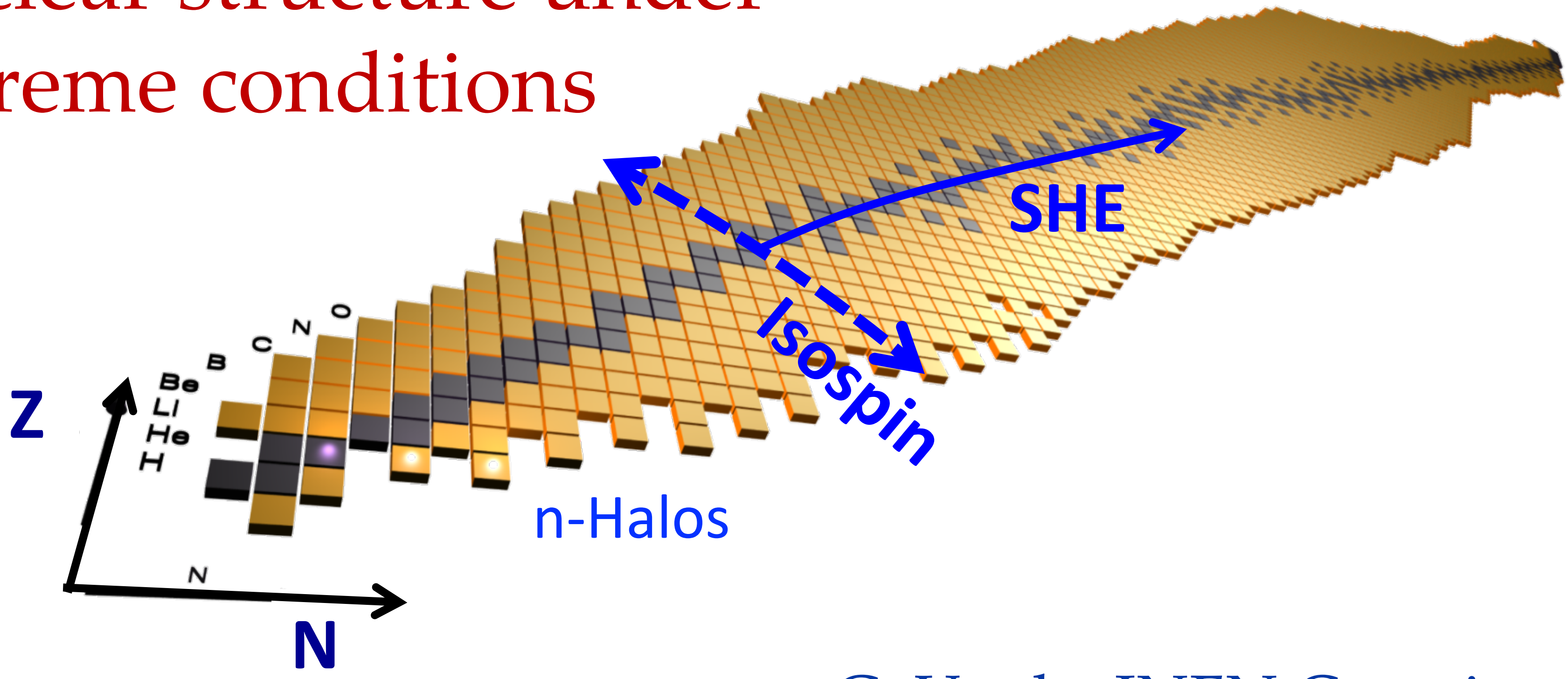
# Dynamical aspects of nuclear structure under extreme conditions



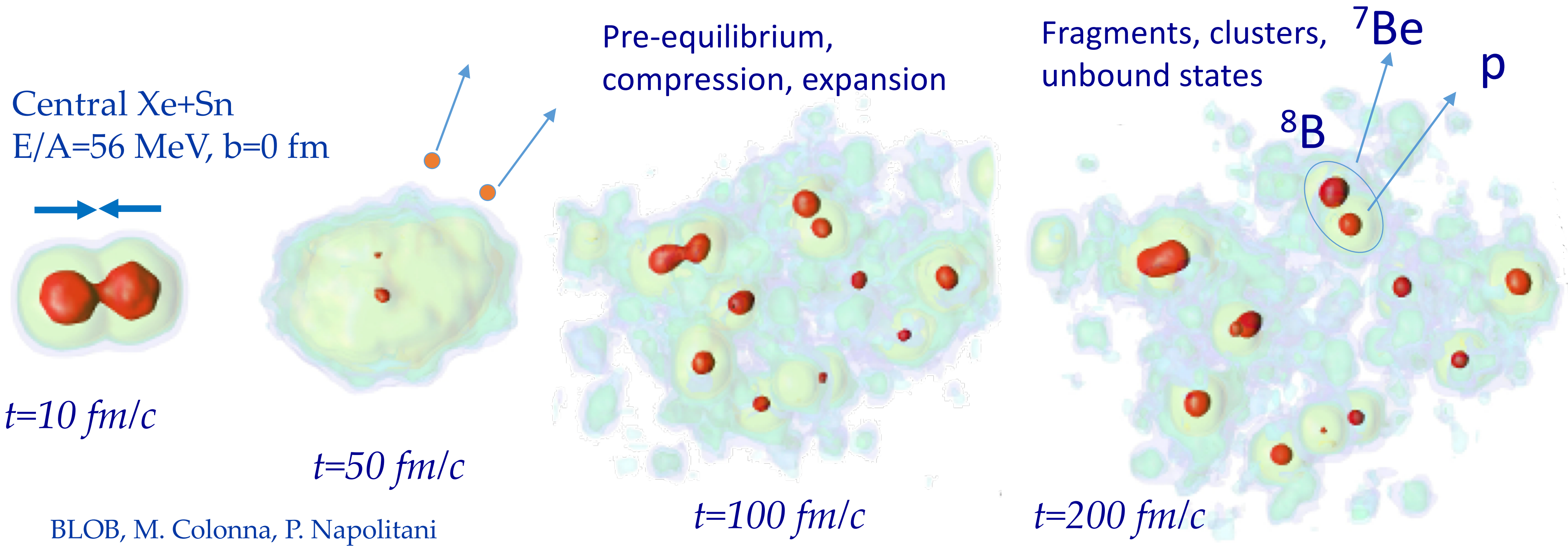

G. Verde, INFN Catania

Special acknowledgements:

FAZIA & INDRA collaborations
D. Dell'Aquila* (IPNO & Univ. Naples)
D. Gruyer (LPC Caen)

* Now at MSU

# Clusters and unbound state decays




Unbound states (even exotic) can be produced in the low density and finite temperature stage of the reaction

→ effects of the **mechanism** and **time scales**?

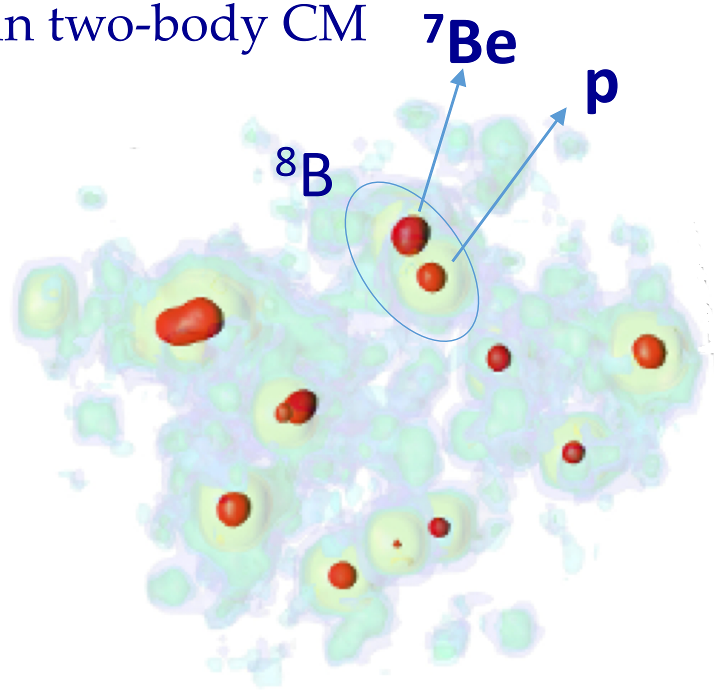
# “In-medium” structure?

- Study nuclear structure properties (resonance positions and widths, branching ratios, spins, decay mechanisms, …) as they are produced and observed during the dynamical evolution of the N-body system
  - Interplays between nuclear structure, reaction mechanism and EoS
- Evolution of observables with
  - Time scales, density, excitation → need both low and intermediate energies
  - N/Z → need both stable and exotic beams at ISOL and In-Flight facilities

# Multi-particle correlation spectroscopy in low density medium

## Intermediate energies

$\vec{v}_p, \vec{v}_{7Be}$ velocity vectors in two-body CM




$$Q_{decay} = M_{8B} \cdot c^2 - \left(M_p \cdot c^2 + M_{7Be} \cdot c^2\right)$$

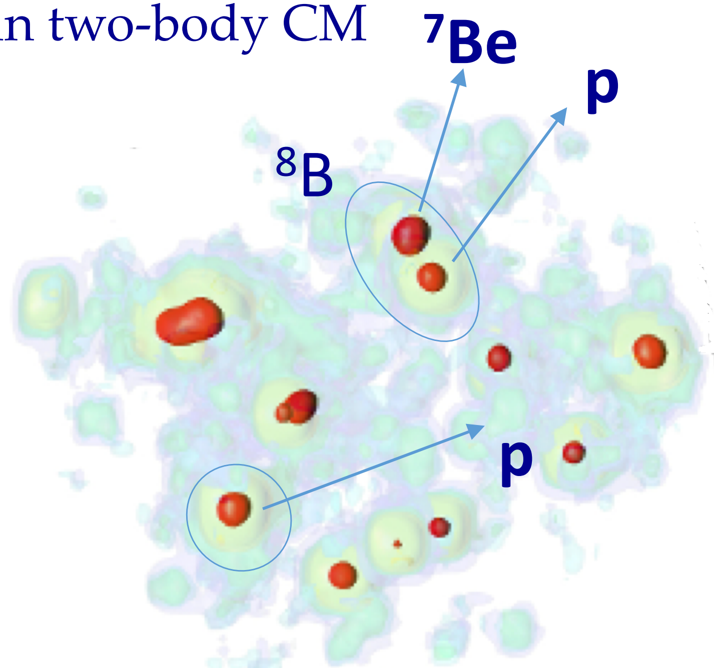
$$E^*({}^8B) = -Q_{decay} + \frac{1}{2} M_p v_p^2 + \frac{1}{2} M_{7Be}$$

