In-flight resonance decay of ^{10}Be, ^{16}C and ^{12}C at intermediate energies

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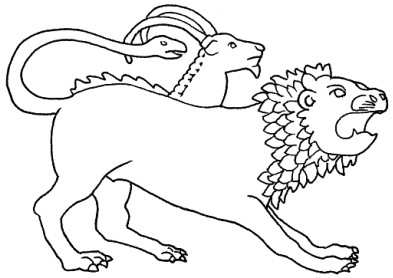
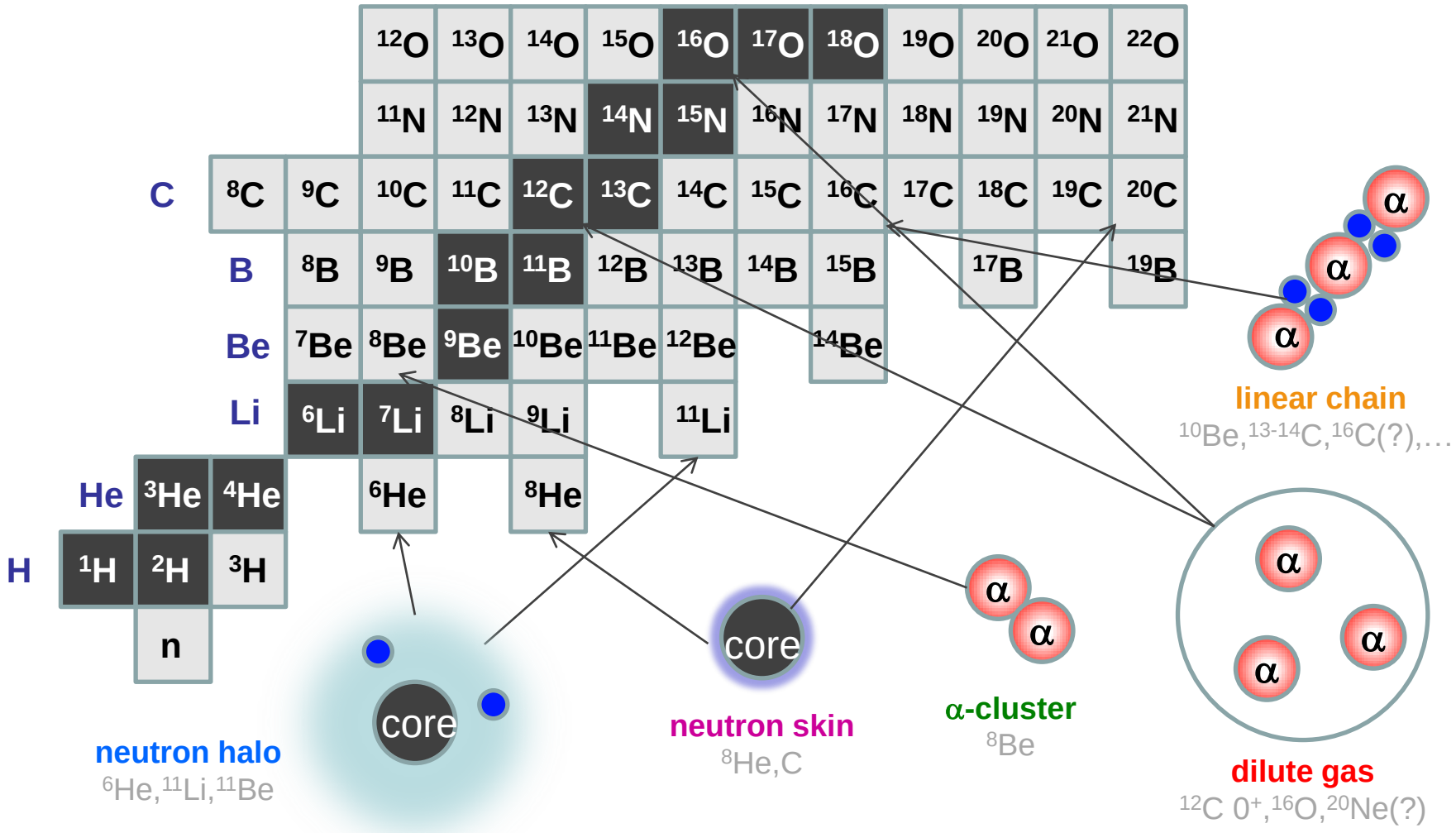
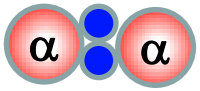


