Cluster correlations effects in $^{12}C+^{12}C$ and $^{14}N+^{10}B$ fusion–evaporation reactions at 2.6 A.MeV excitation energy.

L. Morelli [1]

NUCL-EX Collaboration

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IWM-EC 2014
International Workshop on Multi facets of Eos and Clustering
Catania, Italy, on May 6th-9th

Outline

- ❑Scientific Motivation
- ❑The Monte Carlo Hauser-Feshbach Code (HFℓ)
- ❑The experimental set-up @ LNL-INFN
- ❑The 12C+12C experiment
- ❑The 14N+10B experiment
- ❑Conclusions

Scientific Motivation

- 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 very 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

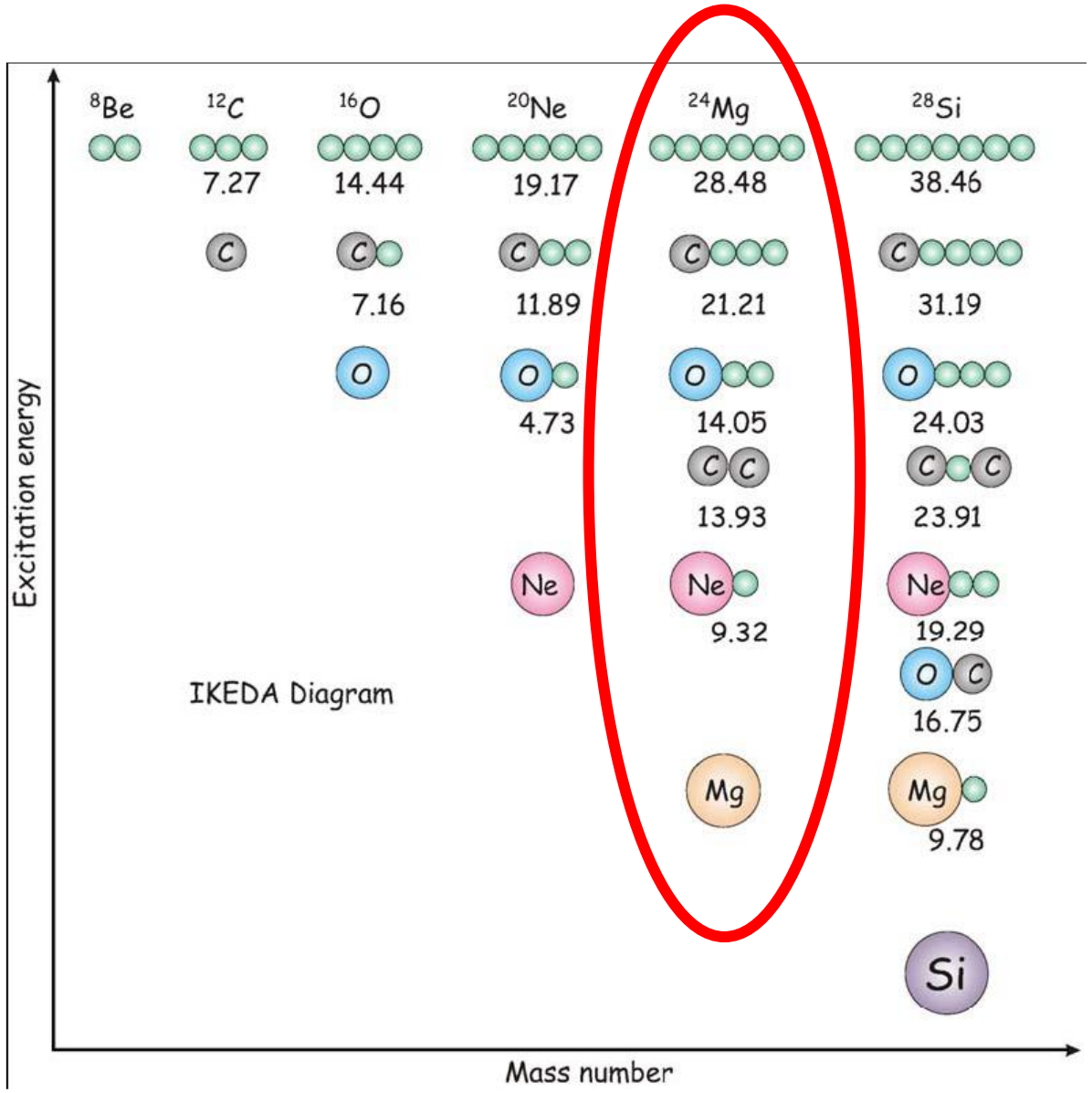
TH: decay codes constrained to available data

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

Monte Carlo Hauser-Feshbach

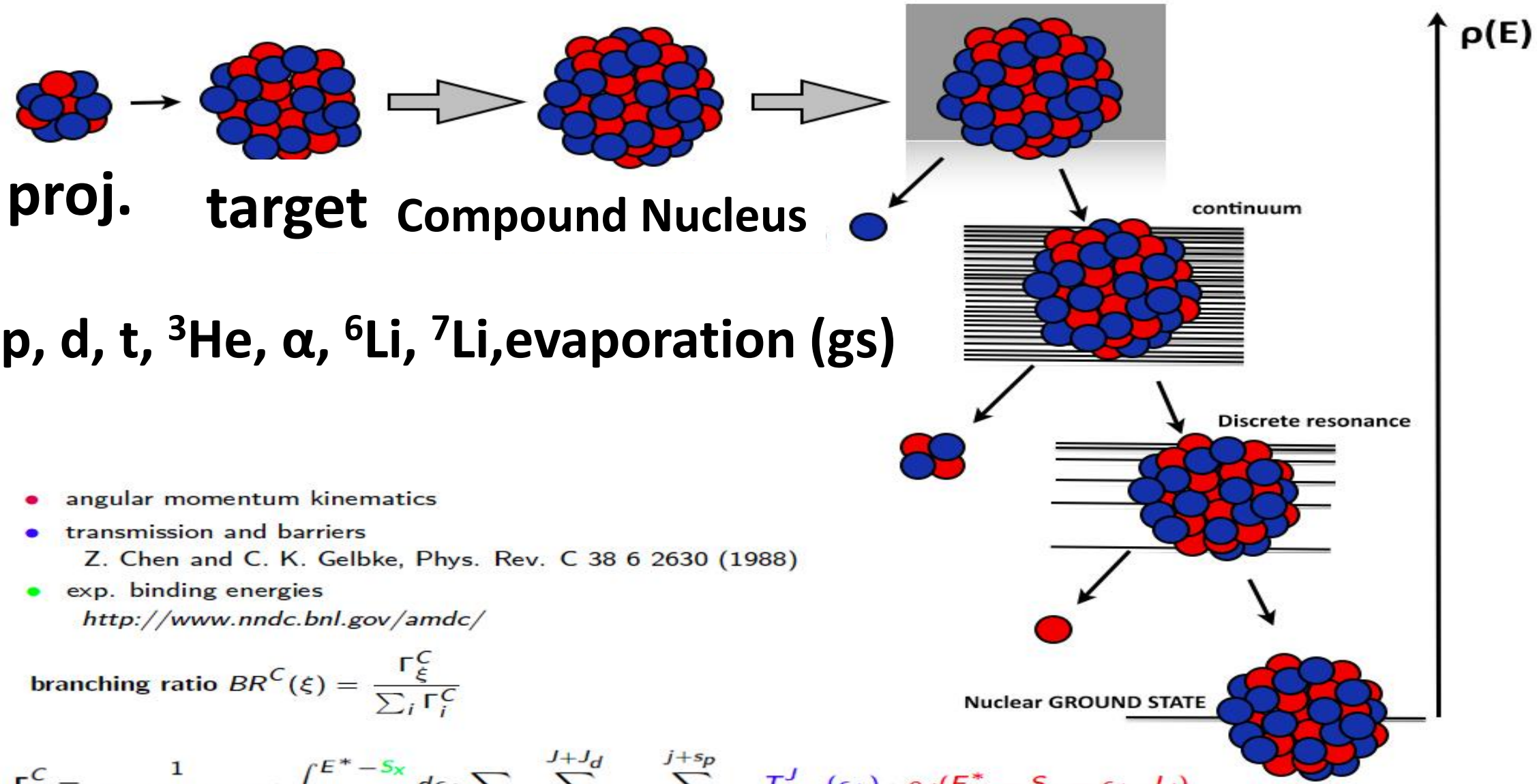
Scientific Motivation

- 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.



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

Monte Carlo Hauser-Feshbach HFℓ



n, p, d, t, ^{3}He, α, ^{6}Li, ^{7}Li,evaporation (gs)

- angular momentum kinematics
- transmission and barriers
  Z. Chen and C. K. Gelbke, Phys. Rev. C 38 6 2630 (1988)
- exp. binding energies
  http://www.nndc.bnl.gov/amdc/

branching ratio $BR^C(\xi) = \dfrac{\Gamma^C_\xi}{\sum_i \Gamma^C_i}$

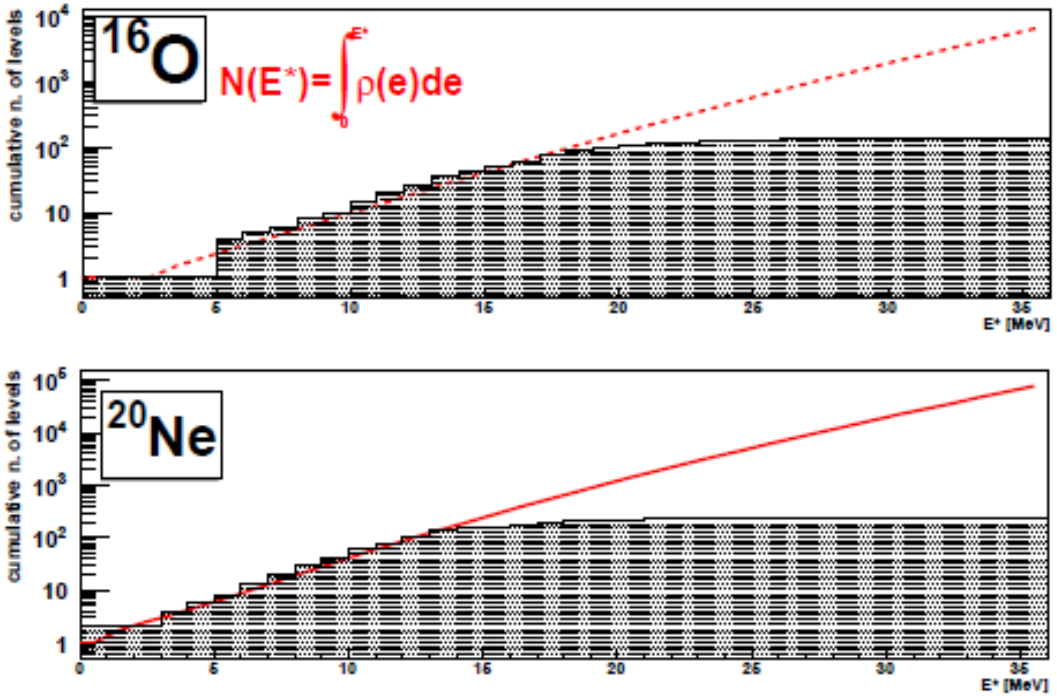
$$\Gamma^C_\xi = \frac{1}{2\pi\rho_C(E^*,J)} \cdot \int_0^{E^*-S_x} d\epsilon_\xi \sum_{J_d} \sum_{j=|J-J_d|}^{J+J_d} \sum_{\ell=|j-s_p|}^{j+s_p} T^J_{j,s_p}(\epsilon_\xi) \cdot \rho_d(E^* - S_x - \epsilon_\xi, J_d)$$

