UNIVERSITÀ DEGLI STUDI FIRENZE

INFN Istituto Nazionale di Fisica Nucleare

Experiemental study of precisely selected evaporation chains in the decay of ^{25}Mg.

Results and perspective with light radioactive beams

Alberto Camaiani and Giovanni Casini

for the NUCLEX Collaboration

Motivations and Scientific Goals

- **Investigation of (non)-statistical decay of excited light nuclei**
- **Search for some α-clustering role at high CN excitation energies**
- **(Study a-cluster configurations in less central collisions for QP and/or QT decay)**

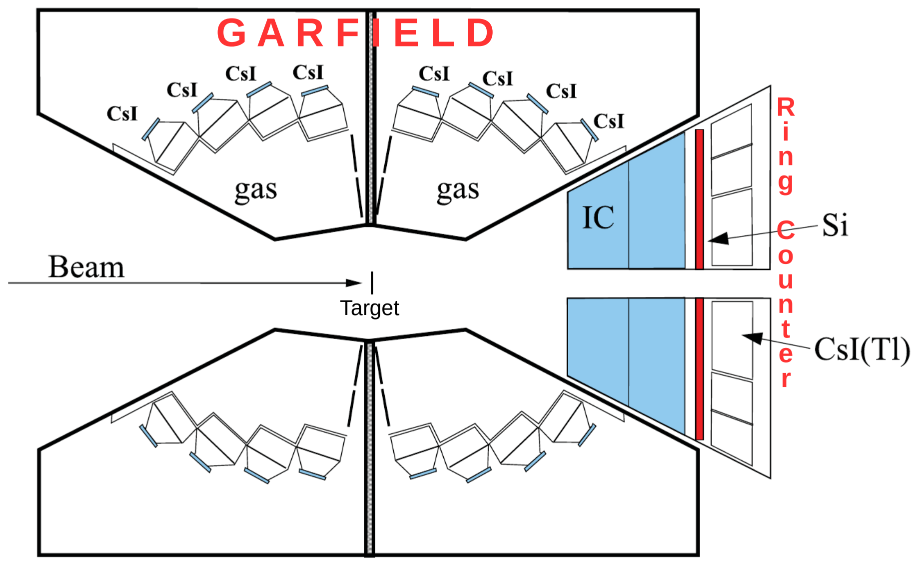
What we are doing with **STABLE BEAMS**:

- $^{12}C + ^{12}C$ @ 95 MeV → ^{24}Mg, E*=61 MeV — L. Morelli et al, J.P.G: Nucl. Part. Phys. 41 (2014) 075108; L. Morelli et al, J.P.G: Nucl. Part. Phys. 41 (2014) 075107; L. Morelli et al, J.P.G: Nucl. Part. Phys. 43 (2016) 045110
- **$^{12}C + ^{13}C$ @ 95 MeV → ^{25}Mg, E*=65 MeV** — **A. Camaiani et al, PRC 97, 044607 (2018)**
- $^{16}O + ^{12}C$ @ 130 MeV → ^{28}Si, E*=72 MeV — See C. Frosin's talk
- $^{24}Mg + ^{12}C$ @ 162 MeV → ^{36}Ar, E*= 70 MeV — See S. Barlini's talk

What we plan to do with **RADIOACTIVE BEAMS**:

- $^{7}Be + ^{12}C$ @ 67.9 MeV → ^{19}Ne, E*=57 MeV
- $^{7}Be + ^{13}C$ @ 51.8 MeV → ^{20}Ne, E*=60 MeV
- $^{17}F + ^{7}Li$ @ 100 MeV → ^{24}Mg, E*=60 MeV
- $^{25}Al + ^{11}B$ @ 130 MeV → ^{36}Ar, E*= 70 MeV

Experimental approach

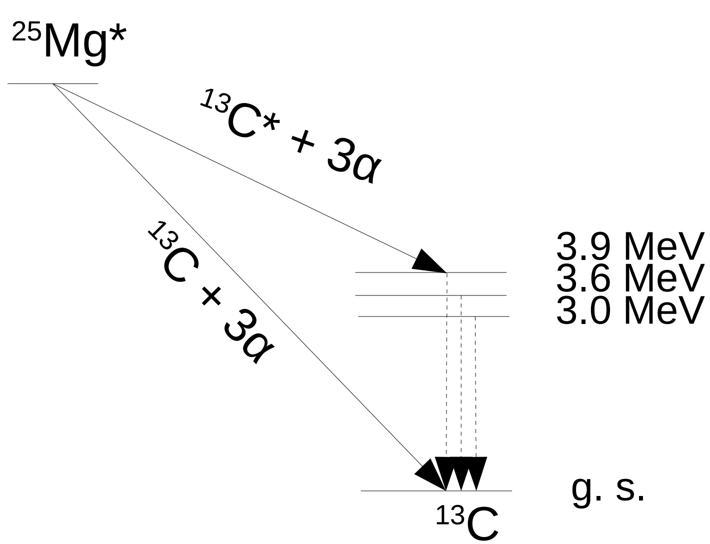


Experimental apparatus:
GARFIELD + Ring Counter

- **488 detection channels**
- **Z-identification from protons up to calcium region**
- **A-discrimination for Z=1,2 everywhere and up to Beryllium below 17º**
- **large acceptance (75% solid angle 4p)**

Allow the **detection of events complete in charge**, i.e. $\sum_i Z_i = Z_{sys}$

Fusion-Evaporation Events

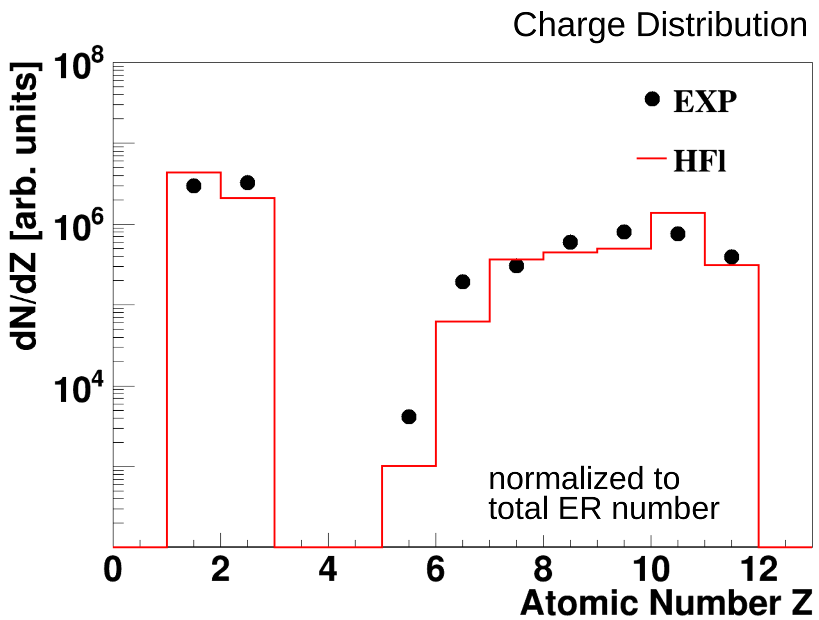


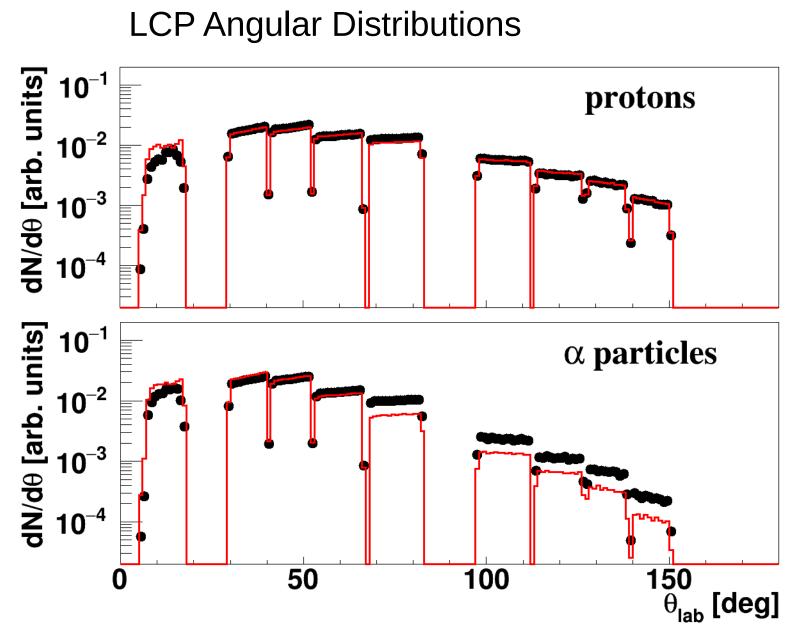
Theoretical framework:
Hauser-Feshbach light (HFl)