$$= -Q_{decay} + \frac{1}{2} \cdot \mu v_{rel}^2 = -Q_{decay} + E_{rel}$$

# Multi-particle correlation spectroscopy in low density medium

## Intermediate energies

$\vec{v}_p, \vec{v}_{7Be}$ velocity vectors in two-body CM




Particle emitting sources extended in phase-space

$$Q_{decay} = M_{8B} \cdot c^2 - \left(M_p \cdot c^2 + M_{7Be} \cdot c^2\right)$$

$$E^*(^8B) = -Q_{decay} + \frac{1}{2} M_p v_p^2 + \frac{1}{2} M_{7Be}$$

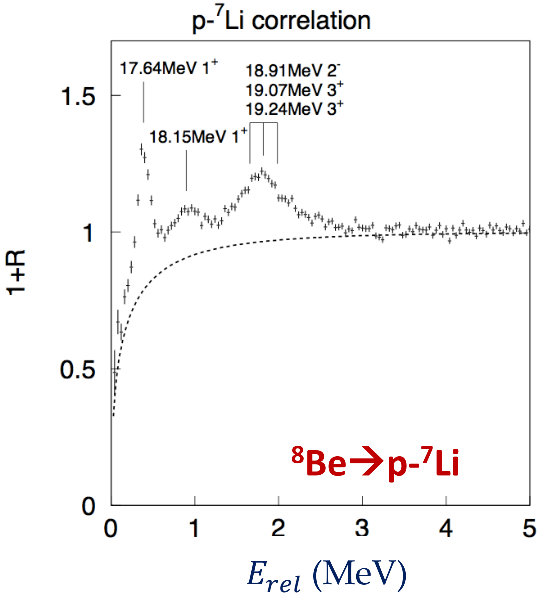
$$= -Q_{decay} + \frac{1}{2} \cdot \mu v_{rel}^2 = -Q_{decay} + E_{rel}$$

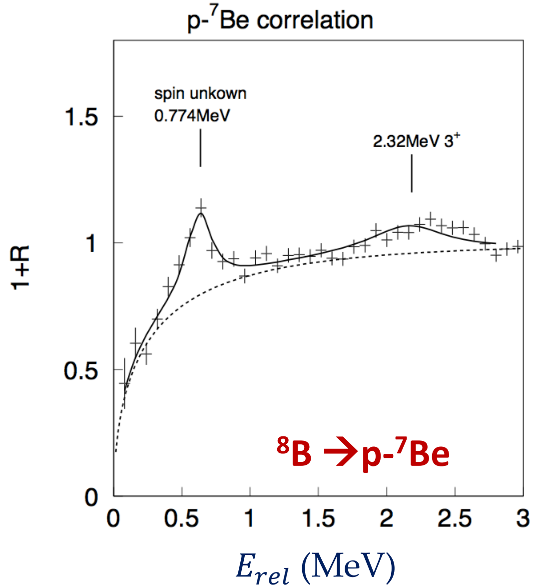
Correlation function:

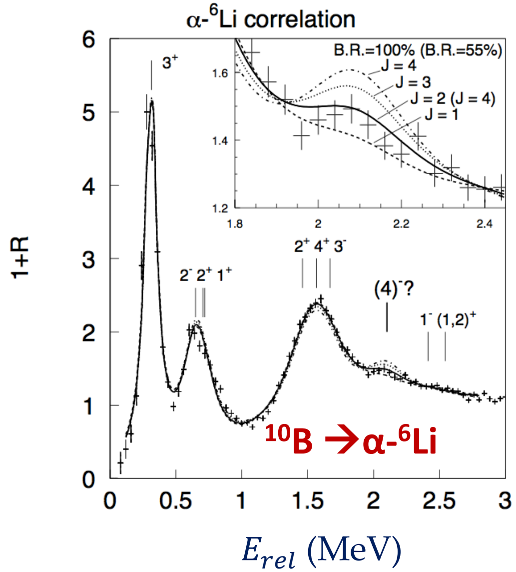
$$1 + R(E_{rel}) = \frac{Y_{coinc}(^7Be, p)}{Y_{evt\ mixing}(^7Be, p)}$$

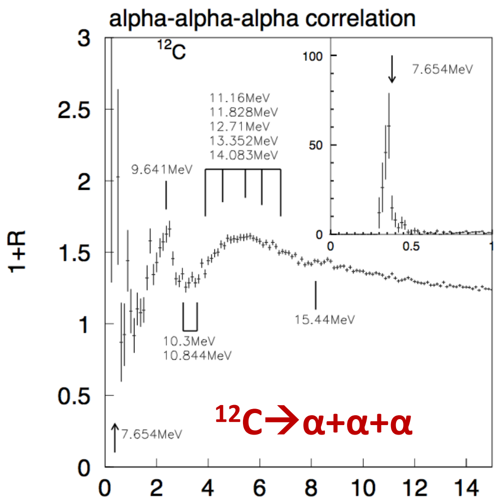
# Multi-particle correlations in thermal and dilute nuclear medium

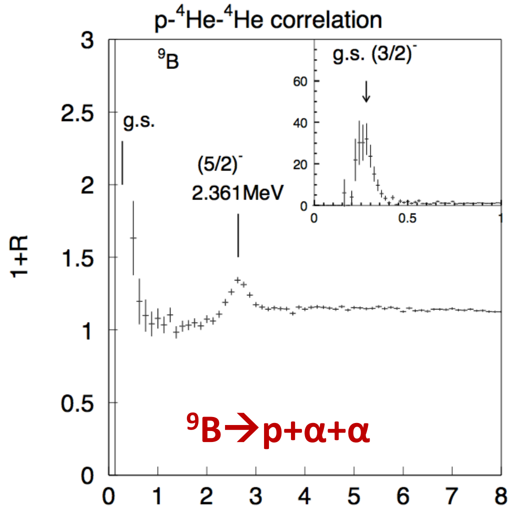
$^{112}$Sn+$^{112}$Sn E/A=50 MeV … in just one single experiment

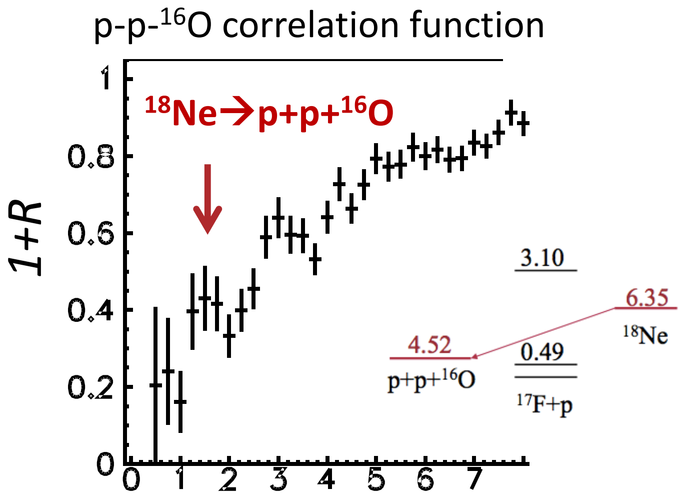


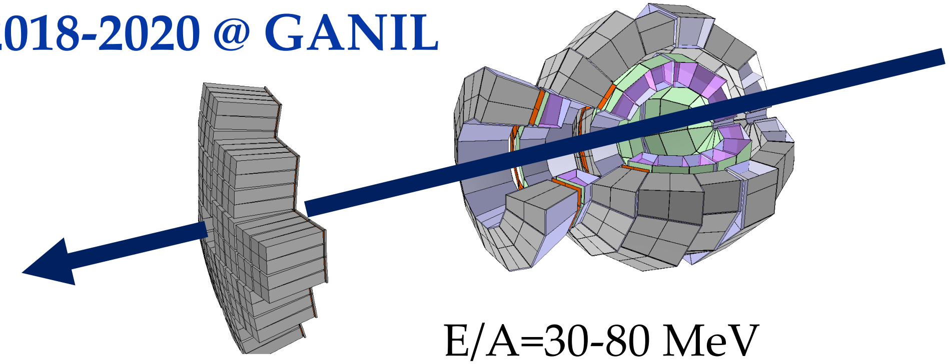



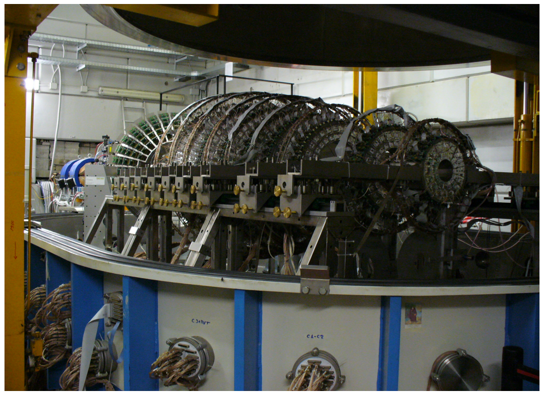

$E_{k,1}^{CM} + E_{k,2}^{CM} + E_{k,3}^{CM}$ (MeV)