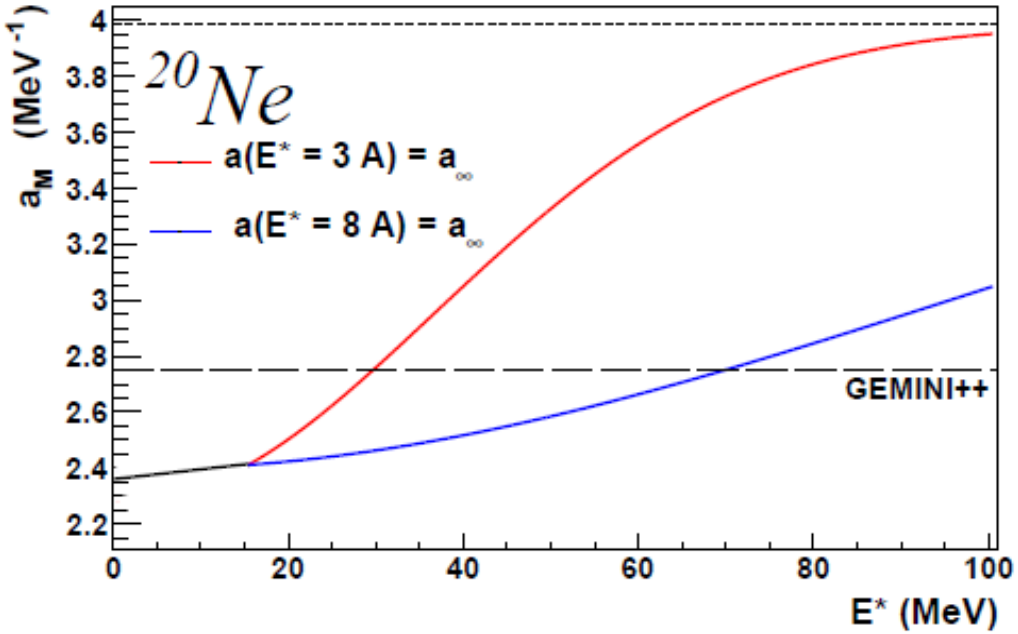
Monte Carlo Hauser-Feshbach HFℓ

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

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

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





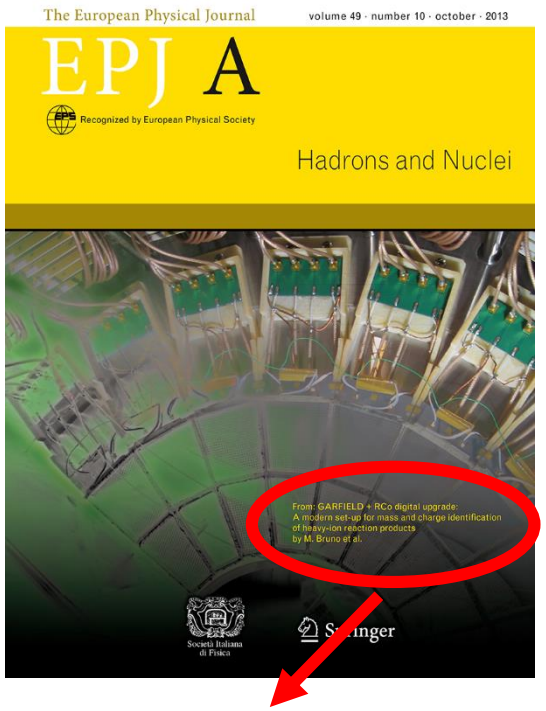
a∞

- 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)

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

Experimental set-up @ LNL-INFN

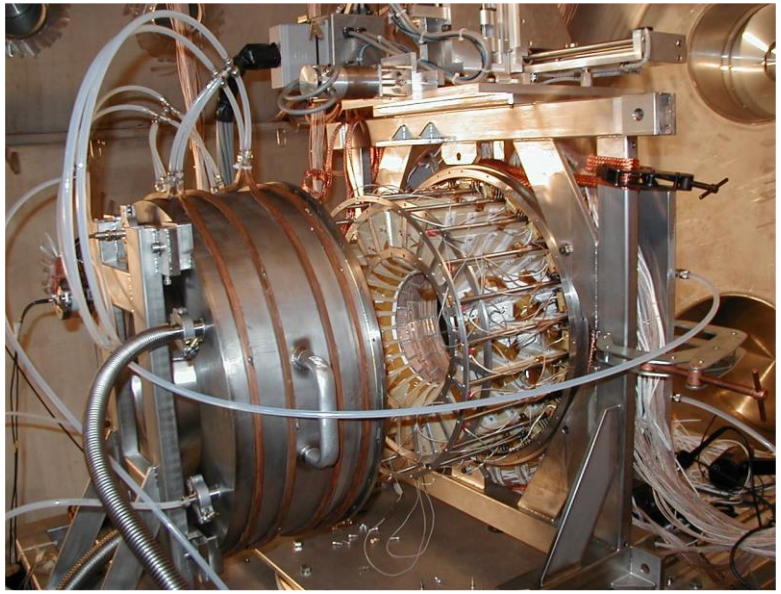
European Physical Journal A



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

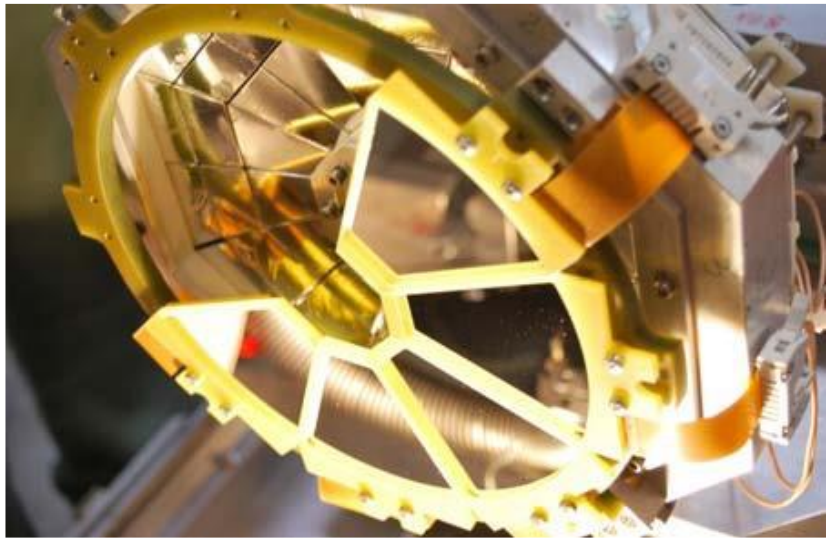
μSGC + CsI(Tl), 180 CsI
detection of LCP and fragments:

- ✓ low identification thresholds (0.8–1MeV/*u*)
- ✓ angular coverage $30^o<\theta_{lab}<150^o$ 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: 0.8^o for $5^o<\theta_{lab}<17^o$
- ✓ energy resolution of Si strips and CsI(Tl) given by 0.3% and 2-3%



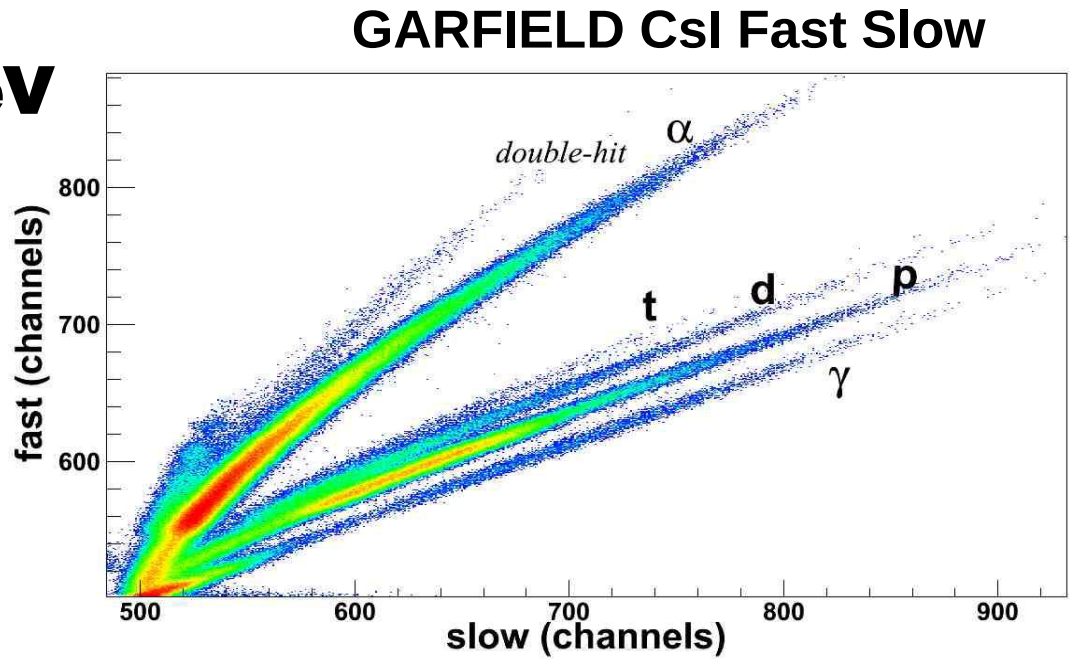
Experimental set-up at LNL-INFN

^{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)