Statistical model keeping into account the population of excited levels during the decay chains

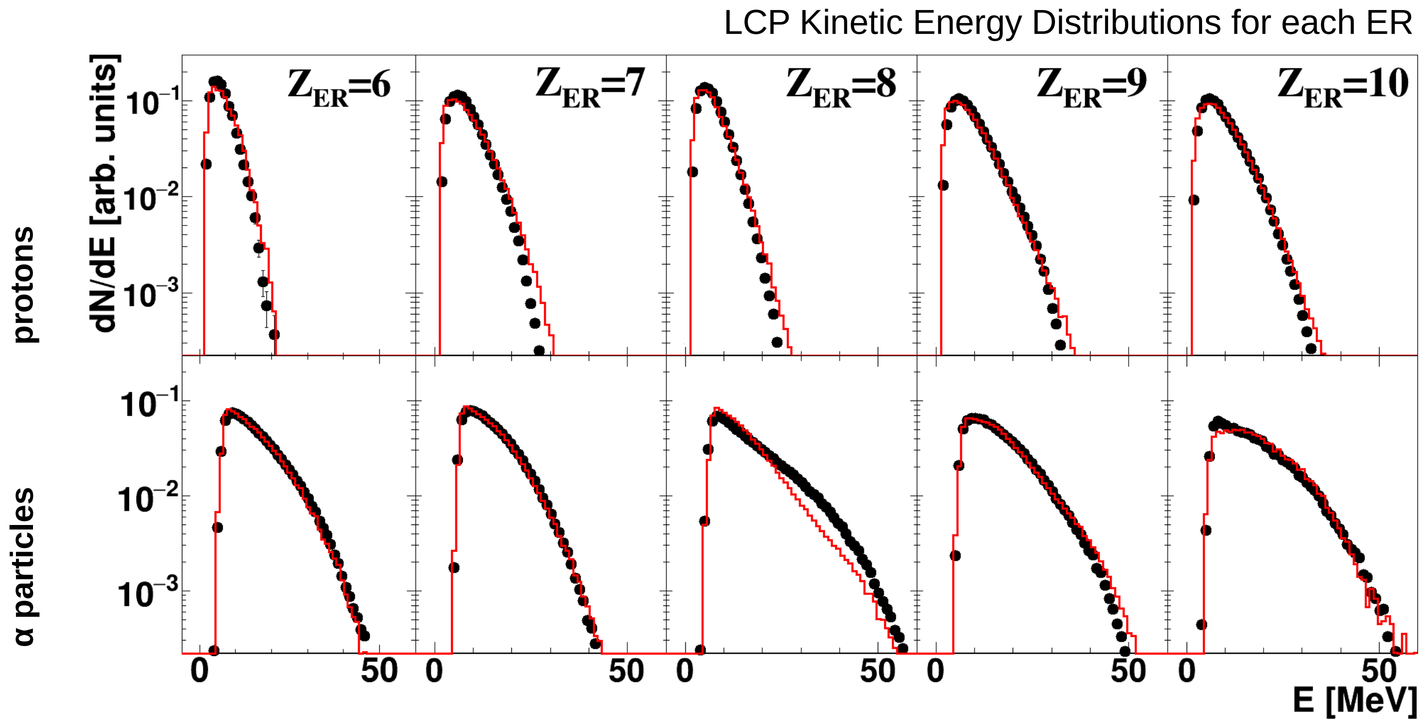
Validity of Statistical Decay

FUSION EVENTS
COMPLETE IN CHARGE
^{25}Mg, E*=65 MeV





normalized to area

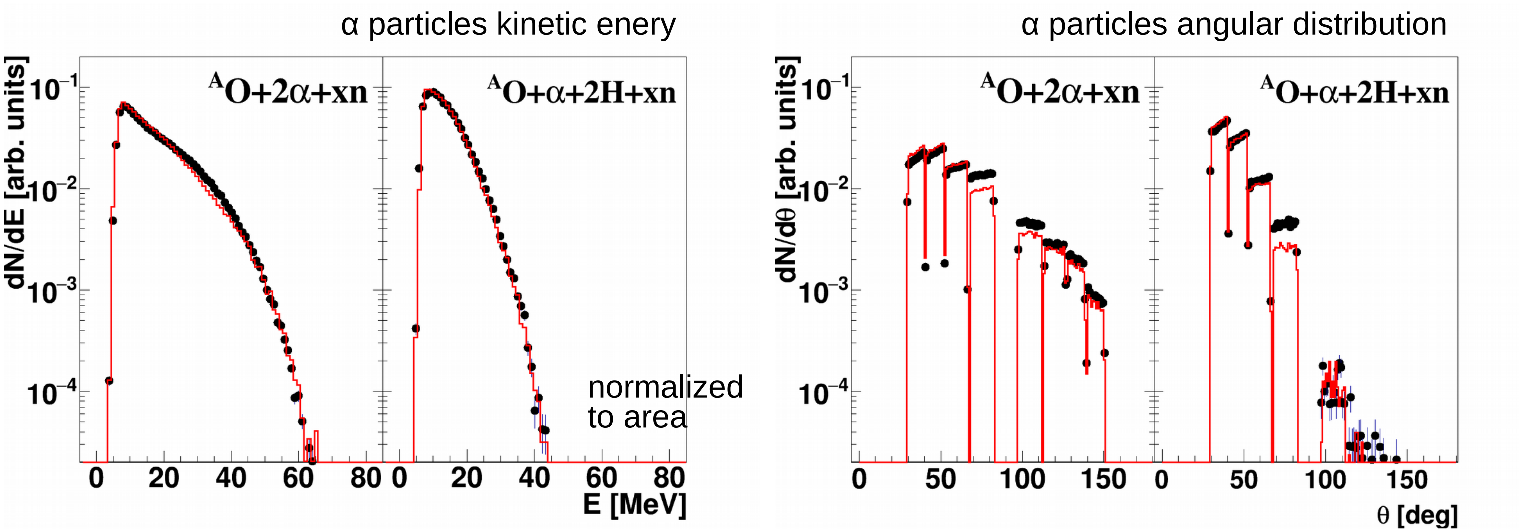


normalized to area

Non-Statistical Effects

^{25}Mg, E*=65 MeV

Disentangling decay channels..



Good reproduction of the decay kinematics

but looking to the Branching Ratios of the decay channels:

N.B.
Each channel is normalized to the amount of Z_{ER}

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

Similar results in ^{24}Mg decays:

L. Morelli et al, J.P.G: Nucl. Part. Phys. 41 (2014) 075108)

Evidence of an **BR excess**, with respect to the model, **in the channels where the evaporation of only α particles can occur,** i.e. where the ER are Ne, O or C

