Evolution of cluster production with fragmentation degree

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(INDRA Collaboration)

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Evolution of cluster production with fragmentation degree

- Reminder on the statistical description of phase transition signals in heavy ion collisions
- Presentation of experimental data
  - 58Ni+58Ni@INDRA@GANIL
  - Selections and sorting variables
- Characteristics of the cluster production
- Highlight on the specific role of 4He cluster.
- Delimitation of the coexistence zone of the nuclear phase diagram.

Phase transition

Phase transition

- As the nuclear force shape is close to the Van der Waals one, a liquid-gas like phase transition is expected and has been successfully evidenced in experimental data collected in Heavy Ion reactions (HIC).
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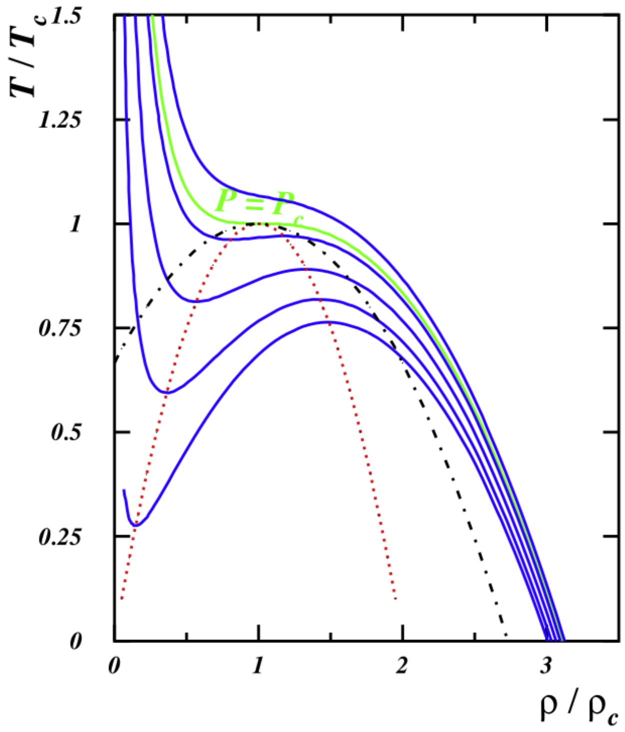

B. Borderie and J.D. Frankland
Progress in Particle and Nuclear Physics 105 (2019)

Phase transition

- As the nuclear force shape is close to the Van der Waals one, a liquid-gas like phase transition is expected and has been successfully evidenced in experimental data collected in Heavy Ion reactions (HIC).
- Respect to nuclear matter, nucleus is finite and has surfaces. Then, the entropy of the system which undergoes to phase transition is no more additive and exhibits a residual convexity. From this specific feature, phase transition signatures differ from that it will be expected in the infinite limit.
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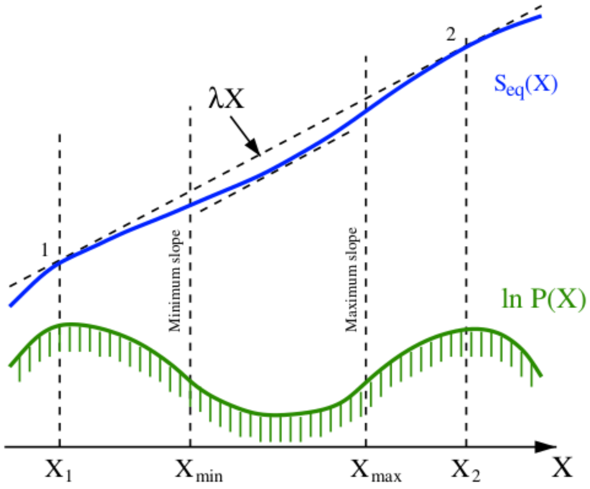
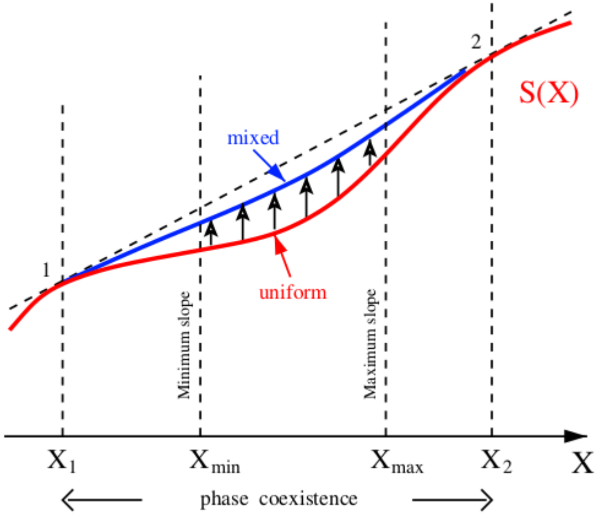
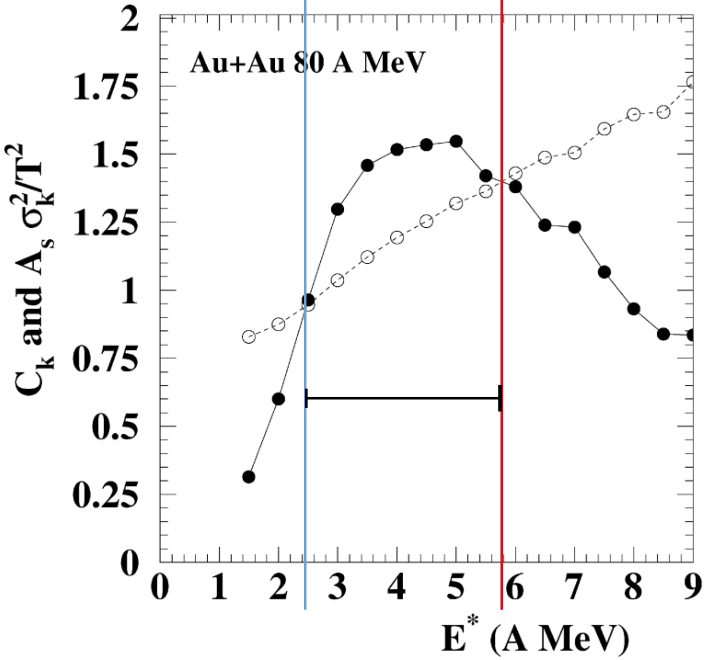




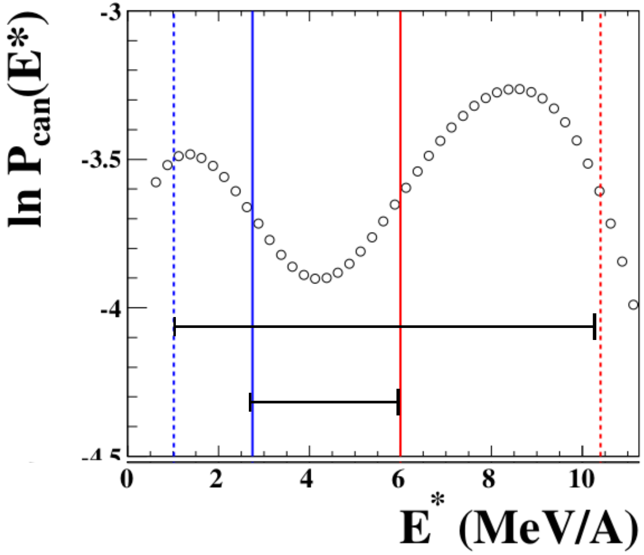
P. Chomaz et al. / Physics Reports 389 (2004) 263 – 440

Phase transition

- The experimental signatures such Negative Heat Capacity, Spinodal decomposition and Bimodality signal validate the description of phase transition in finite system.



Negative Heat Capacity signal
N. Le Neindre et al, NPA 795 (2007)



Bimodality signal
Adapted from E. Bonnet et al, PRL 103, (2009)

Phase transition

- The experimental signatures such Negative Heat Capacity, Spinodal decomposition and Bimodality signal validate the description of phase transition in finite system.
- From these signatures, the delimitation of the spinodal and the coexistence zone of the phase diagram have been determined.

Boundaries for heavy systems (A>200) :

Coexistence Zone :
- Liquid side: E* ~ 1.0 MeV/A
- Gas side: E* ~ 10.5 MeV/A

Spinodal Zone :

Liquid side: E* ~ 2.4 MeV/A

Gas side: E* ~ 5.8 MeV/A

Phase transition

- The experimental signatures such Negative Heat Capacity, Spinodal decomposition and Bimodality signal validate the description of phase transition in finite system.
- From these signatures, the delimitation of the spinodal and the coexistence zone of the phase diagram have been determined.
- From bimodality signal, Zmax, the charge of the biggest fragment of each event, is reliable to the order parameter of the phase transition occurring in nuclei. From microcanonical statistical model results, it is also an experimental estimation of the Freeze-Out volume.