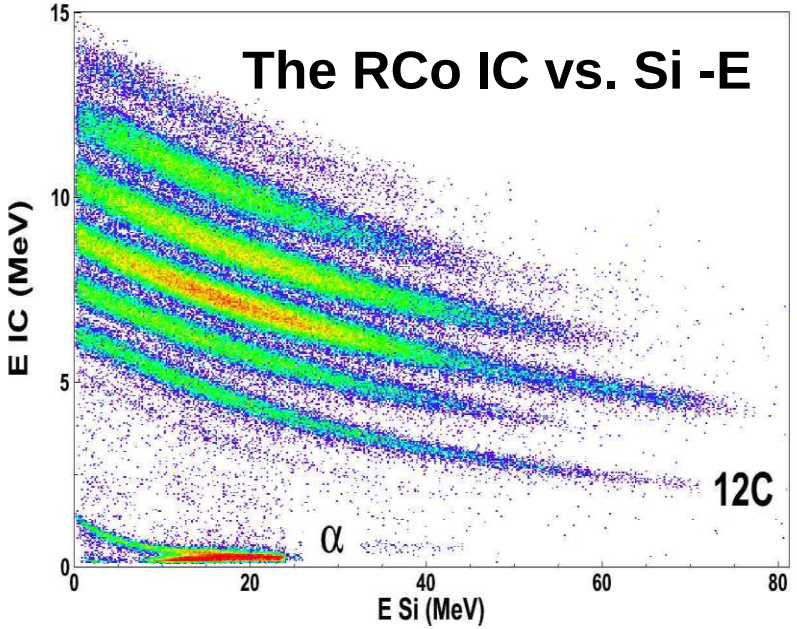
energy spectra of evaporated particles

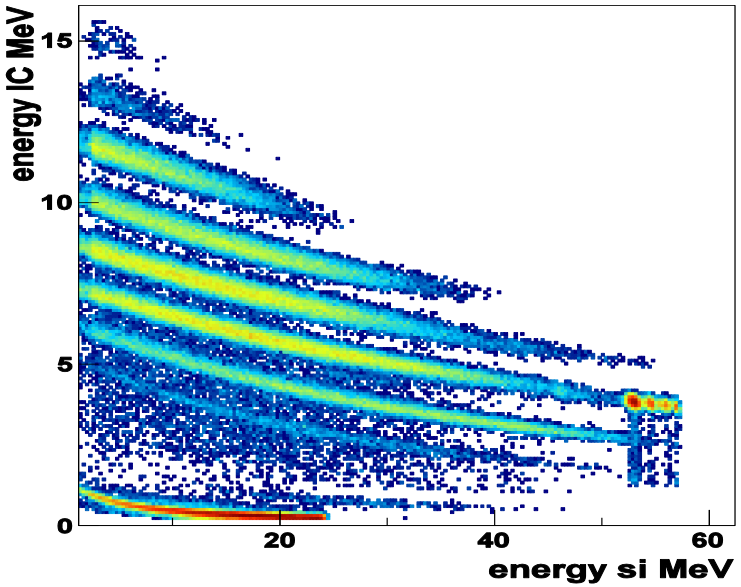


ΔE-E Z identification

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

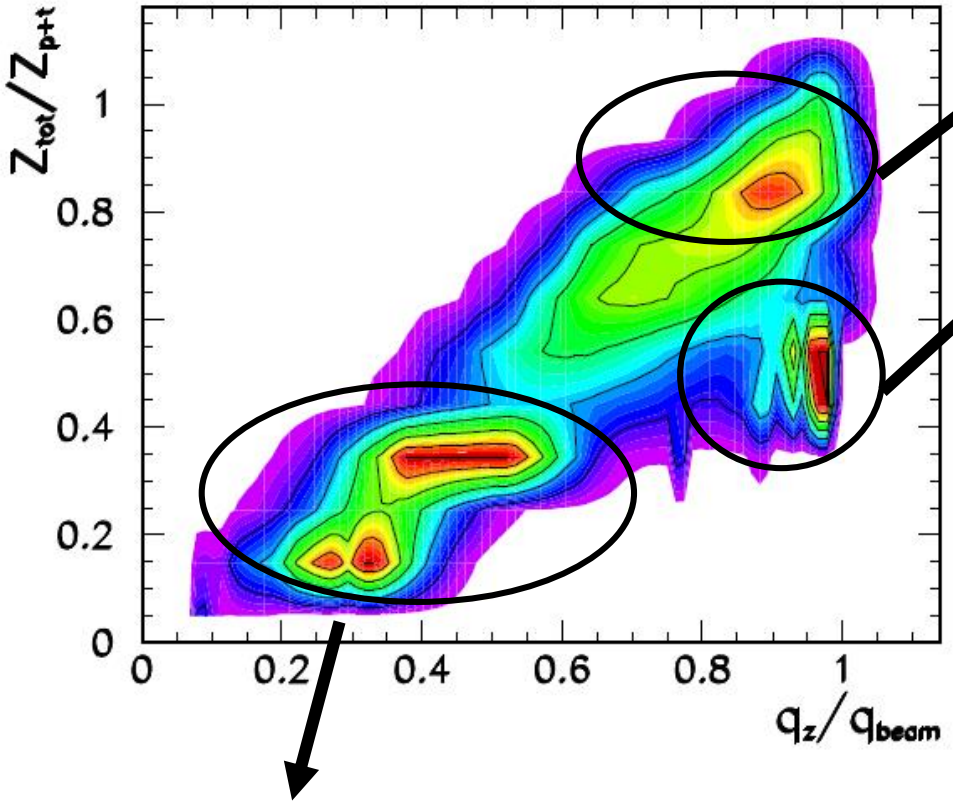
gate on evaporation residue





Event selection

Total events



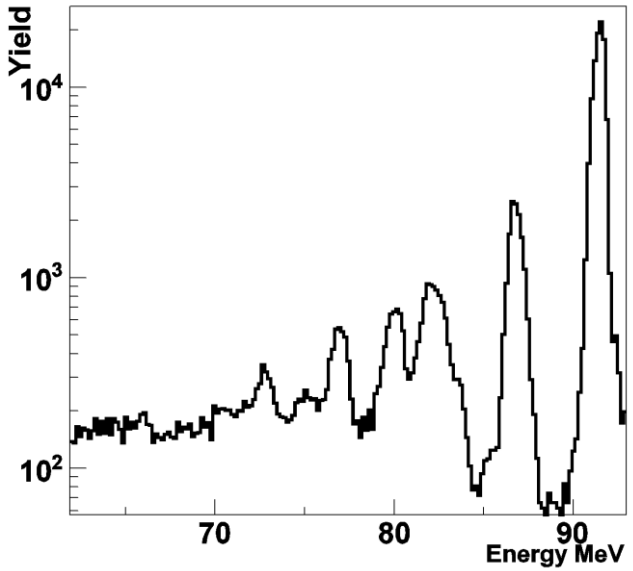
- Incomplete events
- No ER detection
- Only LCP in GARFIELD

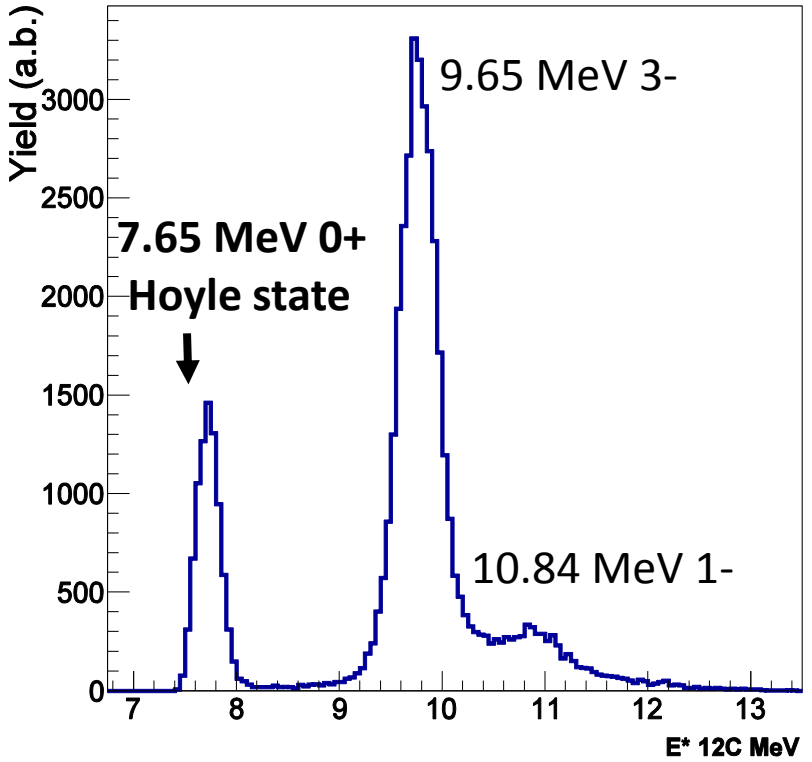
quasi-complete events

- ❑ Total charge detected $10 \leq Z_{tot} \leq 12$
- ❑ Longitudinal momentum $q_z/q_{beam} > 0.6$

PROJECTILE

- **12C* decay in 3-α particles**
- **12C excited state**





Invariant mass method

Event selection

Fusion Evaporation channel selection:

- completeness of the detection Zdet 100% (Zproj+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.
L. Morelli J. of Phys. G IN PRESS

Monte Carlo Hauser-Feshbach HFℓ

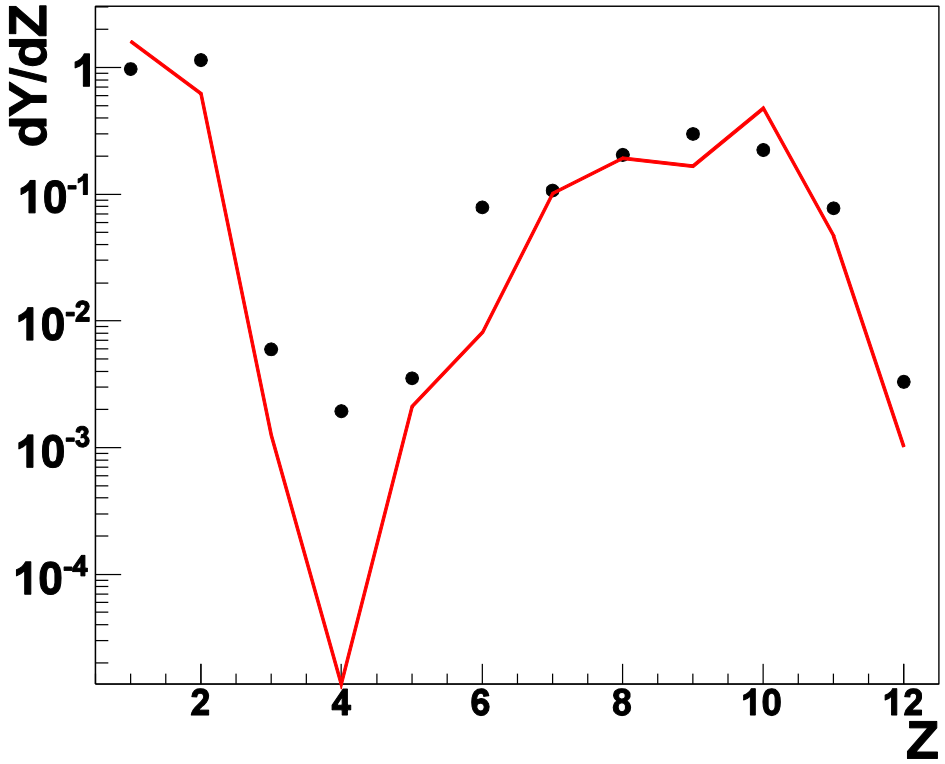
- Complete Fusion
  ^{24}Mg (E*= 62 MeV) decay
- Angular momentum from systematics:
  - ^{12}C + ^{12}C maximum value J_0 max = 18 ħ
  - ^{14}N + ^{10}B maximum value J_0 max = 15 ħ