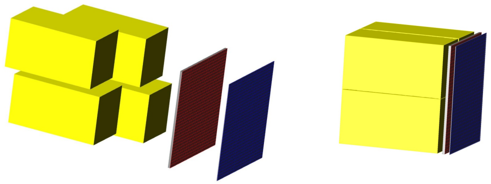
# Instrumentation

**INDRA-FAZIA**
**2018-2020 @ GANIL**

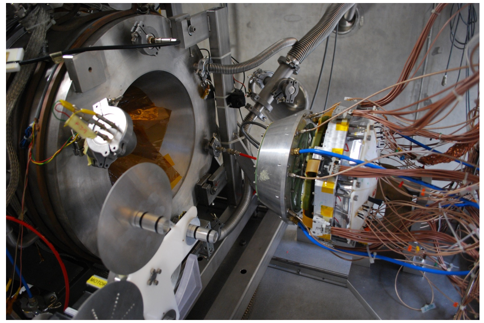


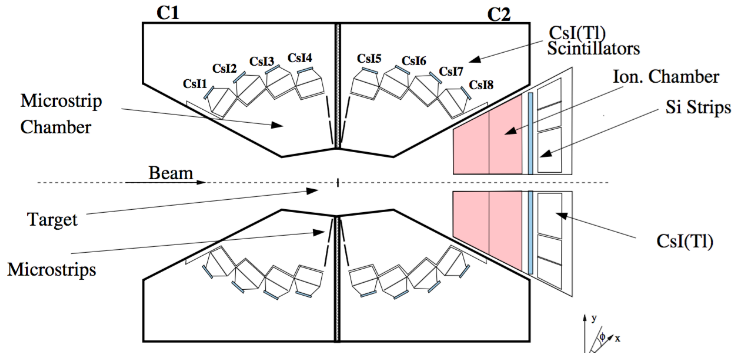
E/A=30-80 MeV





**Chimera-Farcos @ LNS**





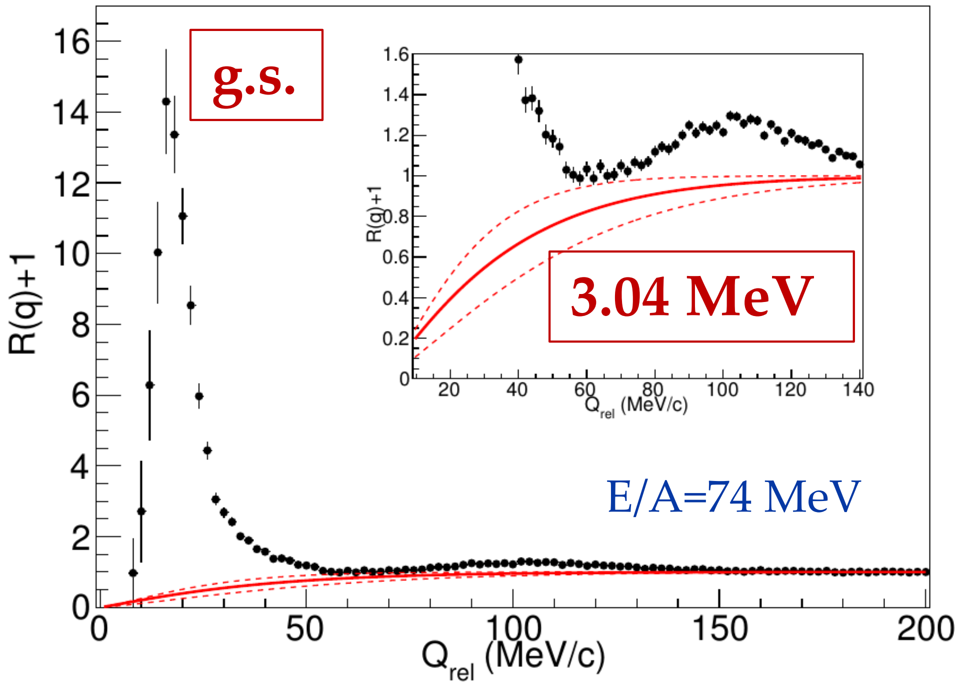

**Garfield-RCo @ LNL**

# Two-alpha thermometer

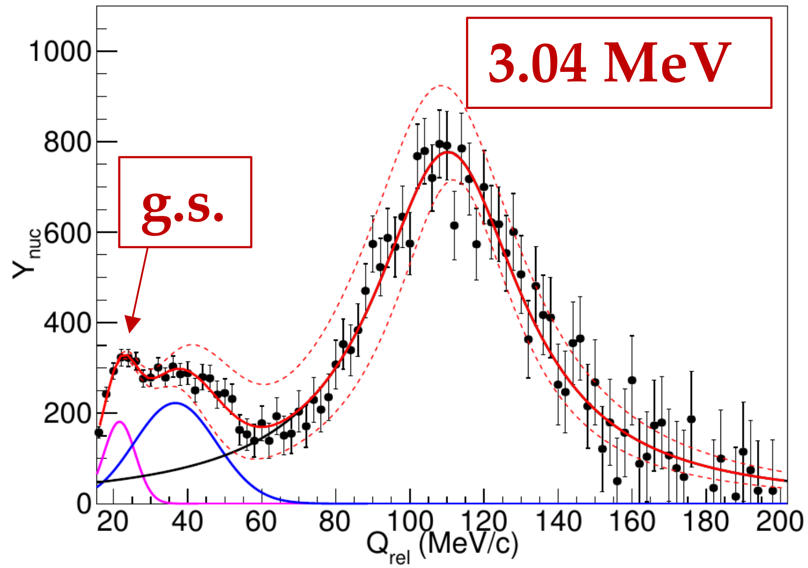
Ar+Ni, E/A=32-95 MeV – central → $^{8}$**Be → α + α**

**INDRA @ GANIL**

$$Y_{nucl}(E^*) =$$
$$= \frac{N}{\pi} e^{-E^*/T} \sum_i (2J_i + 1) \left[ \frac{\Gamma_i/2}{(E^* - E_i)^2 + \Gamma_i^2/4} \right]$$




Experimental $Y_{nucl}$




$$1 + R(q_{rel}) = \frac{Y_{coinc}(\alpha,\alpha)}{Y_{evt\ mixing}(\alpha,\alpha)}$$

D. Dell'Aquila, PhD thesis

# Two-alpha thermometer

Ar+Ni, E/A=32-95 MeV – central → **$^8$Be → α + α**

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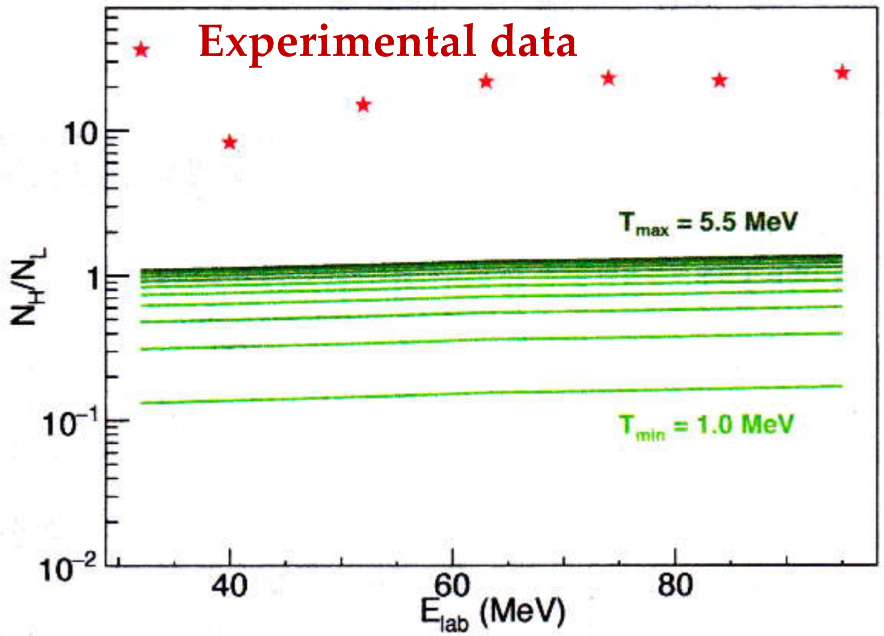



Experimental overpopulation of the state at 3.04 with respect to the g.s.

Thermal-only mechanism cannot reproduce data

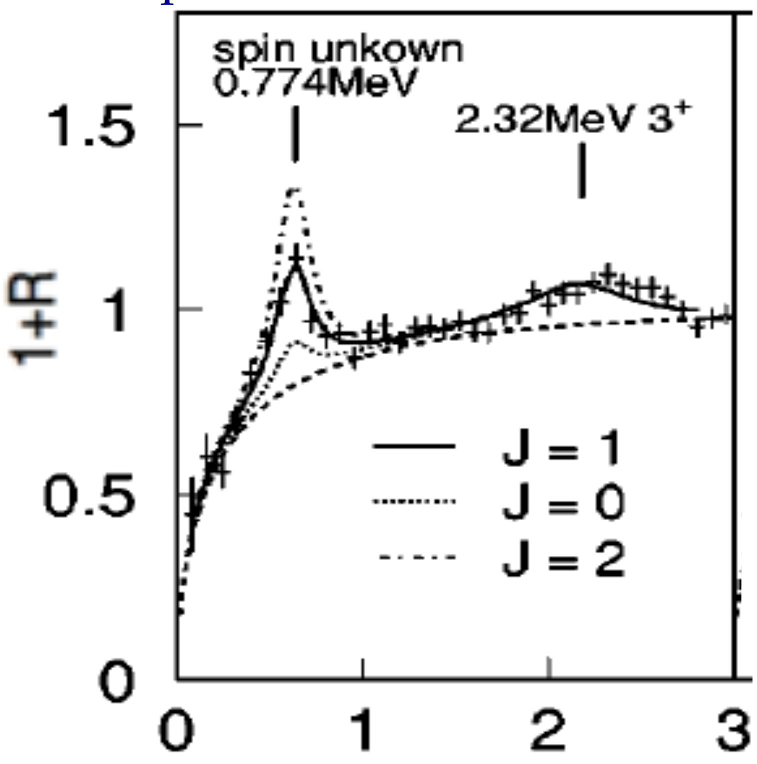
D. Dell'Aquila, PhD thesis

# In-medium structure: spin

Xe+Au E/A=50 MeV central collisions (LASSA data @ MSU)

p-$^{7}$Be correlation function

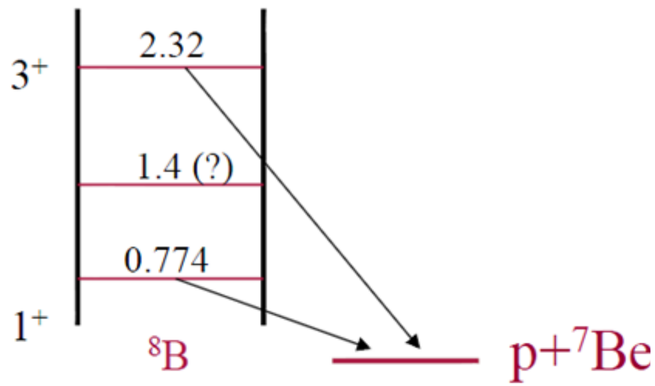
$$1 + R(E_{rel}) = \frac{Y_{coinc}(^{7}Be, p)}{Y_{evt\ mixing}(^{7}Be, p)}$$




Decay

$^{8}B^{*} \rightarrow p + {}^{7}Be$

$Q_{decay} = -0.137\ MeV$




$$Y_{nucl}(E^{*}) = \frac{N}{\pi} e^{-E^{*}/T} \sum_{i} (2J_i + 1) \left[ \frac{\Gamma_i/2}{(E^{*} - E_i)^2 + \Gamma_i^2/4} \right]$$

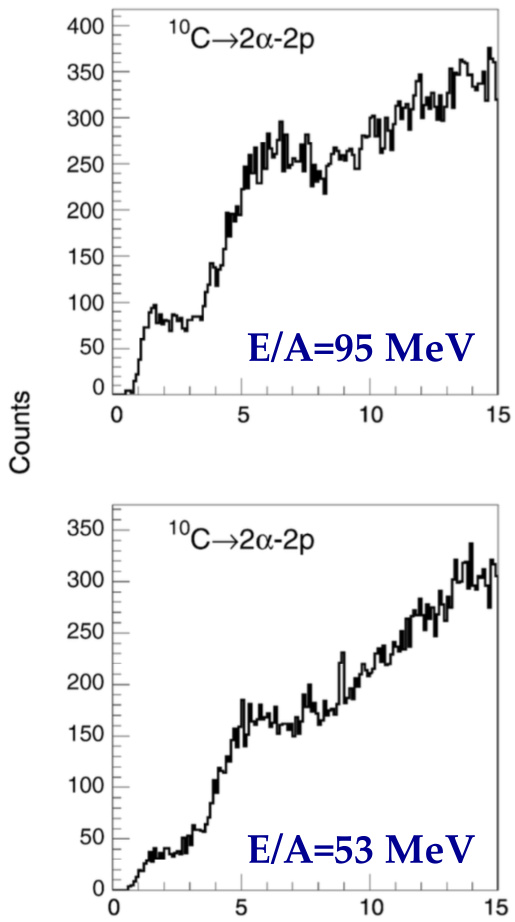
W.P. Tan et al. Phys. Rev. C69, 061304 (2004)