Statistical description

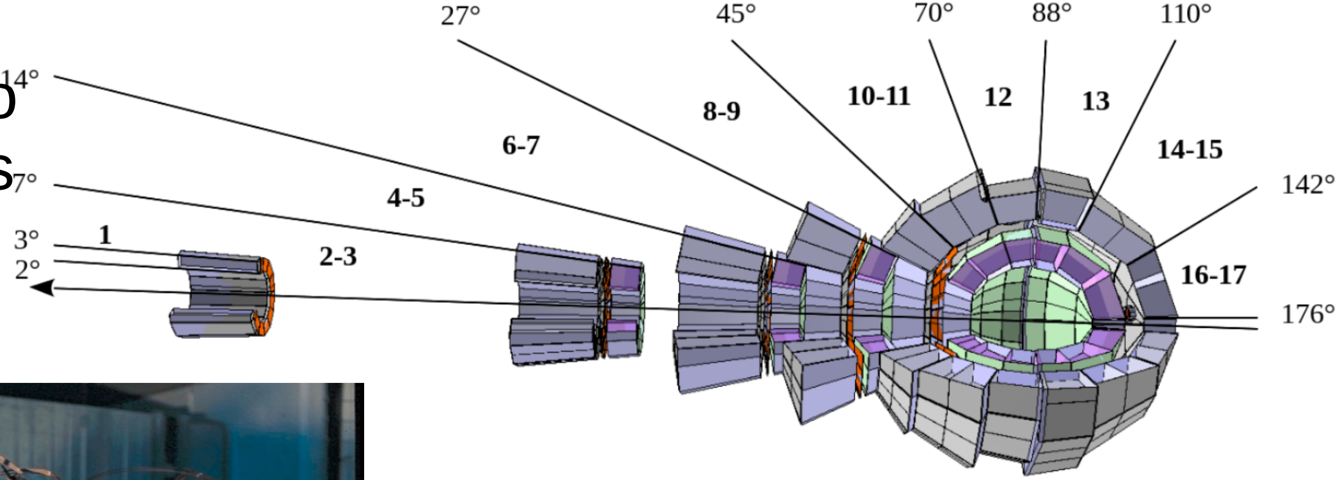
- The properties of partitions produced in HIC can be well reproduced by the statistical approach.
- Whatever the dynamical phase prior to the production of final partitions, ensemble of experimental events can be describe as a statistical ensemble.
- For example a specific Freeze-Out (FO) stage can be defined as the stage when nuclear interaction does not act any more
- At first order, relevant variables of this FO stage are the excitation energy and volume associated to these partitions.

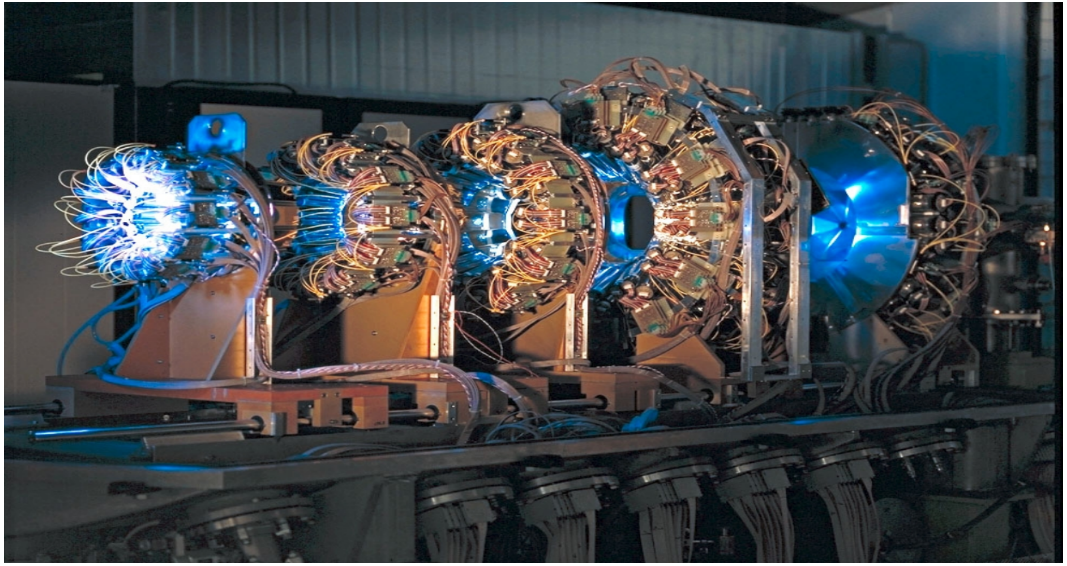
Exploration of the phase diagram

- Furthermore, at a given position in the phase diagram, located with experimental estimation of excitation energy and volume, the considered partitions are fully characterized.
- Sorting experimental events according to excitation energy and volume allows to track specific behaviour when different regions are crossed.
- In this goal, we study in the following the cluster production in 58Ni+58Ni reactions. For this purpose, we will use Zmax and excitation energy (E*) as sorting observables.

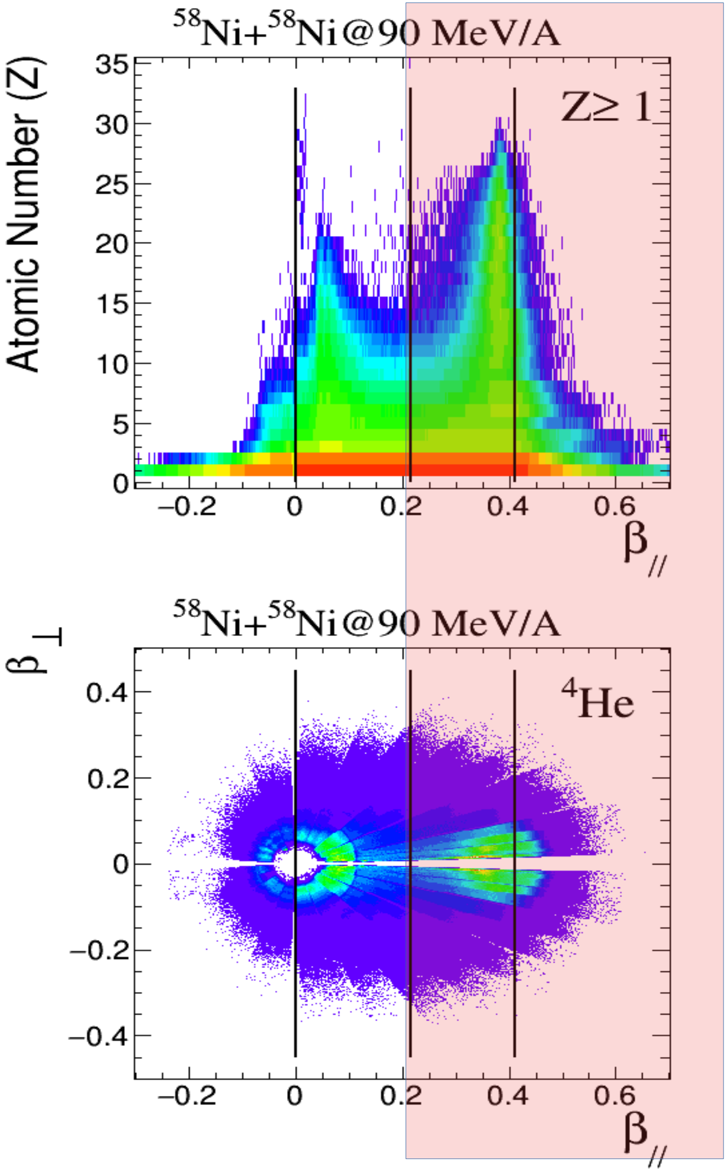
58Ni+58Ni@INDRA@GANIL

4pi apparatus designed to detect all charge products for HIC at Fermi energies





Good granularity
Low detection thresholds
Whole Z identification and
A&Z identification up to Be



^{58}Ni+^{58}Ni@INDRA

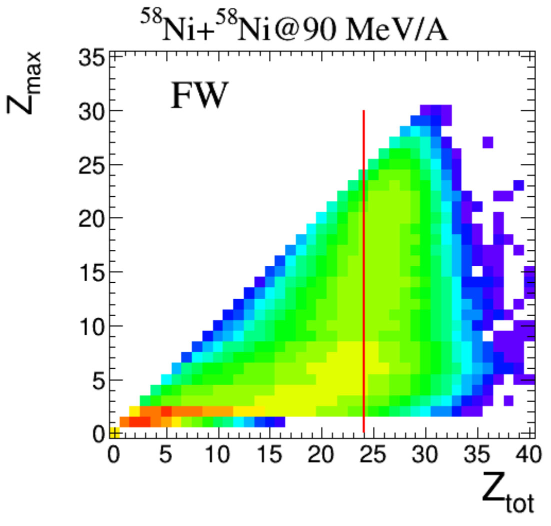
Example of the population of the velocity space of the final products for the 58Ni+58Ni@90 MeV/A reactions.

