Nuclear Physics
Mid Term Plan in Italy

WG2: fusion-evaporation and pre-equilibrium emissions

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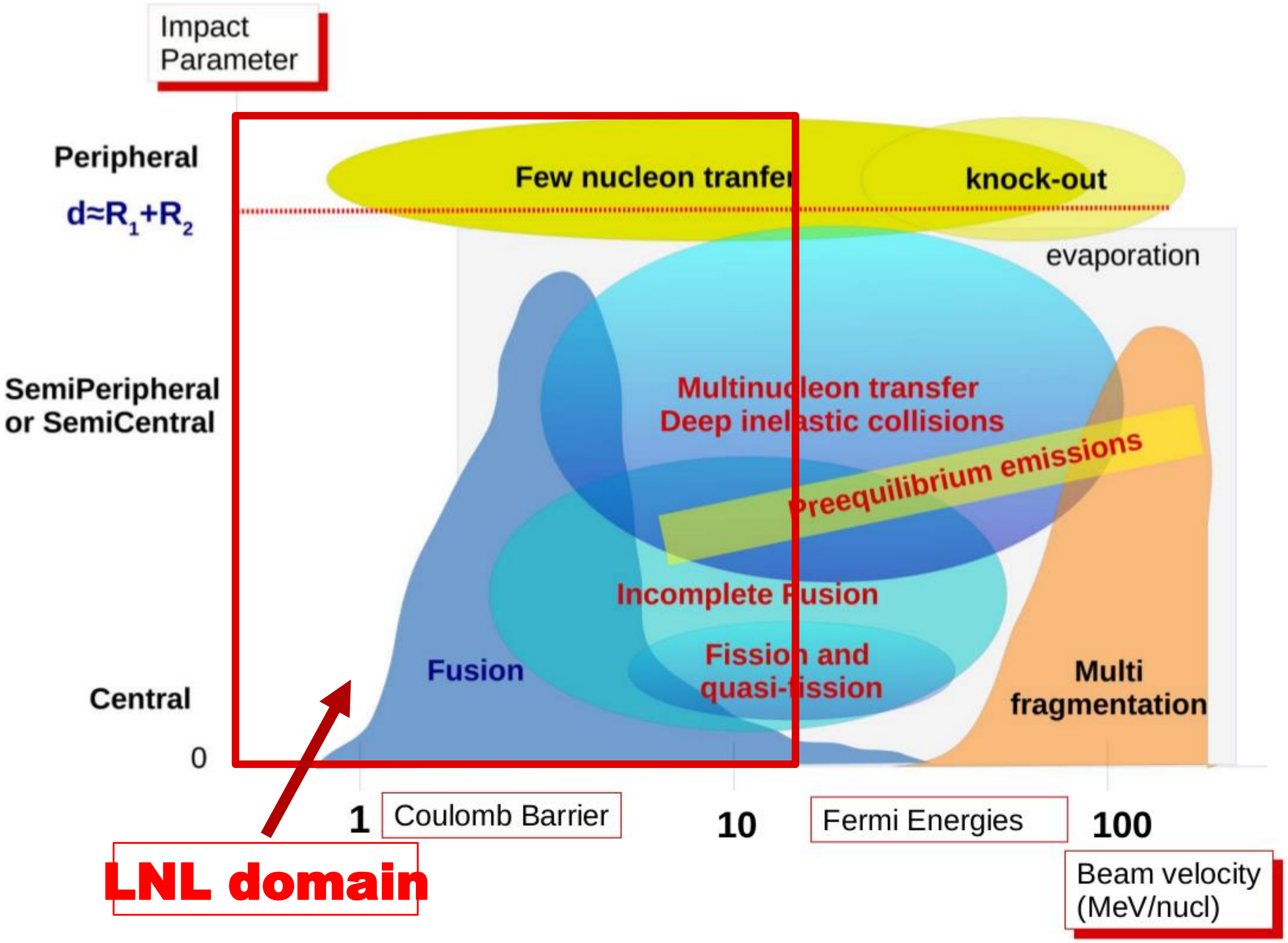


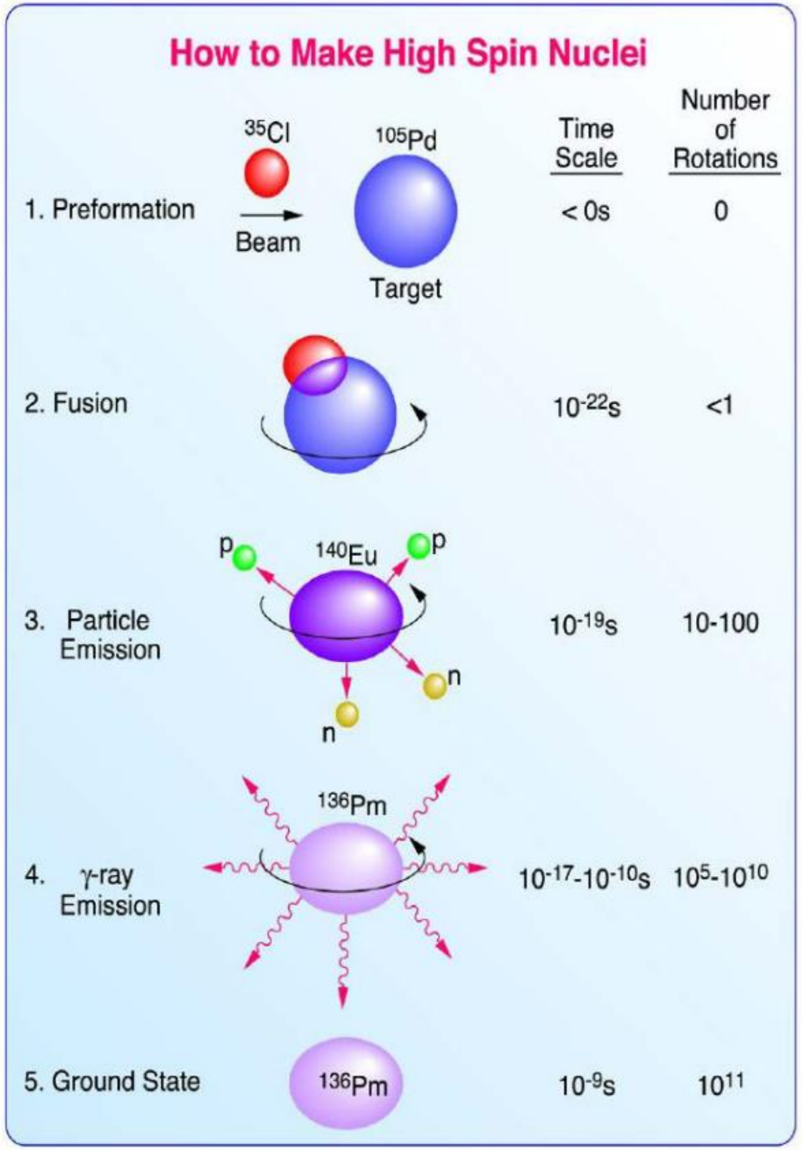
Reaction mechanims considered for LNL:

1. *Fusion and CN decay*
2. *Pre-equilibirium emission*
3. *Incomplete Fusion/Quasifission*

Tools considered for LNL:

