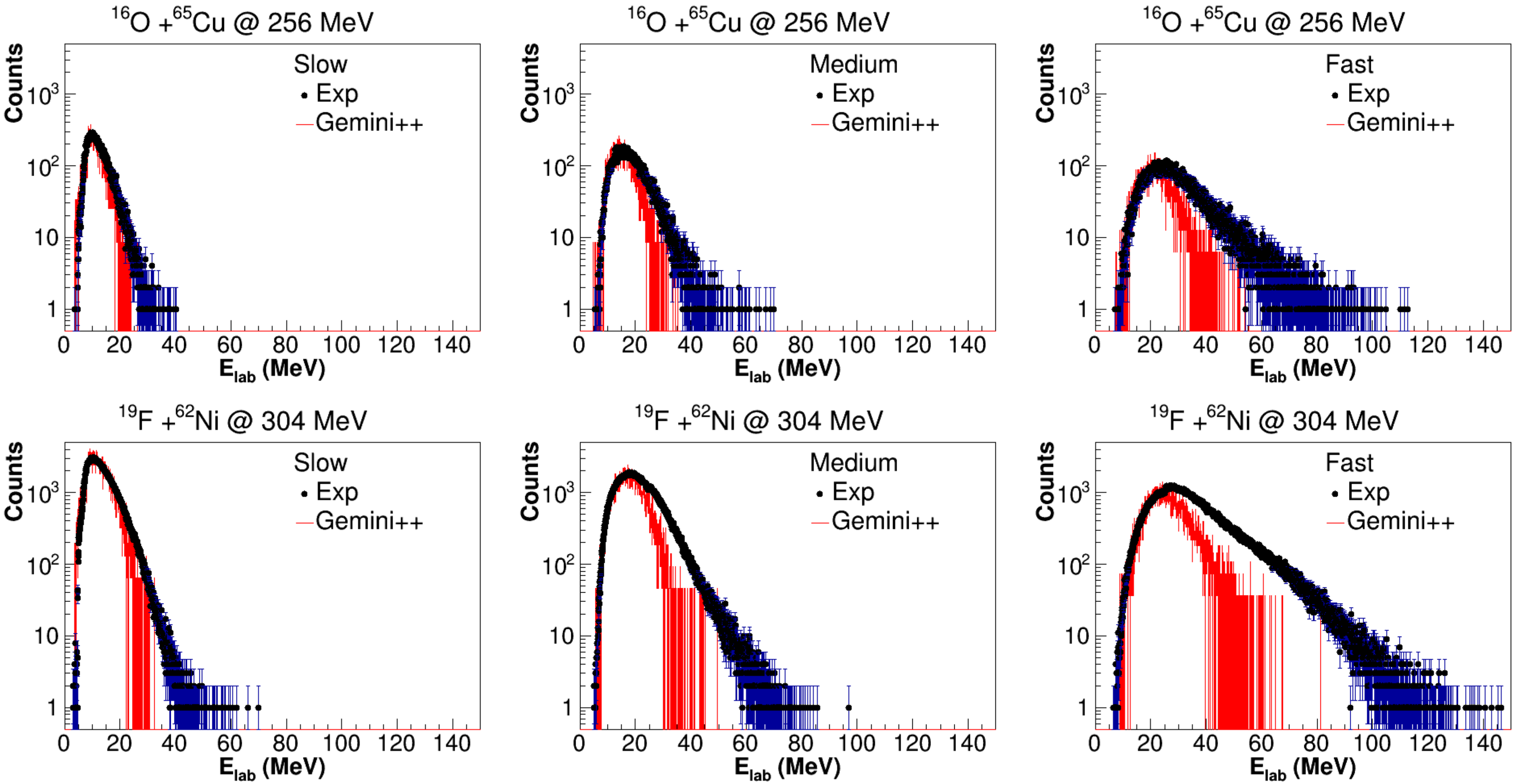
Selected channel: $^{42-x}Ar + 3\alpha + xn$

Selective channels: multiple alpha channels in coincidence with specific ER



Minimum, medium and maximum energy of the **3**α event by event:
Experimental spectra and comparison to Gemini.