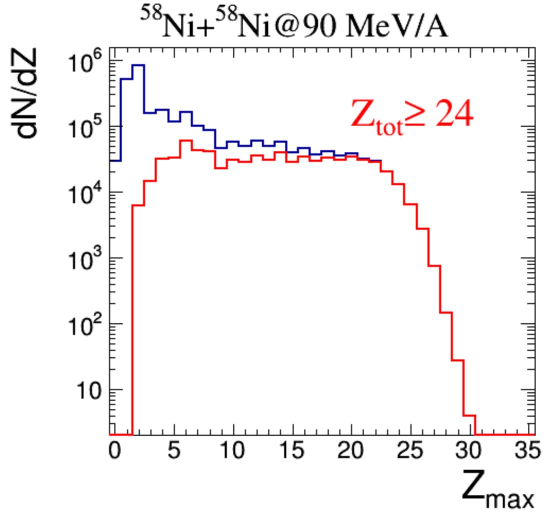
In the present analysis, we focus on the forward part of each event because :

- A complete isotopic identification up to 10Be is achieved
- The detection efficiency is almost independent of the reaction mechanism minimizing possible experimental bias

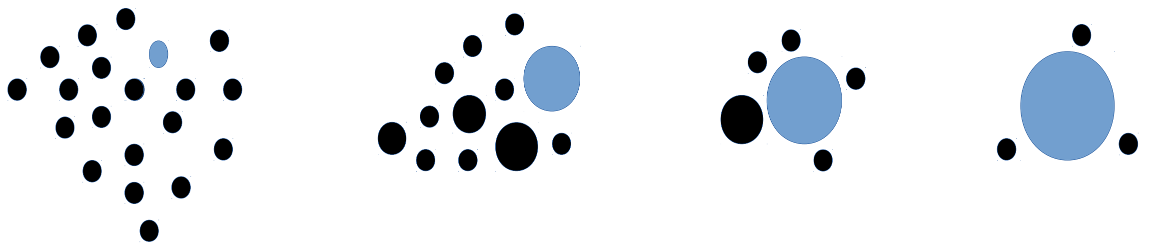
As it is a symmetric system, it gives, in average, a good description of what happens for the whole system

^{58}Ni+^{58}Ni@INDRA



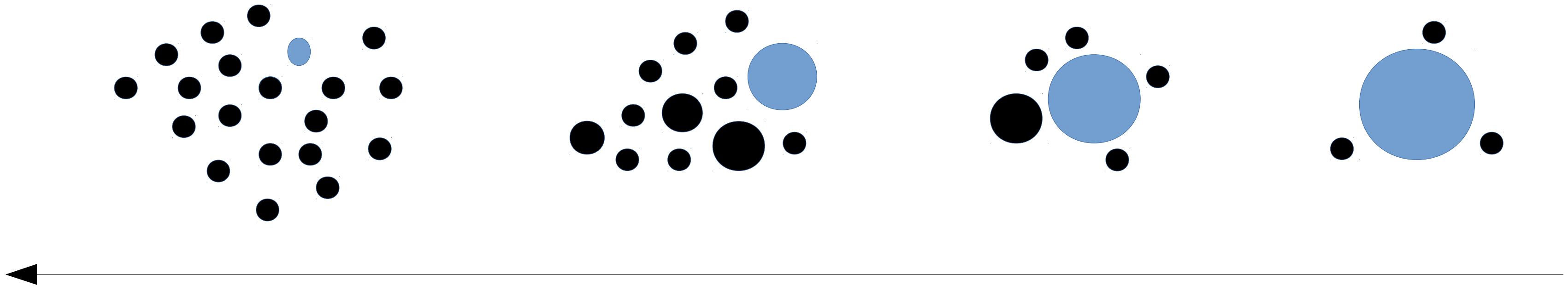


Forward part of each event :
Correlation between charge of the biggest fragment (Zmax) and the total detected charge (Ztot)
We keep events with missing charge less than 5 compare to the 58Ni charge (Z=28) to ensure that the Zmax fragment is part of the event.
→ Ztot>=24 selection
Same procedure is applied for all incident energies : 32, 40, 52, 64, 74, 82 and 90 MeV/A



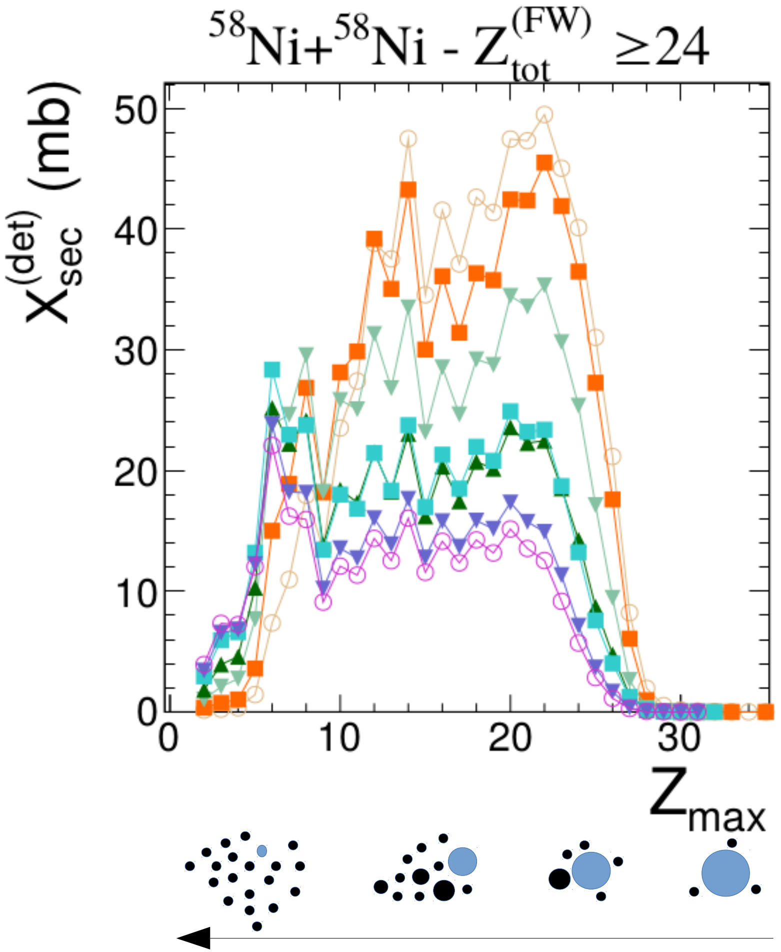
58Ni+58Ni@INDRA@GANIL

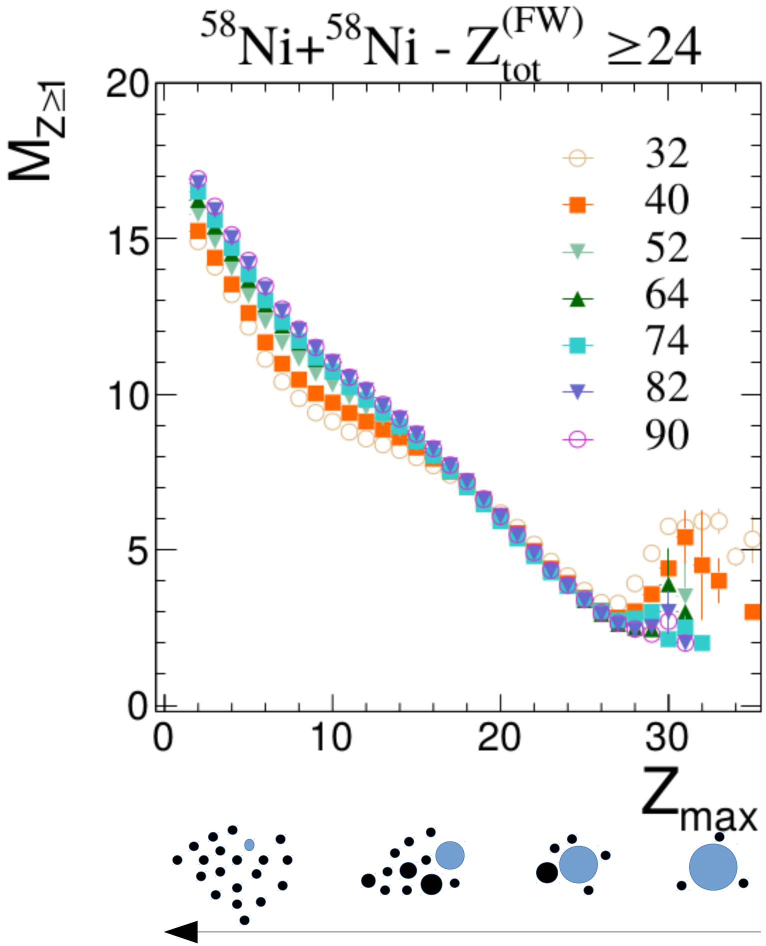
- We study the contribution, according to Zmax, of the following clusters : $^{1,2,3}H$ and $^{3,4}He$. The heavier clusters are gathered in the A>4 family.
- As we discuss about finite system, we have to consider carefully the trivial effect conservation of the total number of nucleons.
- From one fragmentation degree (Zmax) to another, the available nucleons to build “clusters” is not the same.