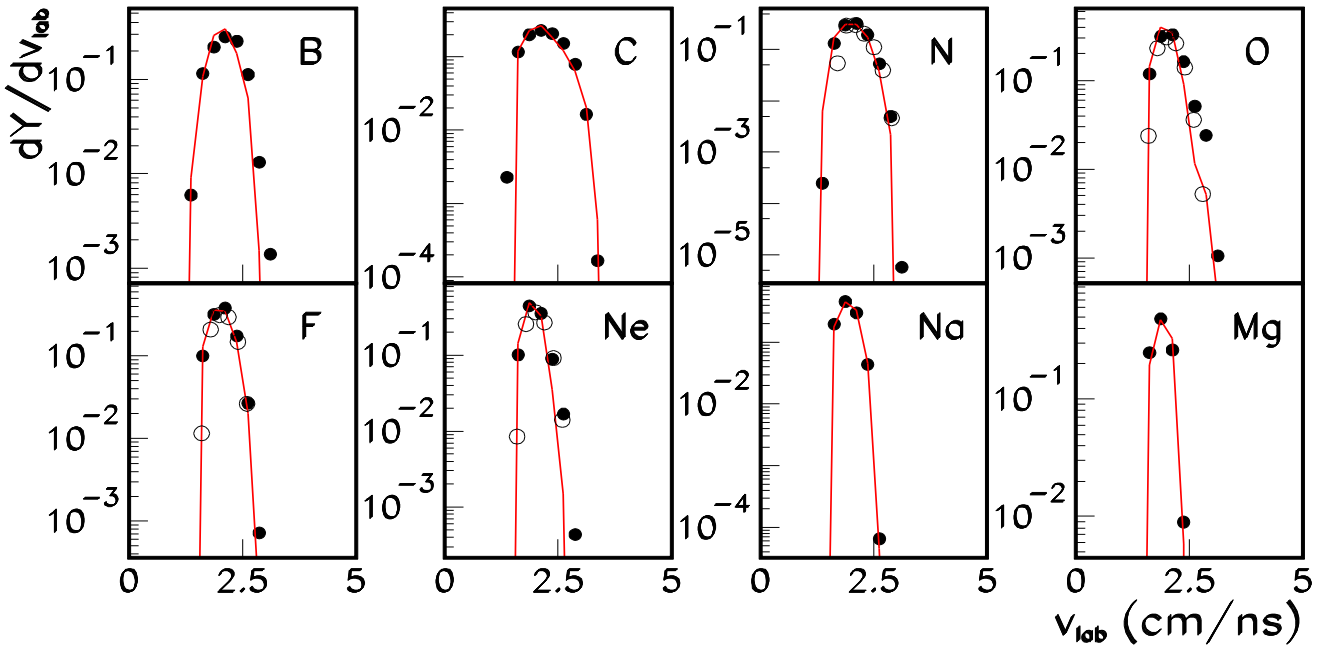
  Ortiz M E *et al* 1982 *Phys. Rev.* C 25 1436
  - diffuseness parameter ΔJ = 2

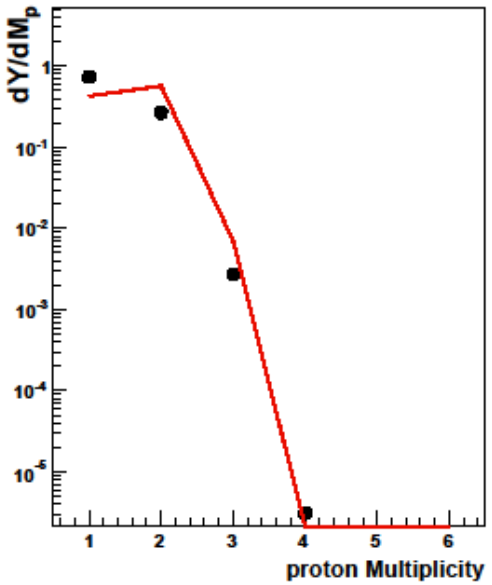
  Tarasov O. B 2003 NIM B 204 174
- HFℓ predictions filtered through a software replica of the experimental set-up

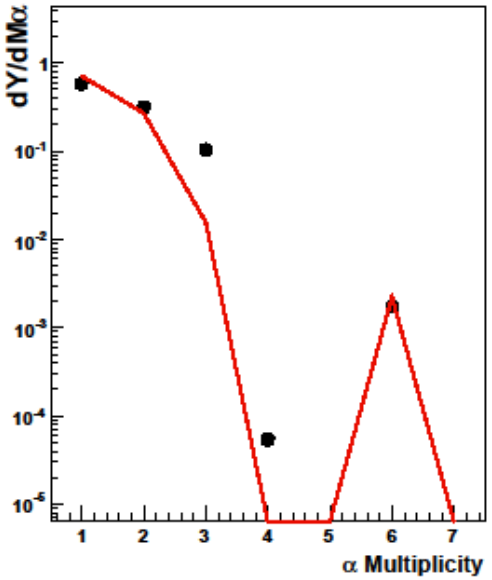
$^{12}C + ^{12}C$ experiment (95 MeV beam energy)

- **data — HF calculation**





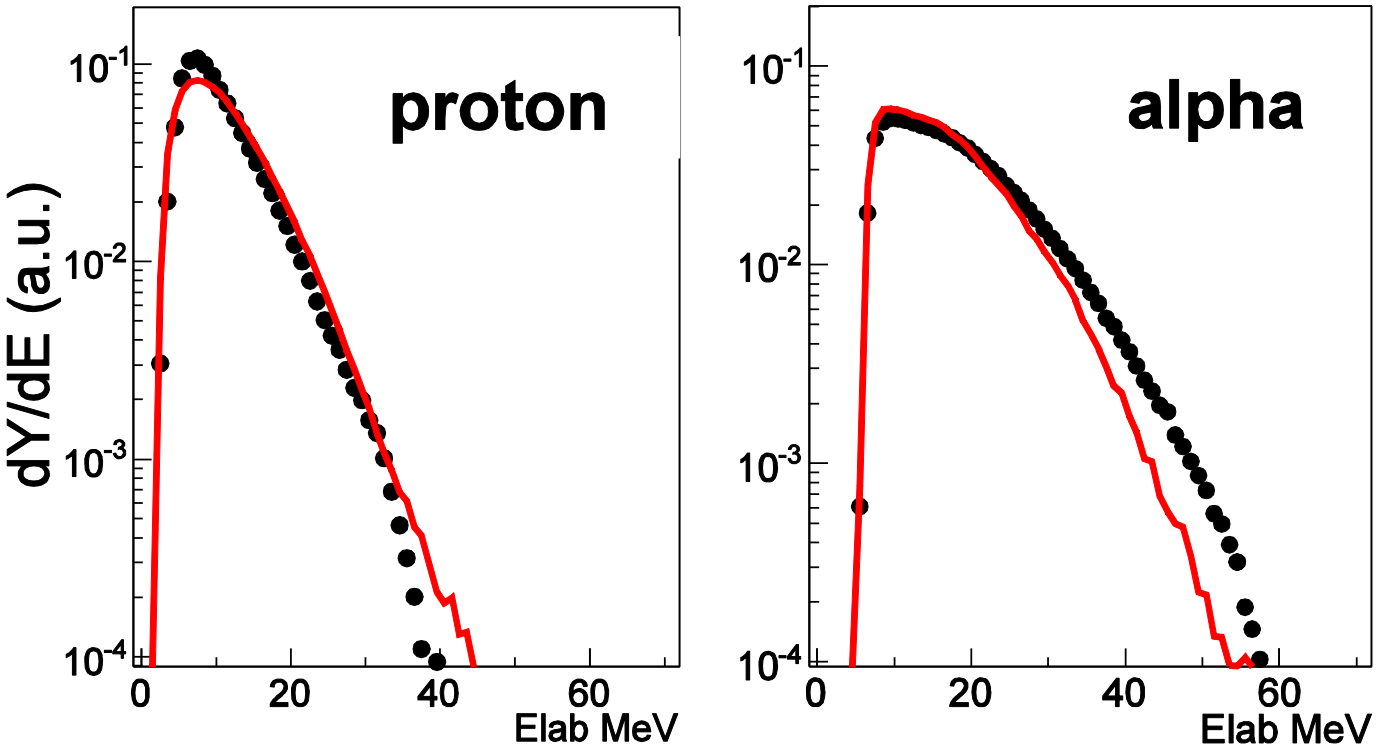




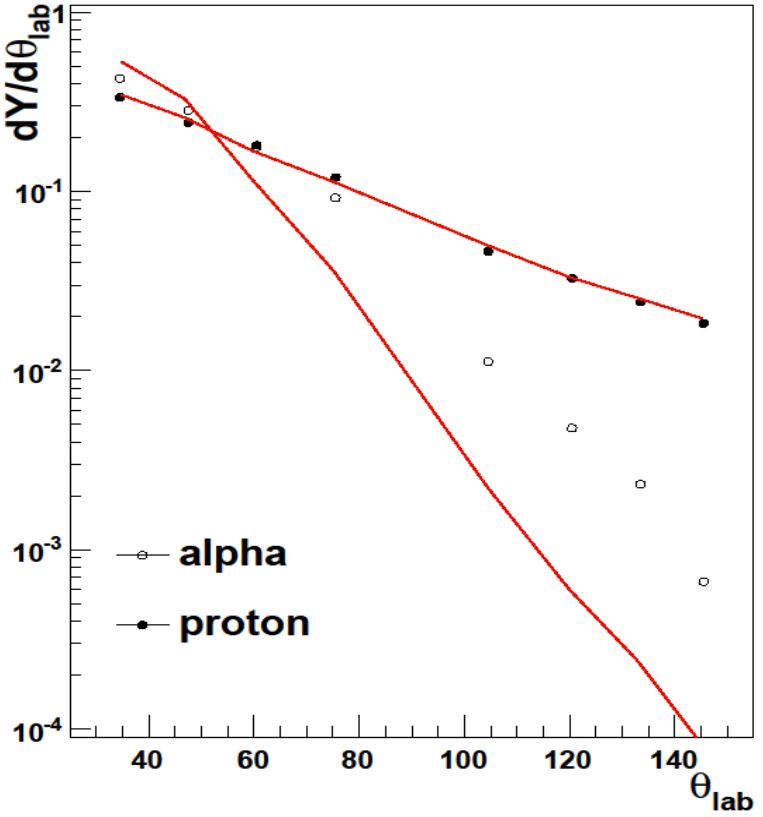
HFℓ calculation for ^{24}Mg (E = 62 MeV) decay

- good reproduction of global variables (Y(Z), multiplicities...)