# Correlation spectroscopy: N>2

$\alpha + \alpha + p + p$

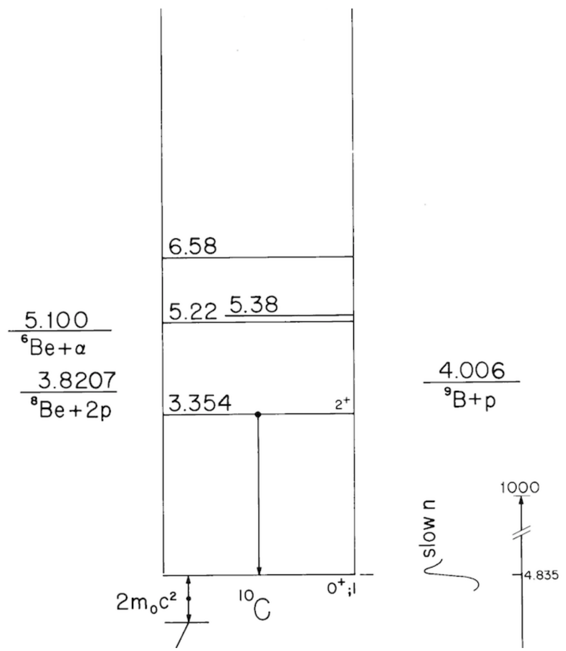
$^{12}$C+$^{24}$Mg E/A=53 and 95 MeV

INDRA Data




$E_{sum}$ (MeV)

**$^{10}$C**




$Q_{decay} = -3.7\ MeV$

$E_{sum} = \sum_{i=1}^{4} E_{k,i}$ (MeV)

F. Grenier et al., Nucl. Phys. A811, 233 (2008)

# Correlation spectroscopy: N>2

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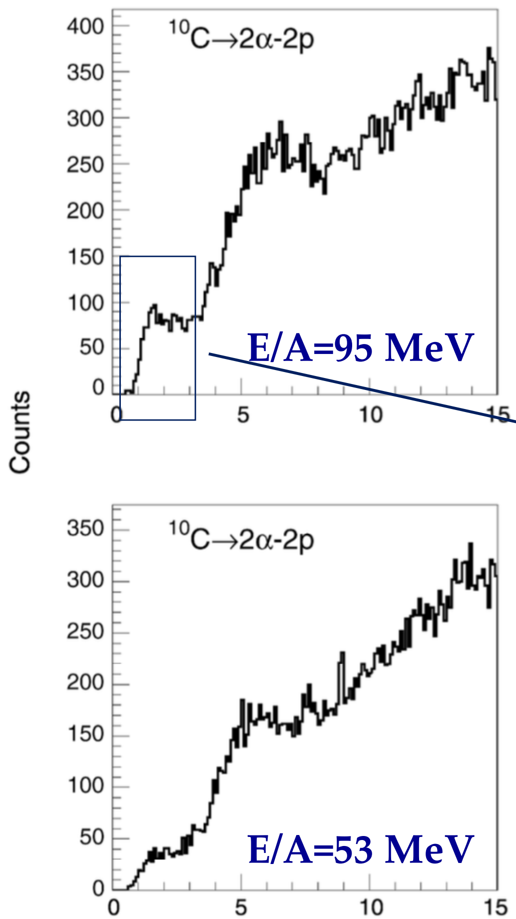
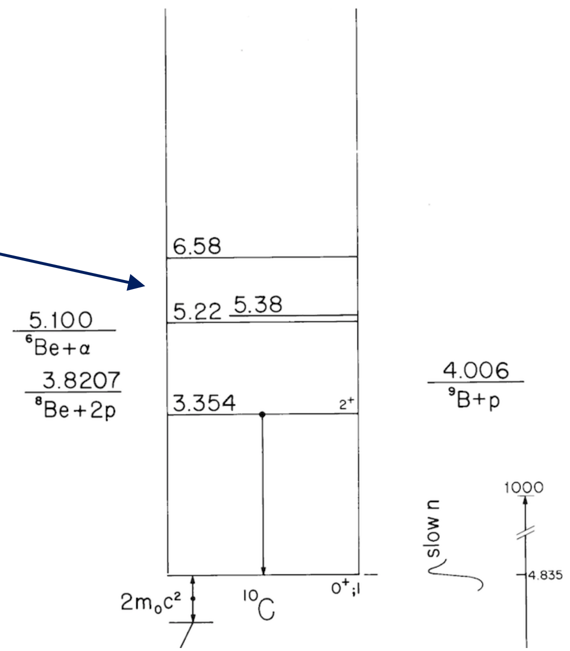



$E_{sum}$ (MeV)

**$^{10}$C**




$Q_{decay} = -3.7\ MeV$

$E_{sum} = \sum_{i=1}^{4} E_{k,i}$ (MeV)

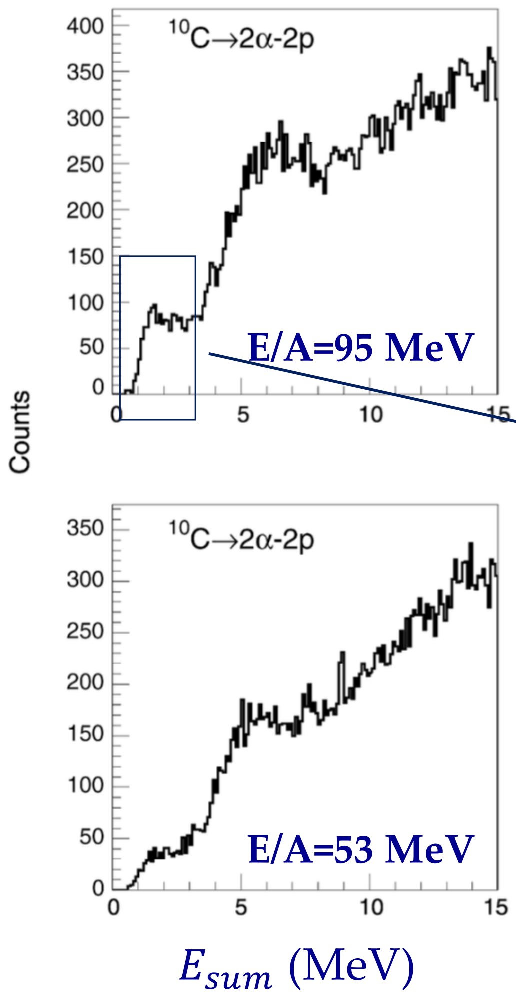
F. Grenier et al., Nucl. Phys. A811, 233 (2008)

# Correlation spectroscopy: branching ratios

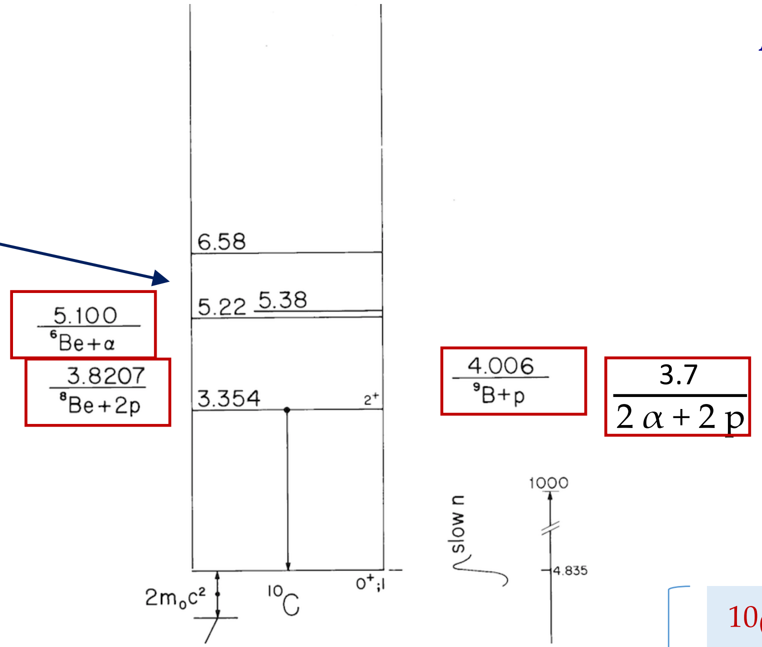
$\alpha + \alpha + p + p$

$^{12}C + ^{24}Mg$ E/A=53 and 95 MeV

INDRA Data




## $^{10}$C




$$Q_{decay} = -3.7\ MeV$$

$$E_{sum} = \sum_{i=1}^{4} E_{k,i}\ \text{(MeV)}$$

Sequential

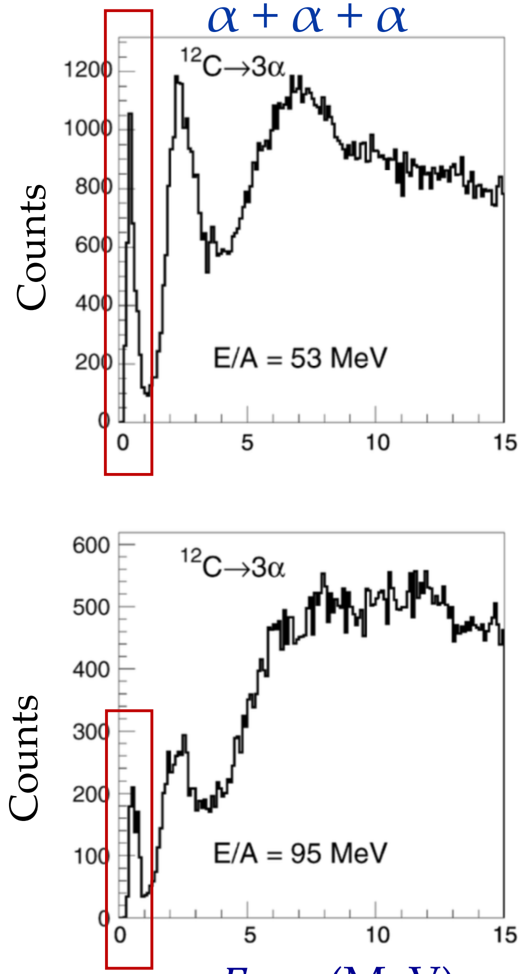
- $^{10}C^* \rightarrow {}^6Be + \alpha \rightarrow (2p+\alpha)+\alpha$
- $^{10}C^* \rightarrow {}^8Be + p + p \rightarrow (\alpha+\alpha)+p+p$
- $^{10}C^* \rightarrow {}^9B + p \rightarrow (p+\alpha+\alpha)+p$