While at higher energy … (ACLUST experiment):



Summary

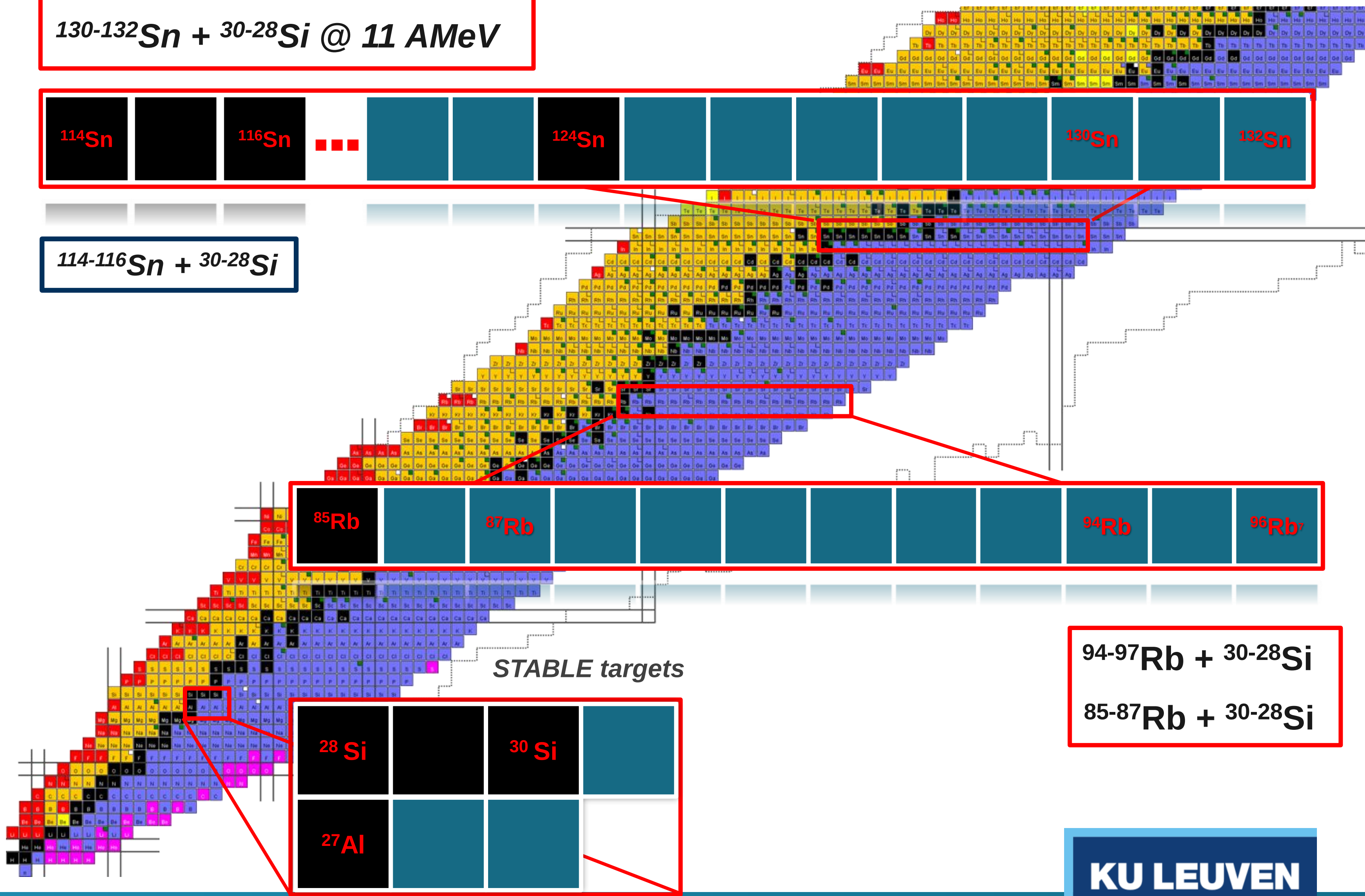
- High granularity and angular coverage allow to study pre-equilibrium processes in a detailed and exclusive way
- A link between light charged particles pre-equilibrium emission and cluster structure can be established but new observables are needed
- A systematic approach is needed, especially in terms of projectile energy

- Radioactive Ion Beams will provide a wider playground in terms of entrance channel combinations