$^{12}C + {}^{12}C$ experiment (95 MeV beam energy)



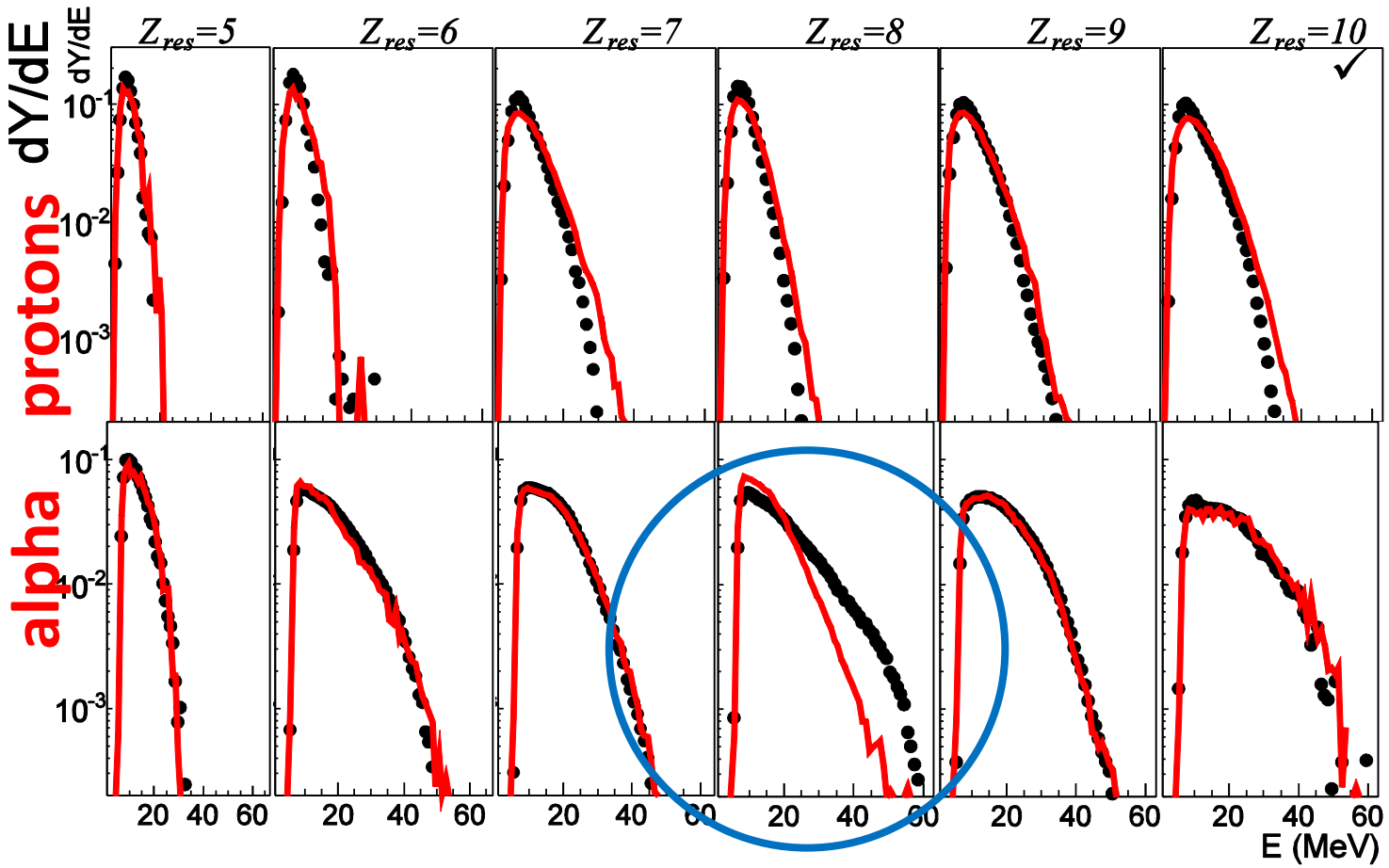
✓ **energy spectra** and **angular distributions of protons and alpha particles**



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

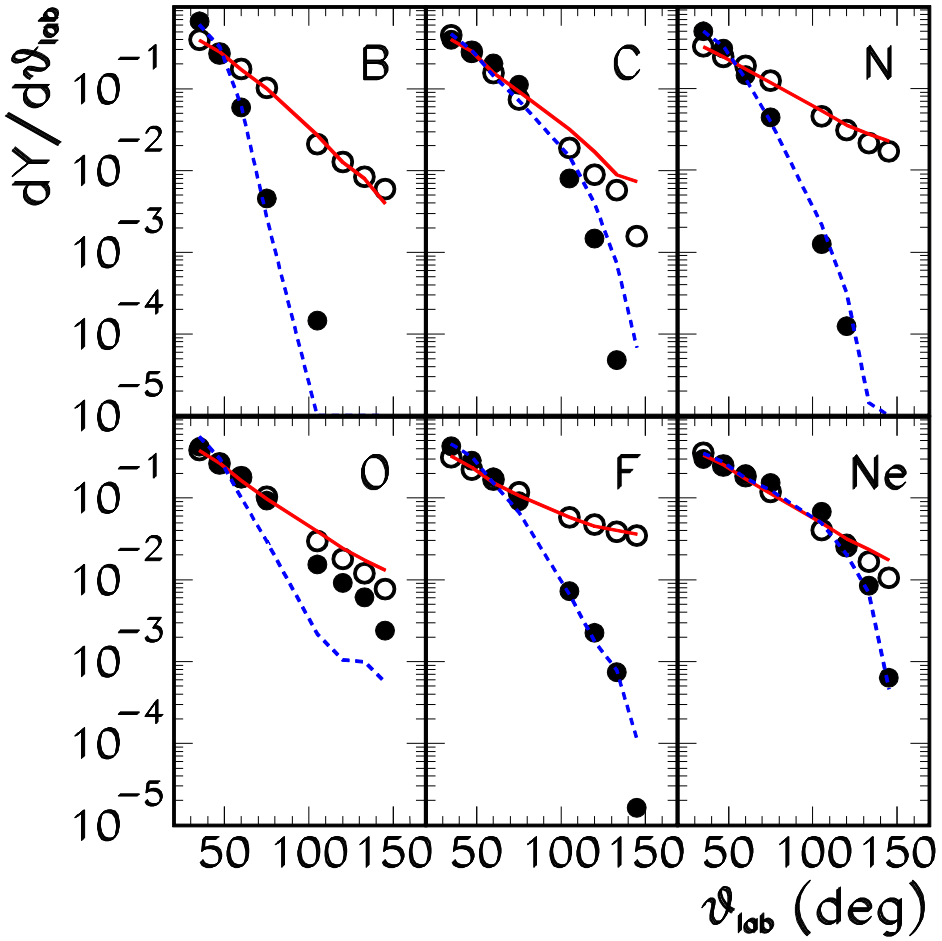
constraints to the LD a(E*=3 A MeV)=a∞
through the good reproduction of p energy and angular distribution...

$^{12}C + {}^{12}C$ experiment (95 MeV beam energy)



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

energy spectra and **angular distributions of protons and alpha particles in coincidence with a residue**



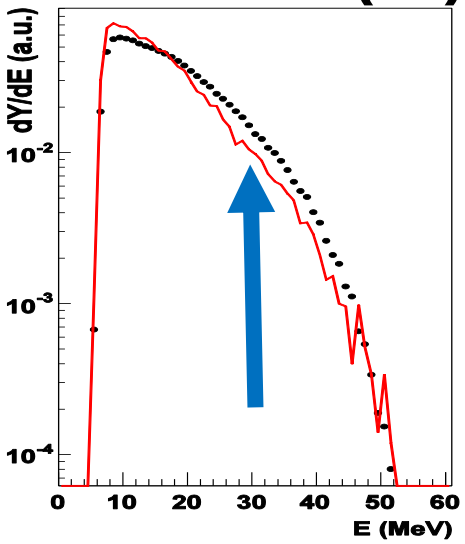
$^{12}C + ^{12}C$ experiment (95 MeV beam energy)

Multiple alpha channels

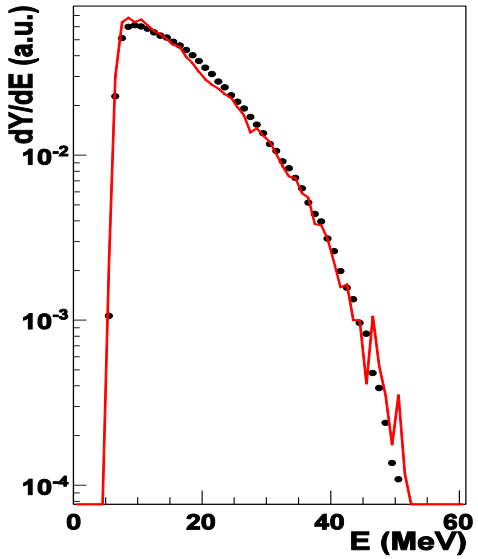
most populated charge channel in the experimental sample

Z_{res}	channel	$BR_{HF\ell}$	BR_{EXP}
5	$^{11-xn}B+xn+p+3\alpha$	100%	99%
6	$^{12-xn}C+xn+3\alpha$	78%	98%
7	$^{15-xn}N+xn+p+2\alpha$	95%	91%
8	$^{16-xn}O+xn+2\alpha$	15%	63%
9	$^{19-xn}F+xn+p+\alpha$	88%	92%
10	$^{22-xn}Ne+xn+2p$	82%	55%

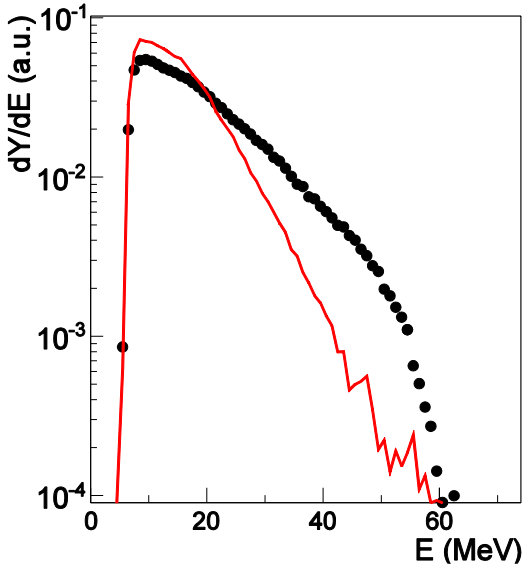
α Zres=6 (all)



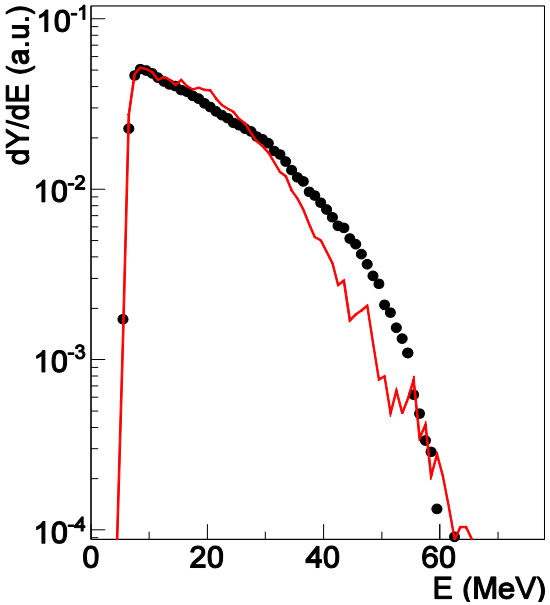
α Zres=6 (C+3α+xn)



α Zres=8 (all)



α Zres=8 (O+2α+xn)