- *GARFIELD + Rco (particles, 4pi)*
- *FAZIA, FARCOS (particles, hi-res)*
- *Corset (heavy fragments, correlations)*
- *PARIS (n-g, high efficiency)*

… and their possible combinations



Conditions for compound nucleus formation:

- Two colliding nuclei must have enough kinetic energy to overcome the repulsive Coulomb barrier, and approach close enough for initiating short-range attractive nuclear forces
- Newly formed dinuclear system must undergo shape evolution towards a compact mononuclear shape near equilibrium deformation
- Compound system must survive statistical fission to form an evaporation residue

Fusion – evaporation, two main topics:

- α-correlations and clustering in light systems
- Isospin dependence of compound nucleus formation and decay

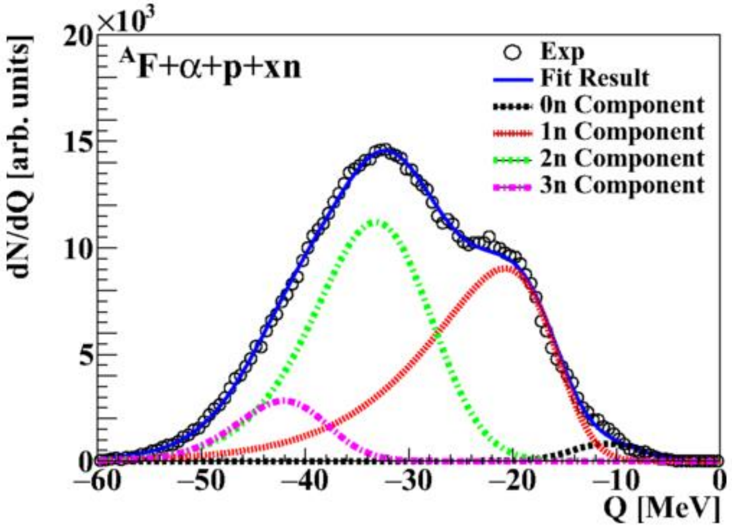
α-correlations and clustering in light systems

Studying the de-excitation chains of the CN. Full event reconstruction (in Z) by measuring coincidences of ER & α-particles:

- comparison of exit channels BR exp vs. predicted by statistical models (with and without specific refinements on nuclear structure).
- Main results
  1. **the experimental branching ratios for these channels are significantly higher than predicted ones.**
  2. **when the α-particle emission is accompanied by neutrons, favored configurations with the α-particles emitted one after the other have been found.**

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

[A. Camaiani et al., PRC 97, 044607 (2018)]



Need of new theoretical efforts, possibly dealing with **absolute cross-section prediction and measurement.**

α-correlations and clustering in light systems

Dynamics of the CN de-excitation: sequential vs simultaneous.

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

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

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

- **Extremely exclusive dataset:** 5 (+1) alpha particles in coincidence with $Z_{sum}=Z_{in}$ and $P_{sum}= P_{tot}$
- **In-house developed evaporation code (HFl)** that contains the discrete levels of all nuclei up to Si (structure) and an optimized tratment of the continuum.

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

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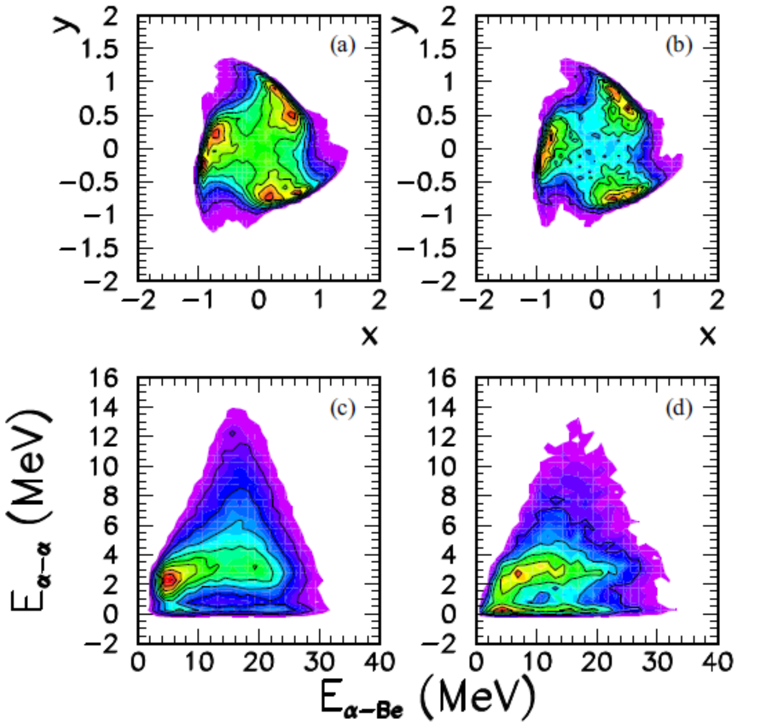


Experimental data in panel (a) are compared with theoretical HFl predictions in panel (b), showing a very good agreement and clearly excluding a dominant simultaneous breakup mechanism.

[L. Morelli et al., PRC 99, 054610 (2019)]

α-correlations and clustering in light systems

$^{16}O + ^{12}C$ @ 130 MeV

1. ***The observed branching ratios are significantly different from the theoretical ones.***
2. ***The bad reproduction of the branching ratio of the Hoyle state is particularly striking.***

Table 4. Branching ratios of different reactions (see text).

Reaction	Exp.(%)	HFℓ As experimental data	(%) 'true'
$^{12}C(^{16}O, ^{8}Be_{gs} + ^{8}Be_{gs})^{12}C_{gs}$	7.5 ± 0.7	20.8	22.1
$^{12}C(^{16}O, ^{12}C_1^* + \alpha)^{12}C_{gs}$	32.0 ± 0.2	53.0	53.0
$^{12}C(^{16}O, ^{12}C_2^* + \alpha)^{12}C_{gs}$	49.0 ± 0.1	19.3	18.3
background	11.5 ± 0.5	6.8	6.5
$^{12}C(^{16}O, ^{8}Be_{gs} + ^{8}Be_{gs})^{12}C^*$	5.2 ± 1.5	11.3	12.9
$^{12}C(^{16}O, ^{12}C_1^* + \alpha)^{12}C^*$	16.2 ± 0.6	52.4	52.4
$^{12}C(^{16}O, ^{12}C_2^* + \alpha)^{12}C^*$	53.0 ± 0.1	24.4	23.3
background	25.6 ± 0.3	11.8	11.7

C_1^* (Hoyle state), C_2^* (9.64 MeV).

[M. Bruno et al., J Phys G, 46 (2019) 125101]

…

We can, therefore, consider that the present measurement imposes ***very tight constraints on the statistical model, and challenges the validity of the statistical approach itself.***

…

An alternative explanation is that the specific well known α-cluster structure of the Hoyle state might influence the Coulomb barrier and the associated transmission coefficients of the corresponding evaporation channel, which are only globally optimized in the HFℓ code to light nuclei, ***without taking into account explicit structure effects [3].***

We plan to explore the possible connection between the branching ratios and structure effects in the transmission coefficients in a forthcoming dedicated study focused on the specific decay of the Hoyle state.

