Clustering effects in reactions with light even-even N=Z nuclei. From the Hoyle state to cluster emission in ^{24}Mg.

L. Morelli [1]

NUCL-EX Collaboration

[1] University and INFN, Bologna, Italy

FUSTIPEN Topical Meeting

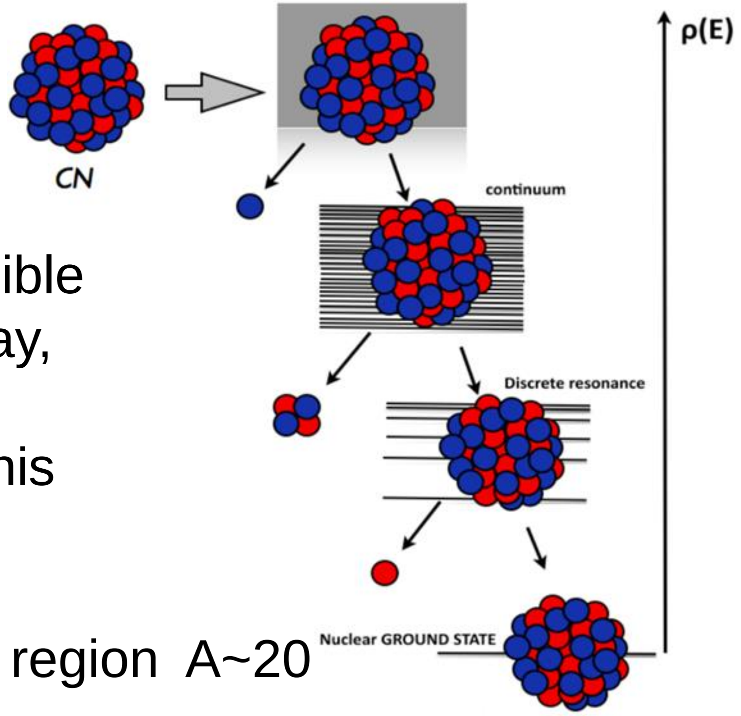
[Dynamical cluster formation and correlations in heavy-ion collisions, within transport models and in experiments]

May 17-19, 2016, GANIL, Caen, France

Outline

- ❑ Scientific Motivation:
  - ✓ Fusion-evaporation reaction.
  - ✓ Monte Carlo Hauser-Feshbach Code.
  - ✓ Clustering.
  - ✓ Hoyle state.
- ❑ The experimental set-up @ LNL-INFN
- ❑ The ^{12}C+^{12}C and ^{14}N+^{10}B experiments:
  - Fusion Evaporation Analisys.
  - Hoyle state in central and peripheral collision.
- ❑ Conclusions and perspectives

Fusion-Evaporation Reactions



- The statistical theory of compound nucleus decay
- Above the thresholds for particle decay, level densities are only accessible in evaporation reactions through the theory of compound nucleus decay,
- mainly inclusive experiments have been used up to now to constrain this fundamental quantity
- few studies exist concerning the evaporation of light nuclei in the mass region A~20

EXP: highly exclusive detection
NUCL-EX collaboration campaign:
STATistical properties of LIGHT nuclei from Fus-Evap.

- ❖ low multiplicity evts. & high detection coverage
- ❖ high energy and angular resolution
- ❖ complete evt. Reconstruction
- ❖ global control on the decay mechanism

GARFIELD+RCo @ LNL

TH: decay codes constrained to available data

- ❖ Compound Nucleus formation and decay
- ❖ Level Density for A ~ 20, e* ~ 3 A. MeV

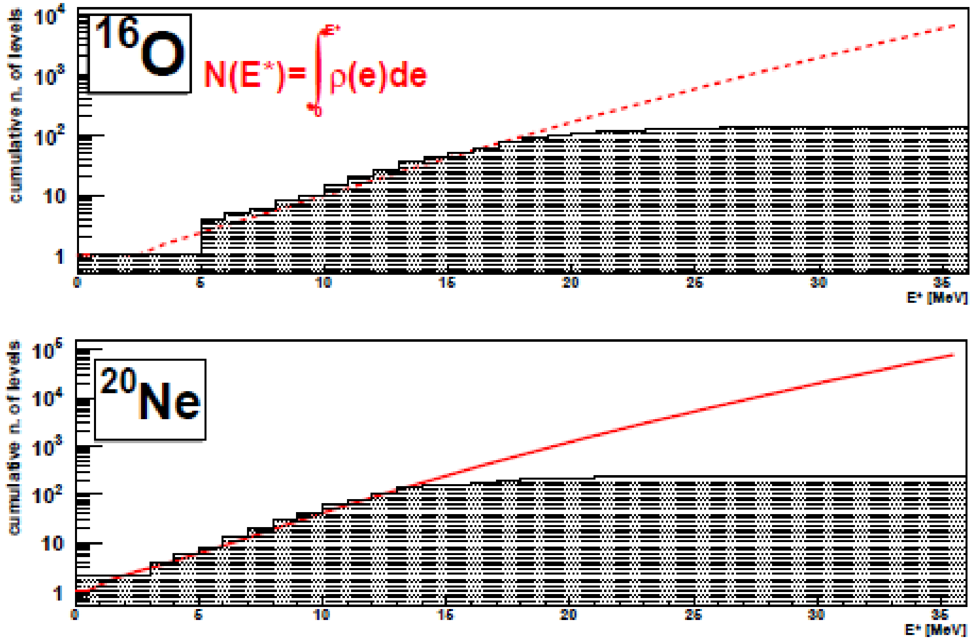
AMD calculations for $^{12}C+^{12}C$

Monte Carlo Hauser-Feshbach

G. Baiocco PhD thesis http://amsdottorato.cib.unibo.it/4295/
G. Baiocco *et al* 2013 *Phys. Rev.* C **87** 054614.

Monte Carlo Hauser-Feshbach HFℓ

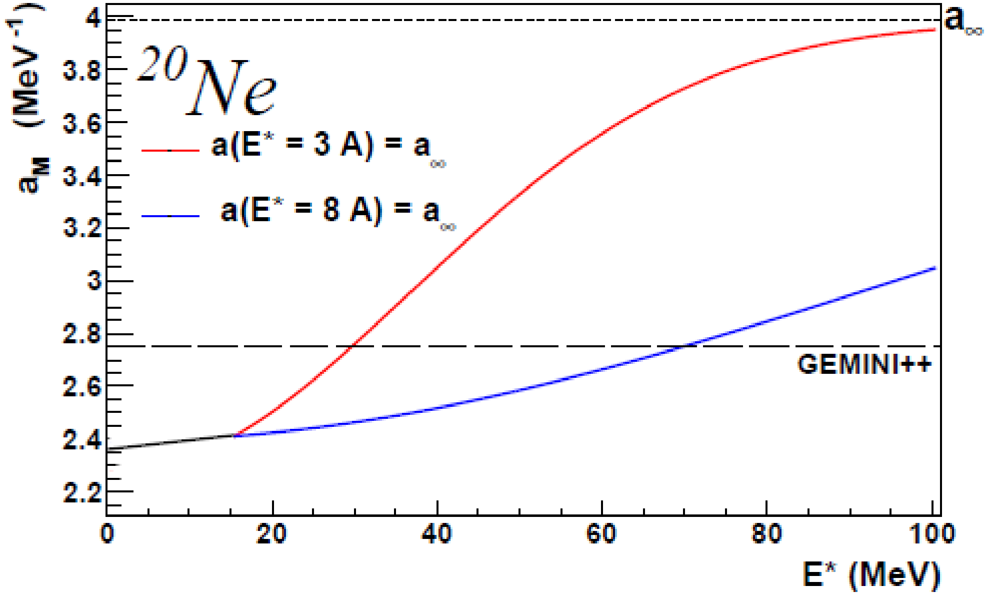
Systematics of LD parameters
D.Bucurescu, PRC 72, 044311 (2005)
Back-Shifted Fermi Gas with a(E)
fitted nuclei between 18F and 251Cf ;



G. Baiocco PhD thesis http://amsdottorato.cib.unibo.it/4295/
G. Baiocco *et al* 2013 *Phys. Rev.* C **87** 054614.

$$a_\infty = \frac{A}{14.6}\left(1 + \frac{3.114}{A^{1/3}} + \frac{5.626}{A^{2/3}}\right)$$

J.Toke, Nucl. Phys. A 372 141 (1981)



a∞

- rapidity of the increase as the only model free parameter
- GEMINI++ as a reference: http://www.chemistry.wustl.edu/~rc/gemini++/
- R. J. Charity, Phys. Rev. C 82 014610 (2010)

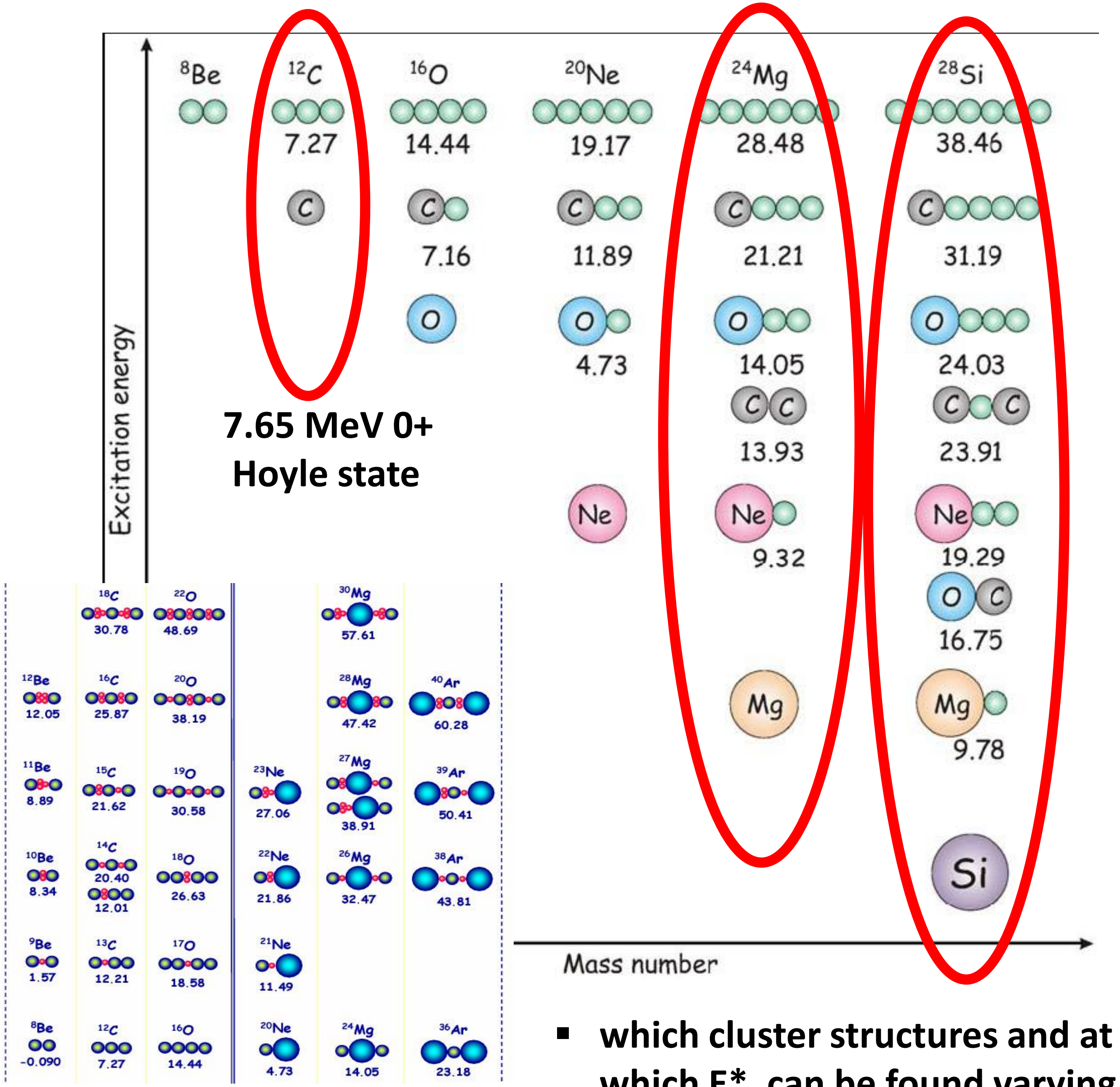
Clustering

- Cluster structures appear mainly at excitation energies close to the thresholds for nucleus decomposition into clusters;

- Evidence for cluster structures comes from decay widths and branching ratios

- Preferential decay to α-structures in daughter nuclei

- Molecular resonances at higher excitation energy.