Outlook

$^{132}Sn + {}^{27}Al$ @ 11 AMeV

$^{130-132}Sn + {}^{30-28}Si$ @ 11 AMeV



$^{114-116}Sn + {}^{30-28}Si$

$^{94-97}Rb + {}^{30-28}Si$

$^{85-87}Rb + {}^{30-28}Si$

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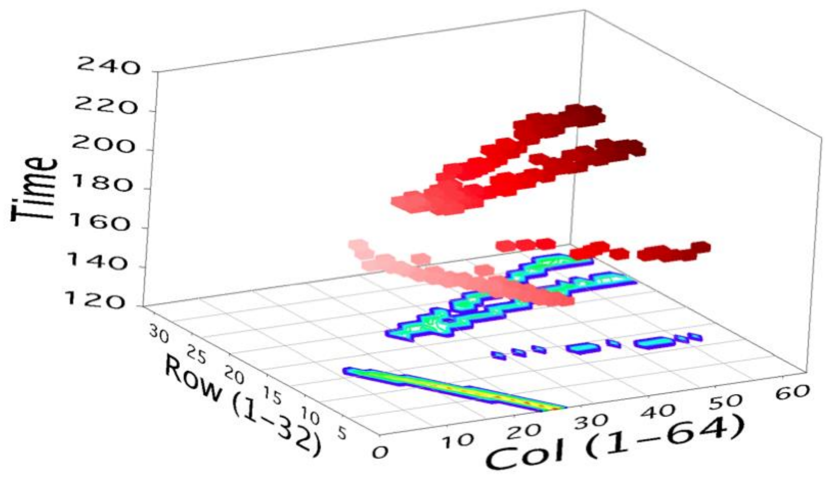
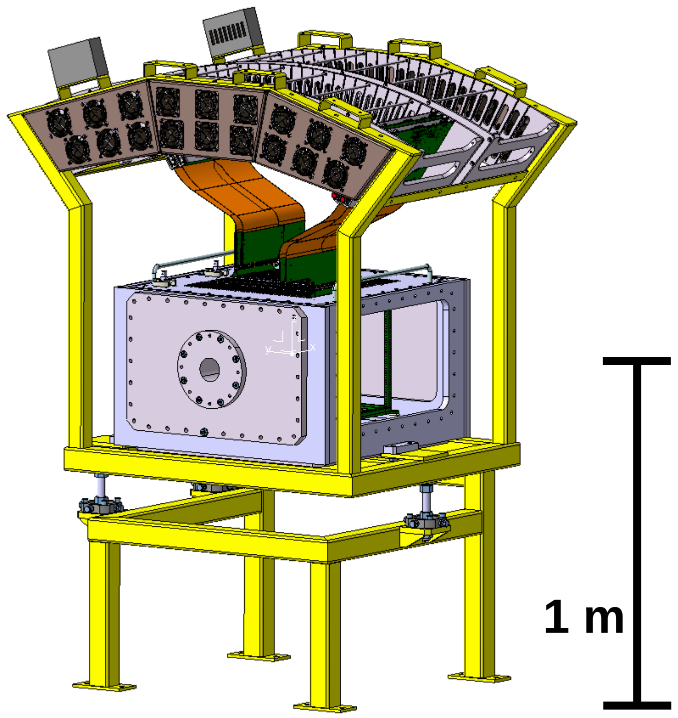
One possible setup

Advantages

- Low thresholds
- Angular coverage





Challenges:

- Heavy beams, dynamic range
- Beam current, Count rate
- High multiplicity
- Resolution (Energy, A, Z)

F. Gramegna[1], **M. Cicerchia**[1,4], T. Marchi[2], G. Mantovani[1,4], D. Fabris[3], M. Cinausero[1], G. Collazuol[3;4], D. Mengoni[3;4], M. Degerlier[5], M. Bruno[6], M. D'Agostino[6], L. Morelli[6], S. Barlini[7], M. Bini[7], G. Casini[7], A. Camaiani[7], N. Gelli[7], D. Gruyer[7,11], A. Olmi[7], P. Ottanelli[7], G. Pasquali[7], G. Pastore[6], S. Piantelli[7], G. Poggi[7], S. Valdré[7], G. La Rana[8], E. Vardaci[8], I. Lombardo[9], D. Dell'Aquila[10], L. Grassi[10] , G. Verde[9],[10]

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11 GANIL, CEA/DSM-CNRS/IN2P3, Caen Cedex, France.