Direct

- $^{10}C^* \rightarrow \alpha+\alpha+p+p$

# Hoyle state in heavy-ion collisions

$\alpha + \alpha + \alpha$

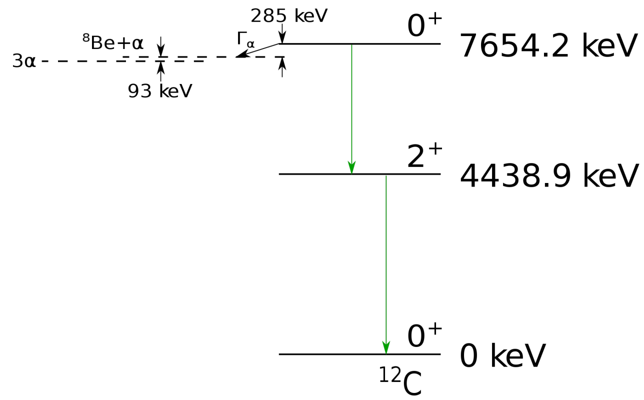



$E_{sum}$ (MeV)

$^{12}C+^{24}Mg$ E/A=53 and 95 MeV
INDRA data @ GANIL → $^{12}C_{Hoyle} \rightarrow 3\alpha$

$$E_{sum} = \sum_{i=1}^{3} E_{\alpha,i}^{CM}$$

$$Q_{decay} = -7.654\ MeV$$



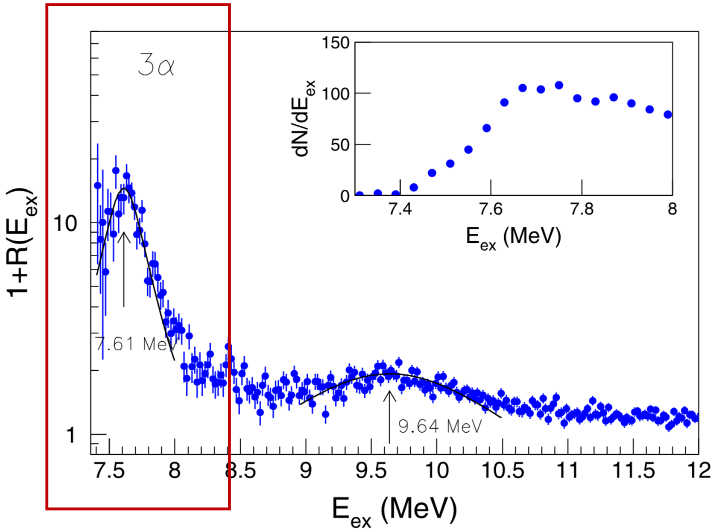

Sequential: $^{12}$C(Hoyle) ➔ $^{8}$Be+$\alpha$ ➔ $(\alpha+\alpha)+\alpha$

Direct: $^{12}$C (Hoyle) ➔ $\alpha+\alpha+\alpha$

Presence of non negligible direct decay contribution

F. Grenier et al., Nucl. Phys. A811, 233 (2008)

# Hoyle state in heavy-ion collisions

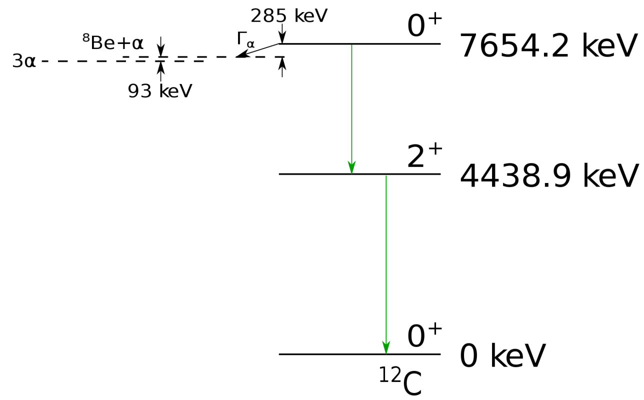


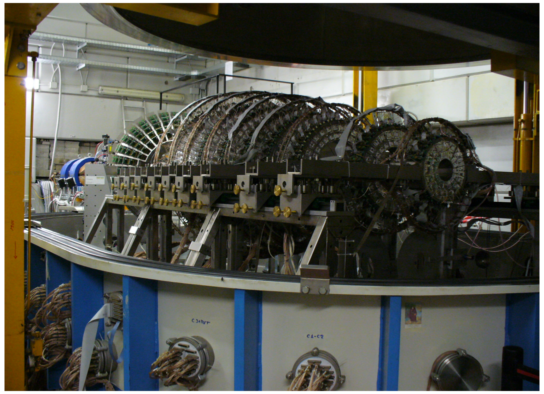

$^{40}Ca+^{12}C$ E/A=25 MeV
CHIMERA data @ LNS

→ $^{12}C_{Hoyle}$ → 3 $\alpha$

$$E_{sum} = \sum_{i=1}^{3} E_{\alpha,i}^{CM}$$

$$Q_{decay} = -7.654\ MeV$$



Chimera @ LNS

Sequential: $^{12}C$(Hoyle) → $^{8}Be+\alpha$ → $(\alpha+\alpha)+\alpha$

Direct: $^{12}C$ (Hoyle) → $\alpha+\alpha+\alpha$

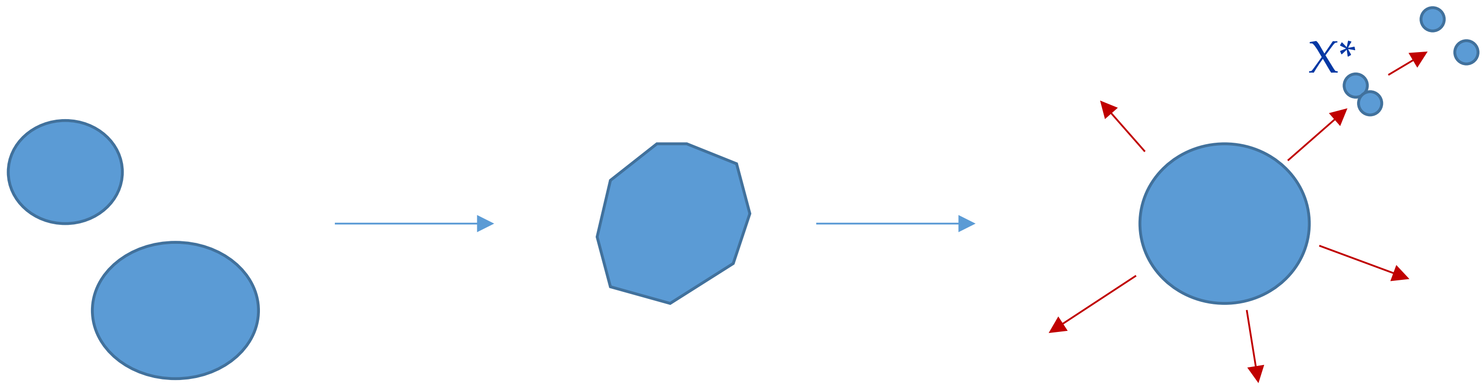
**Direct decay contribution quantified ≈ 17%**
**(7.5% BEC + 9.5% DDL ± 4%)**

A. Raduta et al., Phys. Lett. B 705, 65 (2011)

# Low energies

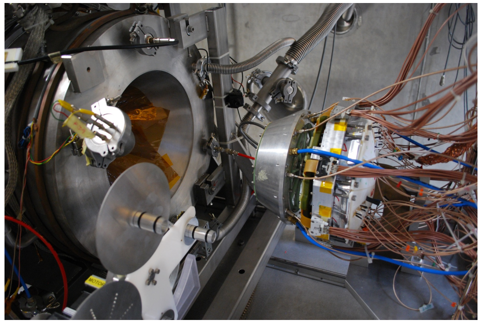
## Example of fusion/evaporation reactions

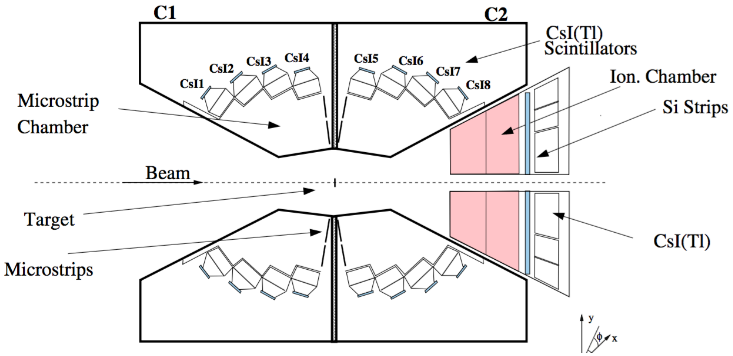
Evaporation of unbound clusters?




- Emission of complex clusters in fusion/evaporation reactions: study both bound states (stable fragments) and unbound states (reconstructed via multi-particle correlations)
- FSI state interactions: resonance feeding and regeneration