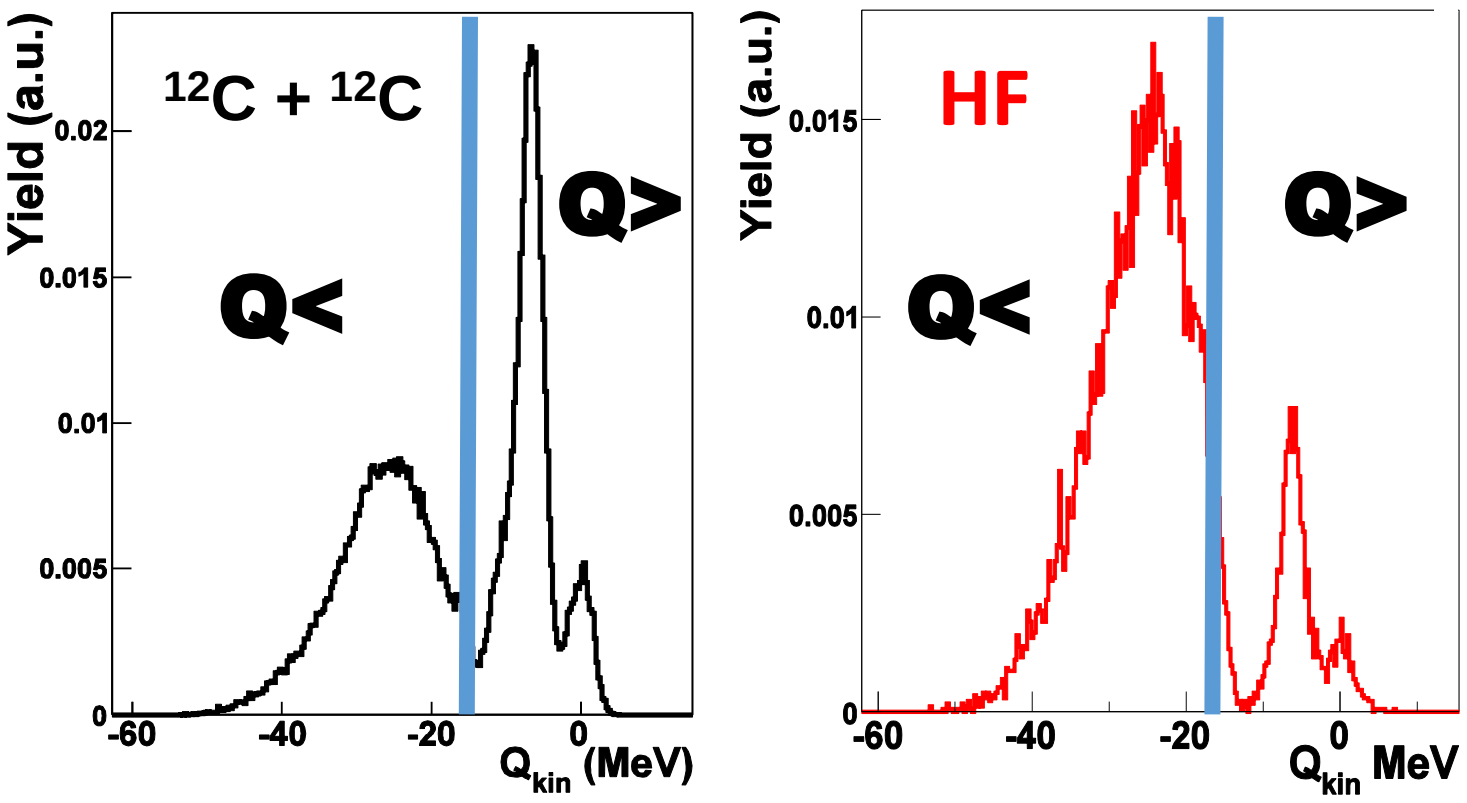
- Oxygen and Carbon channels are not reproduced by HF
- Discrepancy in the BR affects the shape of the alpha spectrur

- ✓ In the Carbon case alpha spectra of the different channels are very well reproduced by HF calculations
- ✓ Deviation only in Oxygen + 2 alpha + x neutron channel.

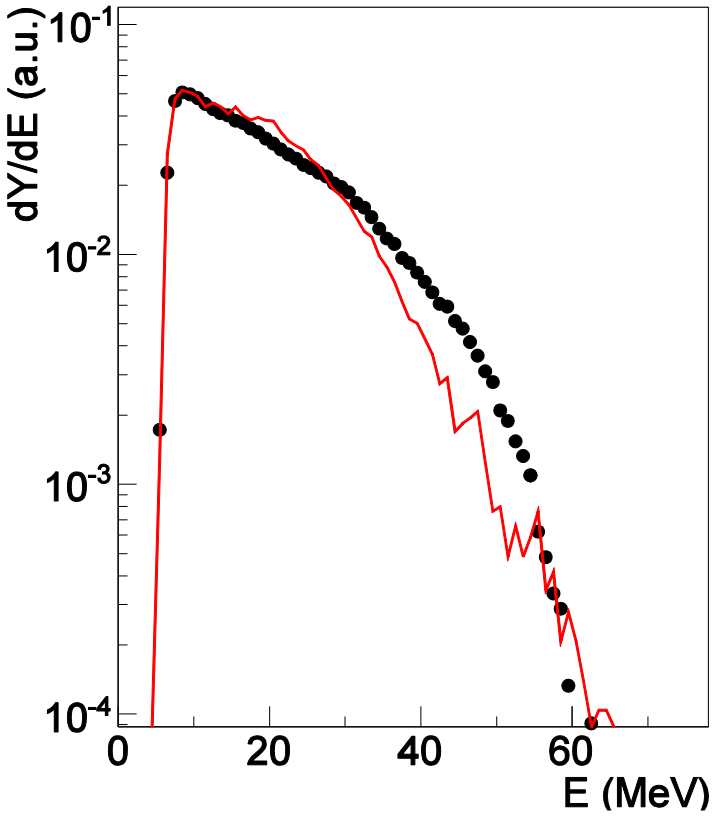
$^{12}C + ^{12}C$ experiment (95 MeV beam energy)

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

Oxygen + 2 α+ neutron(s) channel



α Zres=8 (O+2α+xn)

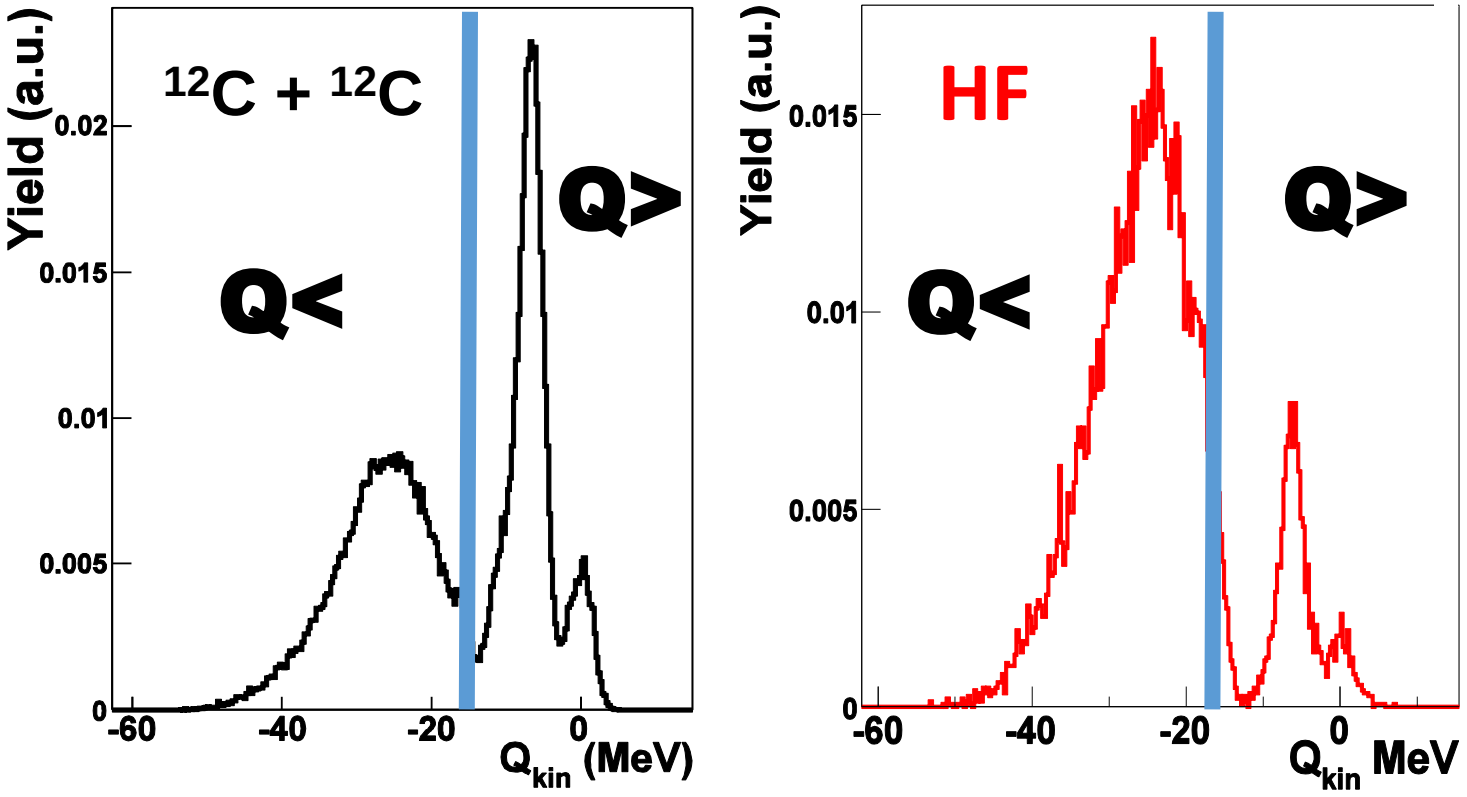


- common pattern for theoretical and experimental Q_{kin}
- Differences in the relative population of the different regions.

$^{12}C + ^{12}C$ experiment (95 MeV beam energy)

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

Oxygen + 2 α+ neutron(s) channel



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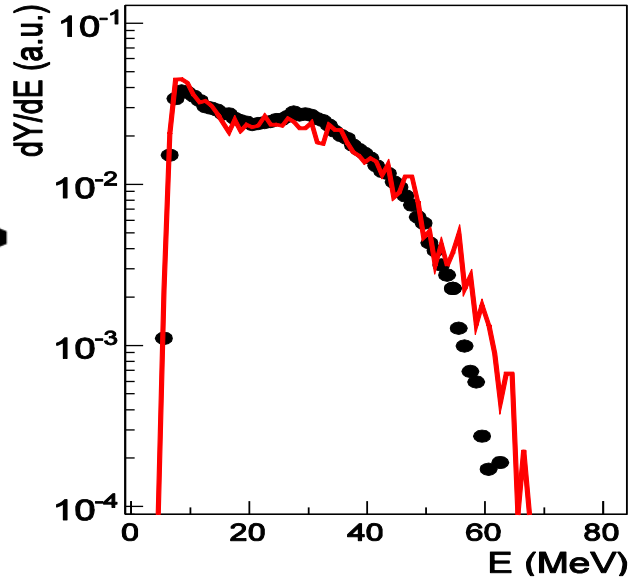