$^{A}O+2\alpha+xn$: neutron emission

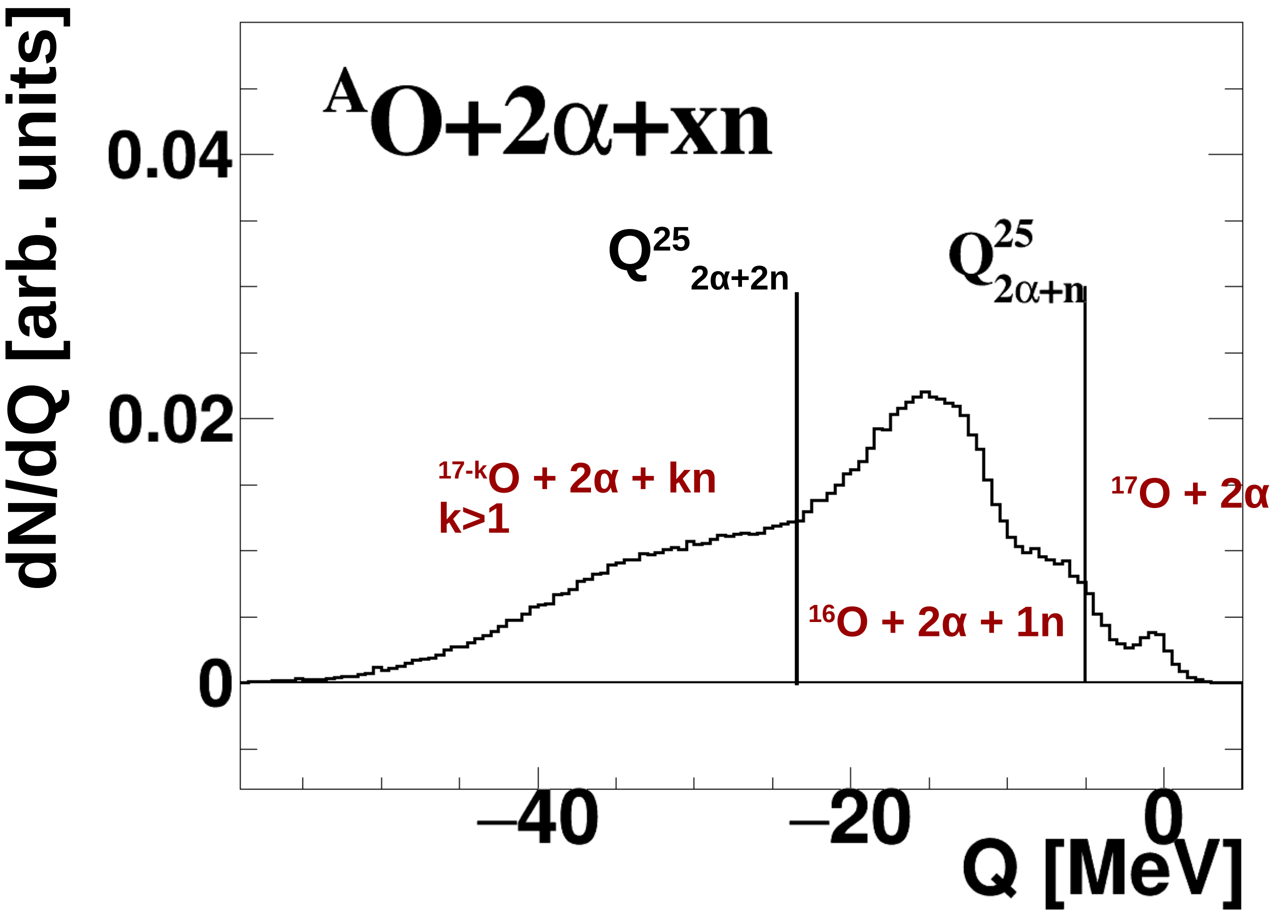
^{25}Mg, E*=65 MeV

We need to extract informations regarding the neutron emission:
we can do it starting from the Q distributions

$$Q = \sum_i E_i - E_{beam}$$

→ It's an estimator of the amount of energy carried away by the neutrons (and not detected)

^{25}Mg*



From this kind of distribution we could extract, through a fit procedure, the ER isotopic distributions in each decay channels

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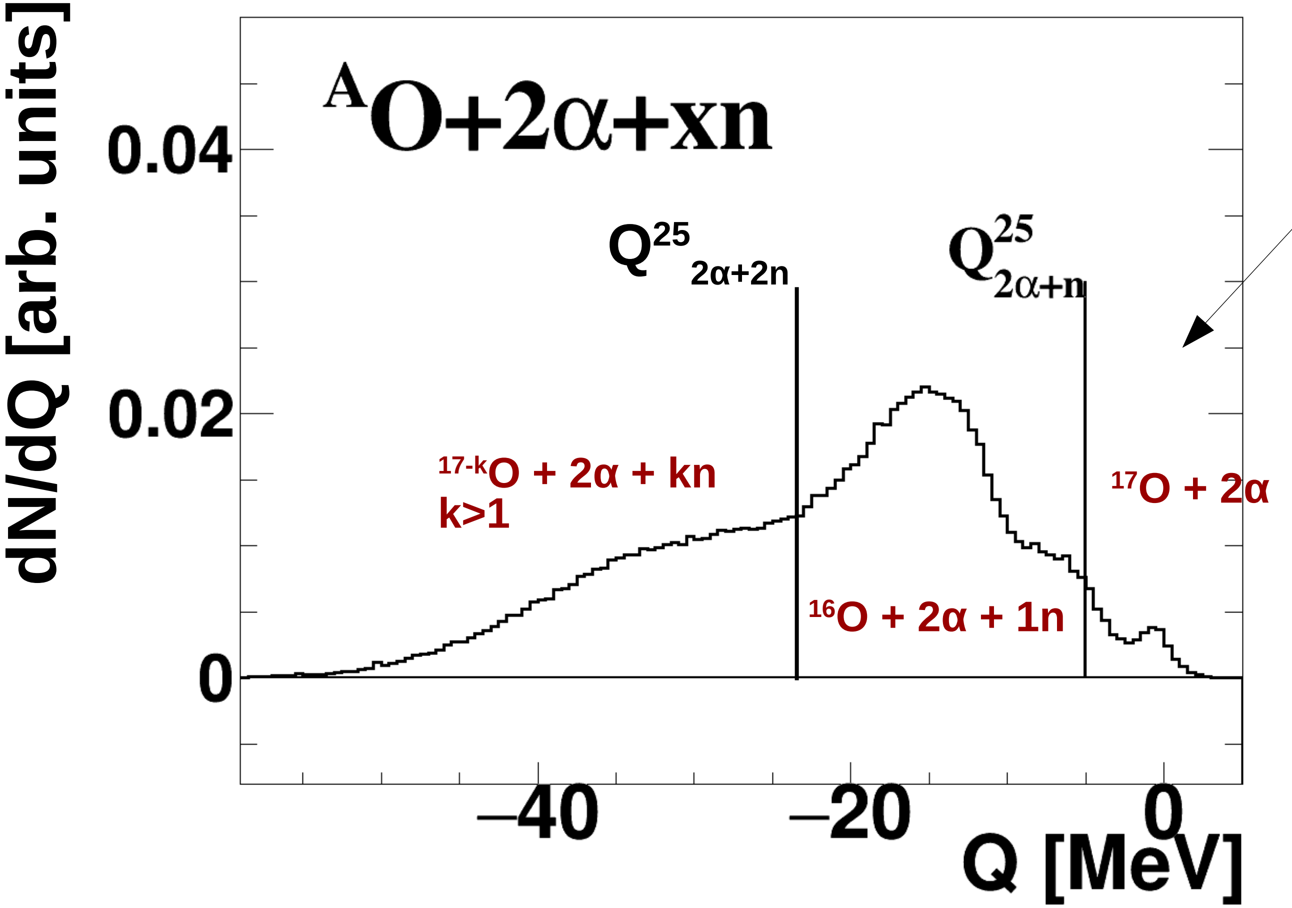