- **which cluster structures and at which E* can be found varying the N/Z in a given isotopic chain?**

T. Ichikawa and W. Von Oertzen, Phys. Rev. C **83**, 061301 (2011)

Hoyle state

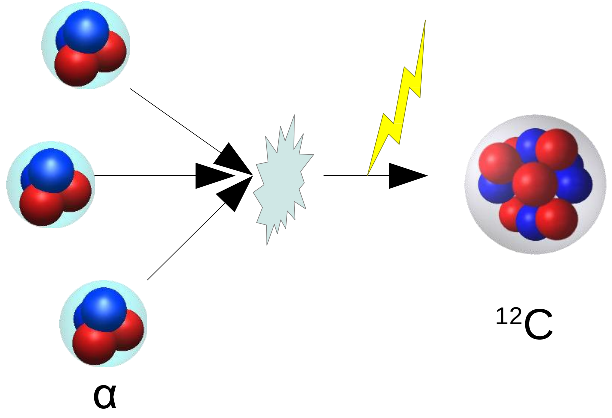
The theory of stellar evolution:

Triple-α reaction (Bethe,Phys.Rev.55(1939)434)

$$3\alpha \rightarrow {}^{12}C + \gamma$$

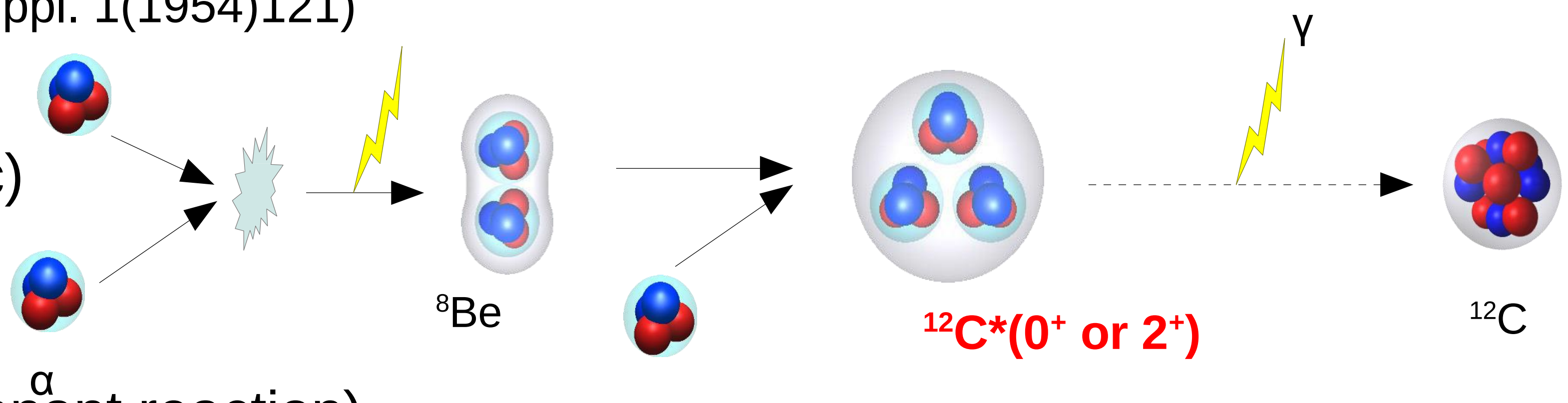
Two-step process (E.Salpeter,Astrophys.J. 115(1952)326)

(non-resonant)



In 1953, Fred Hoyle predicted the third α could be captured through the resonance level in ^{12}C. (F.Hoyle, Astrophys.J.Suppl. 1(1954)121)

$\alpha + \alpha \rightarrow {}^{8}Be$ (Life time=10^{-16} sec)



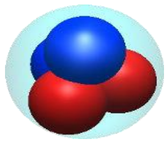
$^{8}Be + \alpha \rightarrow$ **$^{12}C^{*}$** $\rightarrow {}^{12}C + \gamma$ (resonant reaction)

The 7.65MeV 0^{+} state in ^{12}C was found in β-decay of ^{12}B

C.W.Cook, W.A. Fowler, C.C. Lauritsen, and T. Lauritsen, Phys.Rev.107(1957)508

Hoyle state and α cluster model

^{12}C, 7.65 MeV 0_2^+ = Hoyle state

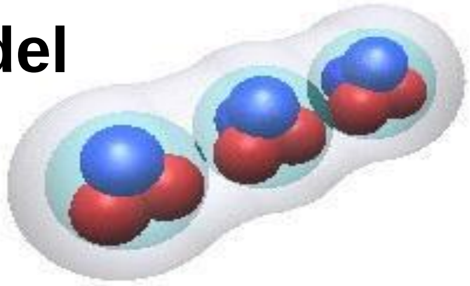


α cluster

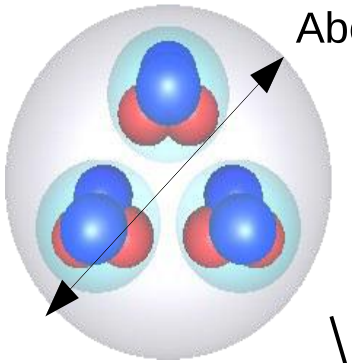
Difficult to explain the structure by the shell model

3α cluster structure (α cluster model)

Linear chain structure
(Morinaga, Phys.Rev.101(1956)254)

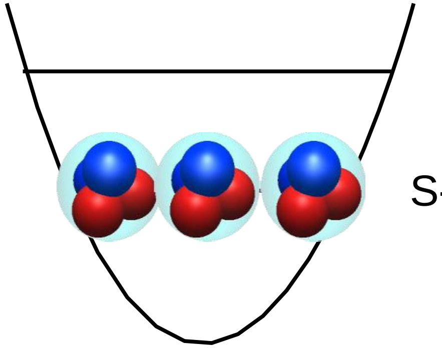


Loosely coupled 3α clusters (gas-like)
(3α OCM: Horiuchi,PTP51(1975)1266)
(3αGCM: Uegaki *et al*,PTP57(1977)1262)
(3αRGM: Kamimura,NPA351(1981)456)



About twice of the 0_1^+

3α-clusters condensate in the lowest S-orbit
(Tohsaki *et al*, PRL87(2001)192501)



S-orbit

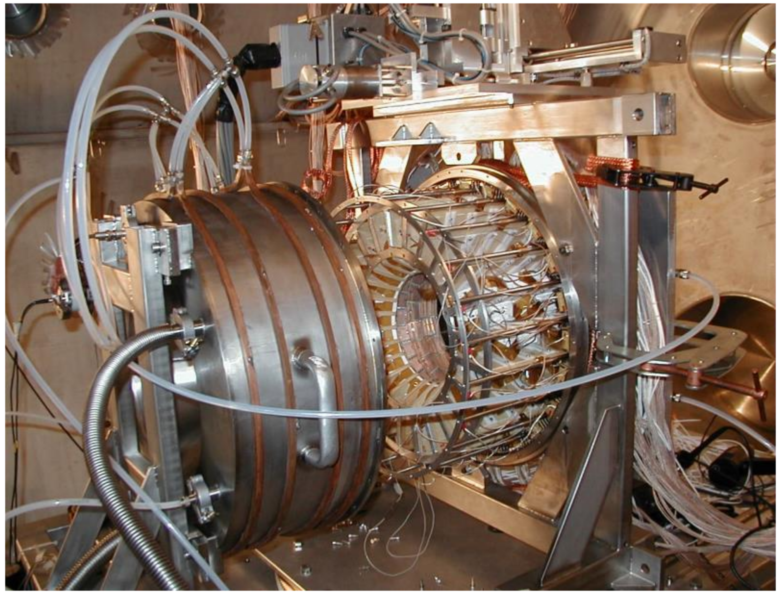
Experimental set-up @ LNL-INFN

European Physical Journal A

GARFIELD + RCo digital upgrade…..
By M. Bruno at al.
Eur. Phys. J. A (2013) **49**: 128

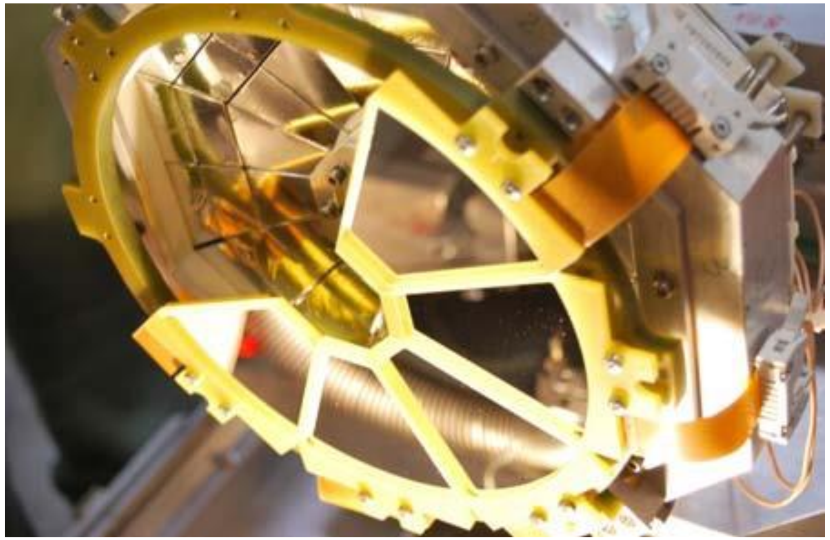
μSGC + CsI(Tl), 180 CsI
detection of LCP and fragments:

- ✓ low identification thresholds (0.8–1MeV/*u*)
- ✓ angular coverage 30º<θ_{lab}<150º 24 azimuthal sector
- ✓ Z identication, A identication for $1 \leq Z \leq 3$



IC+Si+CsI(Tl), 64 telescopes

- ✓ detection of ER, low E thresholds
- ✓ high granularity and θ-resolution: 0.8º for 5º<θ_{lab}<17º
- ✓ energy resolution of Si strips and CsI(Tl) given by 0.3% and 2-3%