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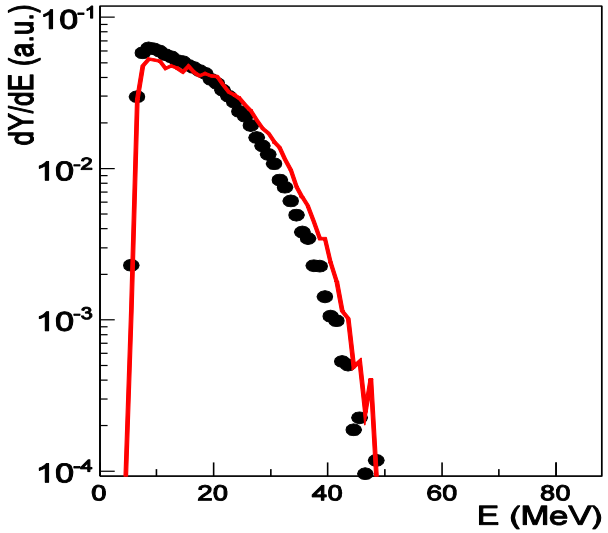
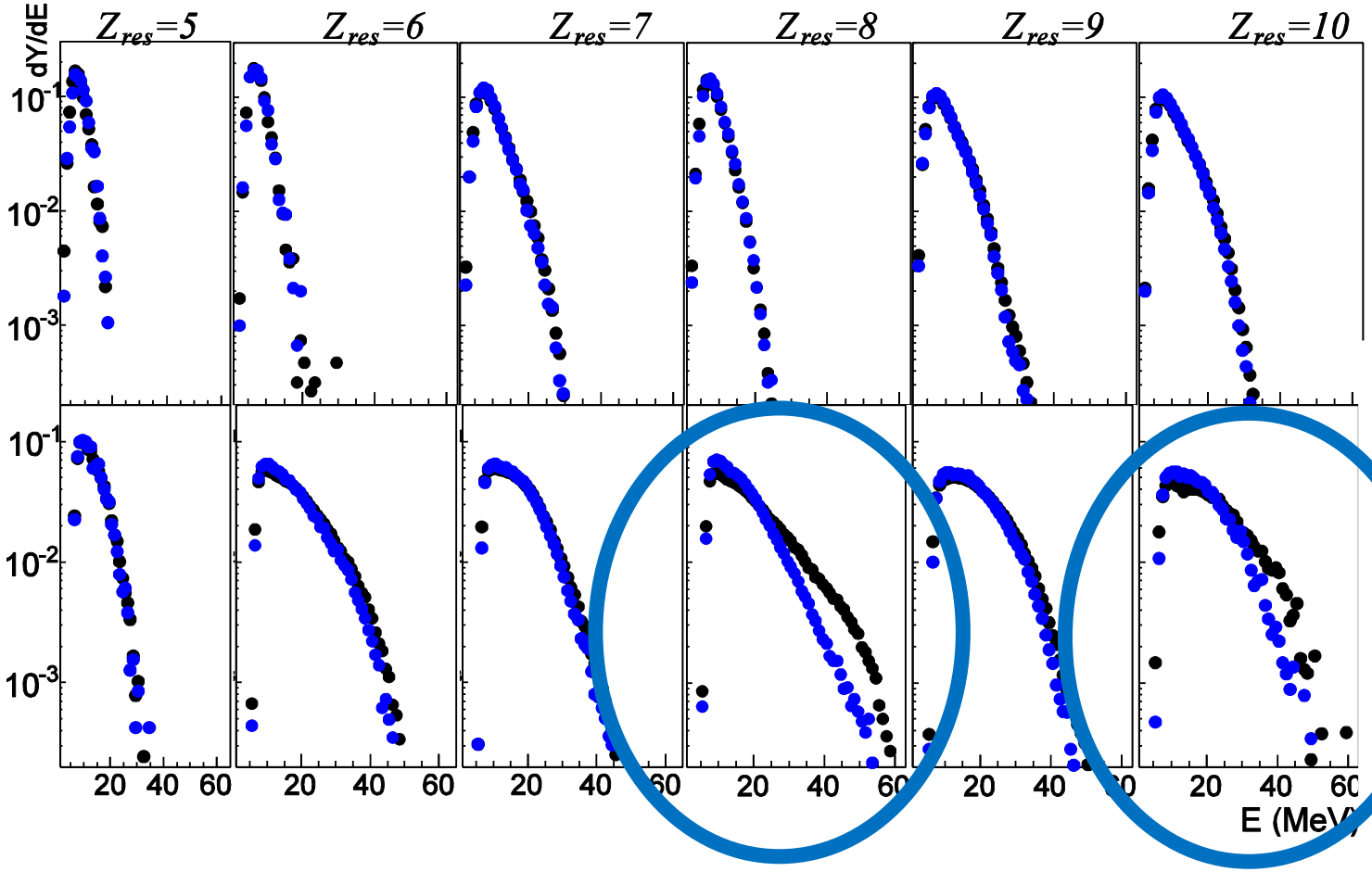


- common pattern for theoretical and experimental Q_{kin}
- Differences in the relative population of the different regions.

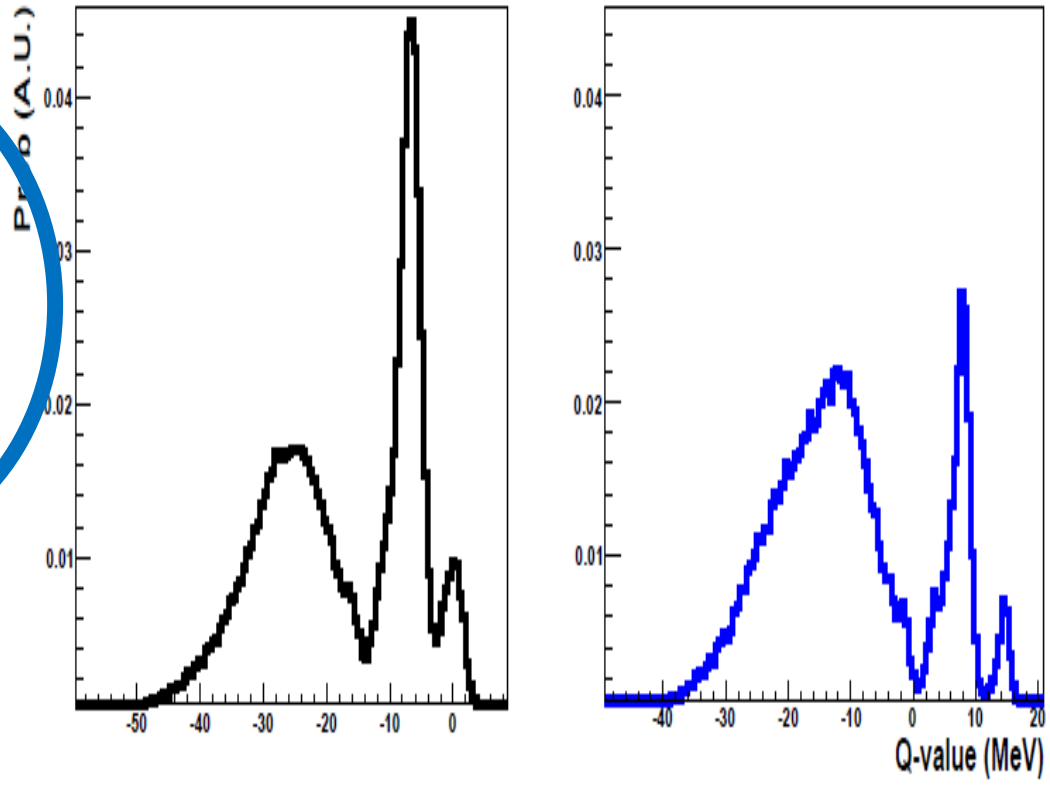
$^{14}N + {}^{10}B$ experiment (80 MeV beam energy)



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

12C + 12C

14N + 10B

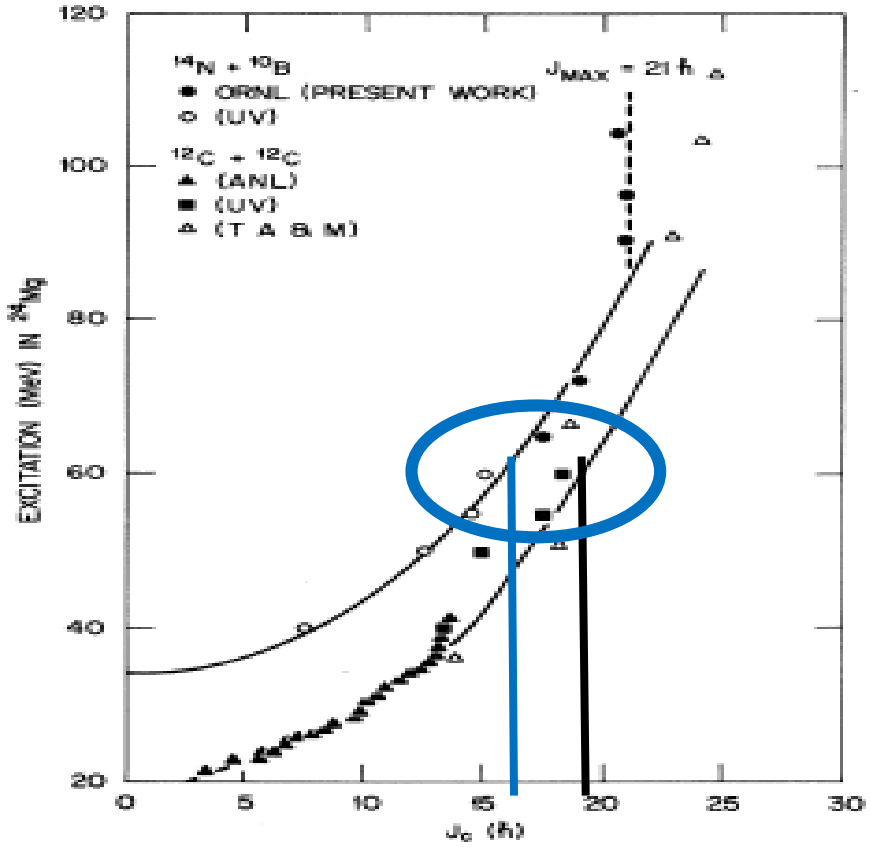


- **deviation appears largely reduced with respect to 12C+12C**

L.Morelli et al, arXiv:nucl-ex/1309.0323

$^{14}N + ^{10}B$ experiment (80 MeV beam energy)