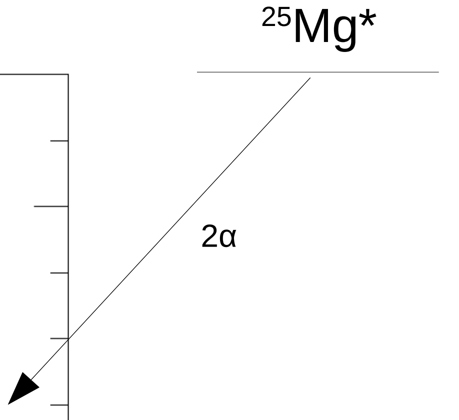

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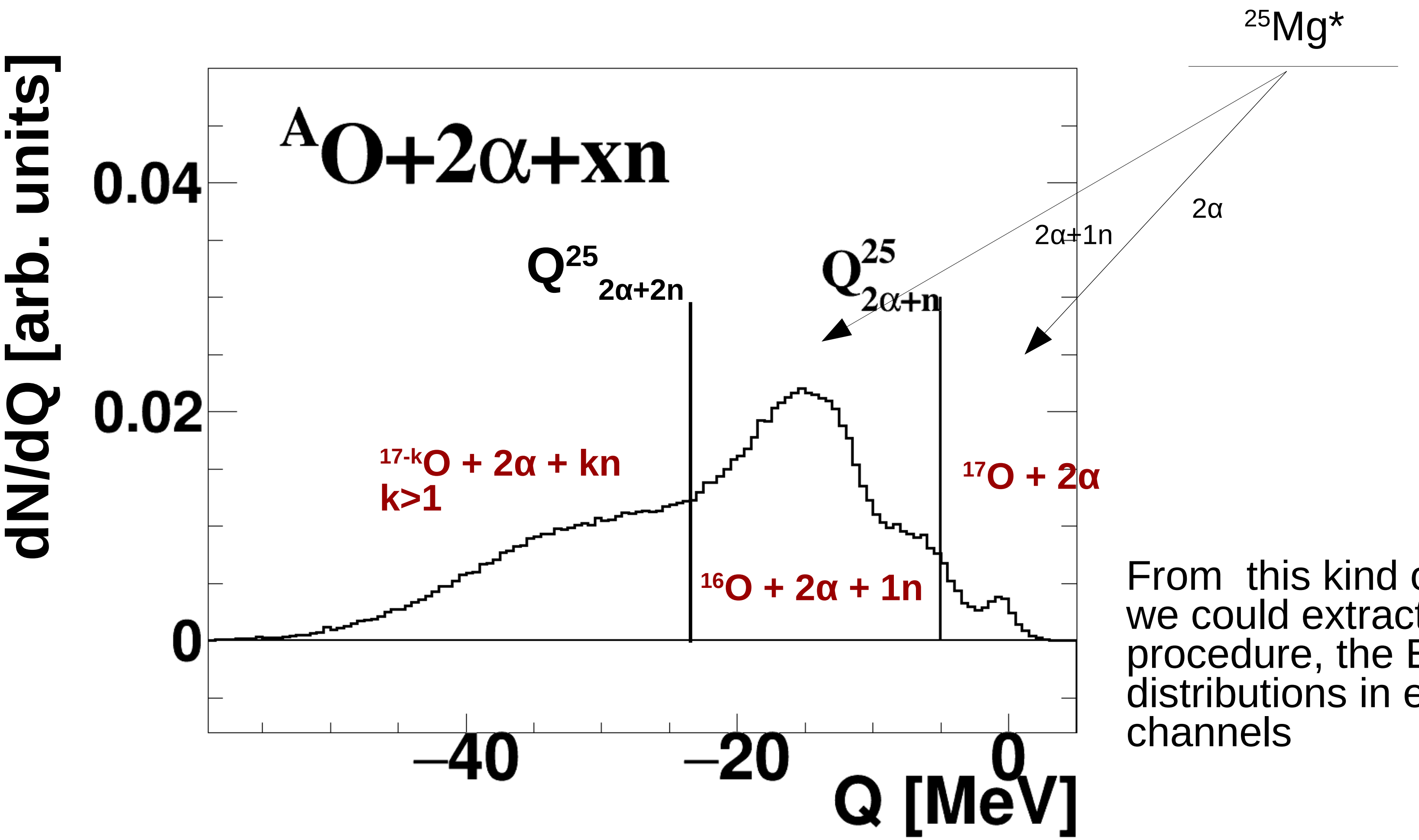

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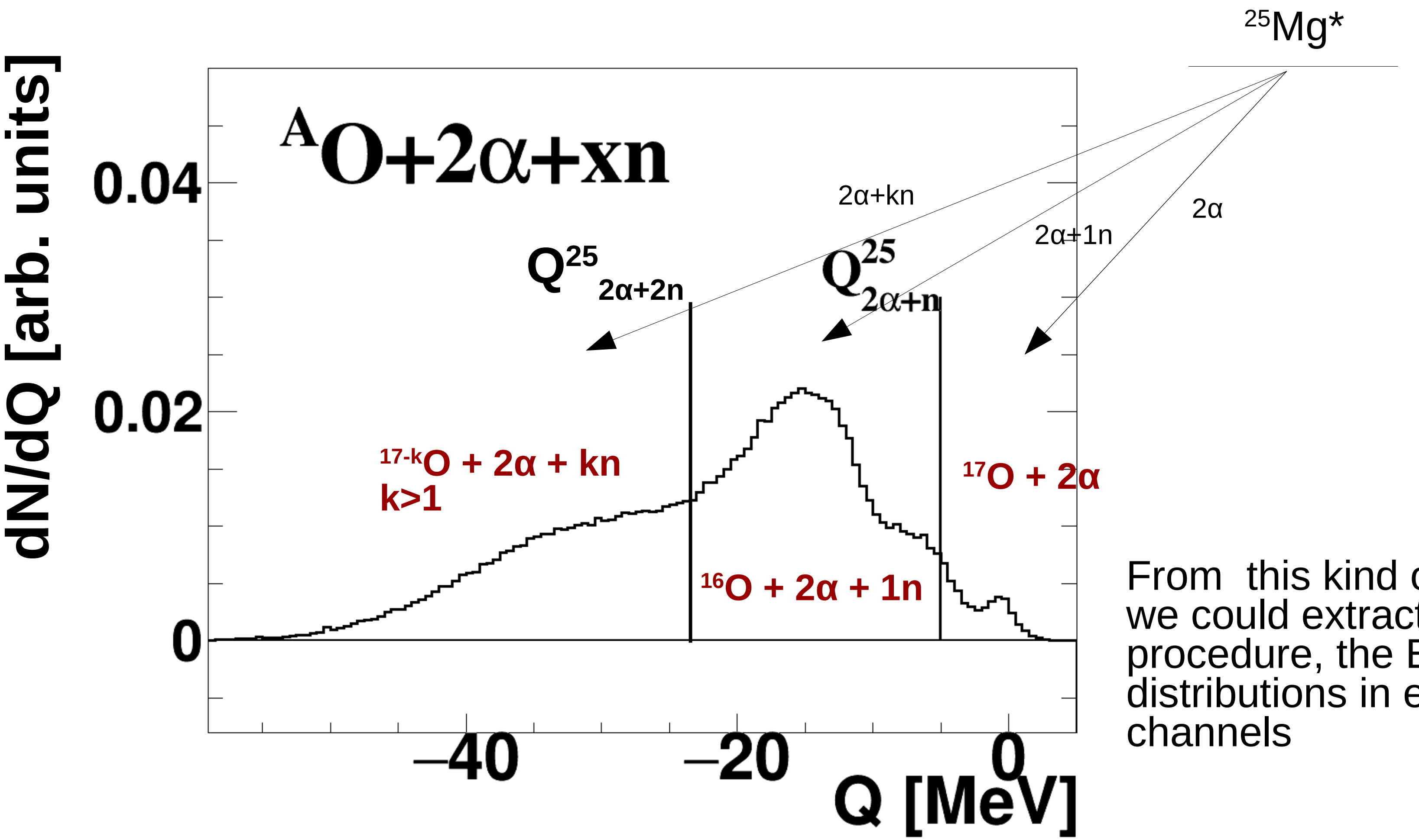

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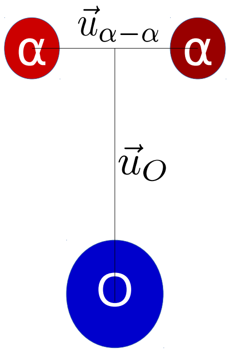
^{16}O+2α+1n: emission pattern

^{25}Mg, E*=65 MeV

Exploiting the Jacobi Coordinates:



$$\vec{u}_{\alpha-\alpha}$$

$$\vec{u}_O$$

$$\epsilon = E_{\alpha-\alpha}/E_{TOT}$$

$$cos(\theta_k) = \vec{u}_O \cdot \vec{u}_{\alpha-\alpha}$$

→ Particulary sensitive to the particles emission order

1st chance emission: ^{25}Mg → n + α + α + ^{16}O

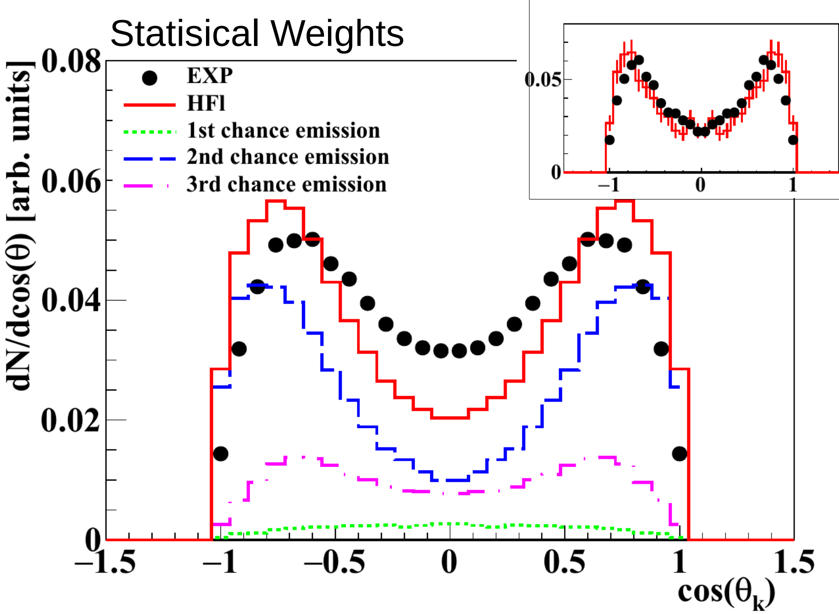
2nd chance emission: ^{25}Mg → α + n + α + ^{16}O