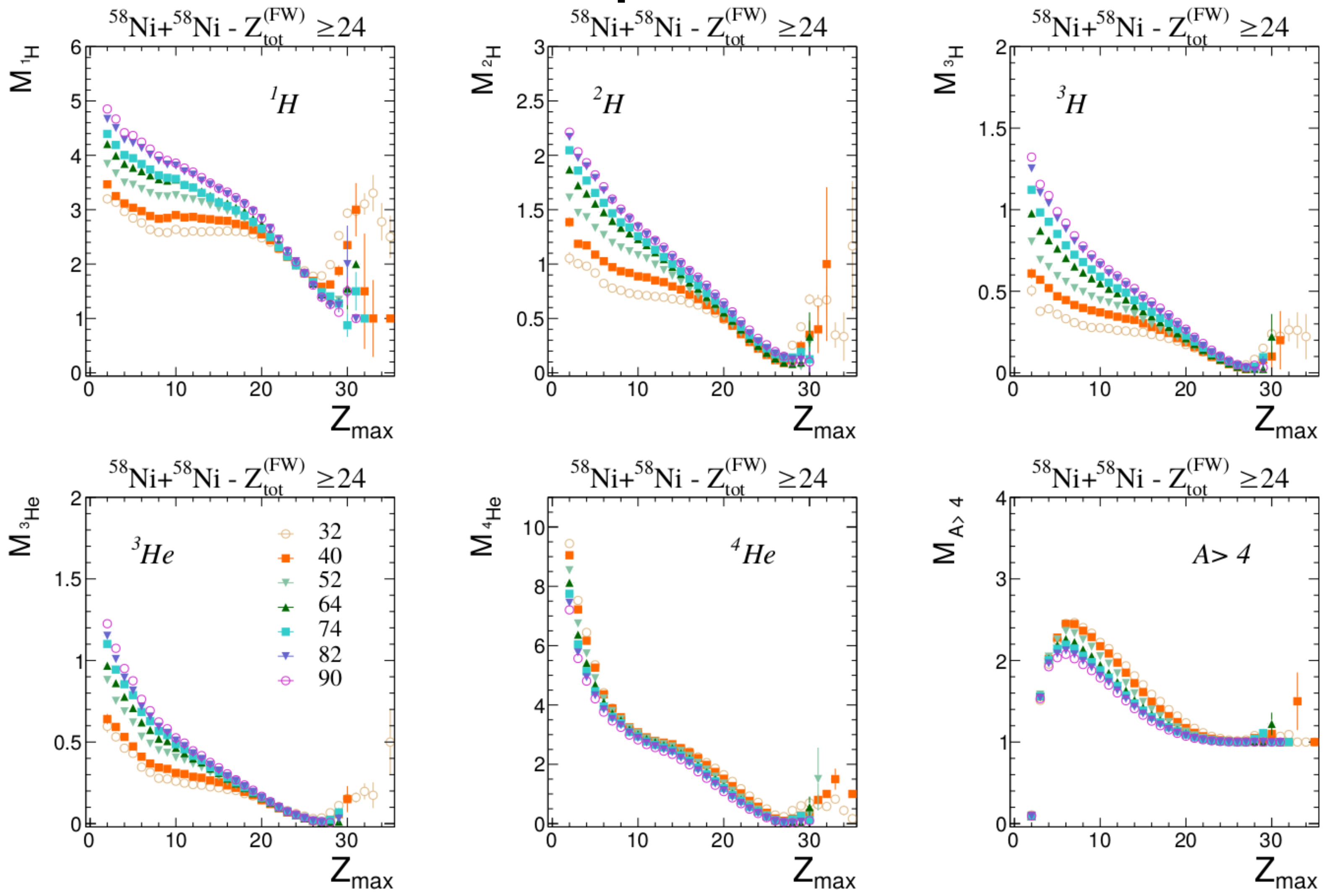
decreasing Zmax = increasing fragmentation = increasing FO volume

Zmax distribution and Total multiplicity





Multiplicities



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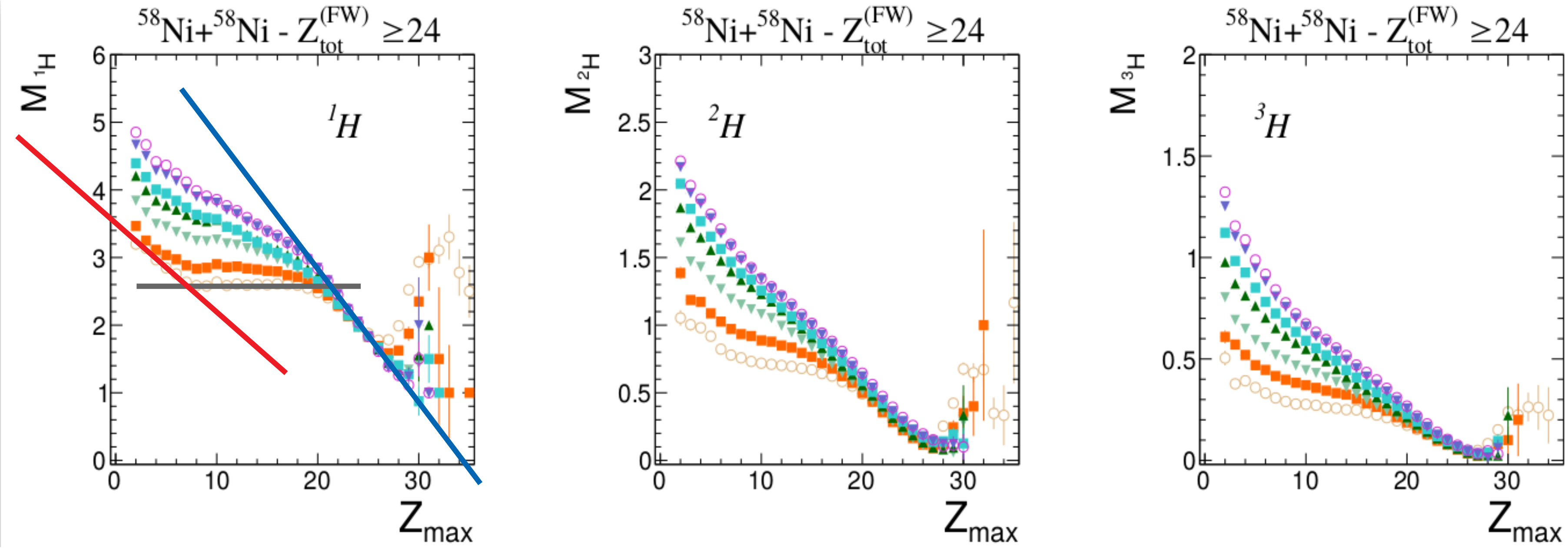
Multiplicities



The evolution of cluster multiplicities can be described as follow :

- Two branches associated to **evaporation (large values of Zmax)** and **vaporisation (low values of Zmax)** regim.
- One plateau or a softened evolution in the multifragmentation regim (intermediate values of Zmax)

Increasing incident energy, these picture is more and more blurred:

the multiplicity goes to a continuous increase when Zmax is decreasing

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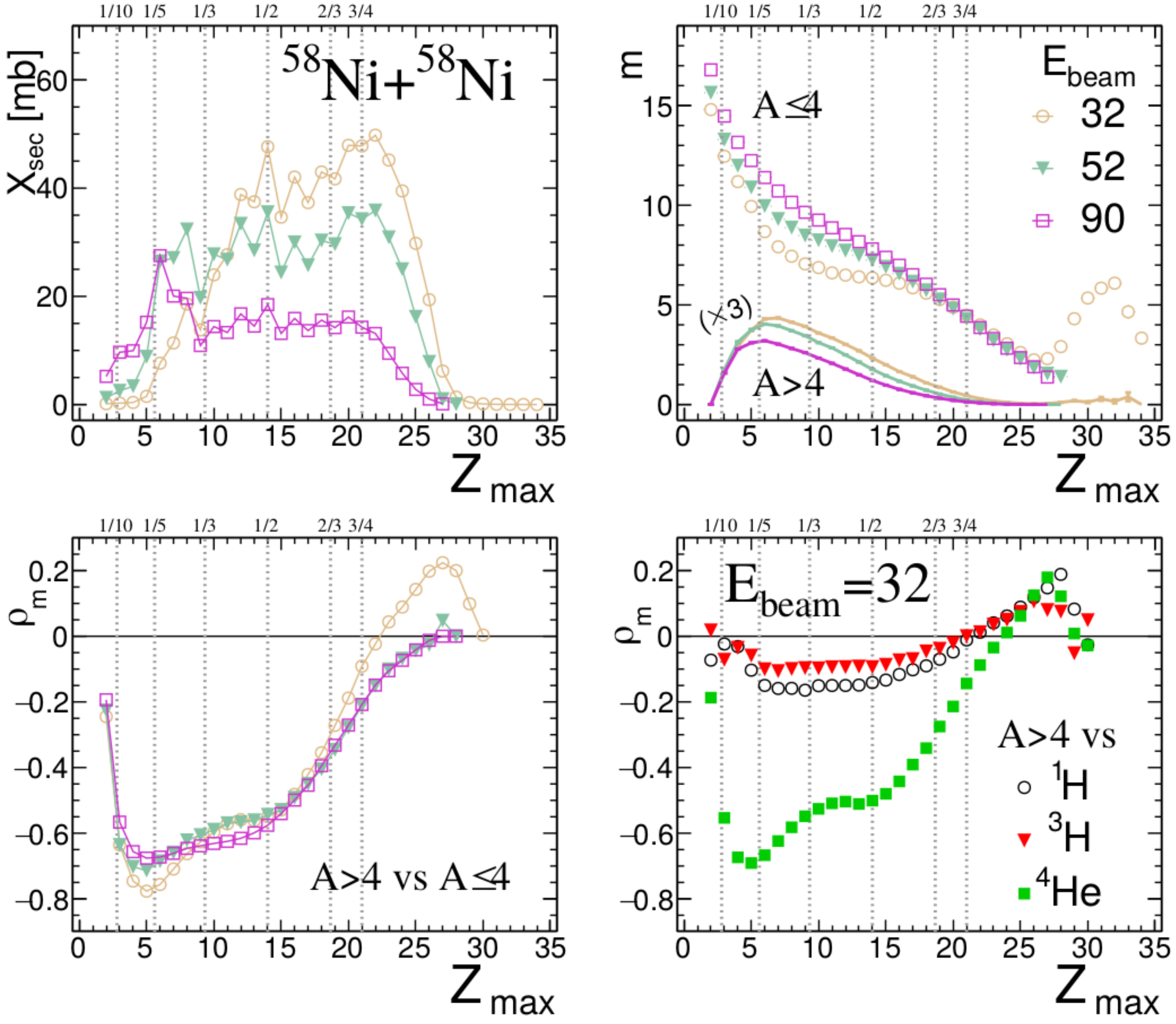