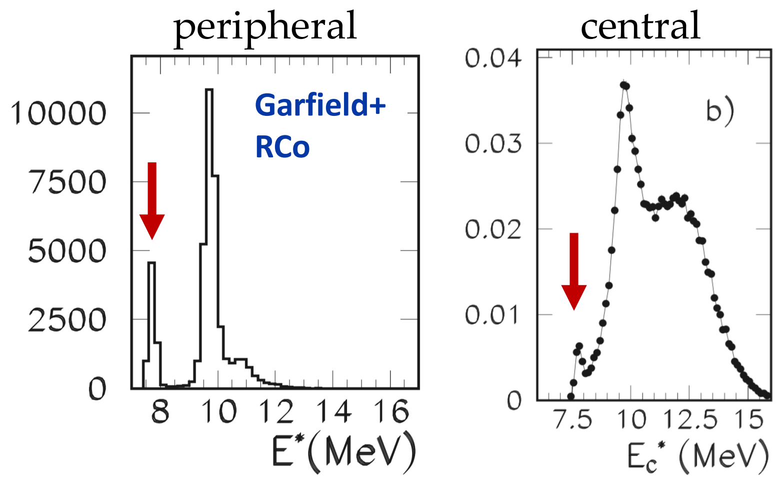
# Hoyle state in HIC at low energies






**Garfield+RCo @ LNL**

$^{12}C+^{12}C$ E=95 MeV → **Hoyle state**



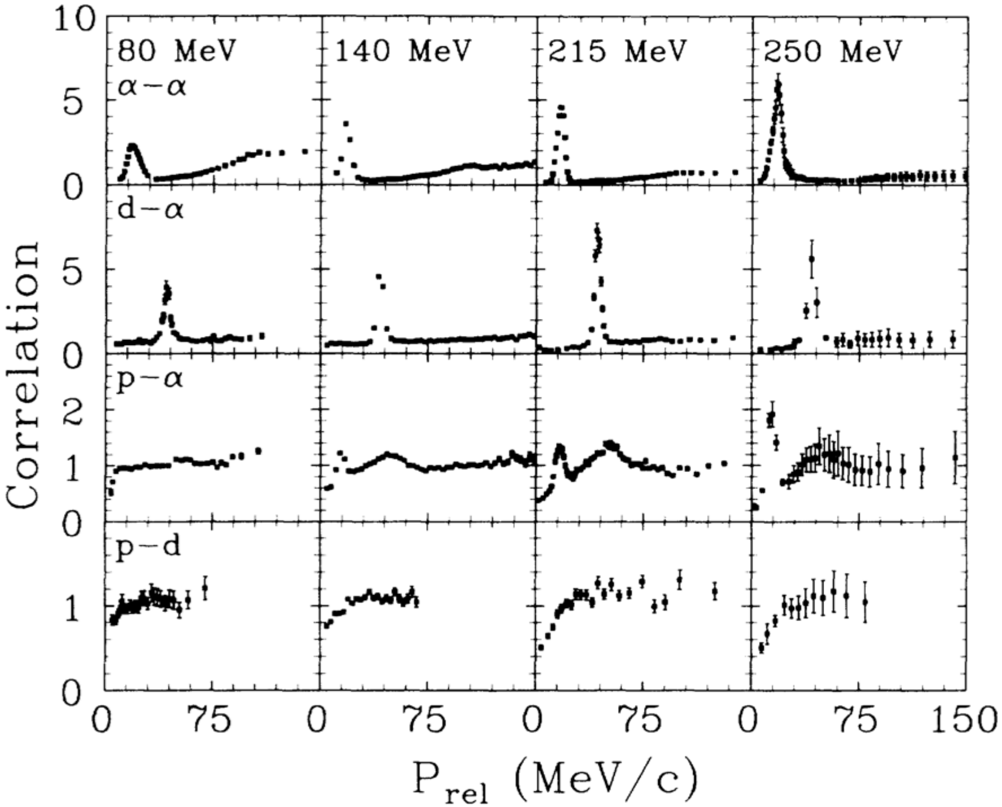

L. Morelli et al., J.Phys.G43, 045110 (2016)

Negligible contribution from 3-body direct decay < 1%

# Resonance decays in low energy reactions

Nuclear systems at finite temperature around saturation densities

$^{16}O + ^{27}Al$ @ E/A=5, 8.8, 13.5, 15.6 MeV




- Pre-formed clusters + decay or Independent emissions + FSI ?
- Correlations in statistical theories?

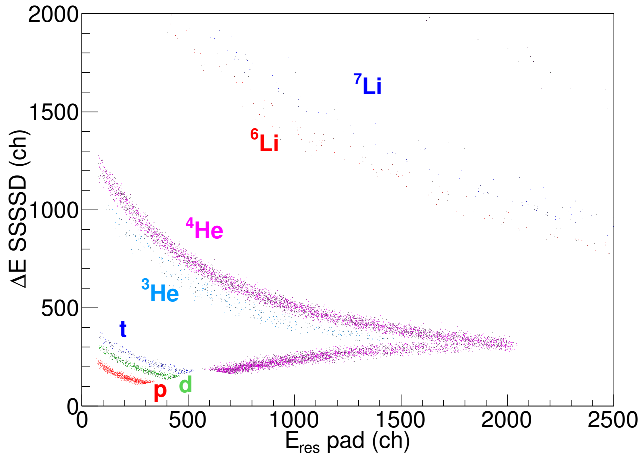
# Instrumentation needs at low energies

**Further efforts needed for low energy HIC:**

- PSD limitations at low energies → thin silicon or gas detectors
- wide dynamic range (102 keV- GeV) → correlations between light particles (Z=1,2 and heavy fragments Z=3-20)

# Oscar: hOdoscope of Silicon for Correlations and Analysis of Reactions


- 1 module 4x4 pads:
  - 1 pad: 300μm silicon (1cmx1cm active area)
  - 20 micron SSSSD : 16 vertical strips ( each about 2mm wide)

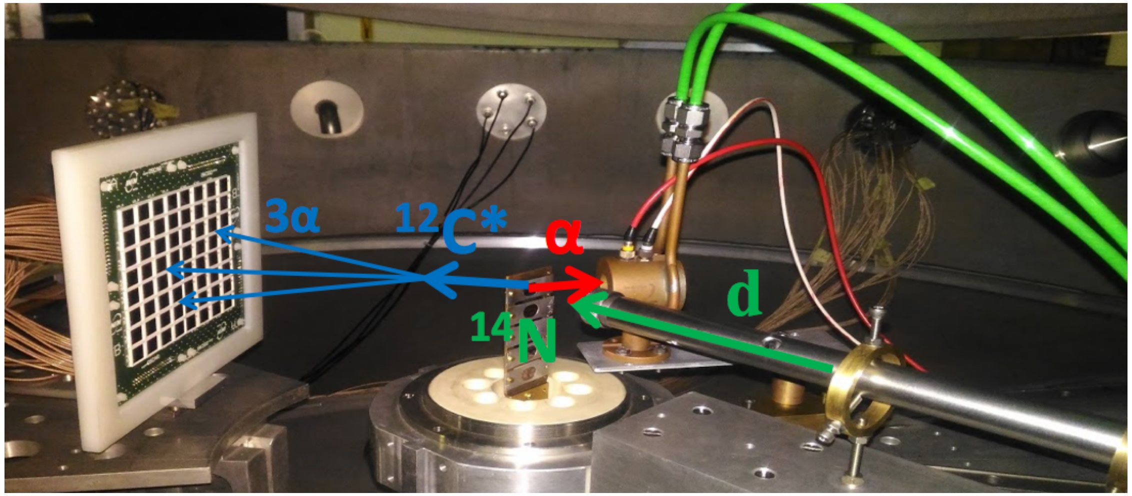



Further details:
D. Dell'Aquila et al.,
NIM 877 (2018) 227

Presently used at LNS and at LNL
→ Opportunity for dynamics and structure studies at SPES

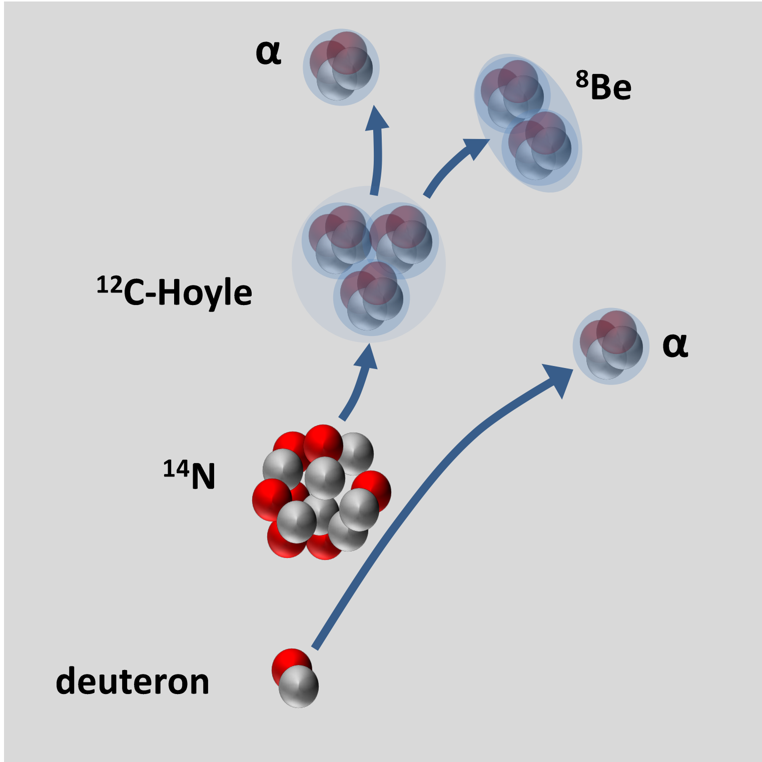
# Direct reaction measurements

OSCAR data @ LNS




D. Dell'Aquila, I. Lombardo, G. Verde et al.,
Physical Review Letters 119, 132501 (2017)

$^{14}N(d,\alpha)^{12}C^*$



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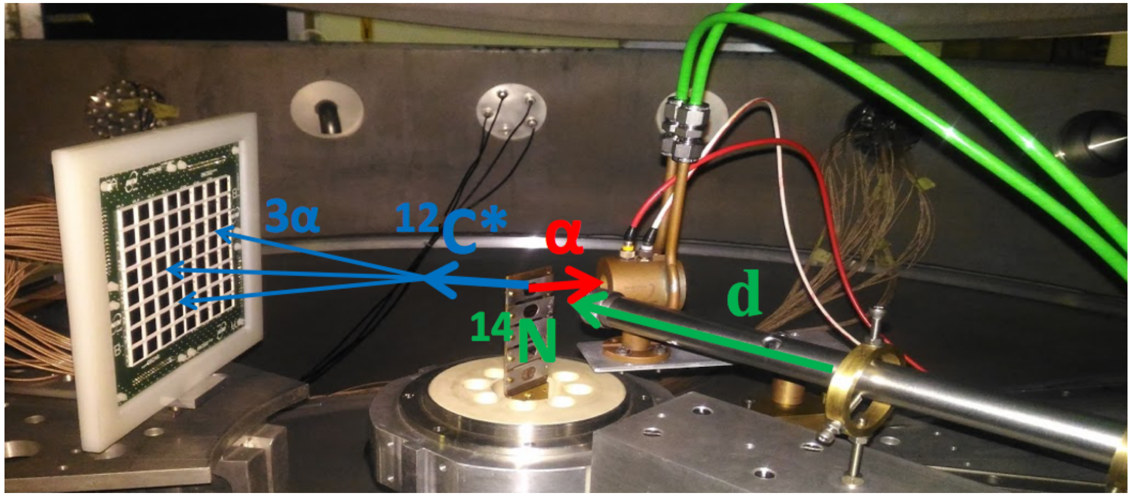