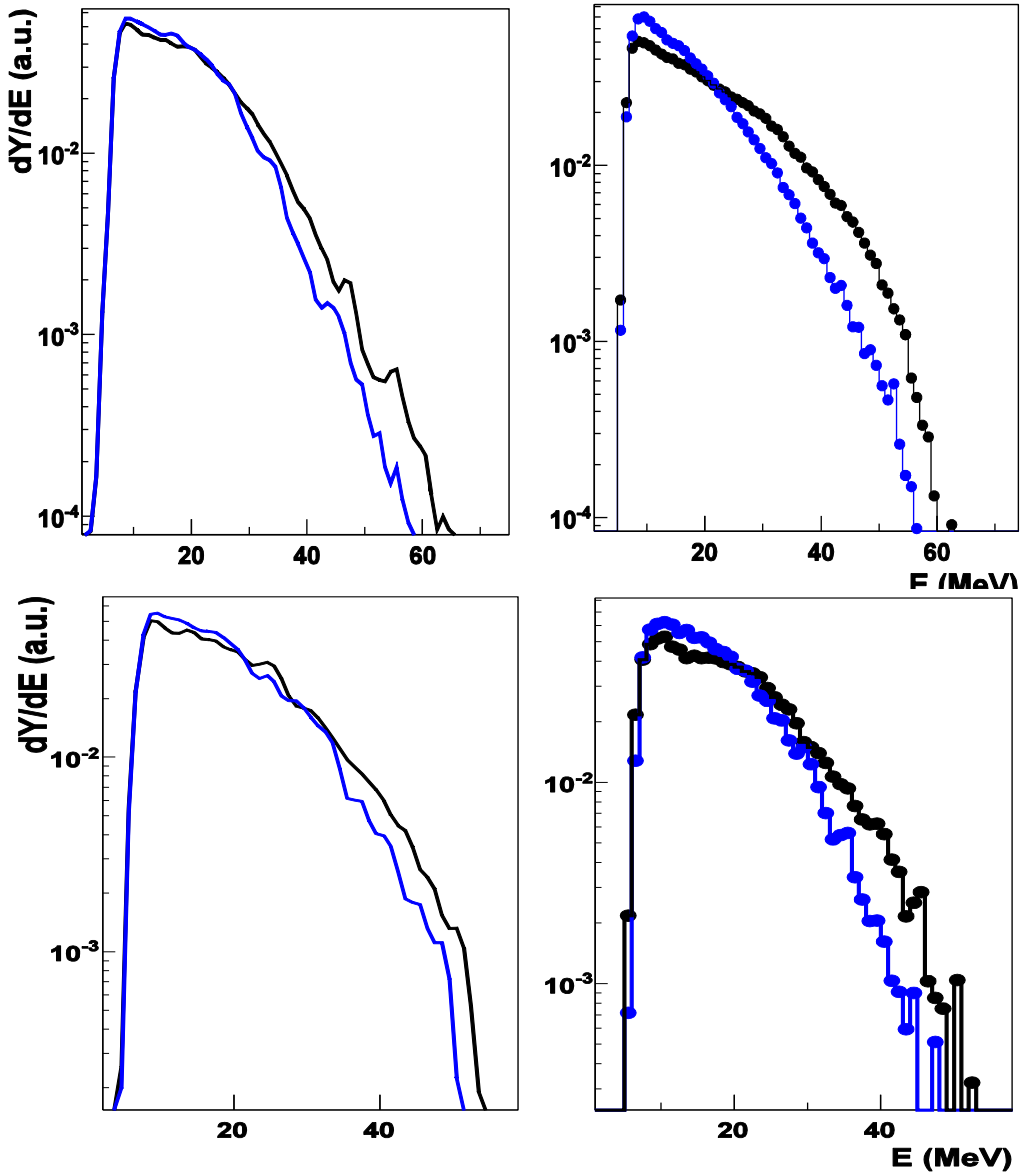
Critical angular momentum VS Excitation 24Mg



$^{14}N + ^{10}B$ J_0 max = 15

Ortiz et al. Phys.Rev.C25,1436
R.L.Parks et al. Nucl. Phys. A 348

HFℓ calculations **DATA**



12C + 12C
14N + 10B

Alpha particles in conicides with:

Oxygen E.R.

Neon E.R.

$^{14}N + {}^{10}B$ experiment (80 MeV beam energy)

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

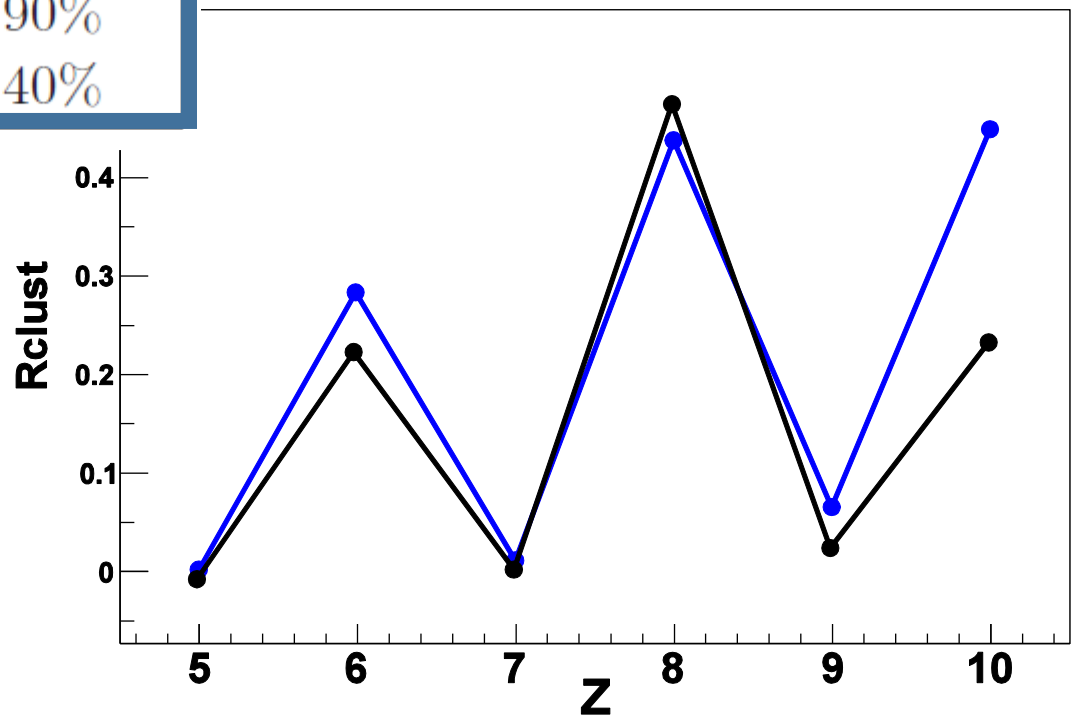
Z_{res}	channel	$BR_{HF\ell}$	BR_{EXP}	$BR_{HF\ell}$	BR_{EXP}
5	$B+xn+p+3\alpha$	100%	99%	100%	99%
6	$C+xn+3\alpha$	78%	98%	65%	90%
7	$N+xn+p+2\alpha$	95%	91%	94%	90%
8	$O+xn+2\alpha$	15%	63%	12%	55%
9	$F+xn+p+\alpha$	88%	92%	86%	90%
10	$Ne+xn+2p$	82%	55%	83%	40%

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; $n_Z\alpha$) coincident 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.**

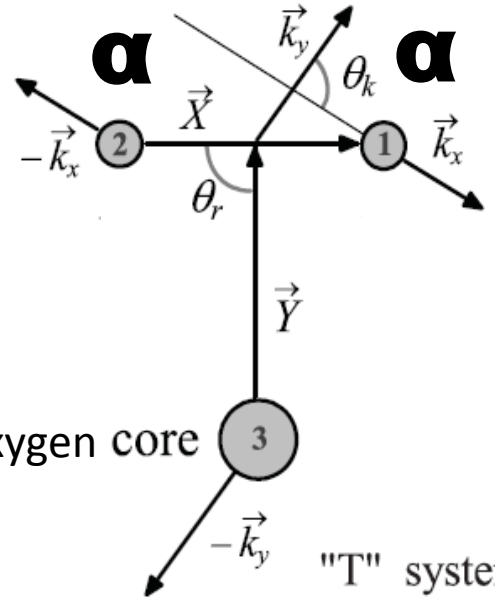
✓ **residual *α* structure correlations in the excited ^{24}Mg or in its daughter nucleus.**

Oxygen – α – α correlations

Jacobi coordinates (T system)

$$E_x = \frac{(m_1 + m_2)k_x^2}{2m_1m_2} \rightarrow E_{\alpha-\alpha}$$

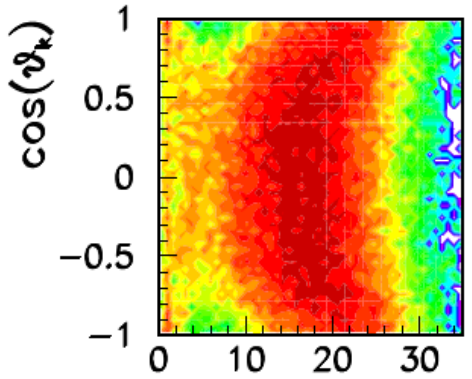
$$\cos\theta_k = \frac{\mathbf{k}_x \cdot \mathbf{k}_y}{k_x k_y} \rightarrow \frac{(Ko \cdot K_{\alpha-\alpha})}{(Ko\, K_{\alpha-\alpha})}$$



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

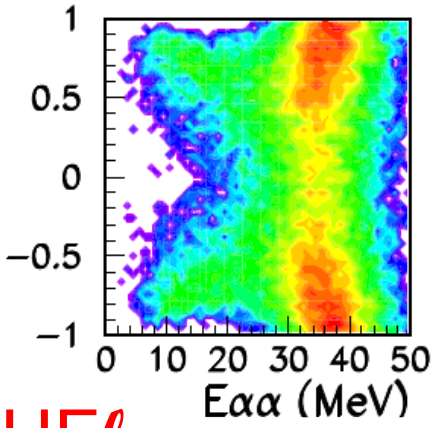
Q<

O+2alpha+xn

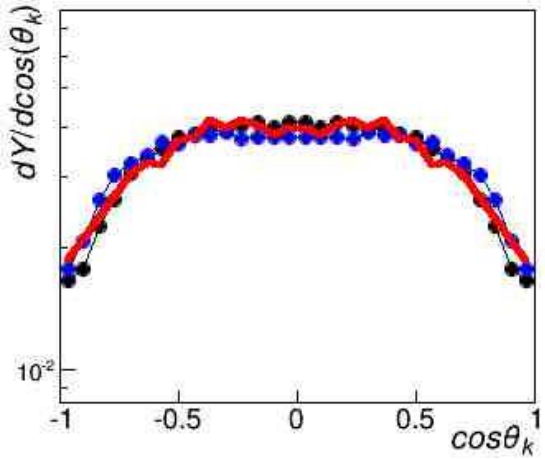


Q>

^{16}O+2alpha

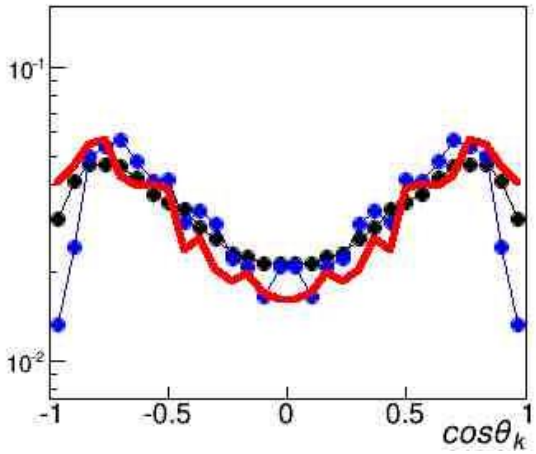


^{12}C + ^{12}C



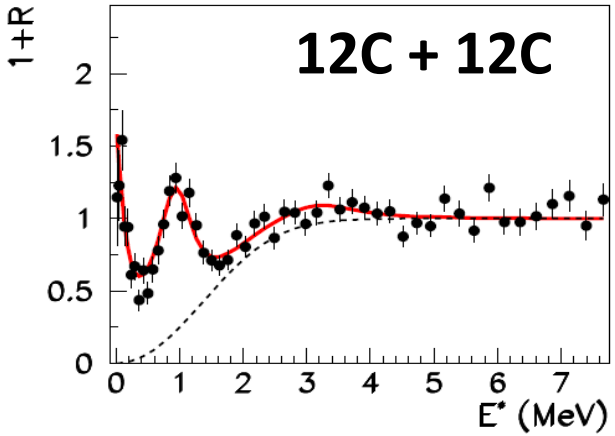
^{14}N + ^{10}B

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

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.
- entrance channel effects attributed to angular momentum limitations for the compound nucleus in the nitrogen plus boron experiment.
- 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.

...thank you for your attention!

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