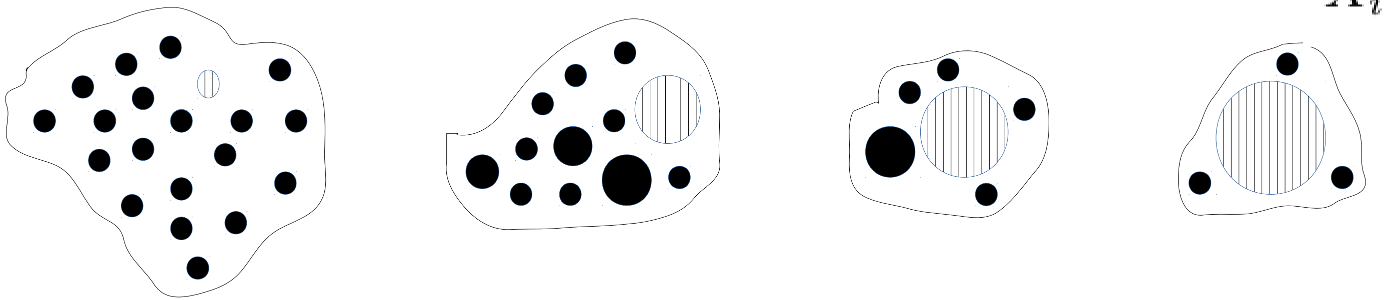
$$\rho_m(i,j) = \frac{< m_i m_j > - < m_i >< m_j >}{\sigma_{m_i}\sigma_{m_j}}$$

Looking at correlation between species,
it appears that 4He clusters and A>4 heavier products are strongly correlated

Mass Fractions

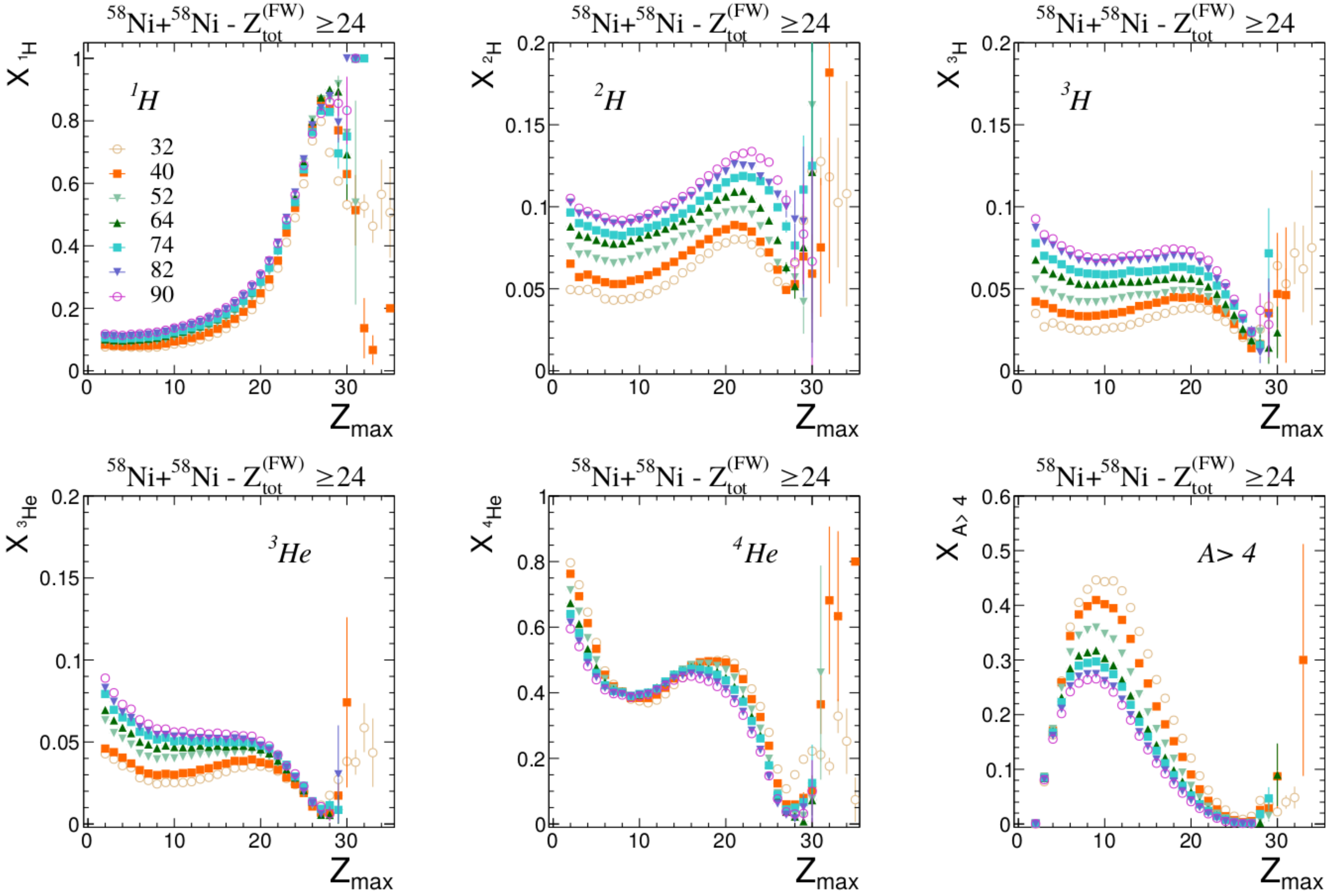
- We are interested looking at nucleons which are not bound in Zmax and how they are shared among the different species.
- We introduce the mass fraction (X) which is the probability for a nucleon to belong to one or an other species.
- We compute these mass fractions on the remaining part removing the contribution of nucleons bound in Zmax

$$X_i = m_i A_i / (\sum_{j=1}^{mtot} A_j - A_{max})$$



- Composition of the remaining part is then studied using Zmax sorting as a volume sorting (FO picture).