Experimental set-up at LNL-INFN

^{12}C (95 MeV) + ^{12}C
^{14}N (80 MeV) + ^{10}B

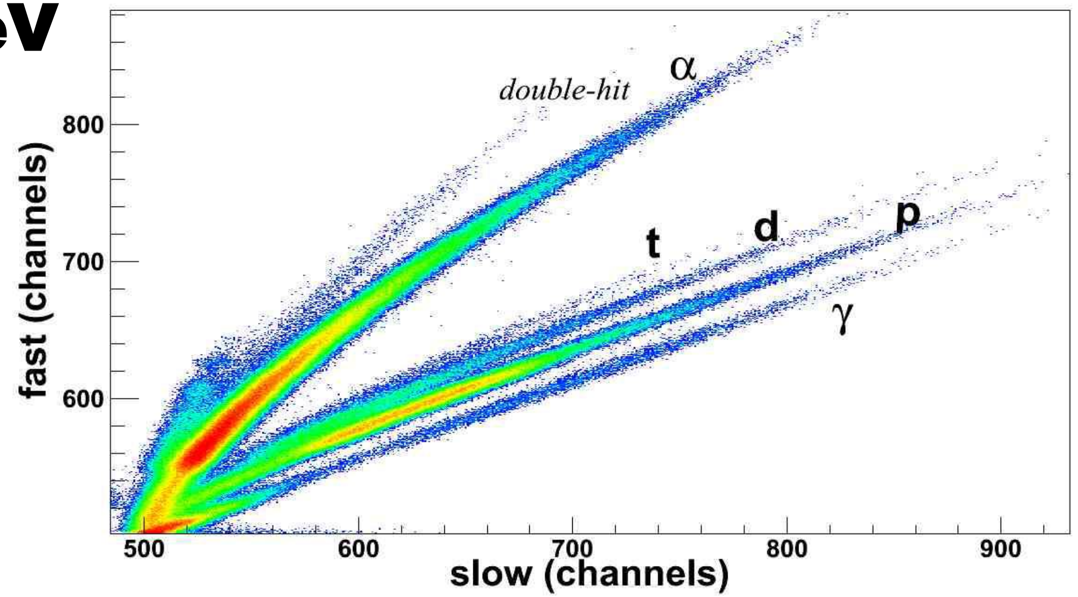
^{24}Mg at 2.6 A.MeV

LCP isotopical identification + energy calib. in CsI

L. Morelli et al.
Nucl. Instr. and Meth. A 620 305 (2010)

energy spectra of evaporated particles

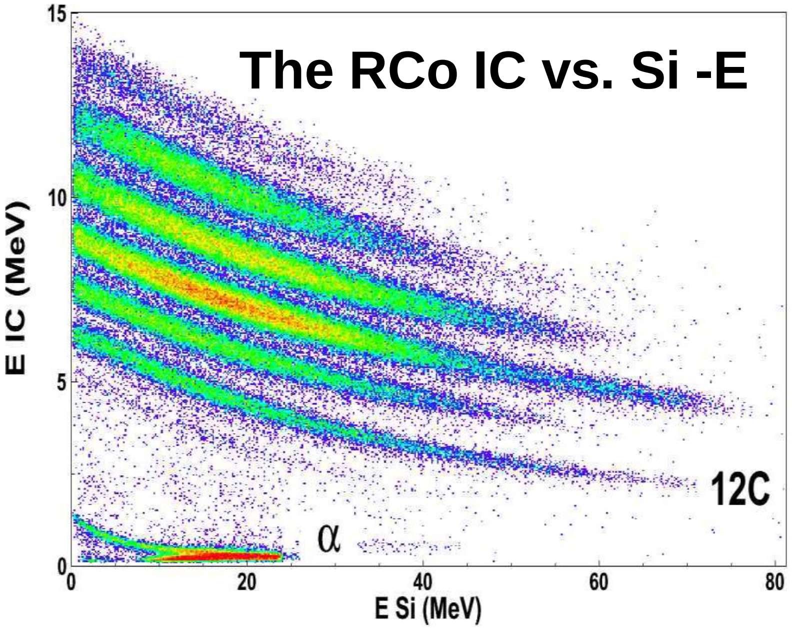
GARFIELD CsI Fast Slow

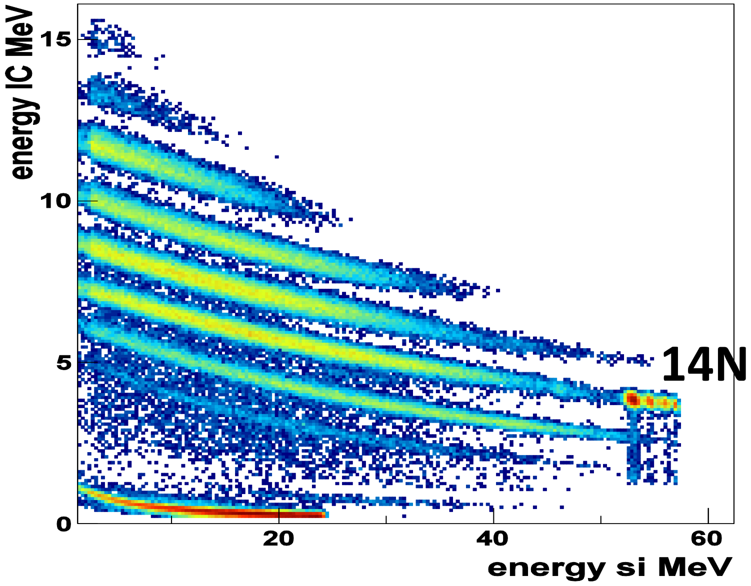


ΔE-E Z identification

N. Le Neindre, et al.,
Nucl. Instr. and Meth. A 490 251 (2002).

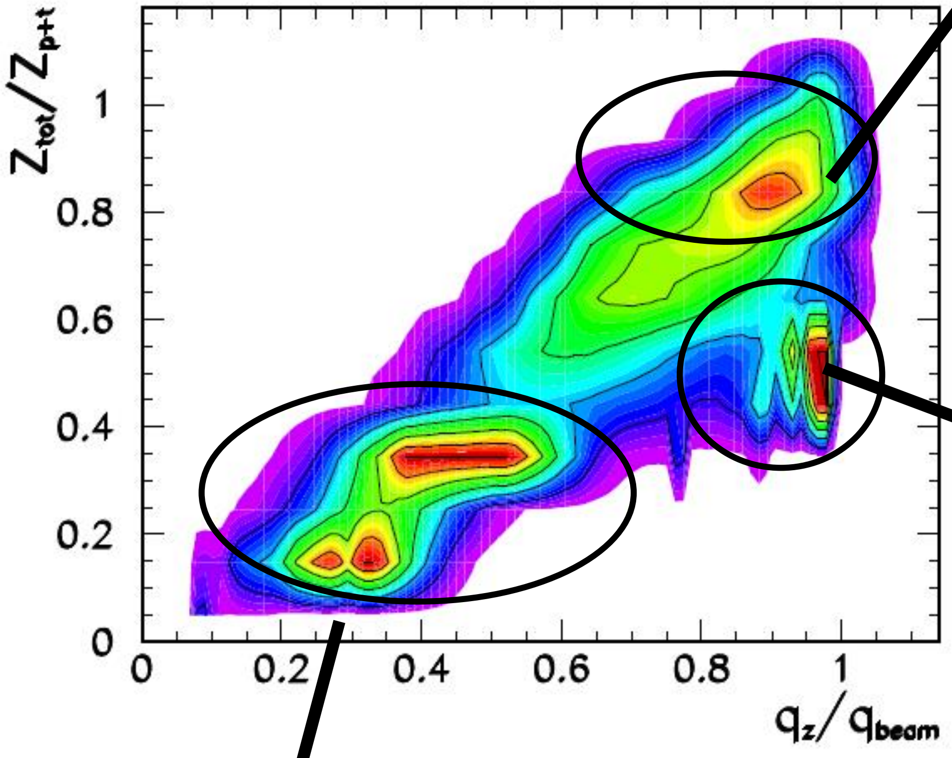
gate on evaporation residue





Event selection

Total events



Fusion-Evaporation channel selection:

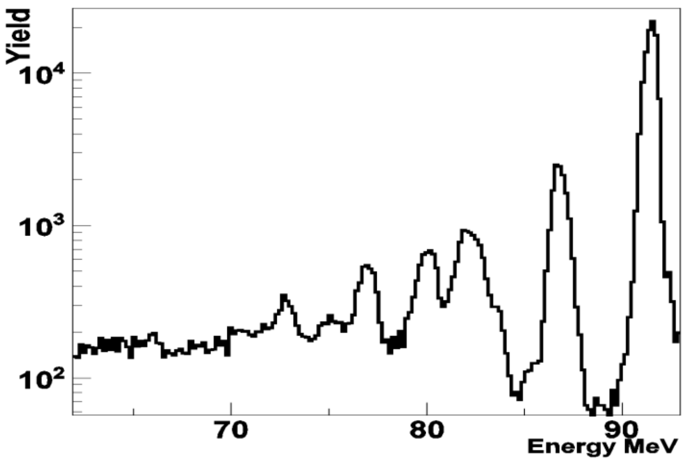
- completeness of the detection Z_{det} 100% ($Z_{proj+targ}$)
- Longitudinal momentum q_z/q_{beam} > 0.8
- coincidence between LCP in GARFIELD and Evaporation Residue in RCo

G. Baiocco 2013 *Phys. Rev.* C **87** 054614.

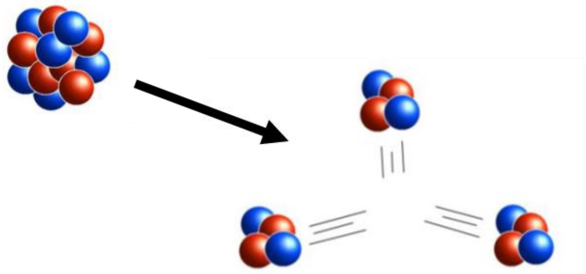
- Incomplete events
- No ER detection
- Only LCP in GARFIELD

PROJECTILE

- **12C excited state**

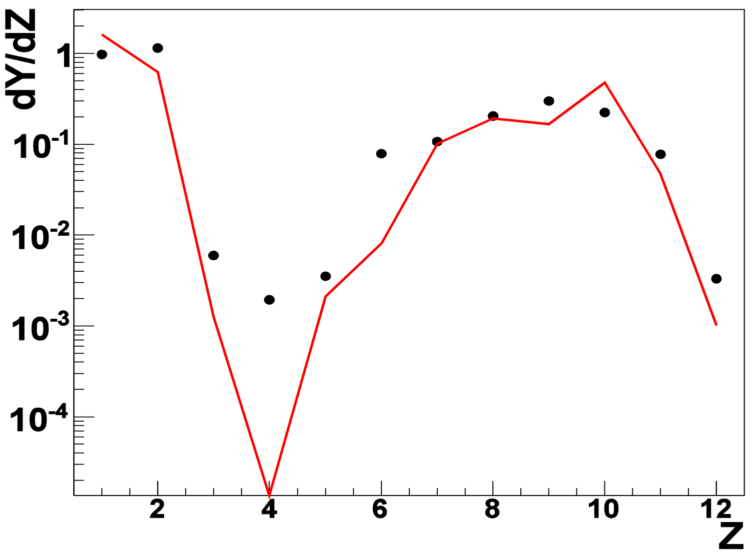


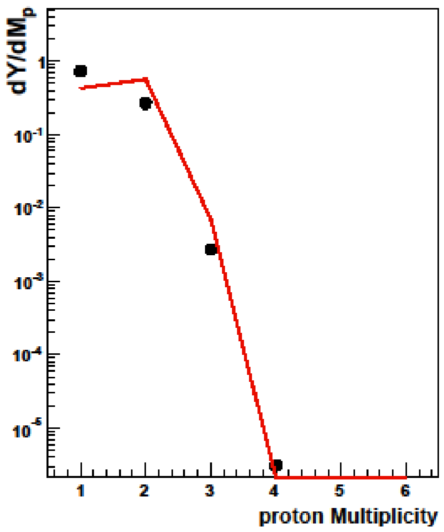
- 12C* decay in 3 α particles

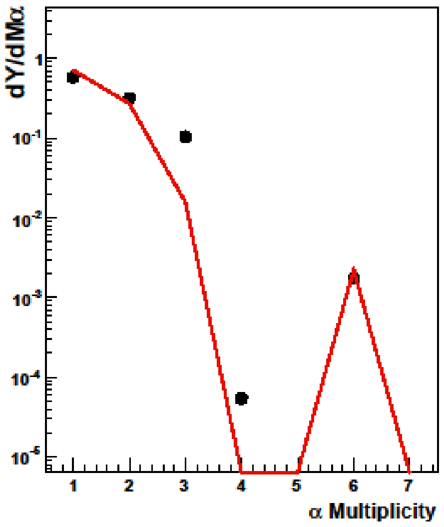


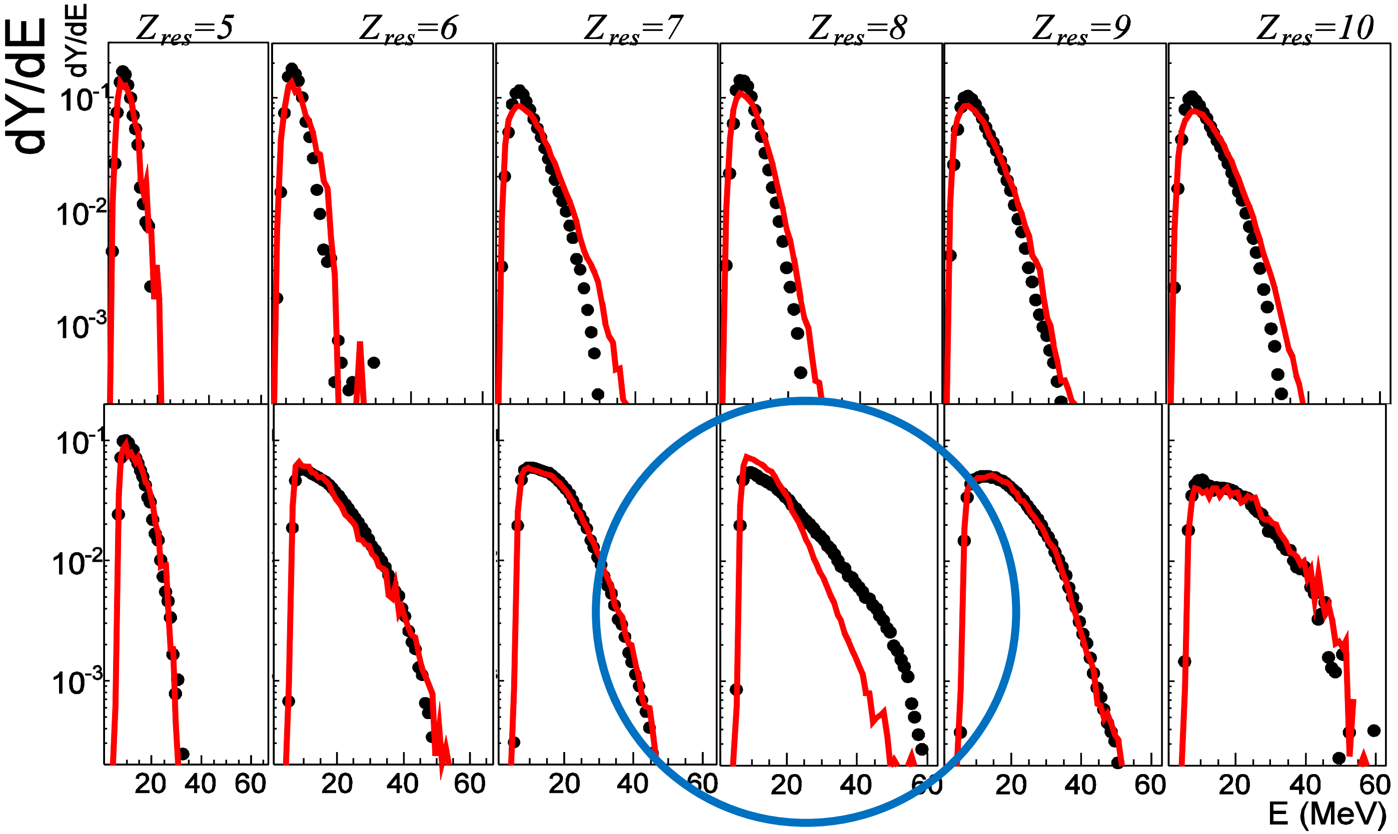
Fusion Evaporation Analisys: $^{12}C + {}^{12}C$ *exp* (@95 MeV)