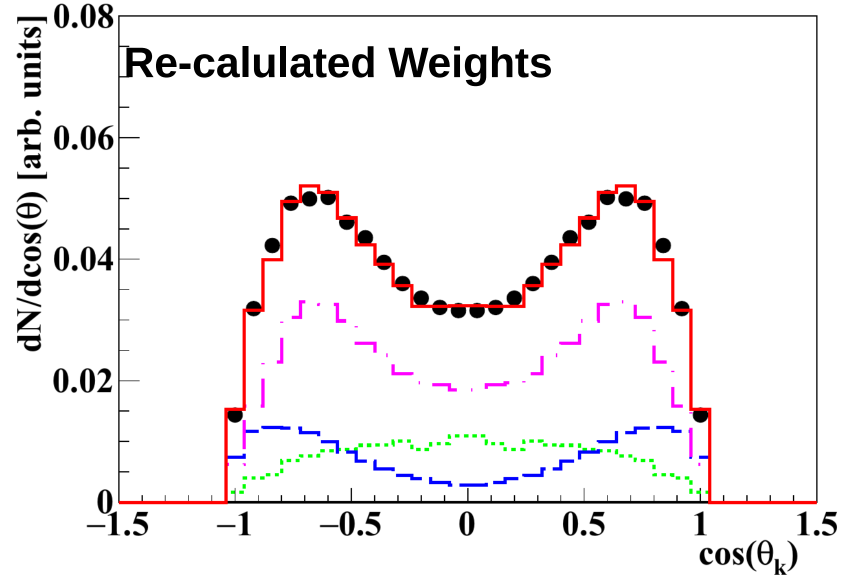
3rd chance emission: ^{25}Mg → α + α + n + ^{16}O

The statistical emission pattern does not reproduce the experimental one

→ Trough a fit procedure we re-calculate the weight for the 1st, 2nd and 3rd chance emission

^{17}O+2α check of Hfl reliability in the absence of neutrons





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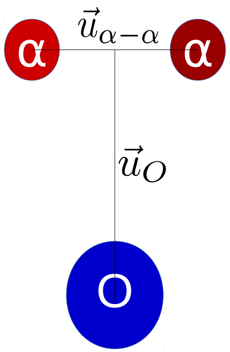


$$\epsilon = E_{\alpha-\alpha}/E_{TOT}$$

$$cos(\theta_k) = \vec{u}_O \cdot \vec{u}_{\alpha-\alpha}$$

1st chance emission: ^{25}Mg → n + α + α + ^{16}O

2nd chance emission: ^{25}Mg → α + n + α + ^{16}O

3rd chance emission: ^{25}Mg → α + α + n + ^{16}O

Quantitatively ...

	HFℓ original code	HFℓ after fit
First chance *n*	5%	$20 \pm 2\%$
Second chance *n*	70%	$20 \pm 2\%$
Third chance *n*	25%	$60 \pm 4\%$

- 1st chance emission four times greater the statistical
- **The favoured patterns are when the α particles are emitted one after the other,** i.e. 1st and 3rd chance emission.

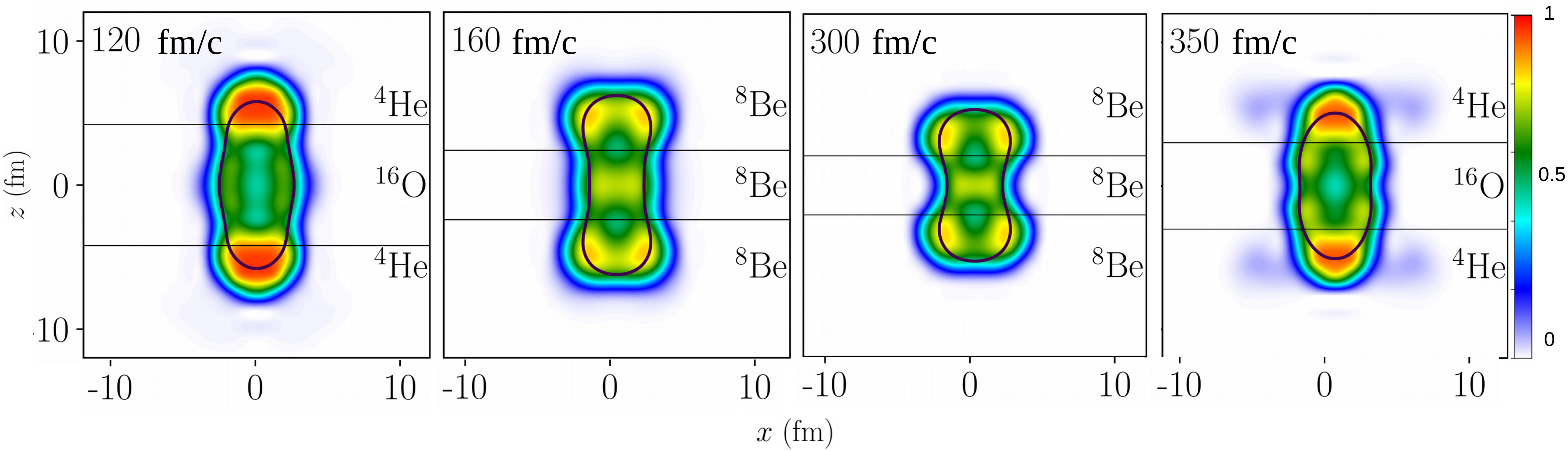
Recently, a paper appeared where in the context of TDDFT calculation, the authors show that α-clustered configurations occur during the precompound phases, and influence the α emission following fusion

See B. Schuetrumpf and W. Nazarewicz PRC 96, 064608 (2017)

Precompound clustering within TDDFT

B. Schuetrumpf and W. Nazarewicz, Phys. Rev. C 96, 064608 (2017) and Private Comm.

12C+12C at 95 MeV: Nucleon Localization Function as a function of time in TDDFT



The system evolves passing through cluster configurations, mainly of He+O+He and Be+Be+Be, finally preferring He+O+He states which could favour the emission of alpha particles during the path to CN (doorway states?)

Present Model limitations:

- **no link between these configurations and alpha emission probability**
- **calculations only for α-conjugate systems**

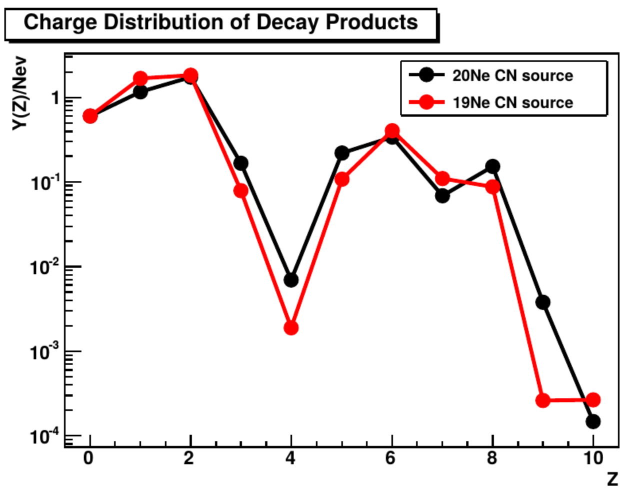
Perspectives towards light RIBs

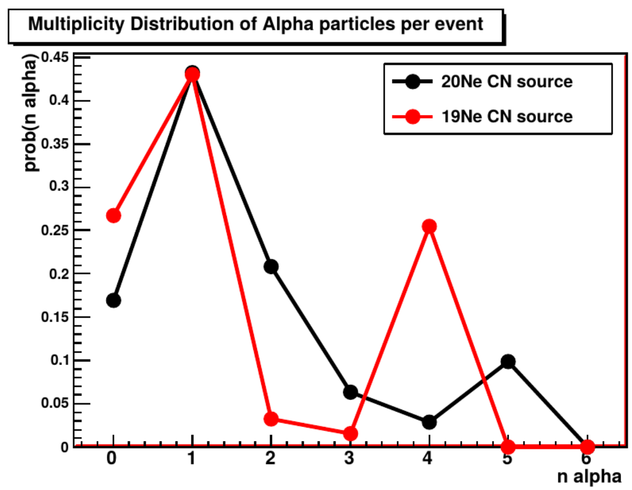
We have **sent three LoI addressed to (complete) fusion-evaporation reactions** involving n-poor radioactive beams, with a special attention to small systems (light projectiles on light targets).