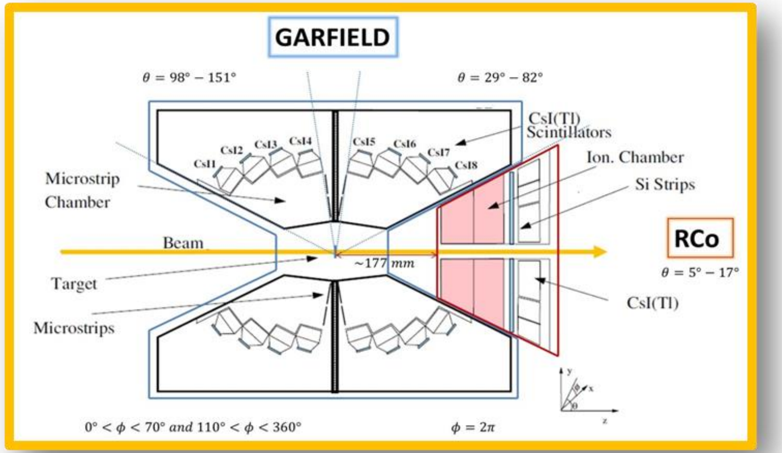
ISOLIGHT campaign $^{18}O+^{12,13}C$ at increasing energies.

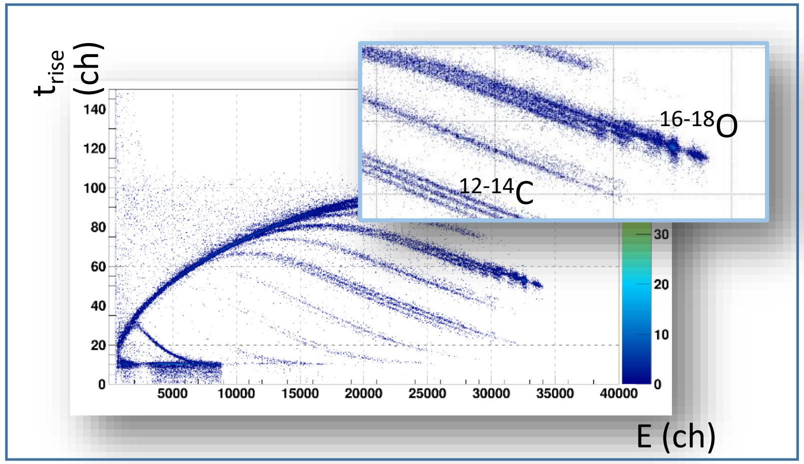
in progress

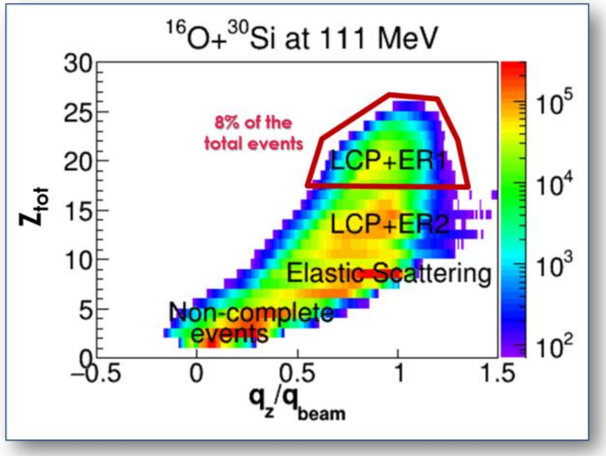
α-correlations and clustering in light systems

Experimental requirements:

- **high angular coverage** -> to detect almost all the charged reaction products -> reconstruction of complete (in charge) events -> study of decay channels
- **good identification of ER**: charge, mass (if it is possible) -> estimation the free neutron multiplicity
- **high granularity** -> particles id (Z, A, angle, ...) -> particle correlations -> to investigate the resonances associated to excited states of nuclei produced one step before the final channel.
- **large acceptance** -> charged reaction products
- availability **n-rich beams** (SPES) -> to extend the previous studies also to n-rich nuclei.

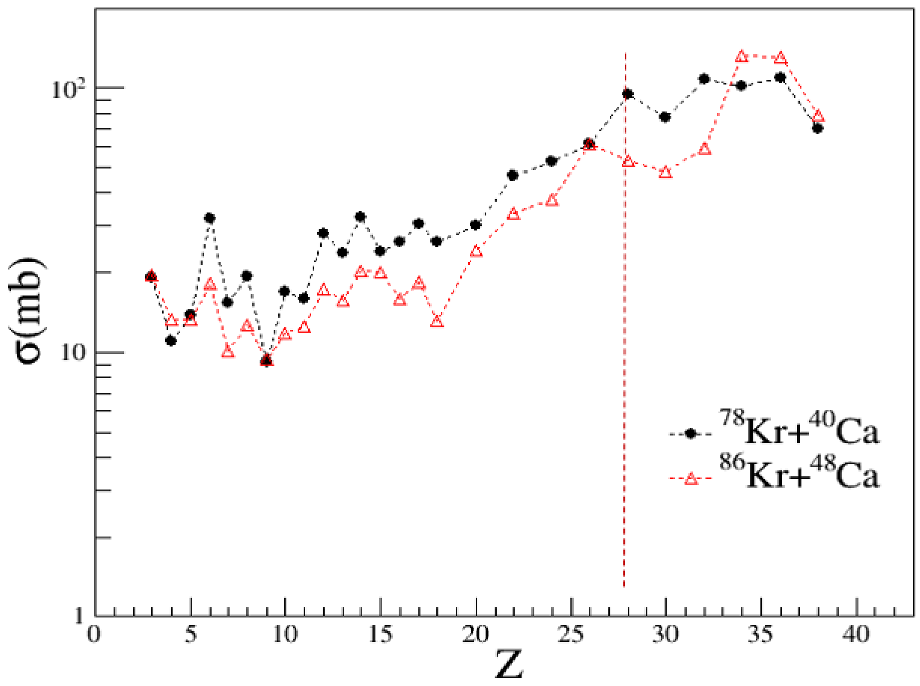






Isospin dependence of CN formation and decay

Synergies with LNS



S. Pirrone, et al., Eur. Phys. J. A (2019) 55, 22

Open questions:

- Produce excited nuclei in unexplored regions of the nuclear landscape
- Study spin and internal degrees of freedom
- Provide additional constraints on the sophisticated models
- Describe better statistical and/or dynamical properties in the formation and decay of excited nuclei
- Fission barriers and level density parameters also depend on the symmetry energy and neutron-proton composition of nuclei.