- **data** — **HFl calculation**









HFℓ calculation for ^{24}Mg (E = 62 MeV) decay

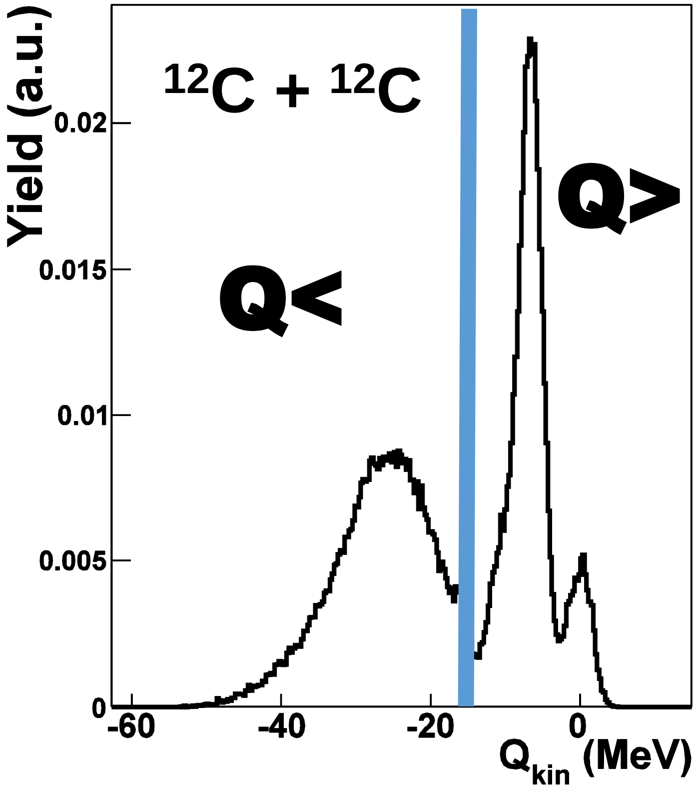
- ➢ good reproduction of global variables (Y(Z), multiplicities...)
- ➢ energy spectra and angular distributions of protons and alpha particles in coincidence with a residue

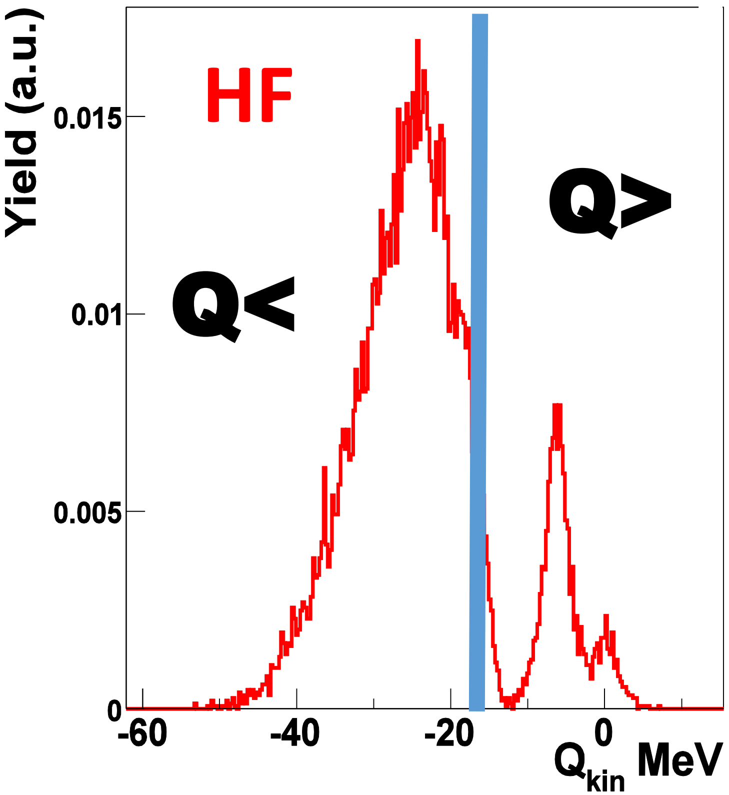
- ➢ **biggest discrepancy for α's in coincidence with Z=8 fragments**

Fusion Evaporation Analisys: $^{12}C + {}^{12}C$ *exp* (@95 MeV)

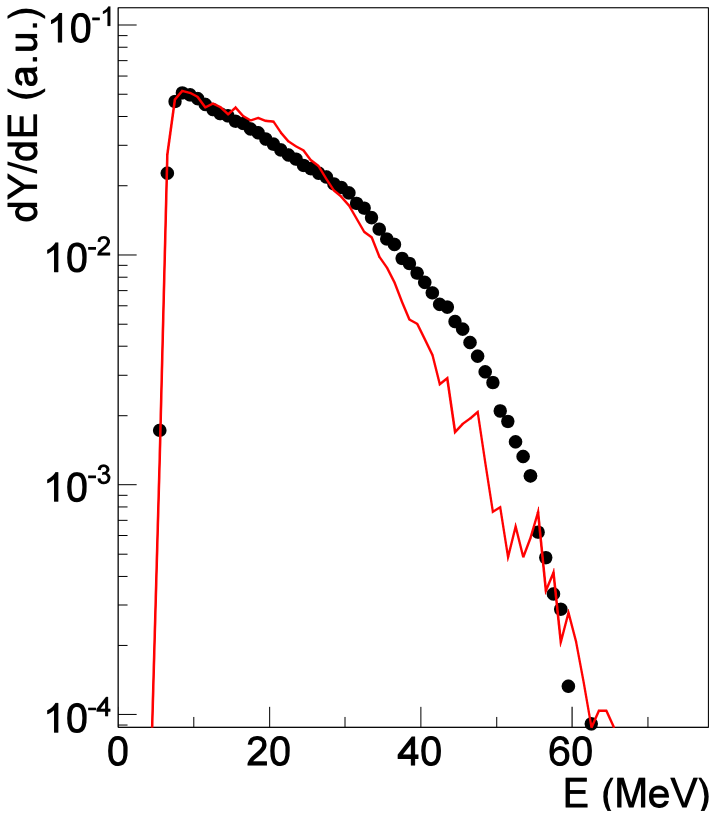
$$Q_{kin} = E_{kin} - E_{beam} = \sum_{i=1}^{N} E_i - E_{beam}$$

Oxygen + 2 α+ neutron(s) channel





α Zres=8 (O+2α+xn)

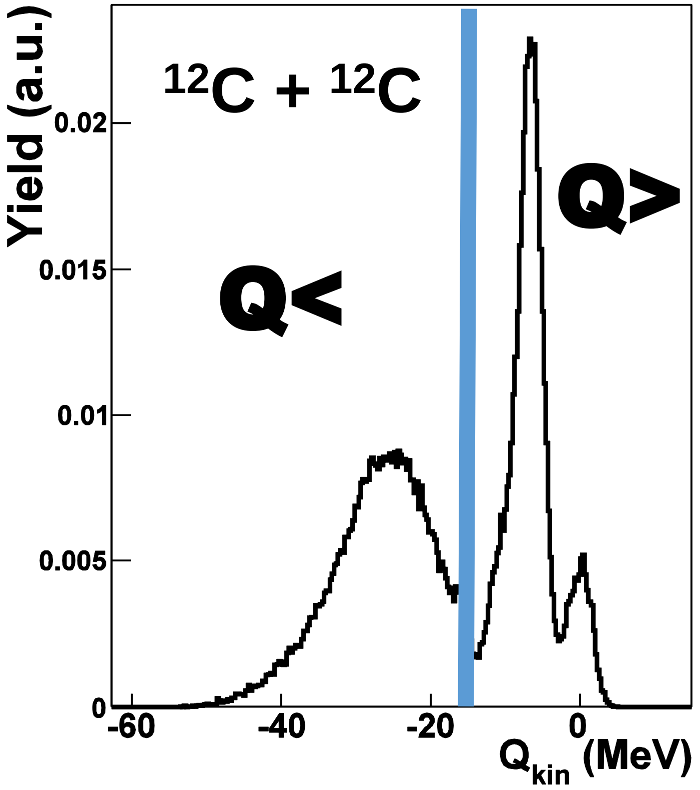


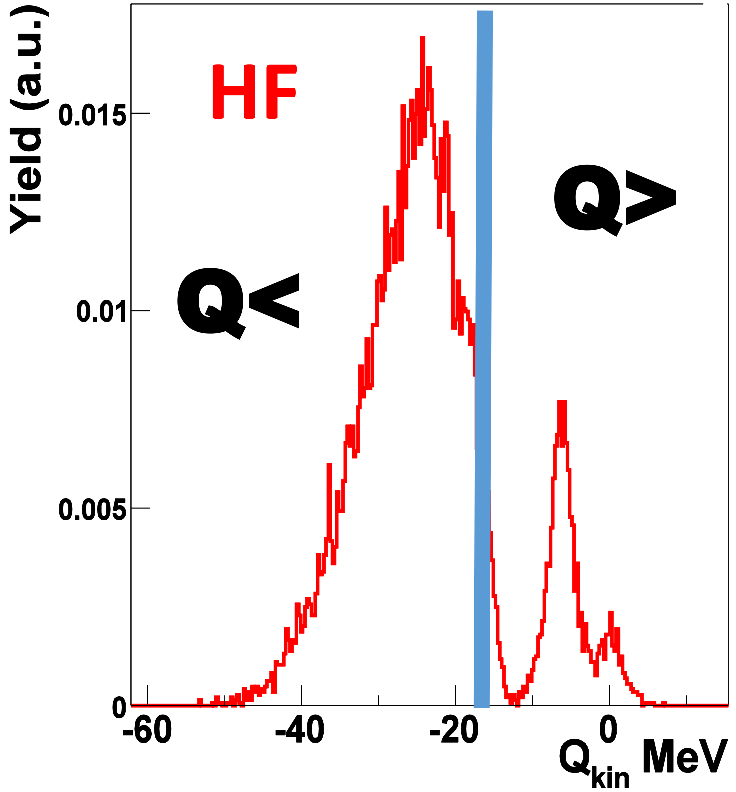
- ➢ common pattern for theoretical and experimental Q_{kin}
- ➢ Differences in the relative population of the different regions.