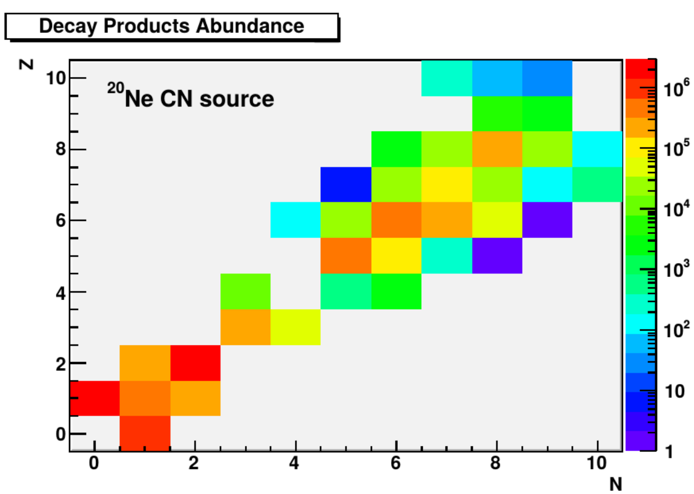
- Fusion-Evaporation reactions are the only kind of study to **acces to the nuclear level density** for energies above the particle decay thresholds;
- Hot light nuclei (A~20, E*~3 MeV/u) are massively produced in multifragmentation reactions: their statistical behavior is thus essential to access the properties of heavy excited sources at break-up time;
- **The decay model itself is not well established** for nuclei in this mass region: besides the **Hauser-Feshbach** theory of statistical evaporation, a different model, the so-called **Fermi break-up** is known: no unique experimental information exists on the transition, if any, between these two regimes.
- See how, and if, the observed **cluster-correlations** are modified when the fused system is formed with different N/Z nuclei, which can indeed be done by creating these nuclei as CN with unstable beams

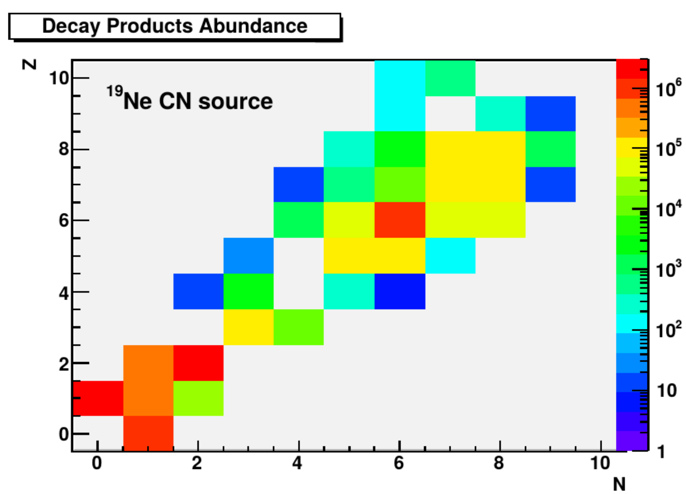
Fusion-Evaporation reactions with RIBs

Reaction	E_{Beam} MeV	θ_{gr} deg	A_{CN}	Z_{CN}	v_{CN} cm/ns	E^*_{CN} $A.MeV$	σ_{CN} mb
$^7Be + {}^{12}C$	67.9	4.6	19	10	1.6	3	348
$^7Be + {}^{13}C$	51.8	6.0	20	10	1.33	3	356









Multi α decay:

- ^{20}Ne → 5α 10%
- ^{19}Ne → 4α 25%

^{19}Ne → 3He + 16O*
→ 3He + 4α

see L. Morelli et al.
J.P.G: Nucl. Part. Phys. 43 045110
for similar analysis

Summary and Conclusion

The results from the reaction 12C+13C @ 95 MeV of bombarding energy have been presented.

Globally we found a good agreement with the pure statistical model but...

- With respect ot the model, **larger Branching Ratio of the channels where only α are emitted has been found** (as well as in 12C+12C, L. Morelli et al, J.P.G: Nucl. Part. Phys. 41 (2014) 075108)
- Moreover, in the case of 16O+2α+n decay, data indicate that **α particles are preferentially emitted <u>one after the other</u>**, and not in the α+n+α configuration, as suggested by the statistical model
- These findings could indicate **α-cluster configurations arising in the pre-compound phase** and/or encountered by the decaying CN during the path to the final states.

Brief introduction of what we plan to do, as extension of theese kind of analysis, exploting Light Radioactive Ion Beams

Thank you for your attention

PHYSICAL REVIEW C **97**, 044607 (2018)

Experimental study of precisely selected evaporation chains in the decay of excited ^{25}Mg

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Recent example from the literature

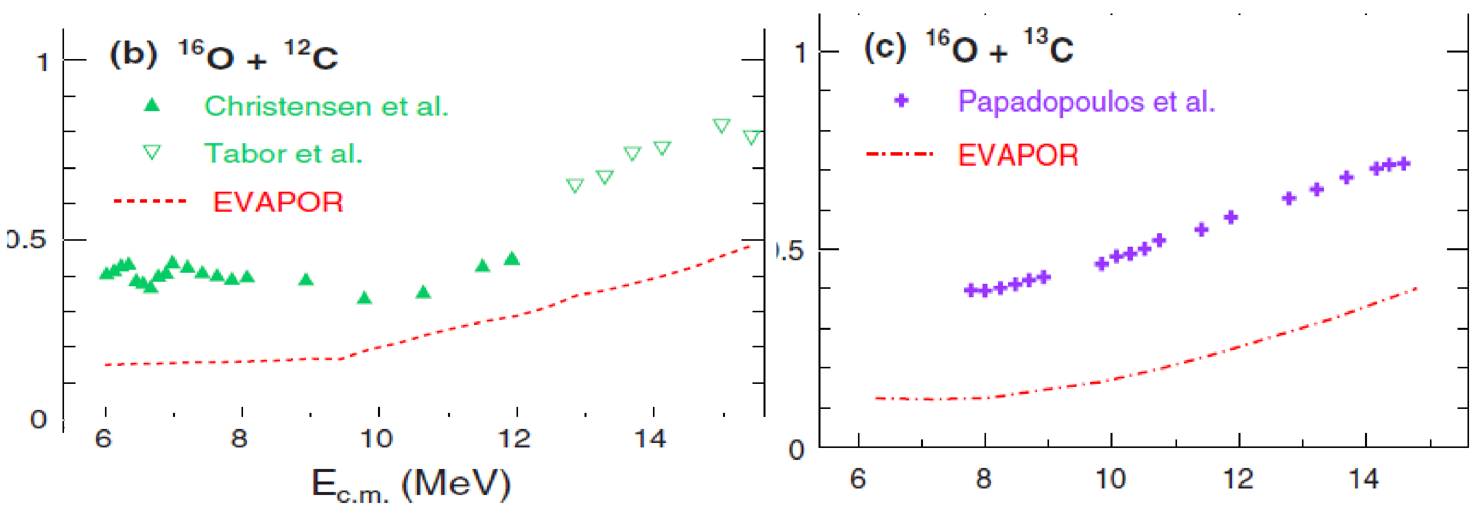
α-overproduction with respect to Statistical Model in fusion reactions between light ions

Very low E

Fusion reactions $^{18}O+^{12}C$, $^{16}O+^{12}C$, and $^{16}O+^{13}C$ Ecm<20MeV

"the α-structure of the initial projectile and target nuclei influences the α emission following fusion. The underprediction of the relative α emission by the statistical model codes emphasizes that the failure of these models to account for α cluster structure is significant"

$\sigma_\alpha/\sigma_{fus}$

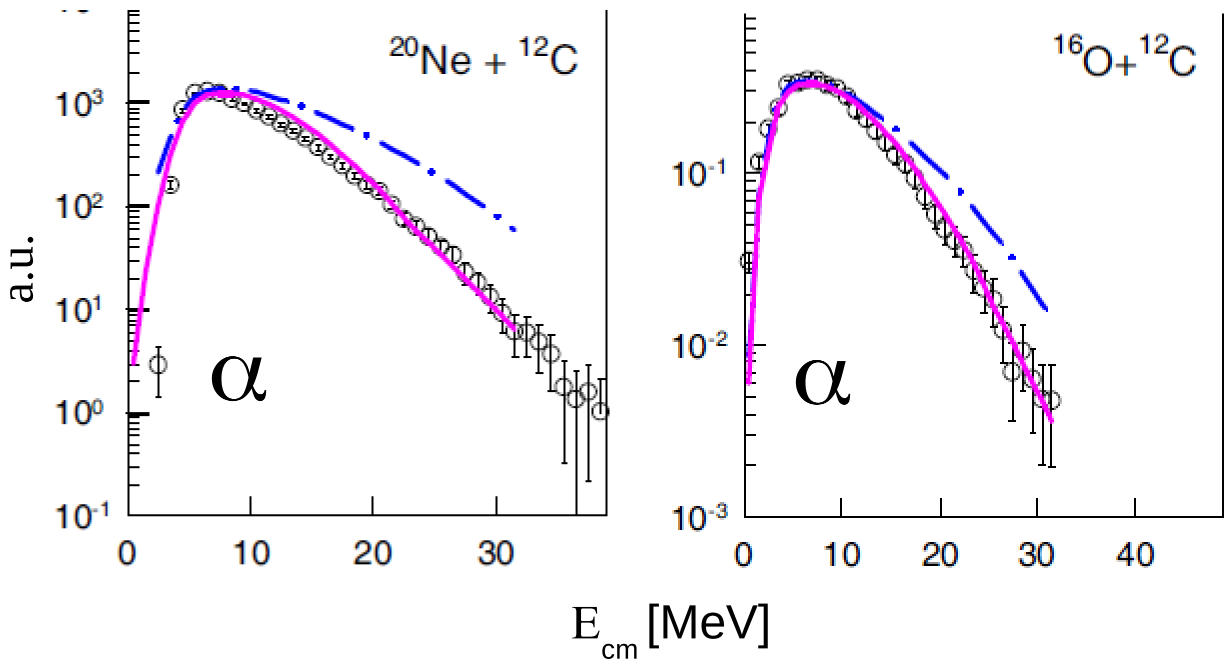


Recent example from the literature

α-Ecm spectra in some light-ion (mainly N=Z systems) fusion reaction: need of larger deformations to better reproduce the shape

beam E =7-10MeV/u

- N=Z systems suggest big deformation (quadrupole like), larger than usual CASCADE
- α-clustering is not the only effect. mass asymmetry does matter