D. Dell'Aquila, I. Lombardo, G. Verde et al., Physical Review Letters 119, 132501 (2017)

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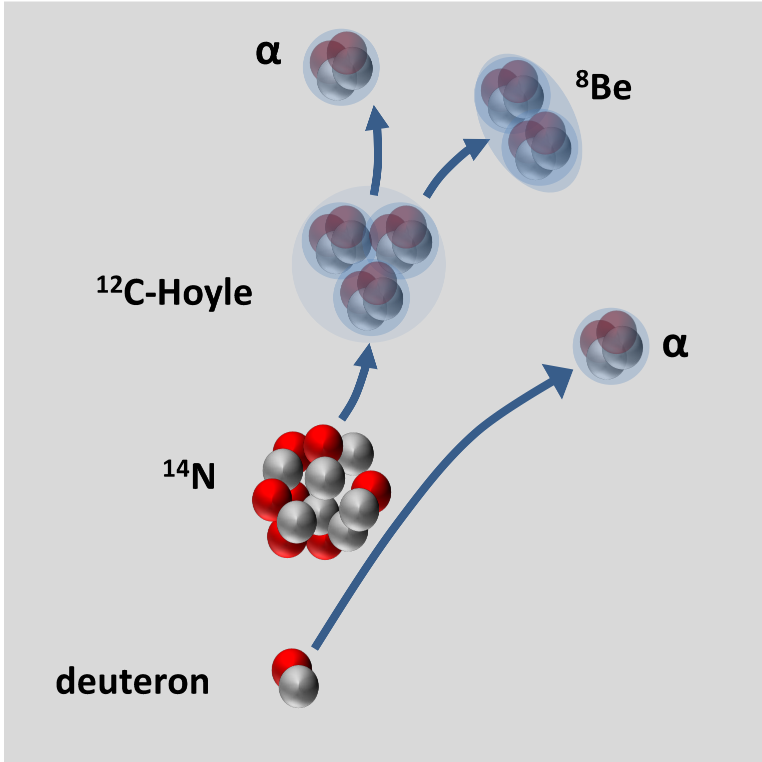
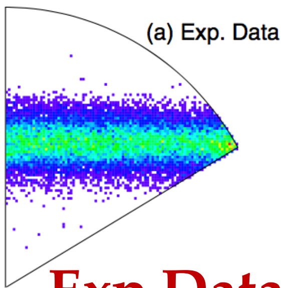
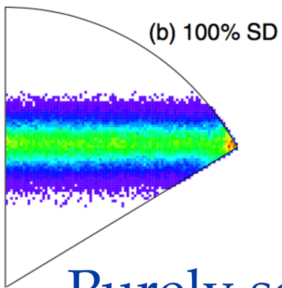
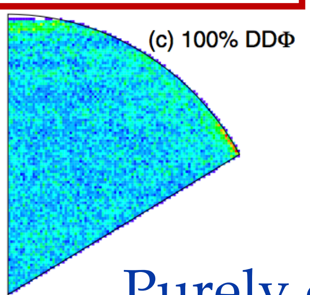



Exp Data




Purely sequential



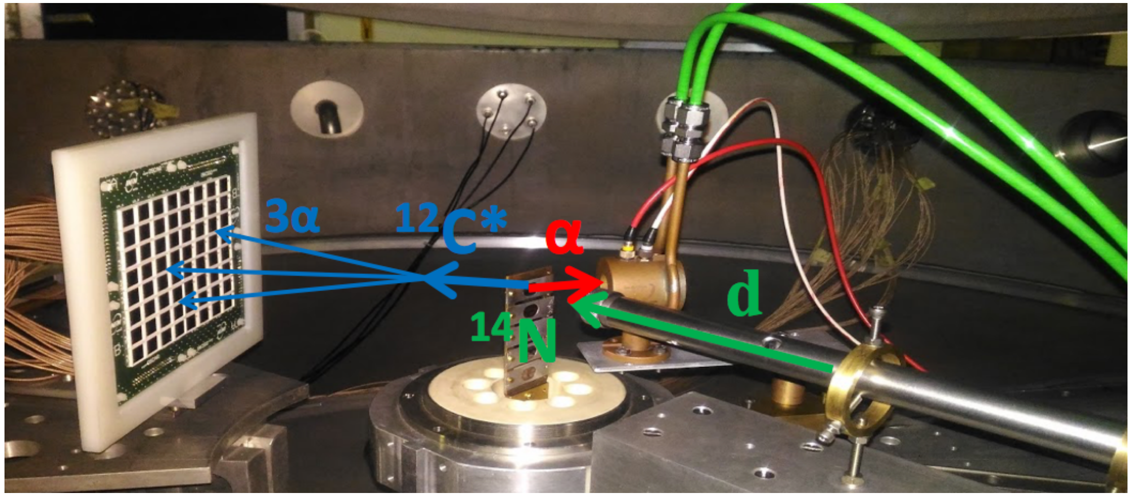

Purely direct

No direct decay

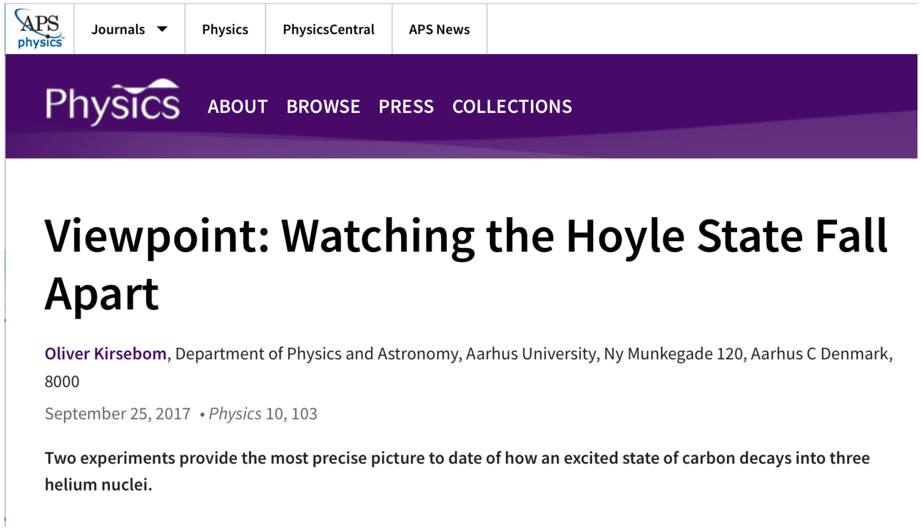
DD < 0.043% (95% C.L.)

# Direct reaction measurements

OSCAR data @ LNS




D. Dell'Aquila, I. Lombardo, G. Verde et al.,
Physical Review Letters 119, 132501 (2017)



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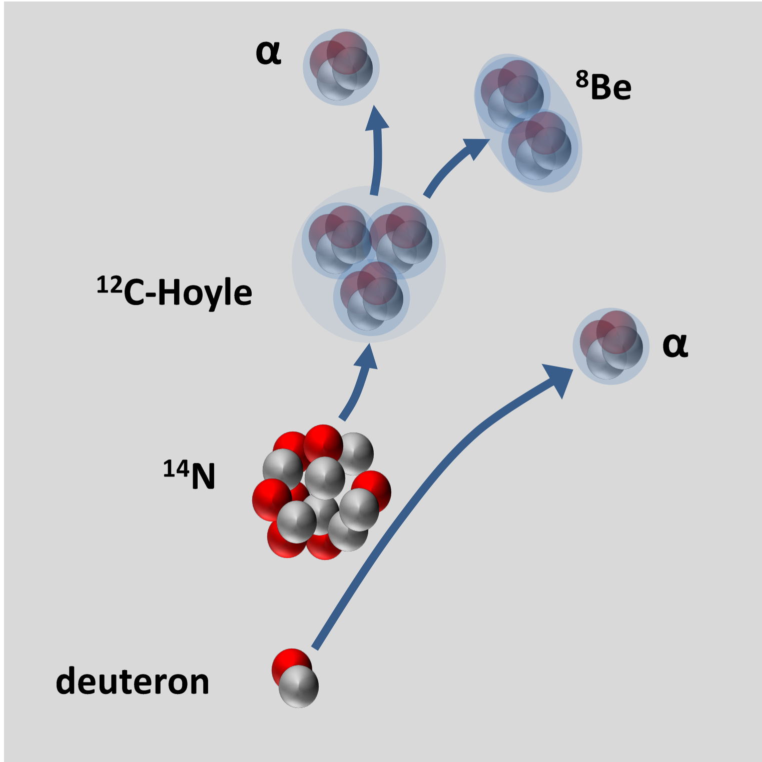
**Viewpoint: Watching the Hoyle State Fall Apart**

Oliver Kirsebom, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, Aarhus C Denmark, 8000

September 25, 2017 • *Physics* 10, 103

**Two experiments provide the most precise picture to date of how an excited state of carbon decays into three helium nuclei.**

$^{14}N(d,\alpha)^{12}C^{*}$




No direct decay

DD < 0.043% (95% C.L.)

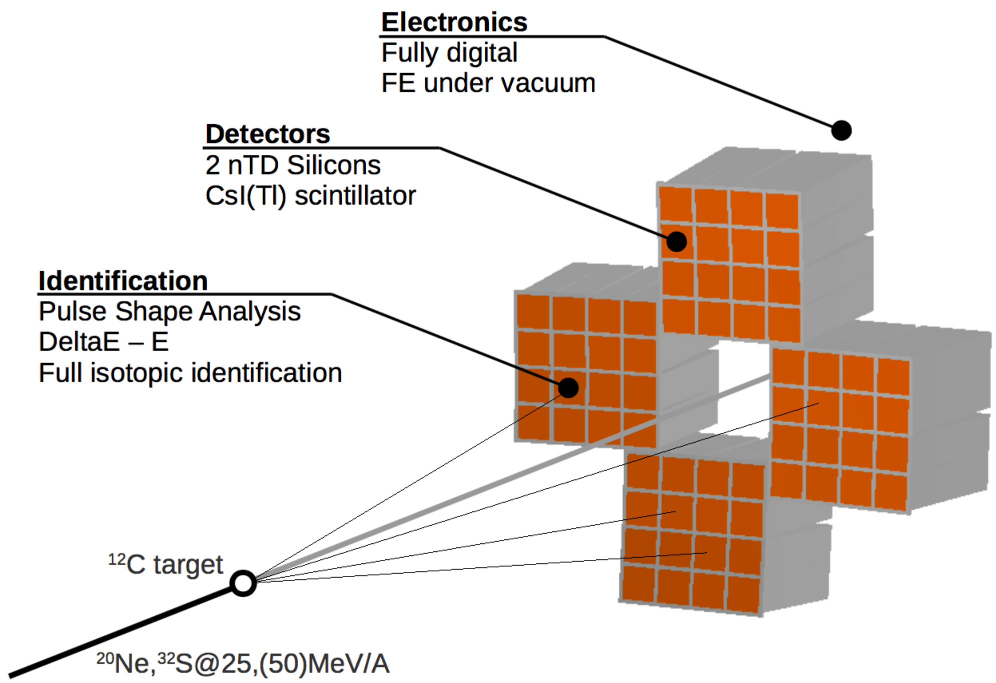
Confirmed also by R. Smith et al., Phys. Rev. Lett. 119, 132502 (2017)