SPES will open a new range of opportunities (LoIs)

1. **E. De Filippo, J.Frankland, S.Pirrone, G.Politi, P.Russotto et al, Isospin dependence of compound nucleus formation and decay**
2. **G. Casini et al, Isospin dynamics and thermodynamics in n-rich heavy-ion induced reactions**
3. **W. Królas et al, Entry distributions for fragments produced in deep-inelastic collisions**

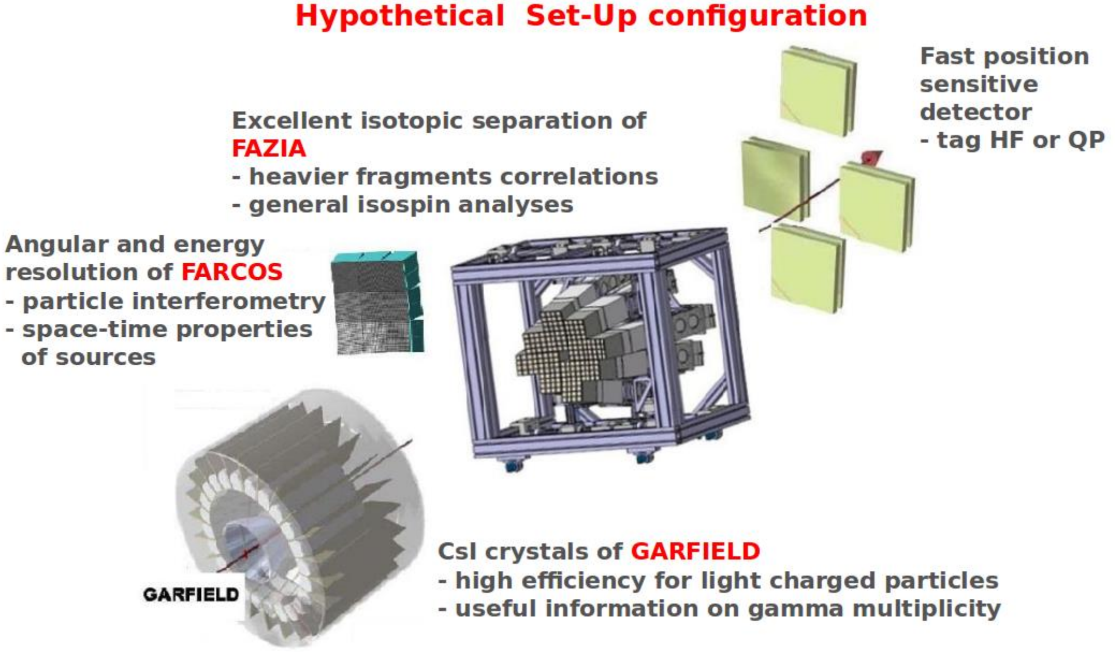
Isospin dependence of CN formation and decay

- Isospin effects on the reaction mechanisms and on IMF production.
- Compound nucleus formation and decay (ISODEC & FAZIA)
  - Level density, fission barrier, viscosity

AT SPES: Broad domain in n/p ratio in entrance channel and compound systems

- Intermediate mass region: Kr, Sr, Sn beams on Ca, Ni
- In particular
- \- $^{88-94}$Kr with 10^5 - 10^7 pps @ E/A = 10 - 12 MeV/A (^{40,48}Ca target)
- \- Sn or Cs exotic beams on target of Ca, Ni and Sn isotopes

Existing detector and facilities in LNL could be complemented with new incoming devices as FAZIA and FARCOS



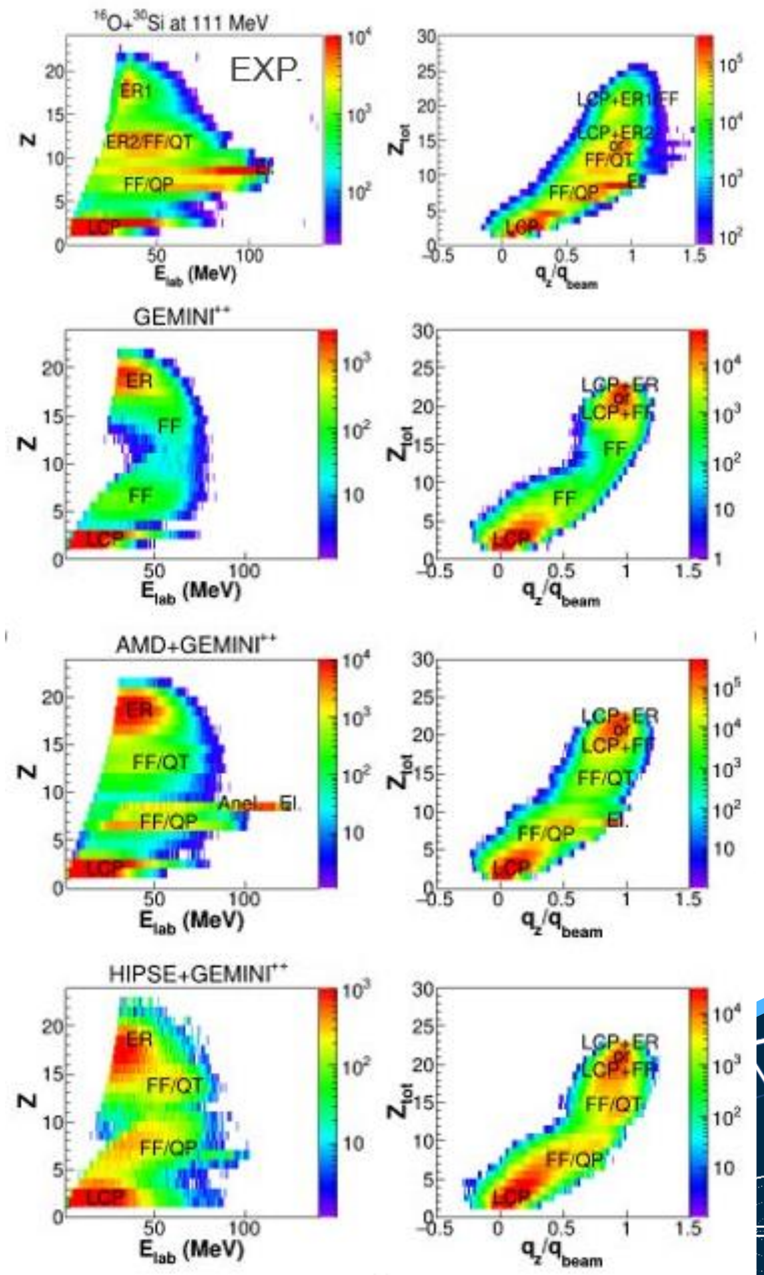
Key observables:
- cross-sections,
- LCP multiplicities,
- LCP correlations,
- angular, energy and velocity distributions for the IMFs - LCPs –FF.

Requirements:
- isotopic resolution,
- high angular resolution
- broad angular acceptance
- low energy thresholds

Fast α-emission in medium mass systems

Possible reactions:
$^{16}O+^{30}Si$ at E_{lab} = 256 MeV
$^{18}O+^{28}Si$ at E_{lab} = 288 MeV
$^{17}O+^{29}Si$ at E_{lab} = 272 MeV
$^{17}O+^{29}Si$ at E_{lab} =119 MeV

Peculiar behavior of branching ratio for the **exit channels where only α-particles** (and possibly neutrons) **are emitted** → common feature that underlines the **importance of nuclear structure effects** in the decay of the α-conjugated compound nucleus.
M. Cicerchia et al., JoPG 48 (2021) 045101



The idea is to set up an experimental campaign to scan the evolution of the non-equilibrium emissions from 7 AMeV (ACLUST2) to 16 AMeV (FASTEM):