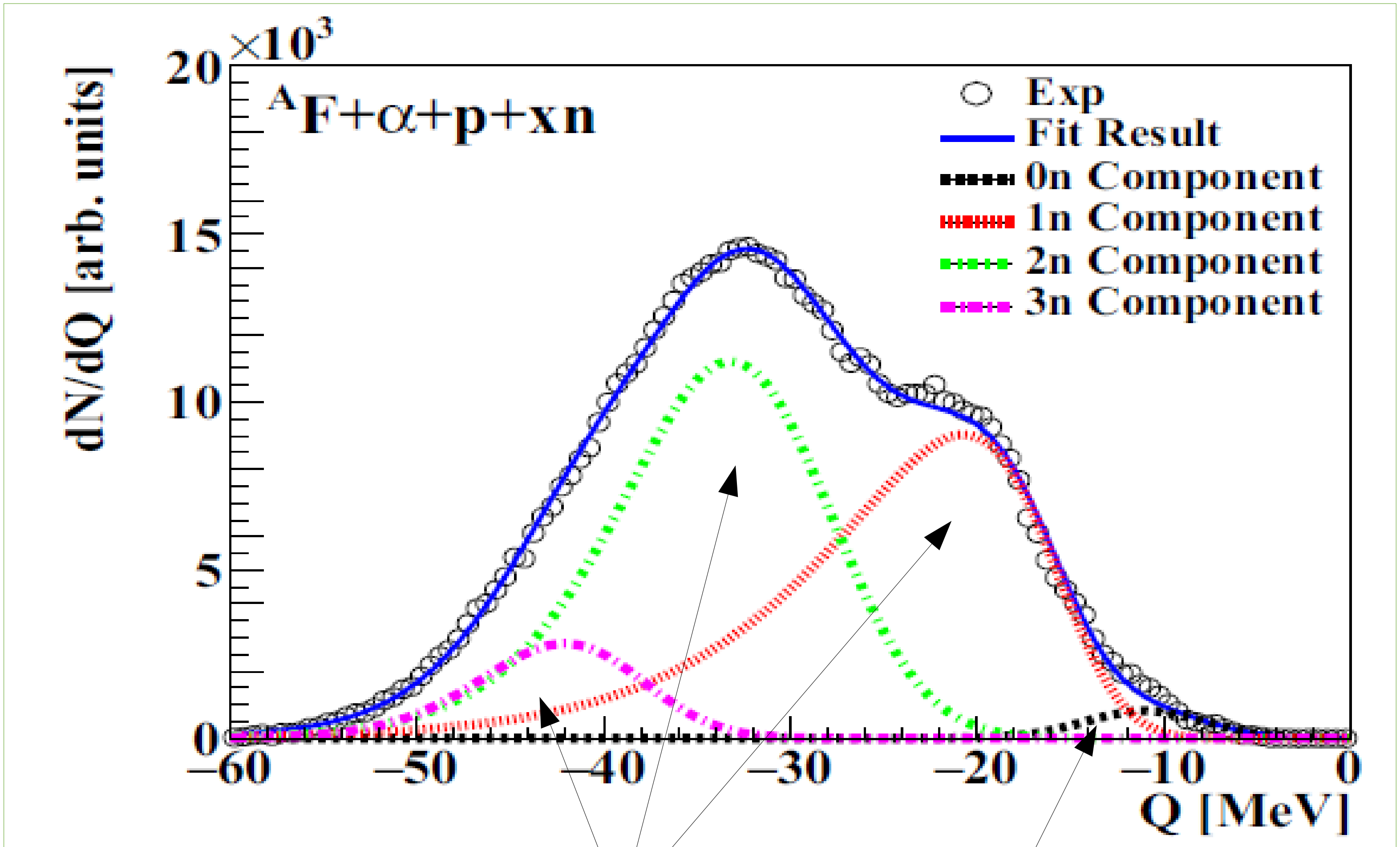


“ ...composites produced by the α -cluster entrance channel require extra deformation to explain the experimental energy spectra in the CASCADE calculation. But some non–α-cluster systems also require extra deformation...... it cannot be concluded that α-clustering is the only reason for the large deformation seen in all these α-cluster systems”

S.Kundu et al. PR C 87 024602 (2013) ;
S.Kundu et al. Eur Phys Journal A 54, 63 (2018) VECC, Kolkata Group
Theory: competition of fission and orbiting in N=Z systems M.Kaur et al. PR C 97 014611 (2017)

$^{A}F+\alpha+p+xn$: fit example

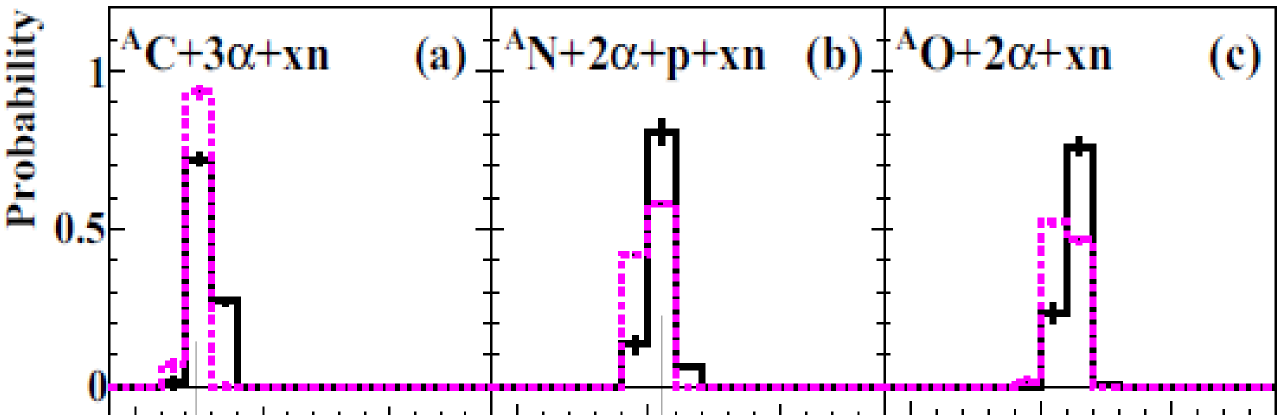
^{25}Mg, E*=65 MeV

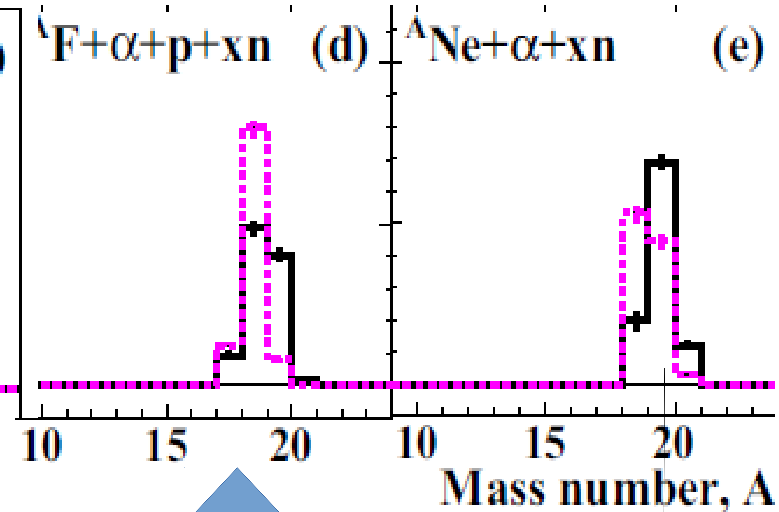


≥1n: Maxwellian.X.Gaussian **0n: Breit-Wigner.X.Gaussian**

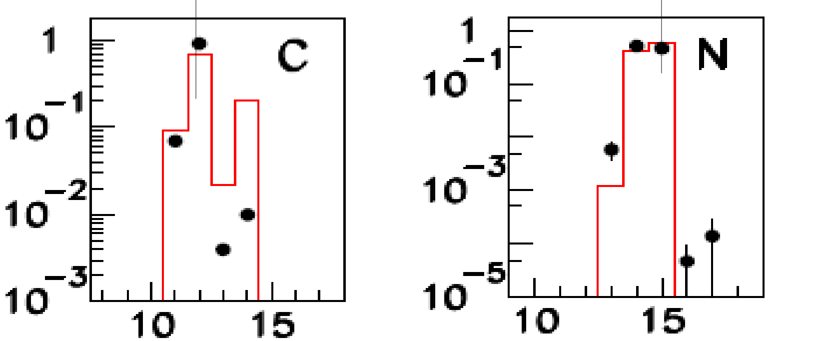
Shape parameters adjusted basing on the Hfl preditiction. Weights are free params