# Role of reaction mechanism and dynamics on in-medium resonance decays

**FAZIACOR experiment (March 2017)**

G. Verde, D. Gruyer, FAZIA Coll.

**$^{20}$Ne, $^{32}$S + $^{12}$C**
**E/A=25 and 50 MeV**



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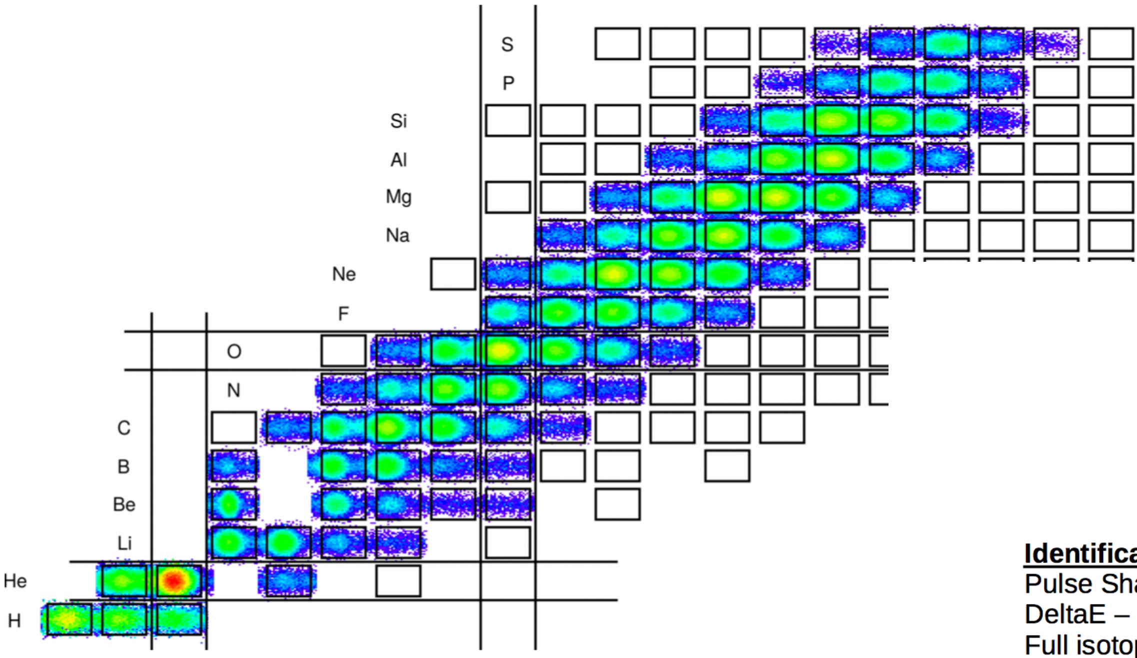
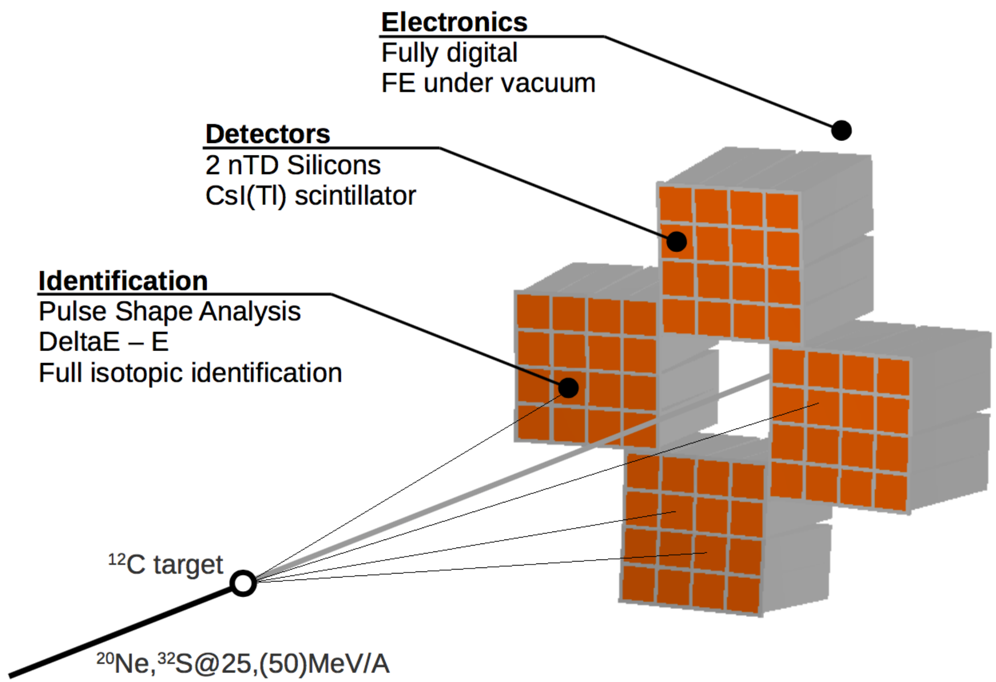
**$^{20}Ne$, $^{32}S$ + $^{12}C$**

**E/A=25 and 50 MeV**

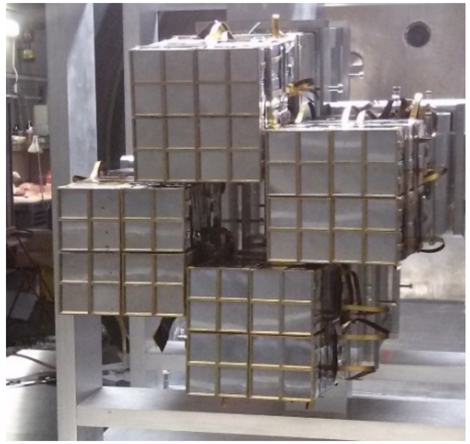


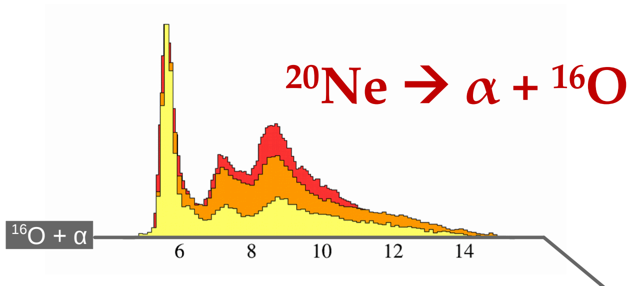



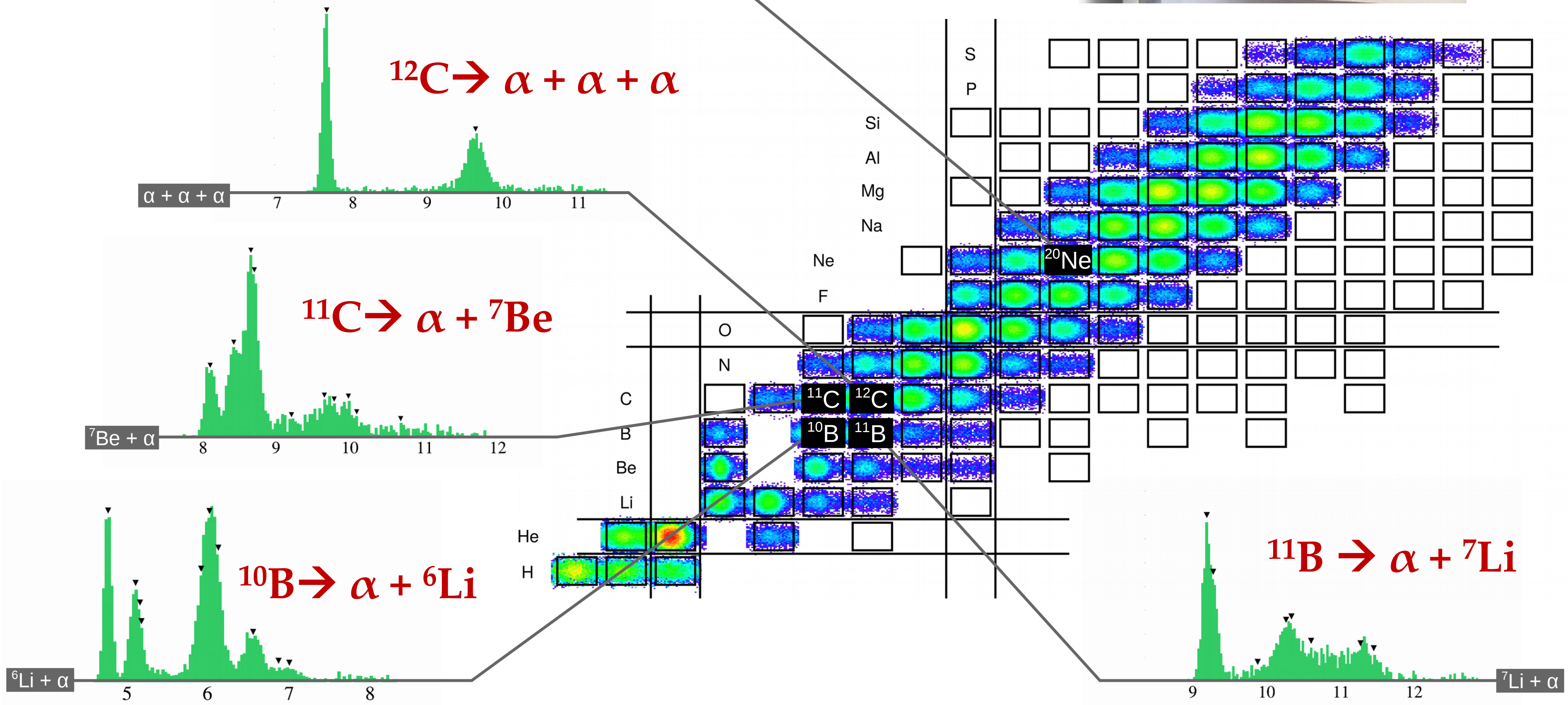

Multi-particle correlations
from projectile rapidity region

# Multiple physics cases

D. Gruyer





# Summary

- Unbound state decays in heavy-ion collisions and direct reactions: tools for nuclear structure
- Interplays structure and reaction mechanism: in-medium structure
  - Resonance regeneration by FSI in dynamical systems: example of the two-alpha decay of $^{8}$Be
  - Spin in $^{8}$B via p-$^{7}$Be correlations
  - Carbon isotope decays ($^{10}C \rightarrow 2\alpha + 2p$, $^{12}C_{Hoyle} \rightarrow 3\alpha$)
- FAZIA and OSCAR as perspectives for both intermediate and low energy studies
- FAZIACOR results: HIC as a tool to produce several species and explore some of their structure properties: in-medium effects on Hoyle state decay
  - Stable and exotic beam experiments