Mass Fractions

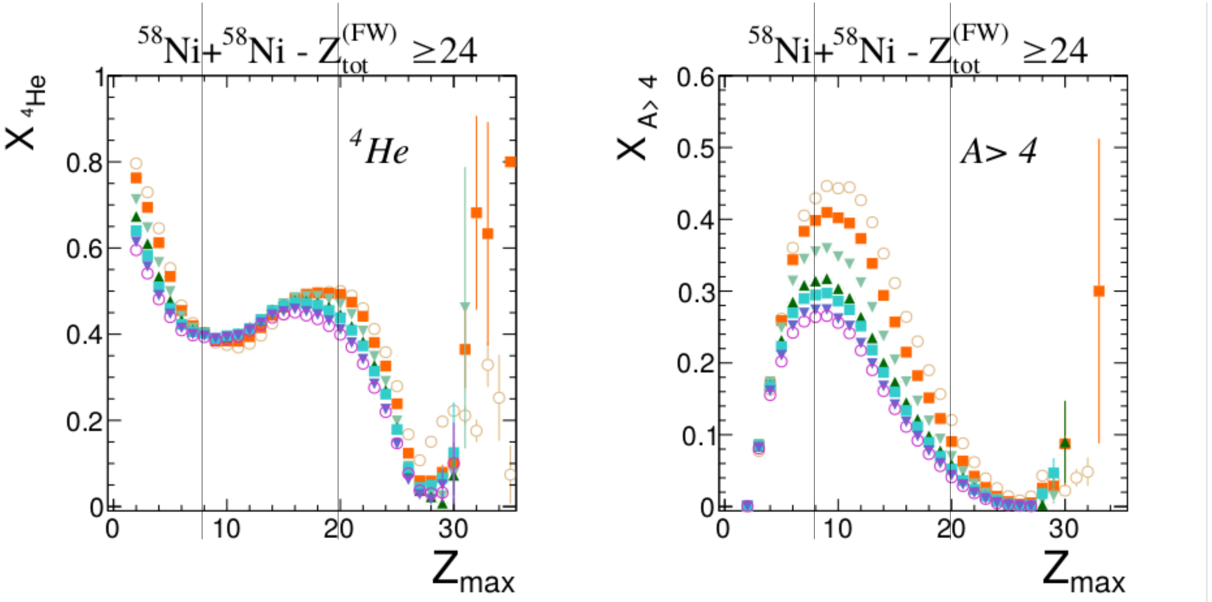


Mass Fractions

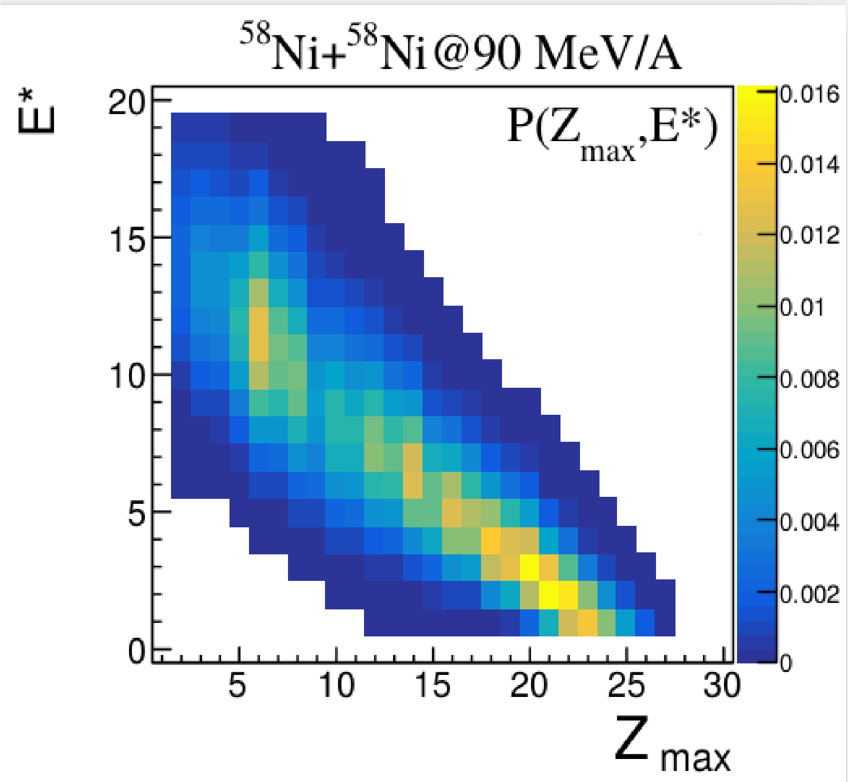
The cluster contributions follow a similar behaviour :
- The contribution starts to increase in the evaporation regim to reach a maximum Around Zmax~20.
- Then the contribution start to decrease or saturate in the mid values of Zmax, Corresponding to the multifragmentation region Zmax~[8-20].
- Finally entering in the vaporization regime, all contributions increase again except for free protons.

The 4He cluster contribution is predominant in the whole range of Zmax values.

Contribution of heavier products gathered in the A>4 family are framed by the clusters.



We introduce the excitation energy (E*) to look at evolution of 4He contribution when the experimental phase diagram E*-Zmax is scanned



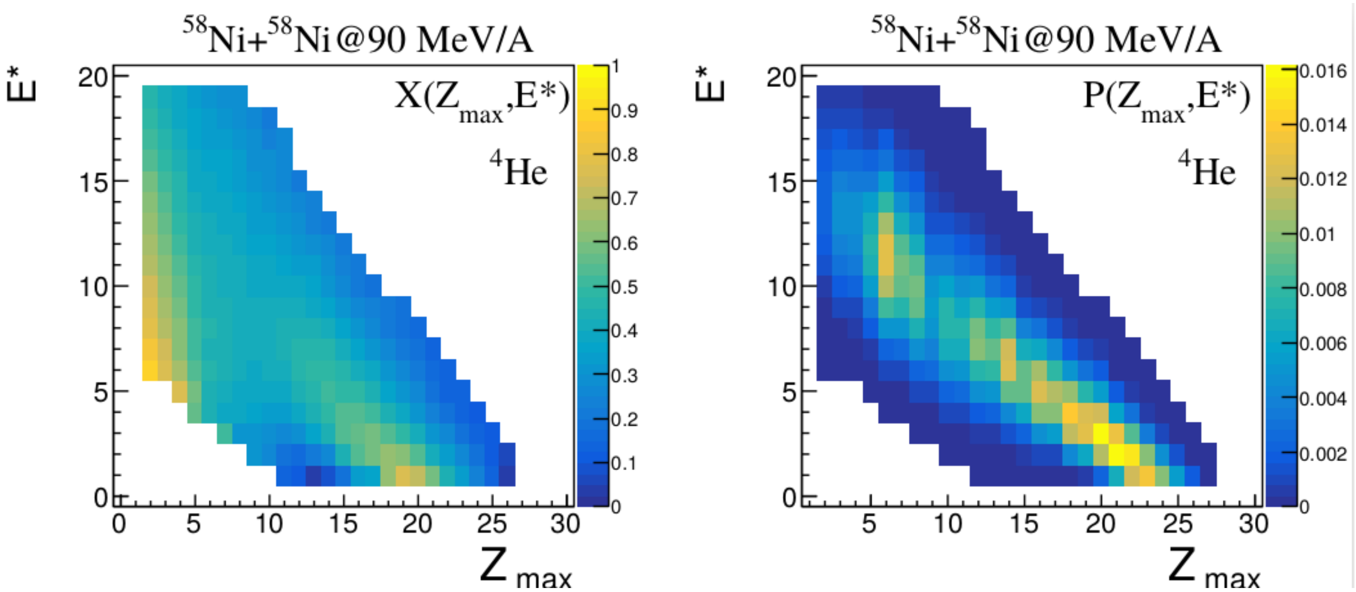
E* is estimated by calorimetry

$$E^* = \sum_{i=1}^{M_{tot}} (\epsilon_k^{(i)} + \delta^{(i)}) - \delta_{ini}$$

As neutrons are not detected by INDRA, assumptions are used to estimate the neutron Contribution (multiplicity and kinetic energy)

$$E^* = \sum_{i=1}^{M_{Z\geq 1}} (\epsilon_k^{(i)} + \delta^{(i)}) + \sum_{j=1}^{M_n} (\varepsilon_k^{(j)} + \delta^{(j)}) - \delta_{ini}$$

Exploration of the experimental phase diagram E*-Zmax
Focus on the 4He clusters



Track the specific behaviour of mass fraction evolution in the multifragmentation regime :
Contribution of 4He clusters decreases although the system is more and more fragmented

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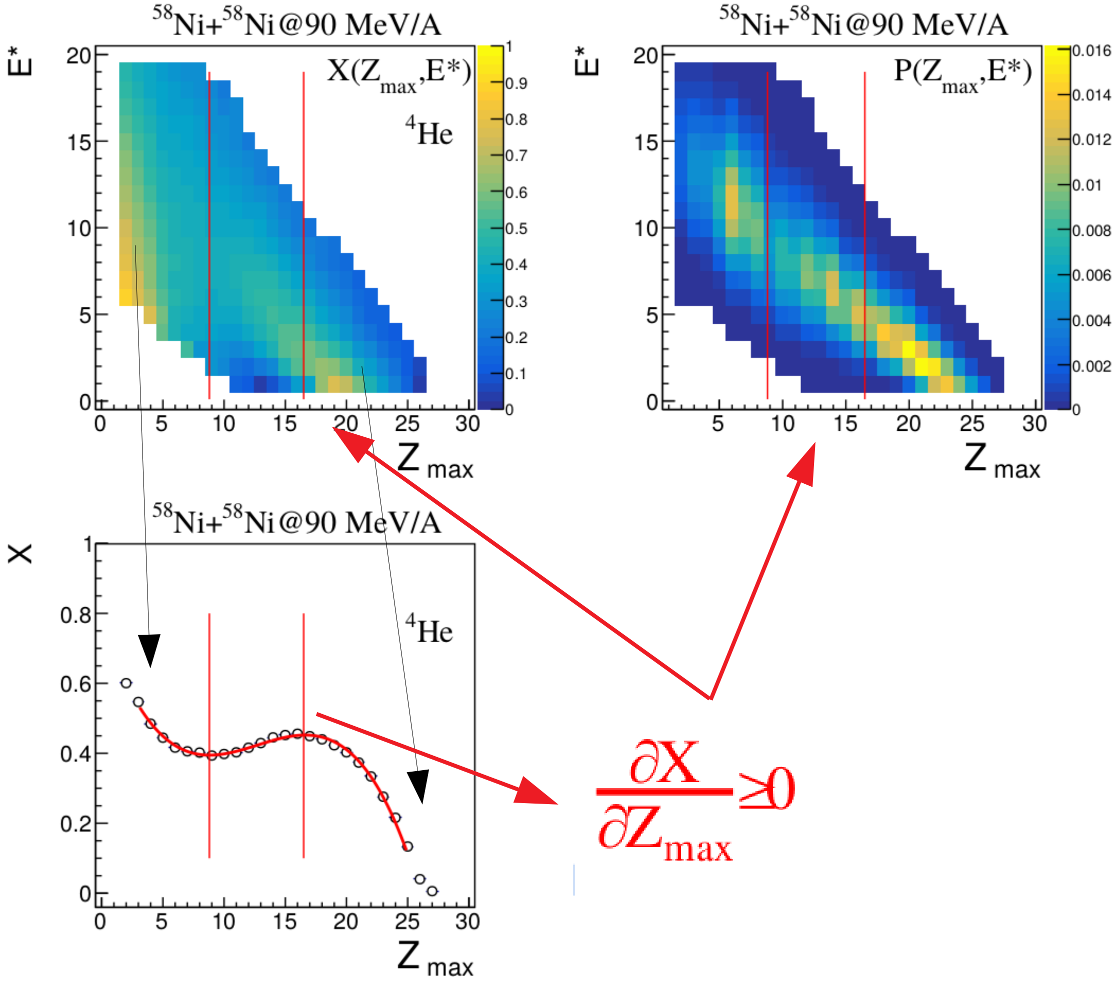