Fusion Evaporation Analisys: $^{12}C + {}^{12}C$ *exp* (@95 MeV)

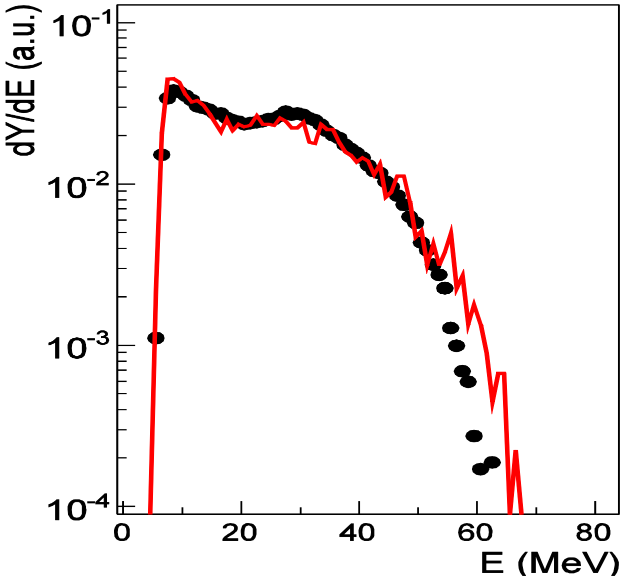
$$Q_{kin} = E_{kin} - E_{beam} = \sum_{i=1}^{N} E_i - E_{beam}$$

Oxygen + 2 α+ neutron(s) channel

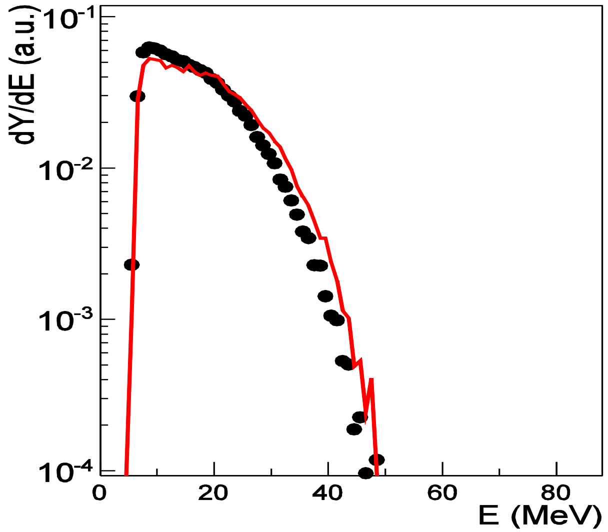




Q>



Q<



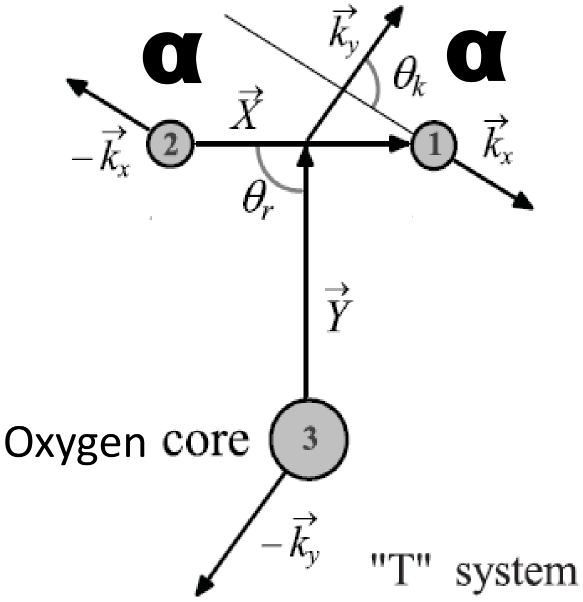
- common pattern for theoretical and experimental Q_{kin}
- Differences in the relative population of the different regions.

Oxygen – α – α correlations

Jacobi coordinates (T system)

$$E_x = \frac{(m_1 + m_2)k_x^2}{2m_1 m_2} \rightarrow E_{\alpha-\alpha}$$

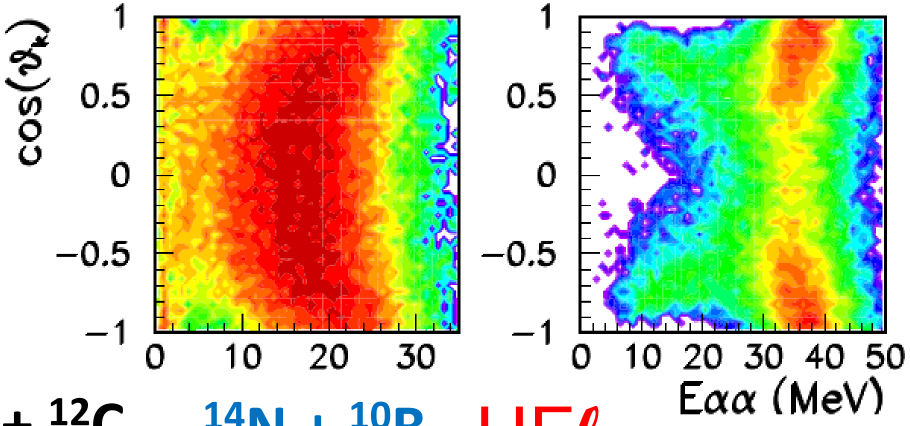
$$\cos\theta_k = \frac{\mathbf{k}_x \cdot \mathbf{k}_y}{k_x k_y} \rightarrow \frac{(K_O \cdot K_{\alpha-\alpha})}{(K_O\, K_{\alpha-\alpha})}$$



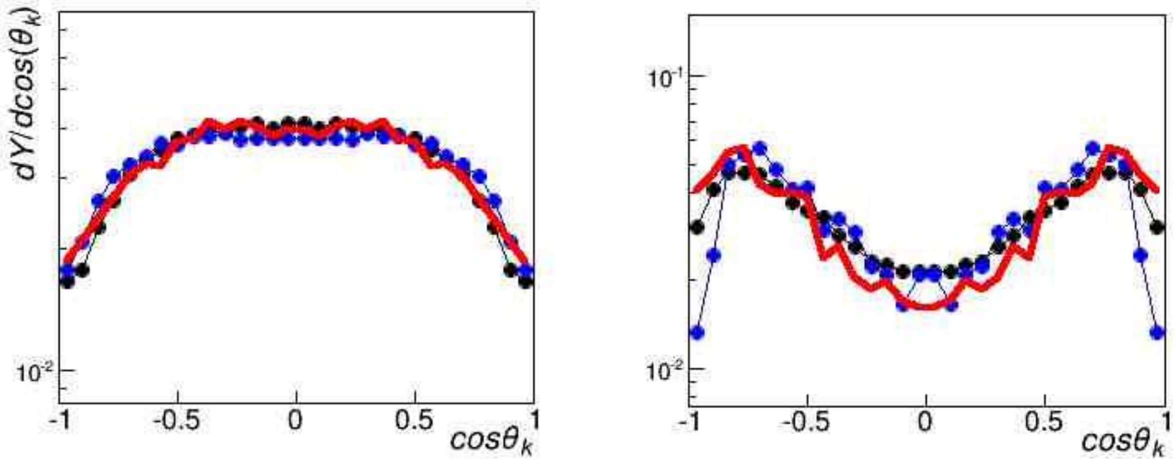
R. J. Charity Phys. Rev. C 84 (2011)

Q< O+2alpha+xn

Q> ^{16}O+2alpha

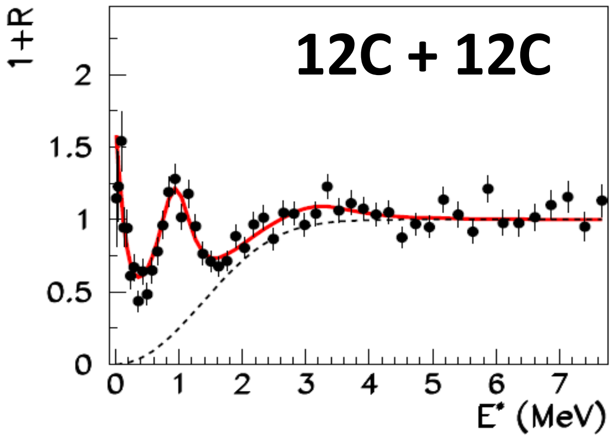


^{12}C + ^{12}C **^{14}N + ^{10}B** **HFℓ**



Jacobi angular correlations are compatible with sequential decay from an evaporation source.

Correlation function of the relative α − α energy in the α−α−O channel

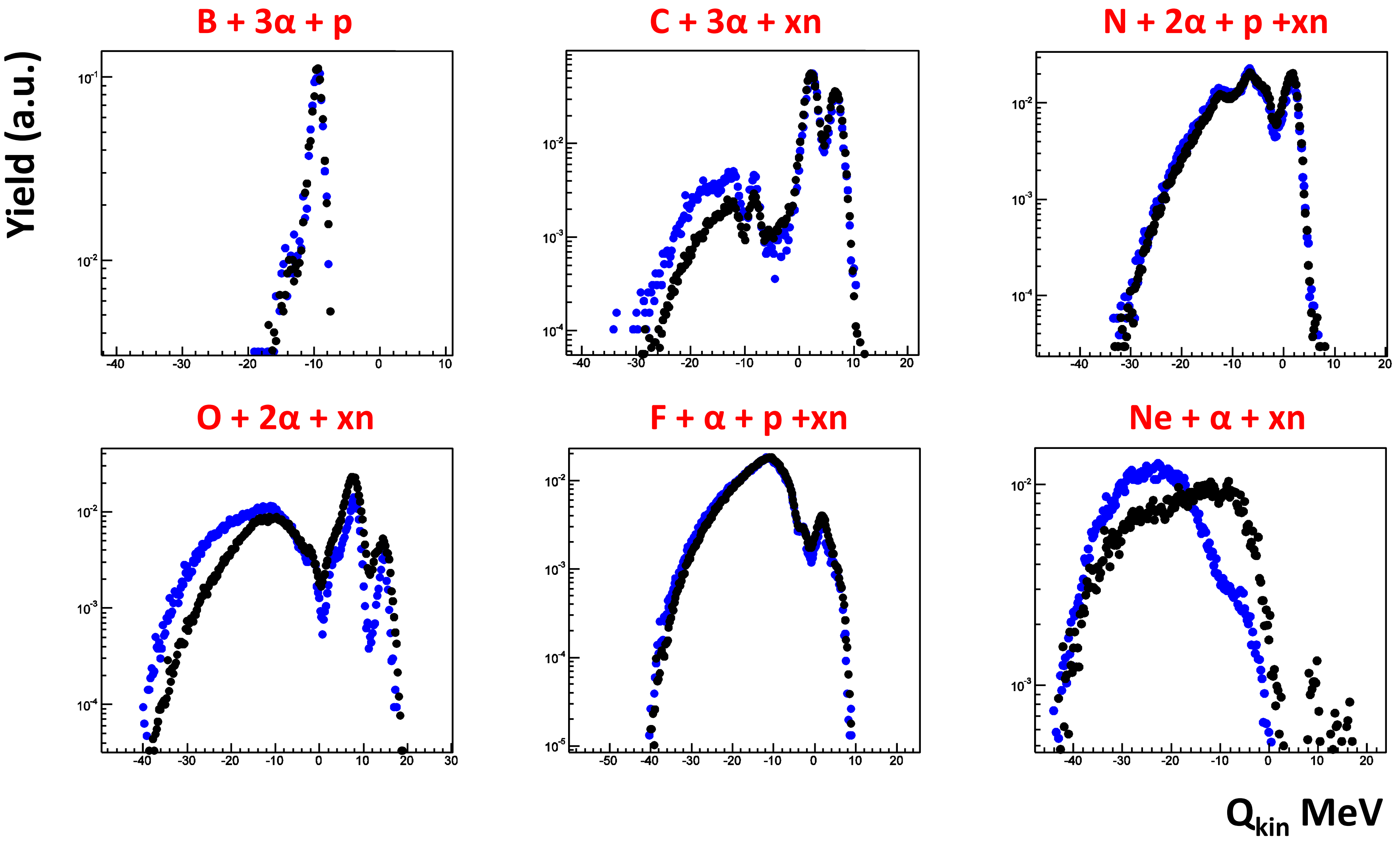


the formation of discrete Be levels does not represent more than 3% of the experimental yield in the ^{A}O−2α channel

Fusion Evaporation Analisys: $^{12}C + ^{12}C$ && $^{14}N + ^{10}B$

$$Q_{kin} = E_{kin} - E_{beam} = \sum_{i=1}^{N} E_i - E_{beam}$$

- Channels with maximum α multiplicity for each residue



- Common pattern for the Qkin-value
- Difference in the relative Q>/< population
- Entrance channel effects confirmed