ER MASS spetra reconstructed from Qvalue spectra



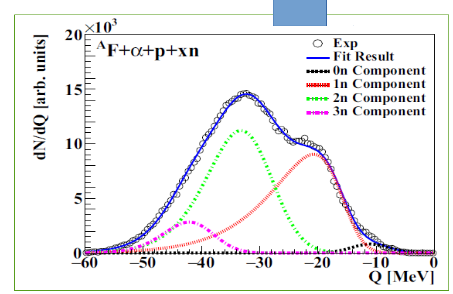


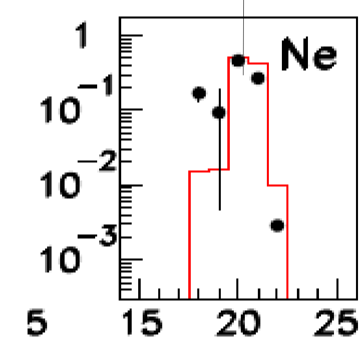
system comparison: 24Mg and 25Mg CN



independent method used in Morelli JP G 41 (2014)

24Mg





Some future Perspectives

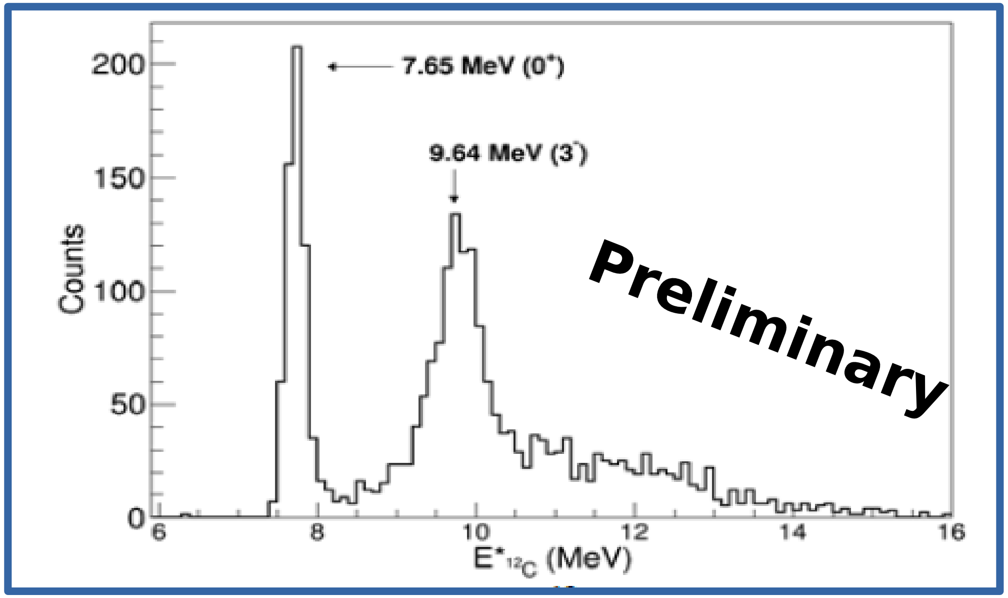
example: $^{16}O+^{12}C$ 130MeV

Managlia et al. ANN REP LNL 2018

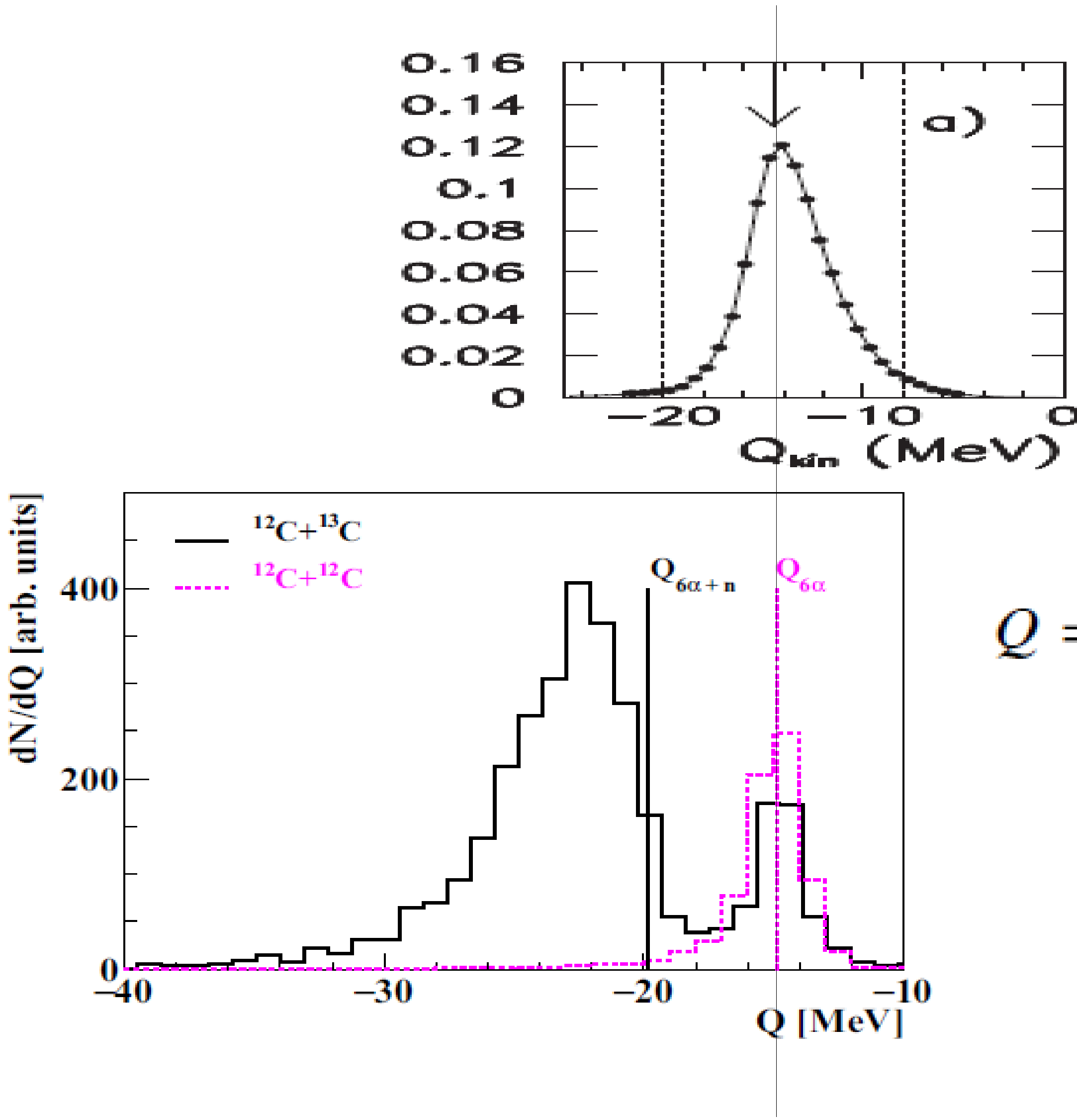
search for 4-alpha decay channel from excited $^{16}O^*$

$^{16}O^* \rightarrow {}^{8}Be + {}^{8}Be$
BR 5%

$^{16}O^* \rightarrow {}^{12}C^* + \alpha$
BR 65% dominating



SIX-alpha emission channel in 24Mg and 25Mg CN



L. Morelli et al, J.P.G: 43 (2016)

12C+12C

$$Q = \sum_{i}^{N} E_i - E_{\mathrm{beam}},$$