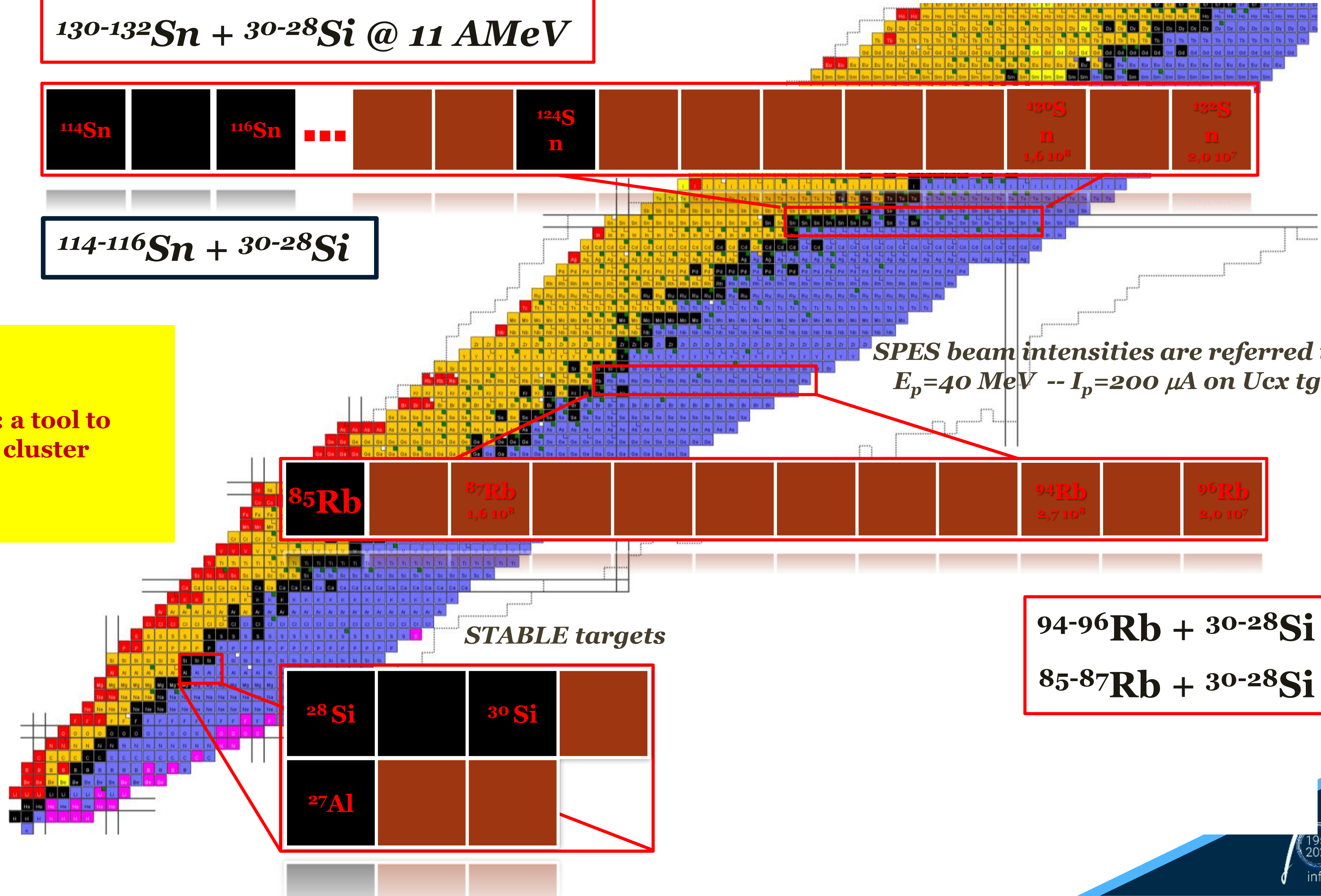
- energy region where the pre-equilibrium emission has the most important role.
- experiment (FASTEM), to study the O-induced reactions at the highest energy (16 AMeV), where the pre-equilibrium part is well assessed.