Fusion Evaporation Analisys: $^{12}C + {}^{12}C$ && $^{14}N + {}^{10}B$

N+B reaction **C+C reaction**

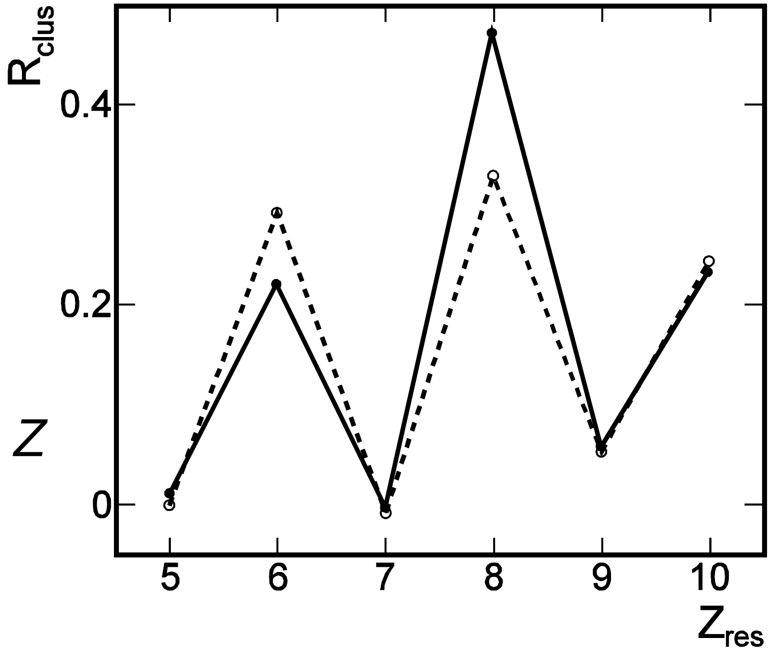
Z_{res}	channel	BR_e (N+B)	BR_t (N+B)	BR_e (C+C)	BR_t (C+C)
6	C+3α + xn	96%	77%	98%	78%
8	O+2α + xn	56%	15%	63%	15%
10	Ne+α + xn	47%	3%	26%	3%

experimental branching ratio excess towards α emission

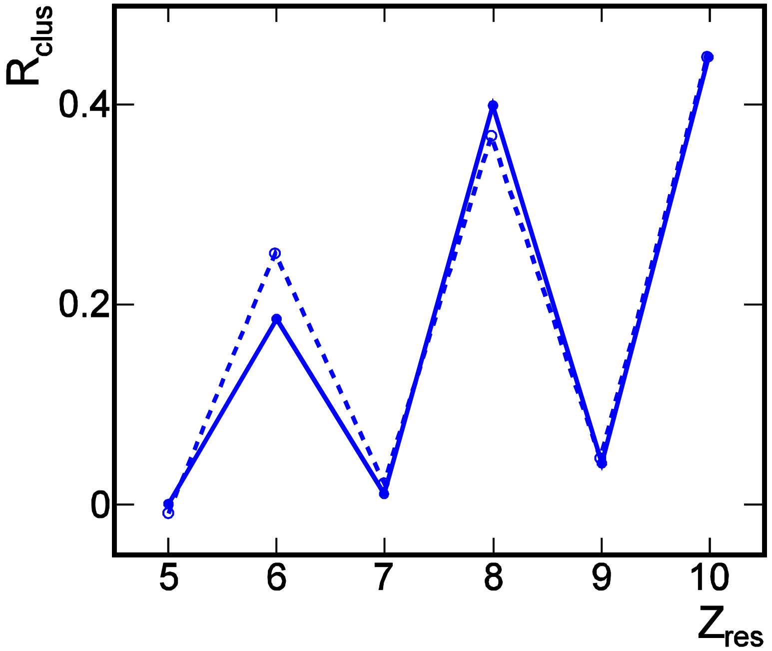
$$R_{clus}(Z) = \frac{Y_{exp}(Z; n_Z\alpha)}{Y_{exp}(Z)} - \frac{Y_{HF\ell}(Z; n_Z\alpha)}{Y_{HF\ell}(Z)}$$

- $Y(Z; n_Z\alpha)$ coincidence yields
- $Y(Z)$ inclusive yields
- n_Z -> maximum α multiplicity associated to the residue of charge Z

$^{12}C + {}^{12}C$



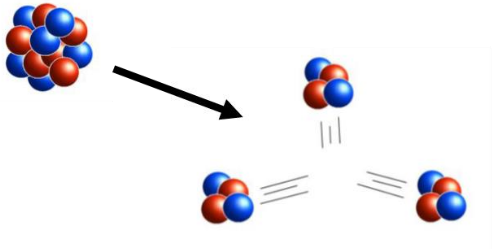
$^{14}N + {}^{10}B$



- ✓ **channels with Carbon, Oxygen and Neon residues show a preferential α decay.**
- ✓ **residual *α* structure correlations in the excited ^{24}Mg or in its daughter nucleus.**

Hoyle State

12C* -> Hoyle State

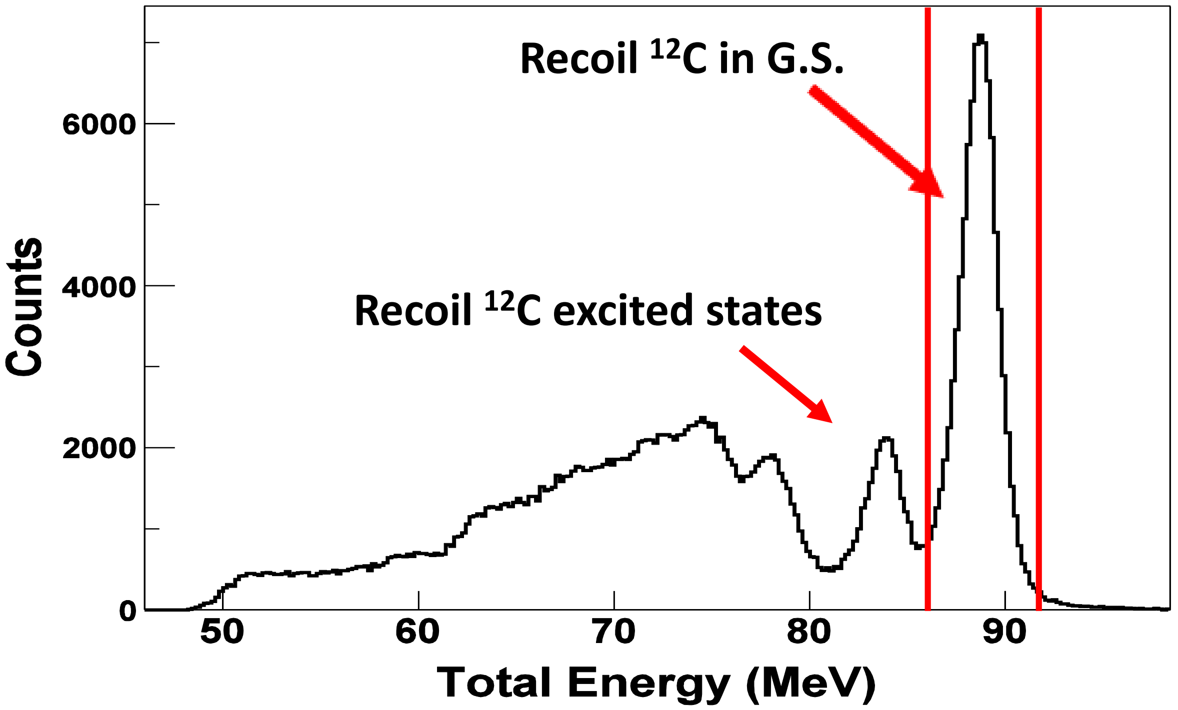


First proposed by Fred Hoyle in 1953 to explain the abundance of carbon in the universe.

- Later found experimentally at the energy which Hoyle had predicted.
- Cannot be explained by the shell model.
- Formed through the ‘triple-α’ process and thought to have a clustered structure.

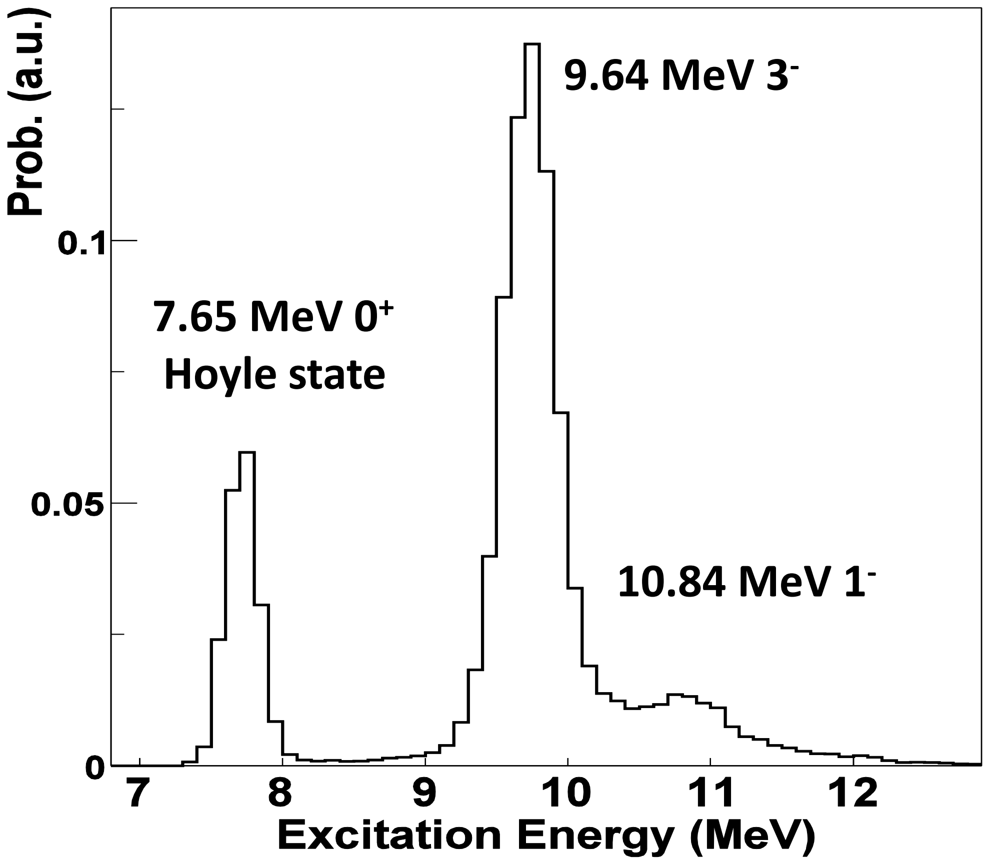
Total Energy Spectrum

$$E_{tot} = \sum_{i=1}^{3} E_{\alpha i} + Erec = Ebeam + Q$$ (Q = -7.272 MeV)



^{12}C Excitation Energy Spectrum

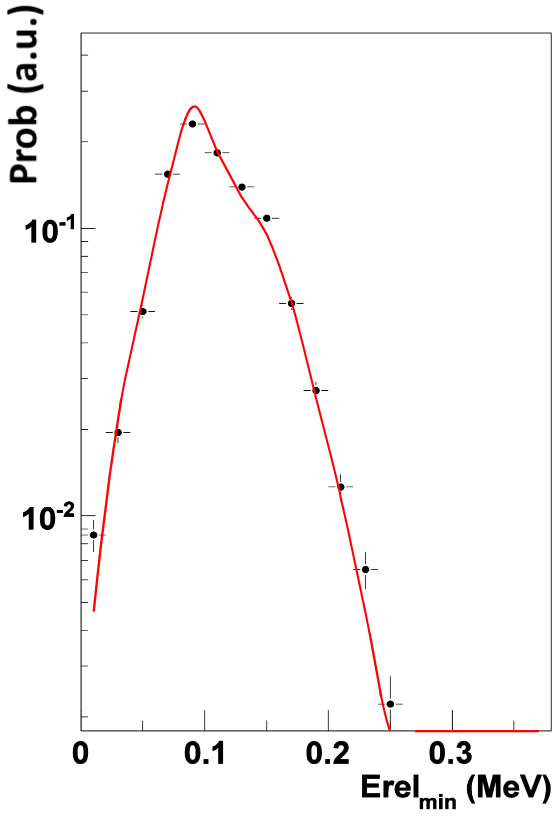
$$E_{^{12}C}^{*} = \sum_{i=1}^{3} E_{\alpha_i} - \frac{P^2}{2MC} + Eth$$