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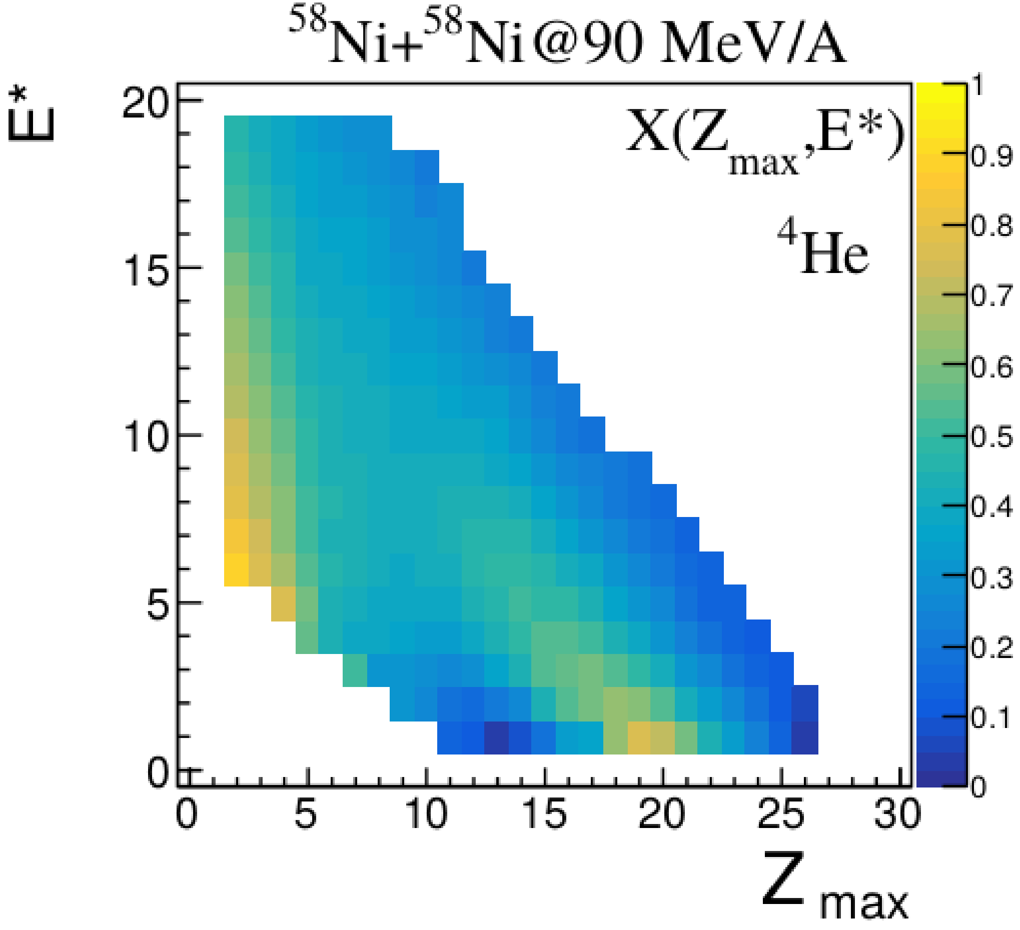

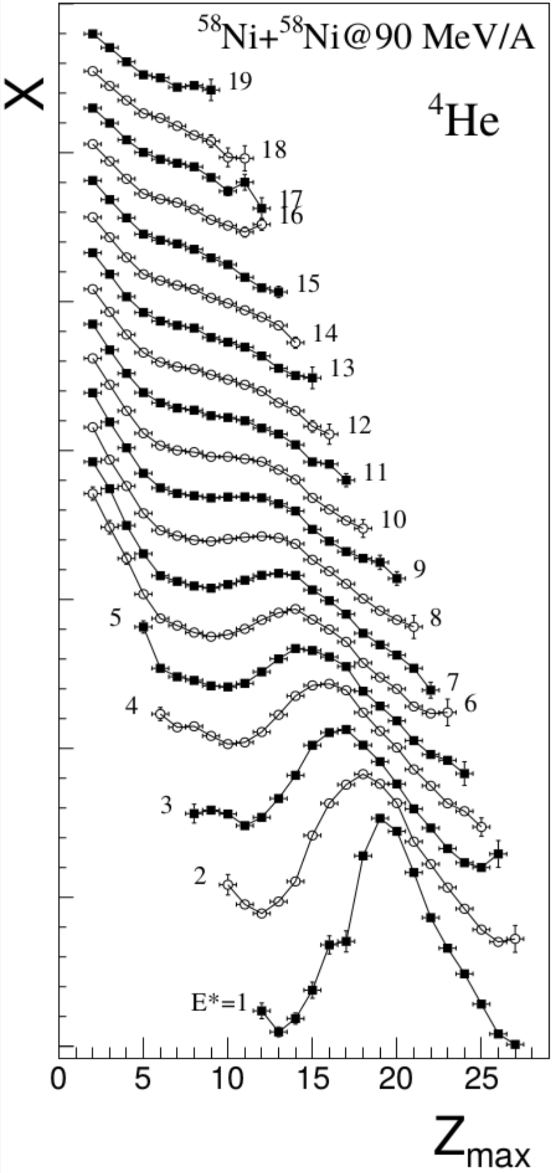

Exploration of the experimental phase d
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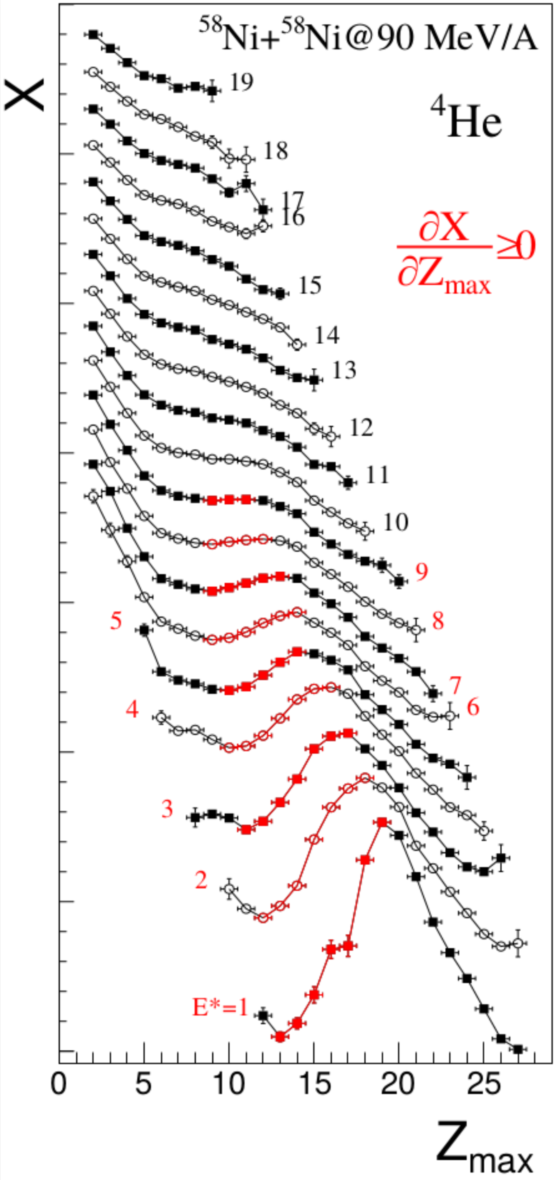