Fast α-emission in medium mass systems

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

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

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



SPES beam intensities are referred to E_p=40 MeV -- I_p=200 μA on Ucx tgt

STABLE targets

$^{94-96}$Rb + $^{30-28}$Si

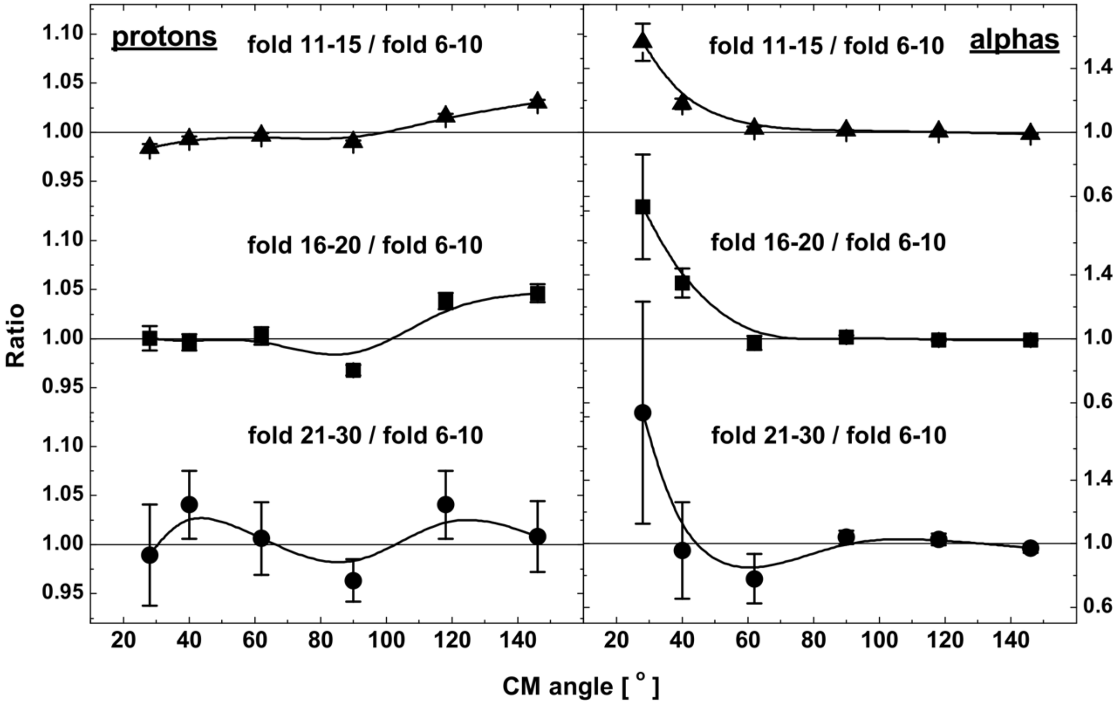
$^{85-87}$Rb + $^{30-28}$Si

T. Marchi et al, Pre-equilibrium emission: a tool to study dynamic effects and cluster structure in exotic nuclei

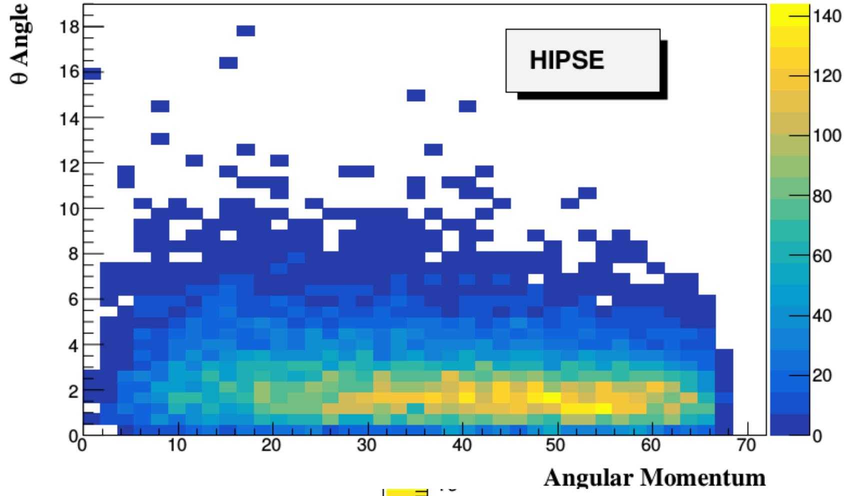
α-emission at highest spins

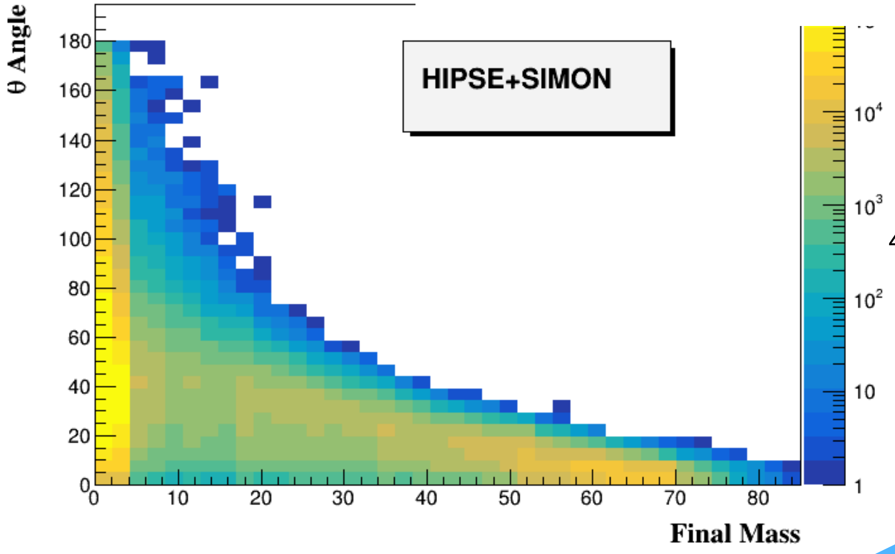
Dominance of the α emission at high spins in pre-equilibrium stage

Observed forward α-emission at high spins



M. Kmiecik et al Acta Phys. Pol. B, 38 (2007) 1437





^{48}Ti(600MeV)+^{40}Ca

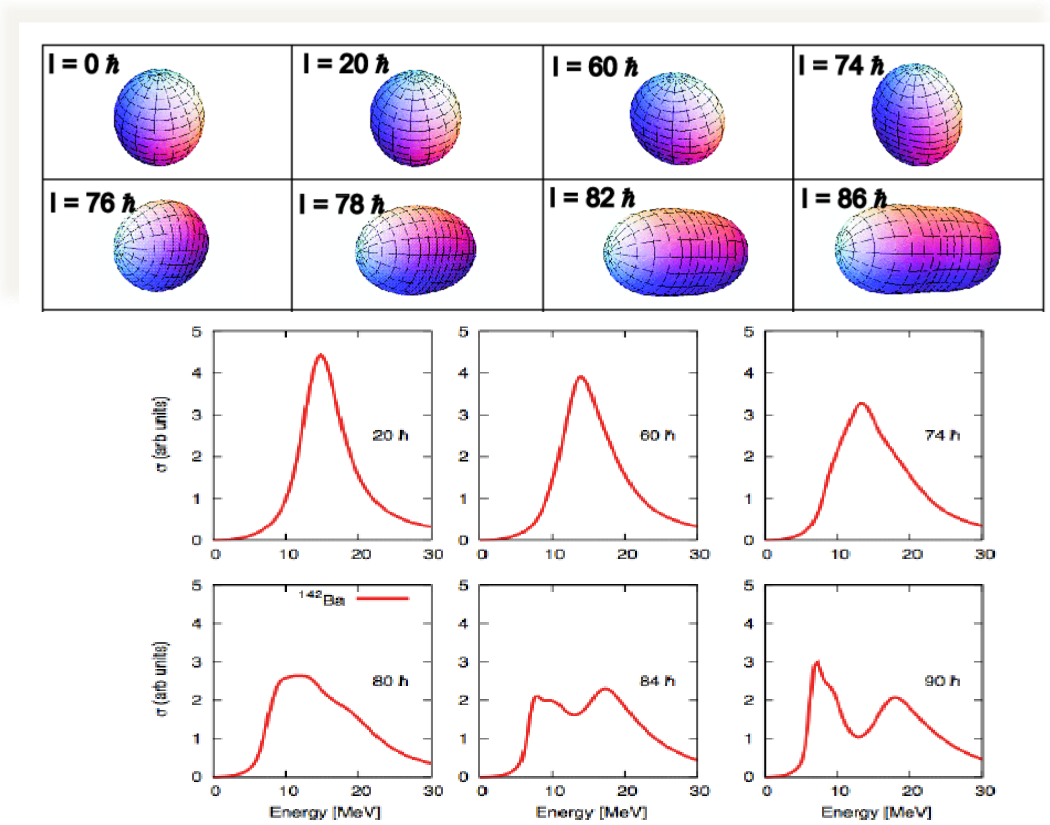
α-emission at highest spins

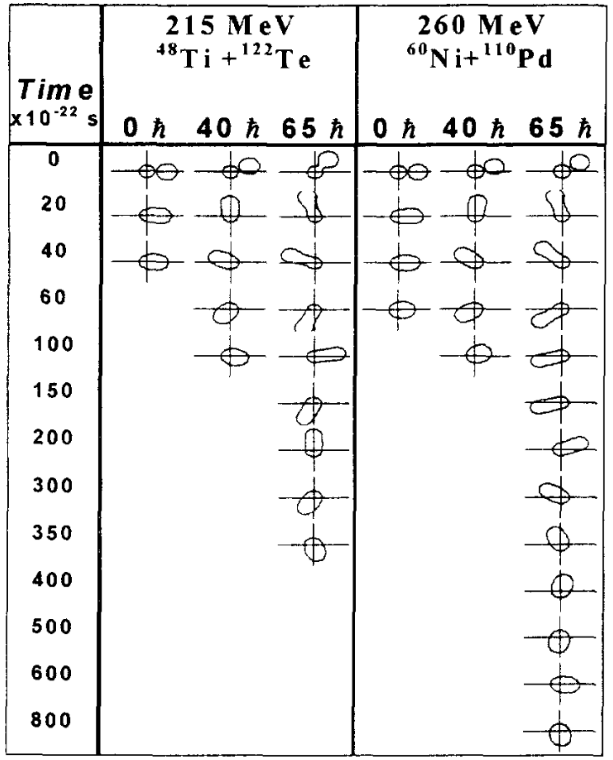
Questions to answer:

- →Is this effect related to **the very large deformations of the CN at high spins**?

(e.g. Emission from the ”poles” of elongated nuclei?)

→Or to **longer equilibration time in mass-symmetric entrance chanel reactions**?