Hoyle State -> decay mechanism

Relative energy distribution of 8Be-like pairs

Sequential -> 92KeV   Direct-> ≈188KeV

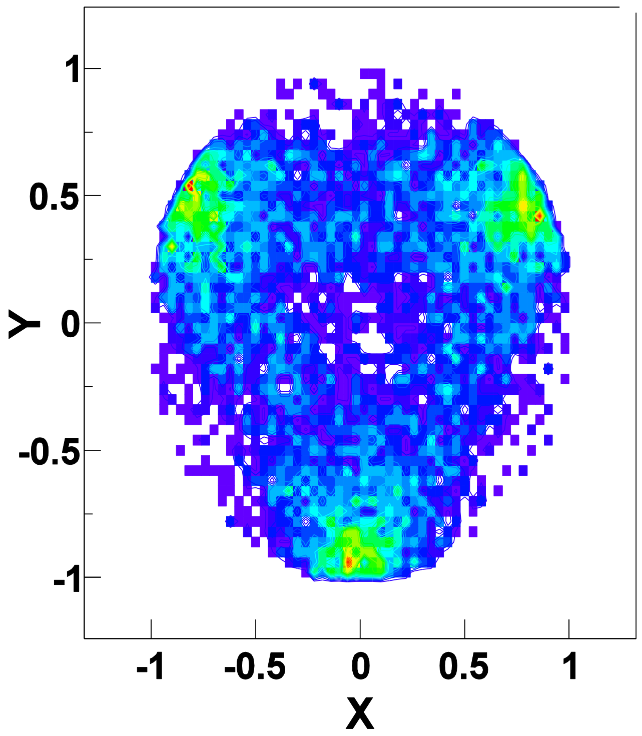


• **data**
-- **HFl**

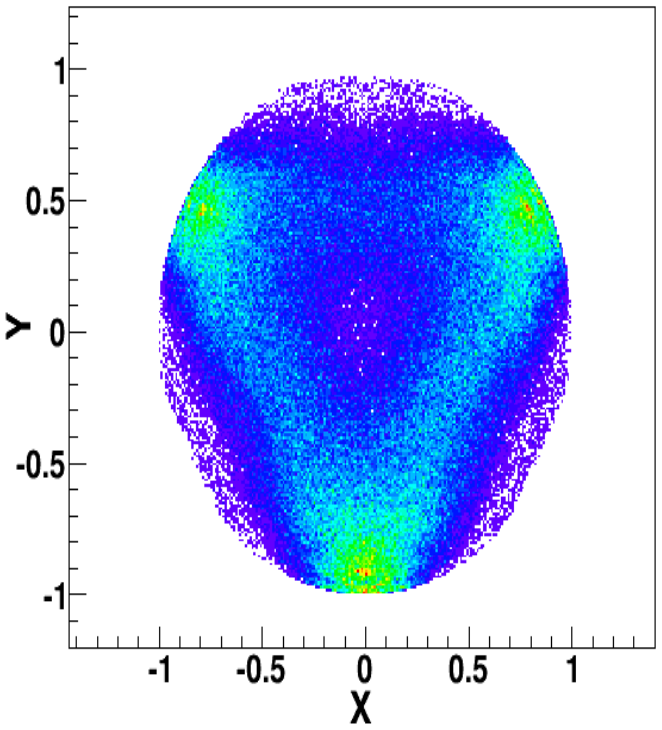
Raduta PLB 705, 65 (2011) (α-particle condensation)
O.S.Kirsebom PRL 108 (2012) (sequential)
J.Manfredi PRC 85 (2012) (sequential)

Energy DALITZ Plot

$$X = \frac{\sqrt{3}(Ei - Ej)}{Etot} \qquad Y = \frac{2Ek - Ei - Ej}{Etot}$$

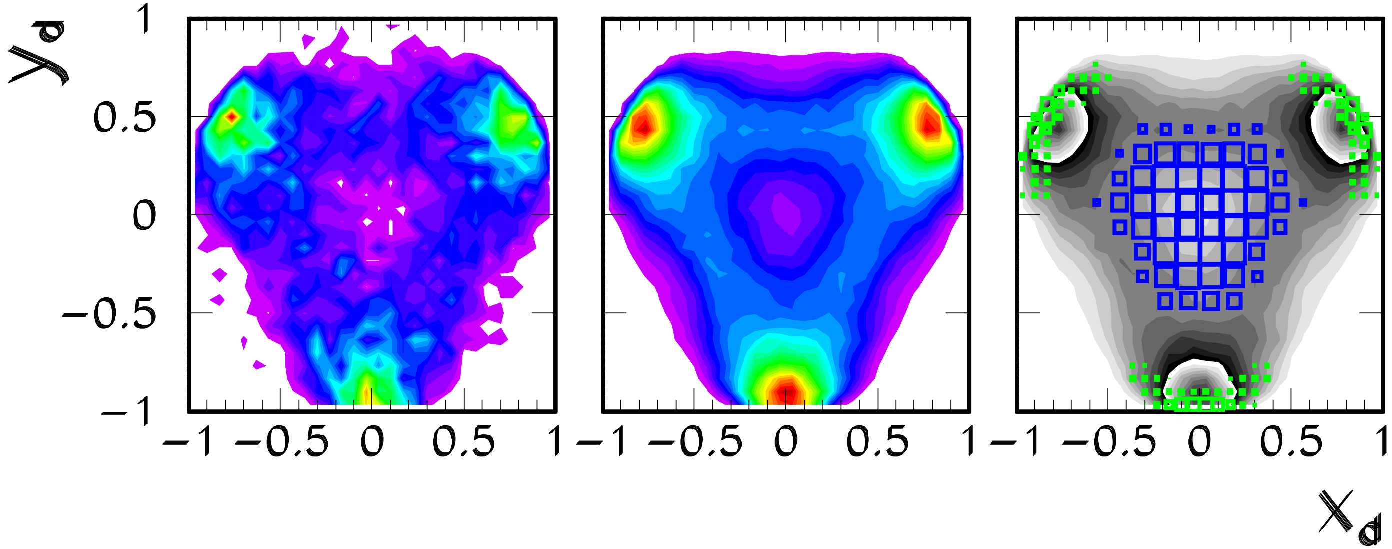


DATA



HFl (sequential)

Hoyle State -> decay mechanism



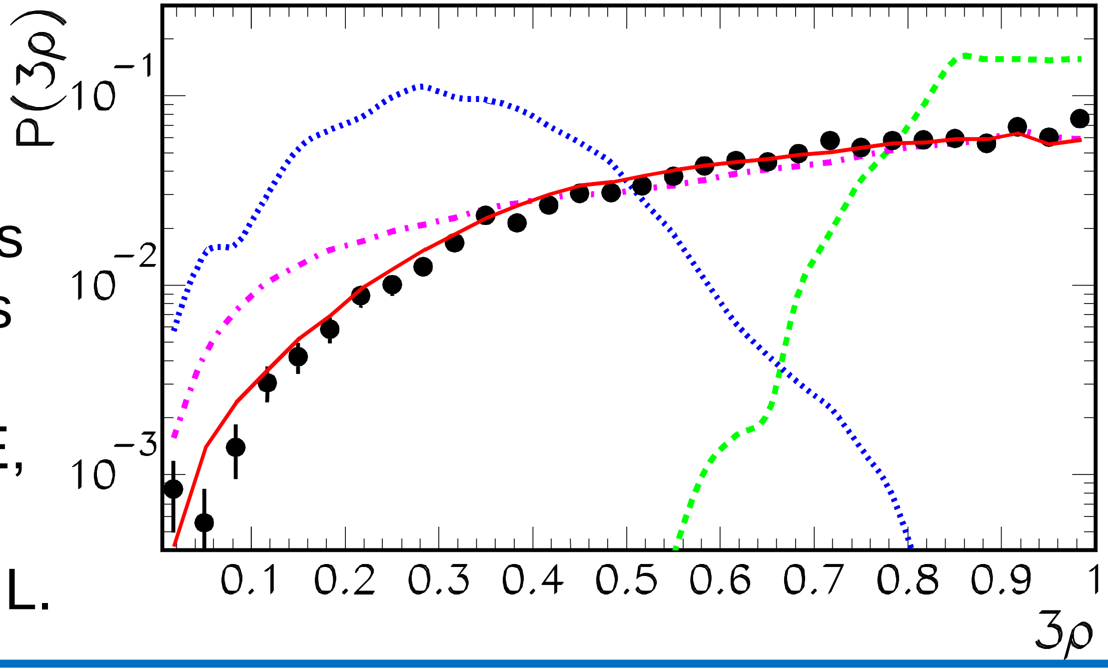
Possible direct decay (DD)

- DDE direct decay with equal energies.
- DDL direct decay in linear chain.
- DDφ direct decay with uniform population of the phase space

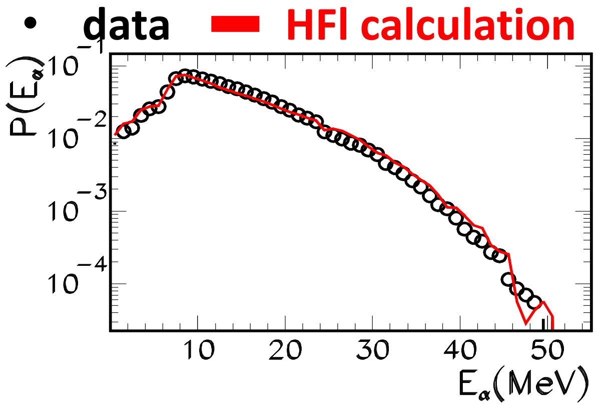
radial projection of the Dalitz plot

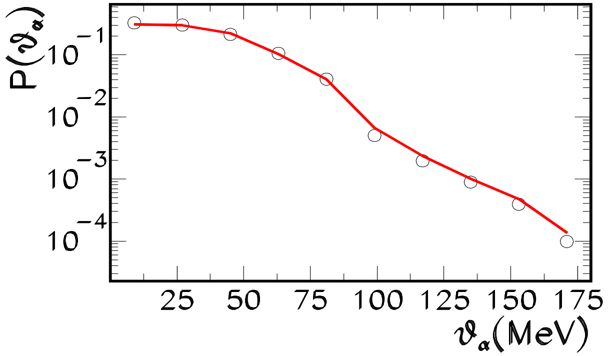
$$(3\rho)^2 = x_d^2 + y_d^2$$

- ➢ data are very well reproduced by HFℓ calculations
- ➢ DDE, DDL and DDφ give bumps at the extremes of the distribution.
- ➢ Fit performed on the 3ρ variable, when HFℓ, DDE, DDL and DDΦ are included.
- ➢ Total DD contribution 1.1 ±0.4% with a 95% of C.L.

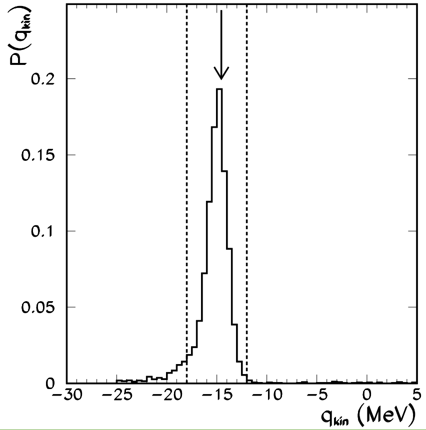


$^{12}C + ^{12}C \rightarrow ^{24}Mg \rightarrow$ 6 α decay channel: the Hoyle state properties



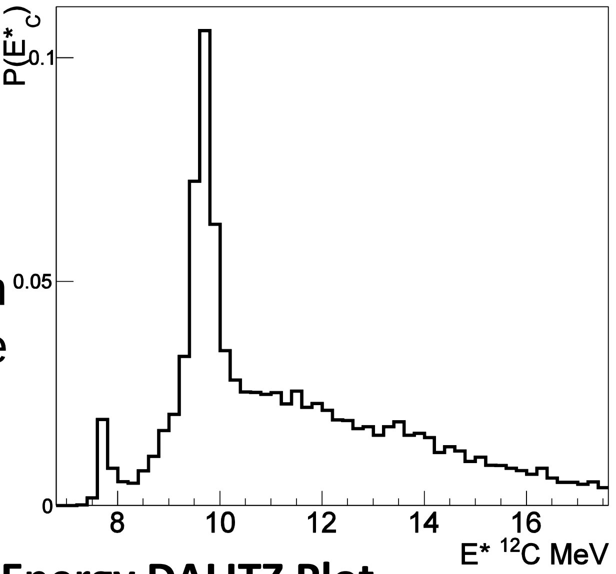


Q_{kin} distribution



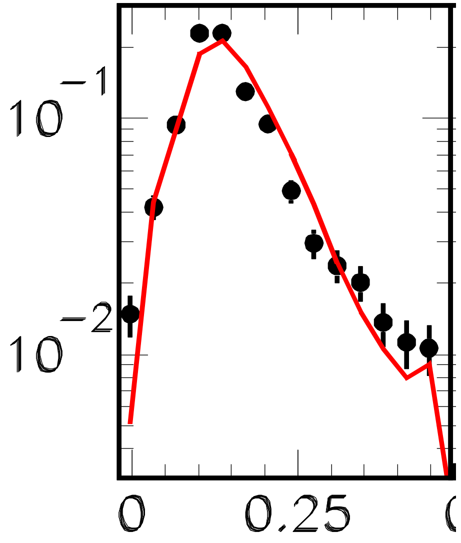
- 6 α particles detected by the apparatus.
- sequential evaporation of the $^{24}Mg^*$ formed in central collisions the decay has to go through the formation of a $^{12}C^*$ intermediate nucleus .
- selected the three (over six) α particles with the minimum total energy and calculate the $^{12}C^*$ excitation energy.