Exploration of the experimental phase d
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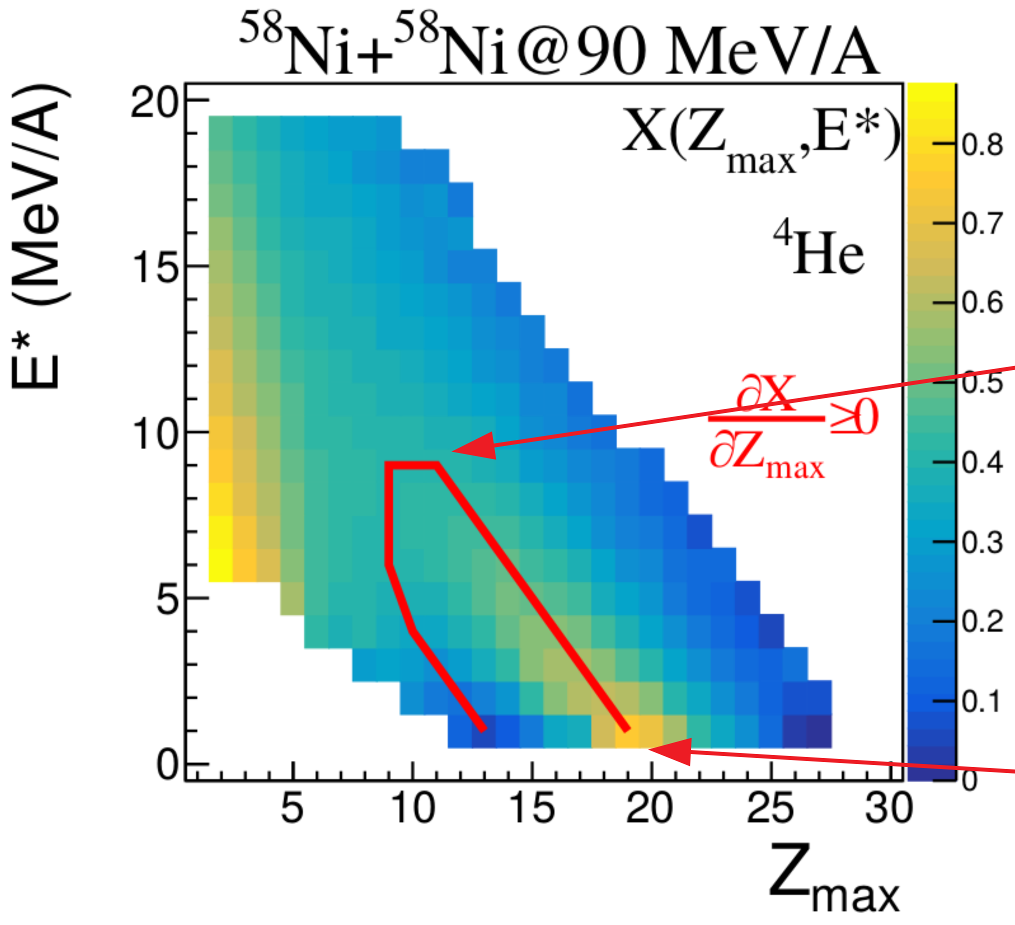

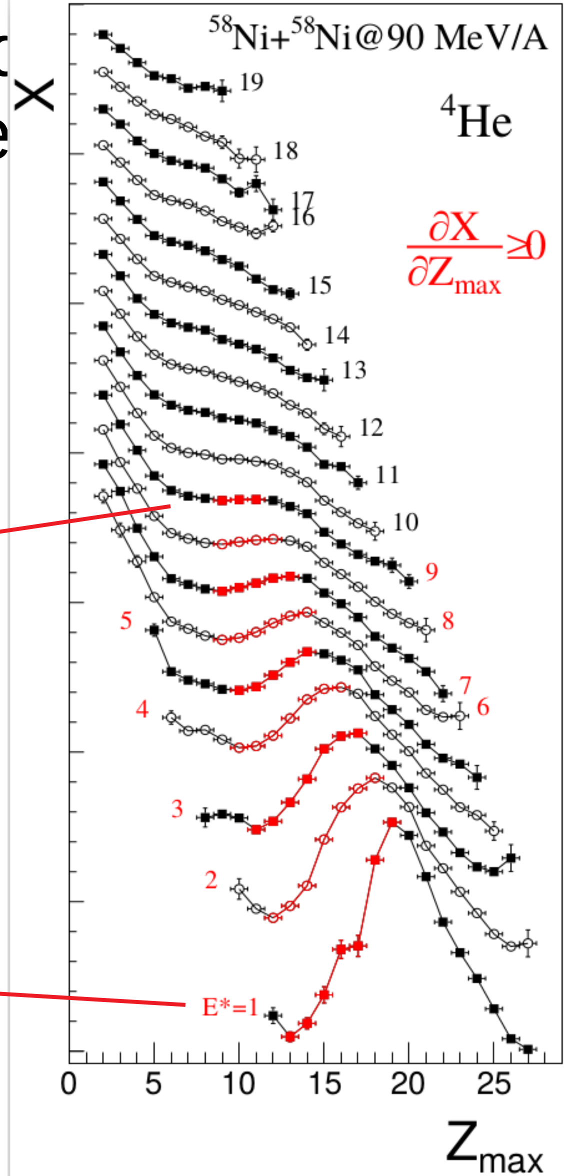

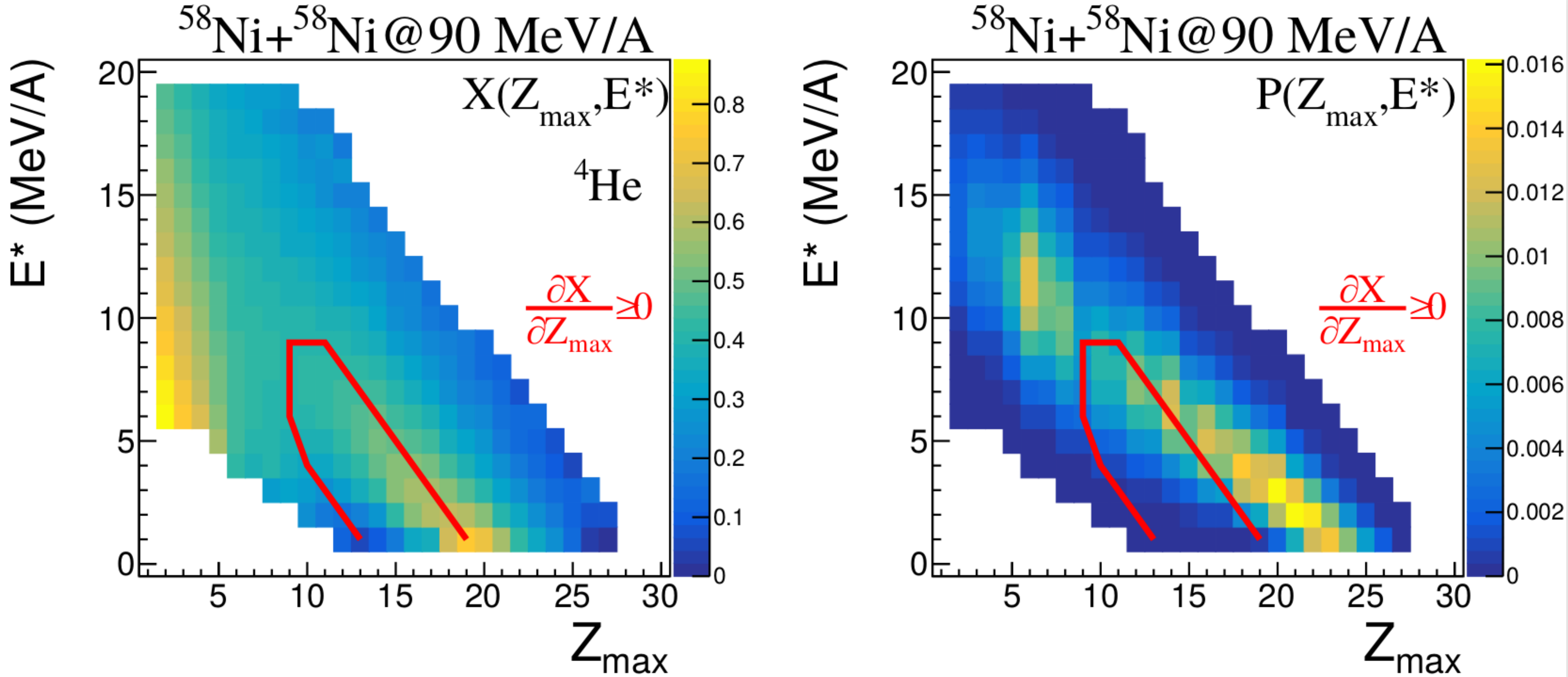

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Spinodal Zone :
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Gas side: E* ~ 5.8 MeV/A

Conclusions

- We have sorted experimental events according to Zmax and see effects in cluster production when different regions of the phase diagram are crossed.
- We found that cluster production is strongly correlated to the different mechanisms which drive the fragmentation of the system.
- Specially, 4He clusters play a major role.
- Their mass fraction (X) shows a specific behaviour when exploring the Zmax-E* experimental phase diagram.
- Considering dX/dZmax>=0 as a consequence of coexistence of mechanisms in the fragment production, we propose a new delimitation of the coexistence zone in Zmax-E* for the light systems produced in Heavy Ion Collisions which is in good agreement with those obtained for heavier systems.

Thank you for your attention