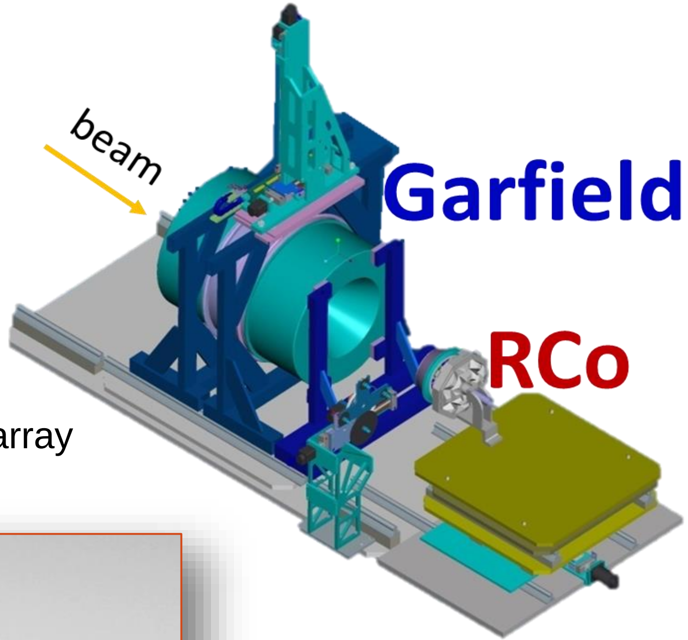
HICOL predictions, A. Maj et al., Nucl. Phys. A649 (1999) 135c

α-emission at highest spins

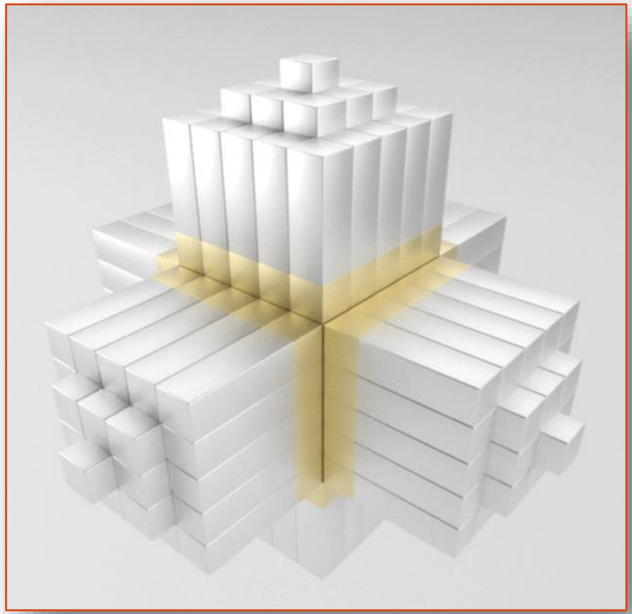
Key observables:

- Shape of GDR strenght function → CN Shape
- Gamma multiplicity → Spin
- Energy spectra and angular distribution of charged particles → signature of pre-equilibrium emission

Detectors:



PARIS + charged particle array (modified GARFIELD)



Possible reactions(at 4-6 MeV/A) with different entrance channel mass asymmetry

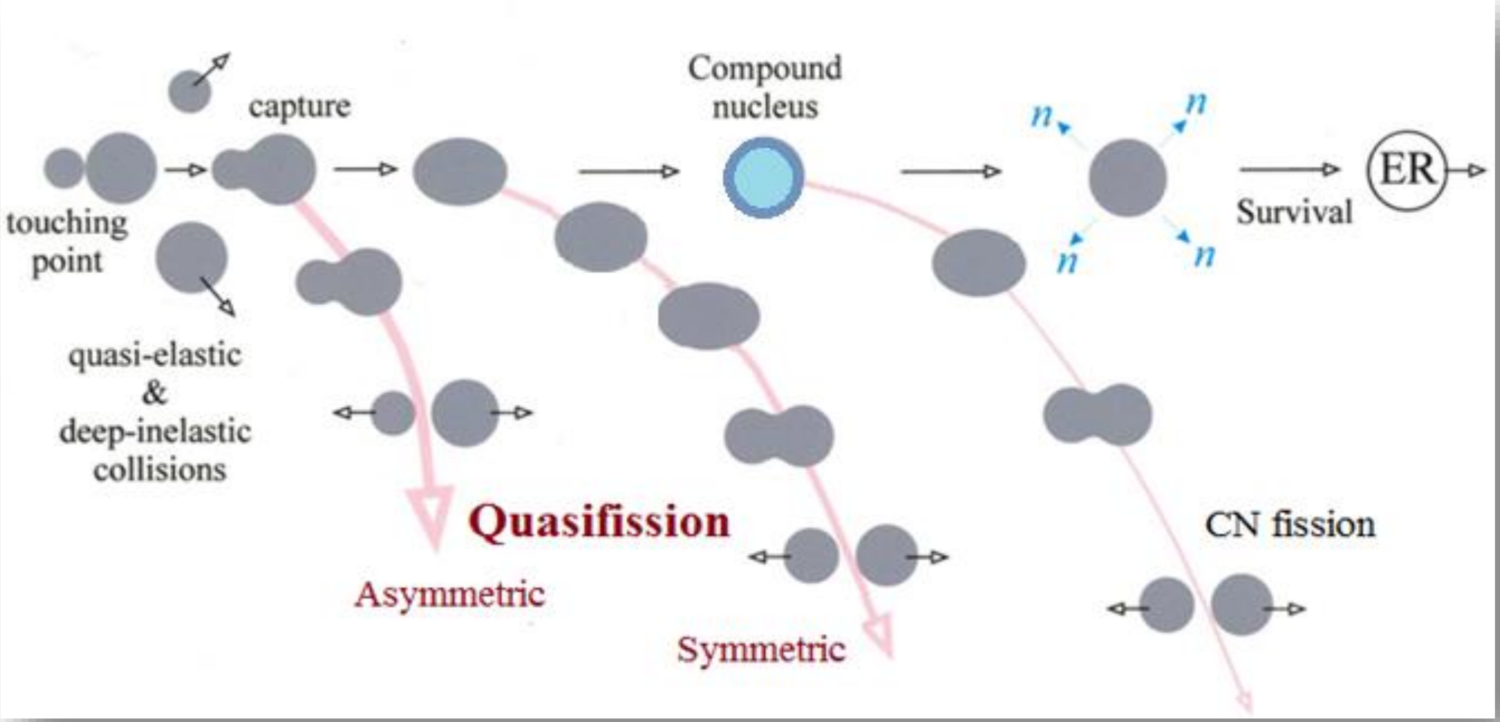
$^{18}O+^{28}Si \rightarrow ^{46}Ti$
$^{22}Ne+^{24}Mg \rightarrow ^{46}Ti$

$^{48}Ti+^{122}Te \rightarrow ^{170}W$
$^{60}Ni+^{110}Pd \rightarrow ^{170}W$

Quasi-fission vs CN formation

CN-Fission and Evaporation
- decay channels of thermalized systems
- Slow process without memory of the entrance channel

Quasifission
- rapid decay of the dinuclear system:
- depends on entrance channel properties:
- charge, mass asymmetry,
- deformation aligment,
- shell effects connected to the driving force guiding the mass flow,
- symmetry of projectile and target, N/Z-isospin dependence