^{12}C Excitation Energy Spectrum



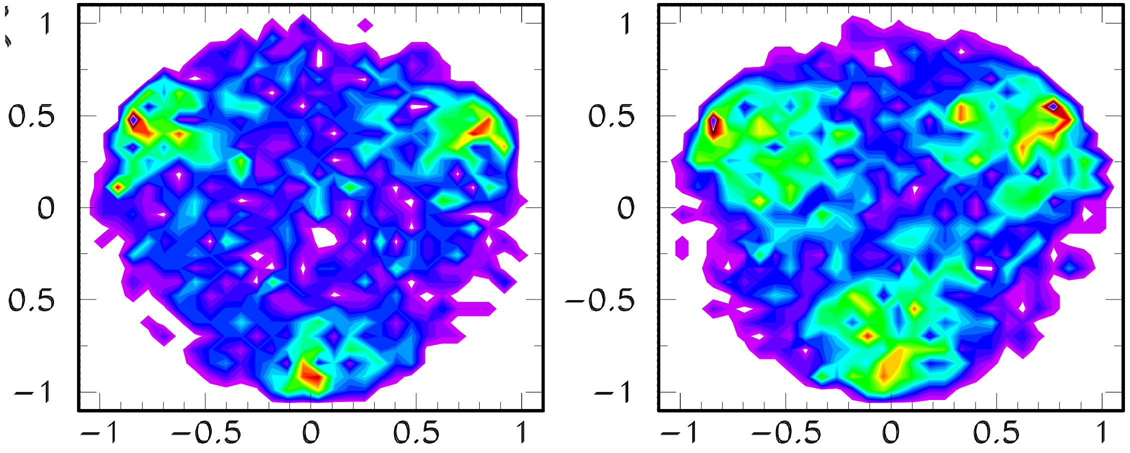
Relative energy of 8Be

Sequential -> 92KeV   Direct-> ≈188KeV



Energy DALITZ Plot

$$X = \frac{\sqrt{3}(Ei - Ej)}{Etot} \qquad Y = \frac{2Ek - Ei - Ej}{Etot}$$



Conclusions:

- The selected sample is compatible with the expected behavior of a complete fusion-evaporation reaction, with the exception of specific channels corresponding to the emission of multiple α particles in coincidence with Oxygen, Carbon and Neon residue.

- Persistence of anomalous Branching Ratio for alpha decay in the fused hot ^{24}Mg in ^{14}N+^{10}B reaction.
- The ensemble of these observations tends to indicate the persistence of cluster structures for ^{24}Mg and/or its daughter nucleus ^{20}Ne.

- The decay of the 7.65 MeV ^{12}C Hoyle state, in peripheral and central reactions, give no indications of deviations from the sequential decay mechanisms.

Indications of in-medium structure

Inelastic scattering

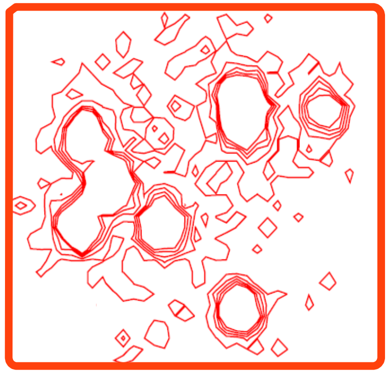
Itoh, PRL **113**(2014)102501 — <0.2 %

Morelli et al. JoPG 43 (2016) — ~1 %

Fragmentation

Raduta, PLB **705**(2011)65 — ~17 %

Direct decay



Interaction with the environment

Structure modification ?

Final-state interaction ?

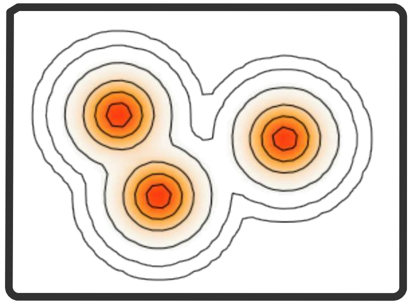
new exp. in 2016 LNS

Four-π A Z Identification Array

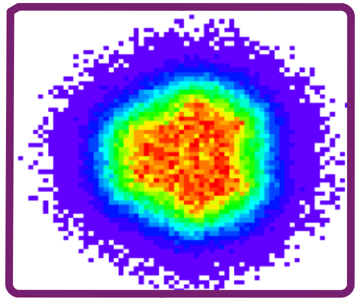
FAZIA-COR : in-medium properties

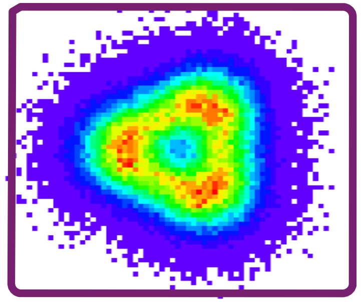
G.Verde, IPN Orsay / D.Gruyer, INFN - Firenze

^{12}C Hoyle state



Direct | **Sequential**

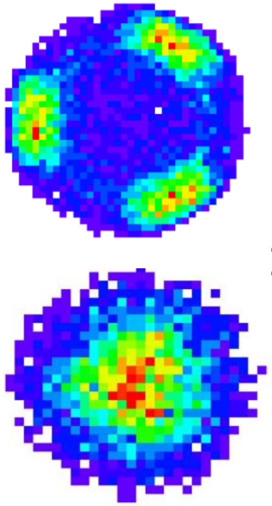




L.Quattrocchi, NN2015

^{12}C

3^-	9.64	
0^+	7.65	^{8}Be+α, 3α
2^+	4.44	
0^+		

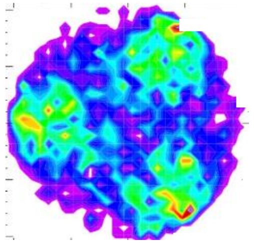


L.Quattrocchi, NN2015
Raduta, PLB **705**(2011)65

Fragmentation

C+Mg@25MeV/A

CHIMERA



L.Morelli, JoP.G

Fusion/ evaporation

C+C@95MeV

GARFIELD

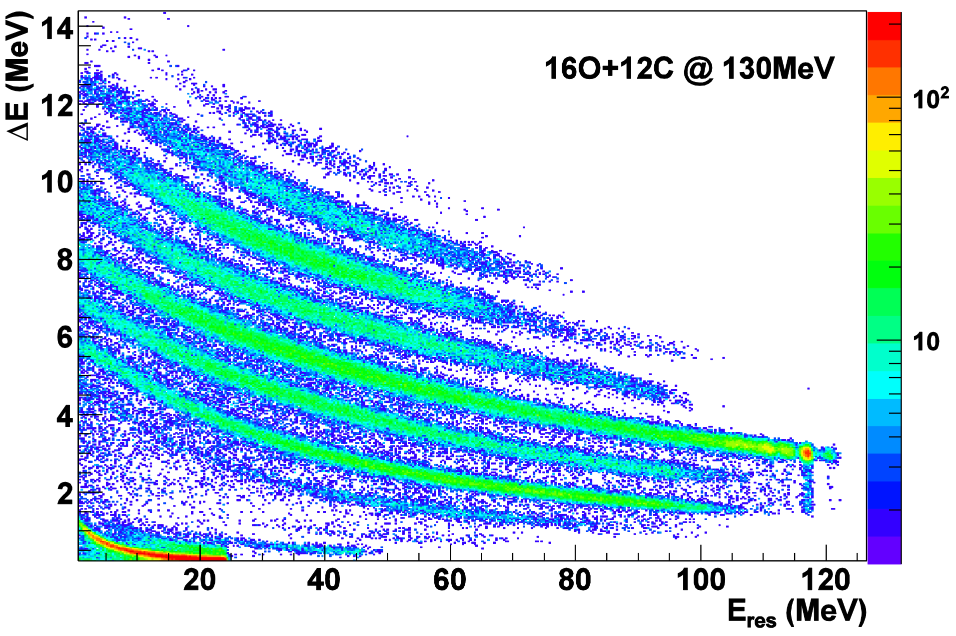
$^{16}O+^{12}C \rightarrow ^{28}Si^*$ ongoing analysis

- Systematics study of even-even N=Z nuclei produced in the fusion-evaporation
- ^{16}O + ^{12}C reaction at three different beam energies E_{beam} = **90, 110 and 130 MeV**
- clustering effects can be differently expressed varying the E* of the system
- investigate R_{clus} as a function of the excitation energy

Proposal approved by LNL PAC in 2014

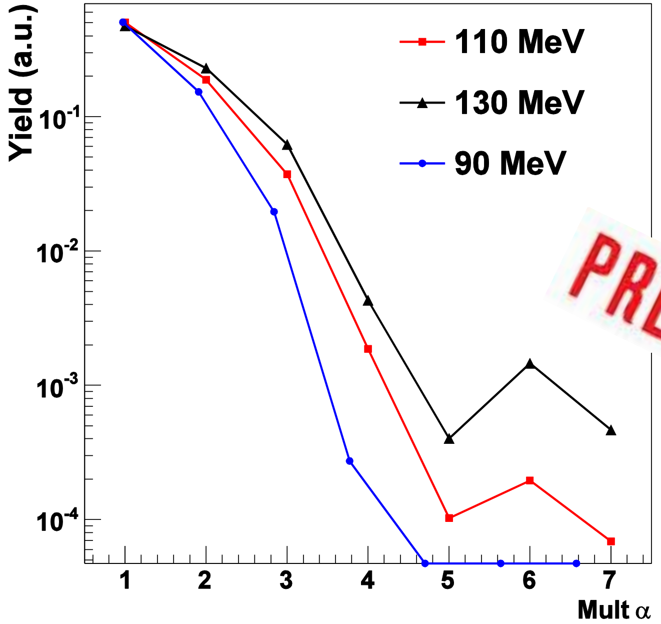
March 2015 : experiment performed

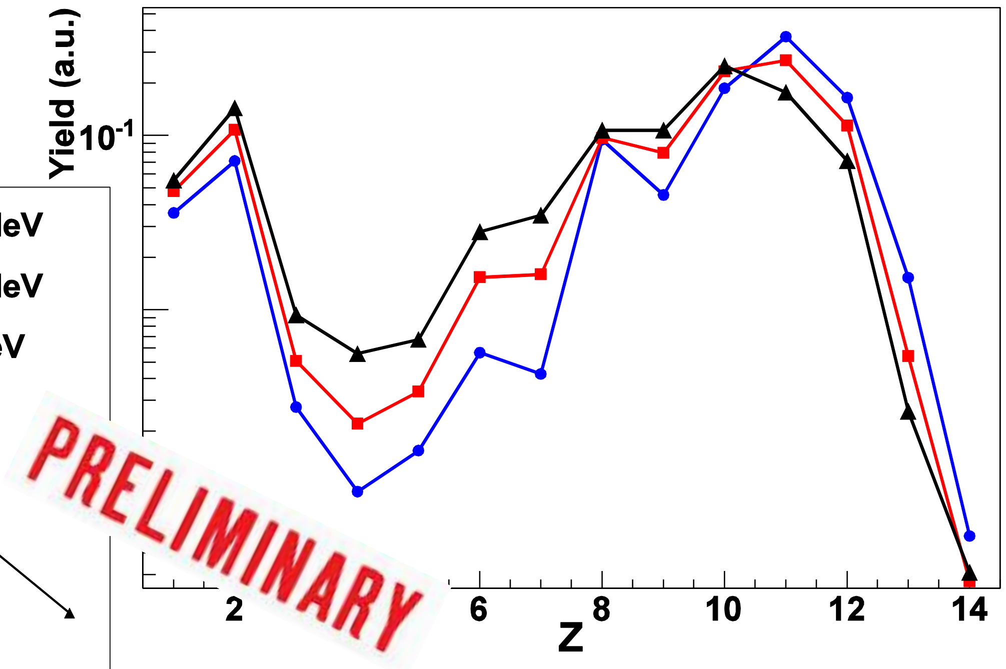
ΔE-E Rco IC-SiE



gate on evaporation residue

α multiplicity





Charge distribution

- the possibility that a 7 α-particle gas-like state might exist in ^{28}Si

...thank you for your attention!

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