Pre-equilibrium γ-emission in hot superheavy nuclei

Larger E_{beam} → larger E_γ before Fission

- At Ex=30-60 MeV for the formation of SHN in warm fusion reactions, where $\sigma_{Fusion\text{-}fission} >> \sigma_{(xn)}$ $(= \sigma_{(ER)})$ by cooling down the system through emission of neutrons and γ-rays one can decrease the fission probability, and increase the production of evaporation residues.
- Such dissipative effects was observed and could be enhanced by reducing the charge asymmetry in the entrance channel
- To see it differences of γ energy spectra measured in reactions at about 15 and 10 MeV/A have to be collected.
- **To separate the fission channel from the quasifission Mass-TKE distributions from CORSET- charged particle detector can be adopted**…

VOLUME 76, NUMBER 7 PHYSICAL REVIEW LETTERS 12 FEBRUARY 1996

Collective Dipole Motion in Highly Excited ^{272}Hs ($Z = 108$) Nuclei

T. S. Tveter,[1,2] J. J. Gaardhøje,[1] A. Maj,[1,3] T. Ramsøy,[1,4] A. Ataç,[5] J. Bacelar,[6] A. Bracco,[7] A. Buda,[6] F. Camera,[7] B. Herskind,[1] W. Korten,[1,8] W. Królas,[3] A. Menthe,[9] B. Million,[7] H. Nifenecker,[9] M. Pignanelli,[7] J. A. Pinston,[9] H. v. d. Ploeg,[6] F. Schussler,[9] and G. Sletten[1]

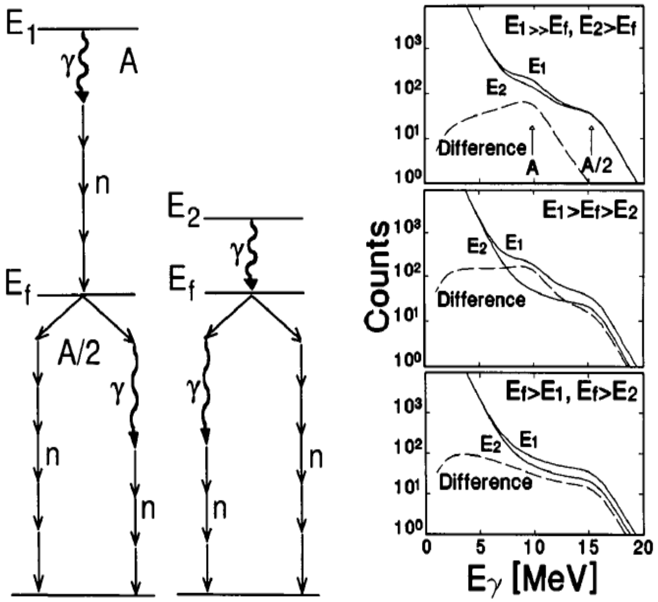


FIG. 1. Left: schematic illustration of the differential method (GDR structures are exaggerated for clarity). Right: the three different scenarios for the difference γ-ray yield as described in the text.

Quasi-fission vs fission

Questions to answer:

- The behaviour of the new observables from fully identified fragments like Z, N/Z, etc… in QF with respect to fission
- Best condition to produce the heavy/superheavy exotic nuclei
- The IVGDR in SHN for determine the temperature of CN
- See the effect of shells in the entrance channel

Key observables:

- γ- multiplicities, energy spectra, angular correlations,
- neutron - multiplicities, energy spectra,
- mass and charge of the fission fragments
- angular, energy and velocity distributions for the IMFs - LCPs,

Requirements:

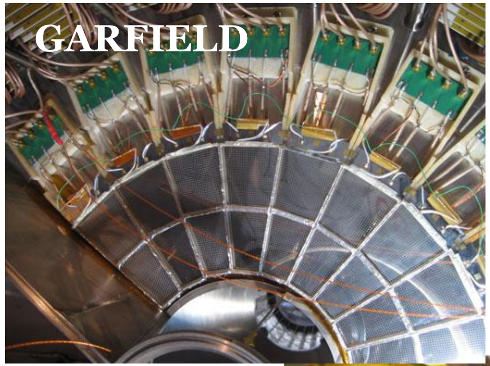
- beams for fusion of masses A>80- TANDEM-ALPI
- high γ-multiplicities, energy spectra- PARIS,
- high angular,mass,charge resolution (CORSET)
- broad angular acceptance for FF
- low energy thresholds for LCPs and IMFs,

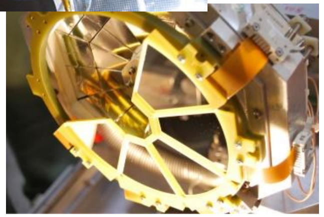
Possible reactions:

- $^{32-34-36}S+^{238}U \longrightarrow ^{270-272-274}Hs^*$
- $^{40}Ar+^{232}Th \longrightarrow ^{272}Hs^*$
- $^{56}Fe+^{208}Pb \longrightarrow ^{264}Hs^*$

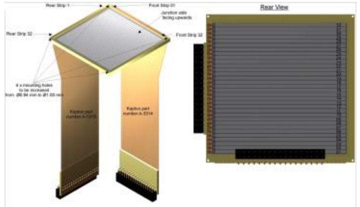
3 different charge asymmetry in the entrance channels for Hs [and also investigation of shell effects in the Entrance channel] to perform at two energies for the comparison of GDR spectra

Charge particle detectors

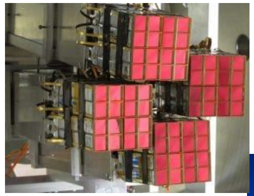




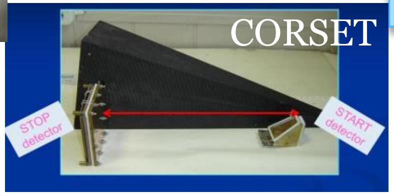
GARFIELD+RCo



FARCOS

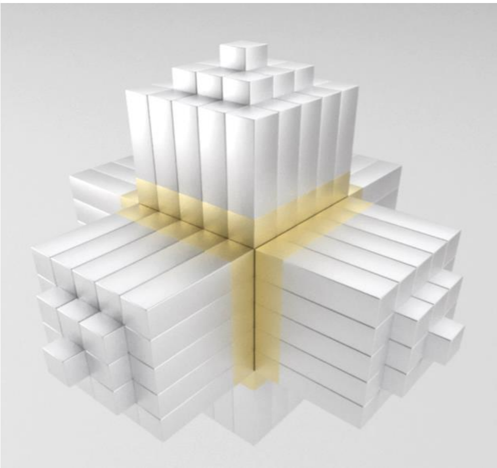


FAZIA



FUS-CN	α-correlations and clustering	• Accurate description of the CN evaporation process • Beyond the statistical model, role of structure and α-clusters • *Basic quantities for primary emission reconstruction at high energy. [https://www.bo.infn.it/nucl-ex/Loi_csym.pdf]*
FUS-CN	Isospin dependence of CN formation and decay	• Entrance channel influence on fusion process. • *Nuclear parameters far from stability: level density, fission barrier and viscosity.*
PRE-EQ	α-emission at highest spins	• Nuclear shapes and structure
PRE-EQ	Onset of pre-equilibrium emission	• Role of clusters
INC-FUS	Incomplete fusion	• Fission – Quasifission • Reaction time scales

High energy γ-ray detector



PARIS
+large LaBr3