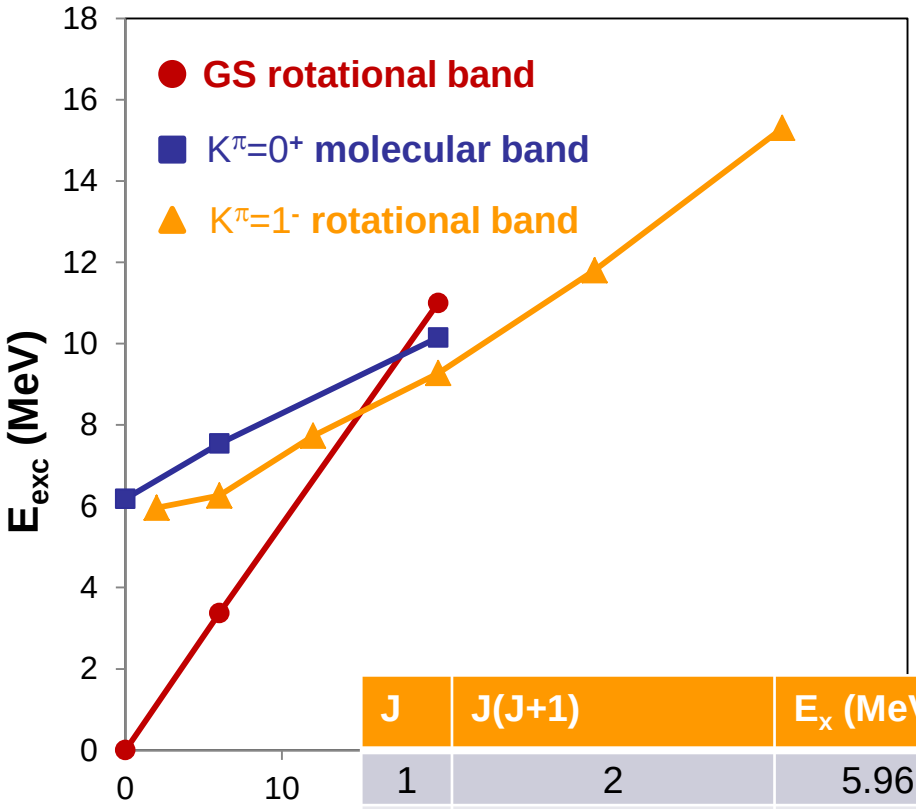
dellaquila@na.infn.it

Complexity of nuclear force → **dominant** phenomena of nucleon-nucleon ***correlations*** which determine a spatial re-organization of the nucleons in bounded **sub-units** → the ***constituent clusters***.



Very big variety of physical phenomena that need investigations





J	J(J+1)	E_x (MeV)
0	0	6.18
2	6	7.54
4	20	10.15 [4]

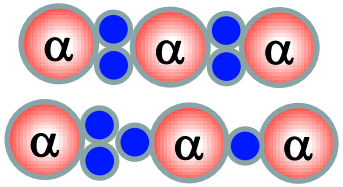
J	J(J+1)	E_x (MeV)
0	0	0
2	6	3.37
4	20	11.78 [14]→11 [2] (?)

J	J(J+1)	E_x (MeV)
1	2	5.96
2	6	6.26
3	12	7.73
4	20	9.27
5	30	11.8
6	42	15.3

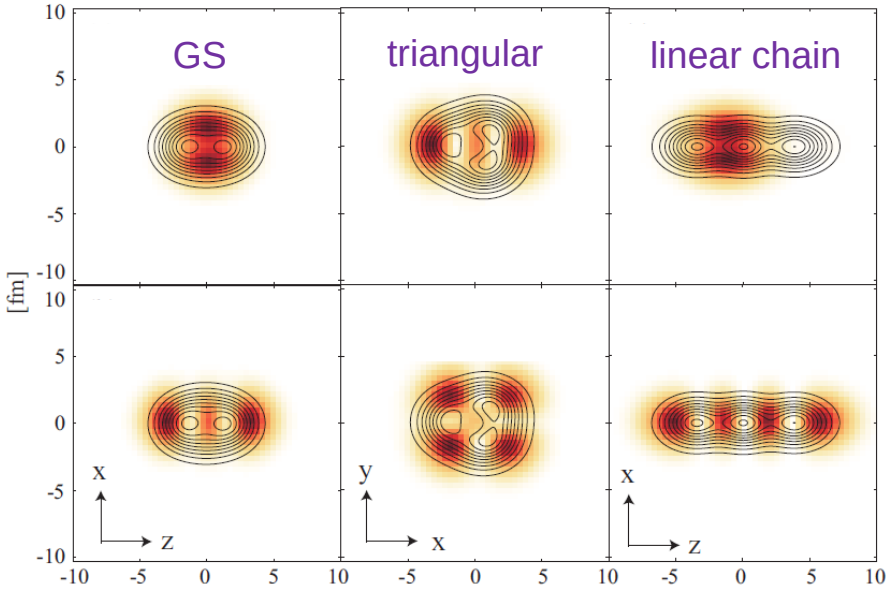
[14] H.G. Bohlen et al., Phys. Rev. **C 75**, 054604 (2007)

[1] Y. Kanada-En'yo, Phys. Rev. **C 91**, 014315 (2015)
[2] D. Suzuki et al., Phys. Rev. **C 87**, 054301 (2013)
[3] Y. Kanada-En'yo, J. Phys. G **24**, 1499 (1998)
[4] M. Freer et al., Phys. Rev. Lett. **96**, 042501 (2006)
[5] N. Soic et al., Europhys Lett. **34**, 7 (1996)
[6] M. Freer et al., Phys. Rev. **C 63**, 034301 (2001)
[7] H.T. Fortune and B. Sherr, Phys. Rev. **C 84**, 024304 (2011)
[8] N.I. Ashwood et al., Phys. Rev. **C 68**, 0107603 (2004)
[9] N. Curtis et al, Phys. Rev. **C 64**, 044604 (2001)
[10] R. Wolsky et al., Phys. of Atom. Nucl. **73**, 1405 (2010)
[11] F. Kobayashi and Y. Kanada-en'yo, J. Phys.: Conf. Ser. **436**, 012042 (2013)
[12] S. Ahmed et al., Phys. Rev. **C 69**, 024303 (2004)
[13] N. Curtis et al. Phys. Rev. **C 73**, 057301 (2006)

Rotational band in dimeric structure → very interesting case

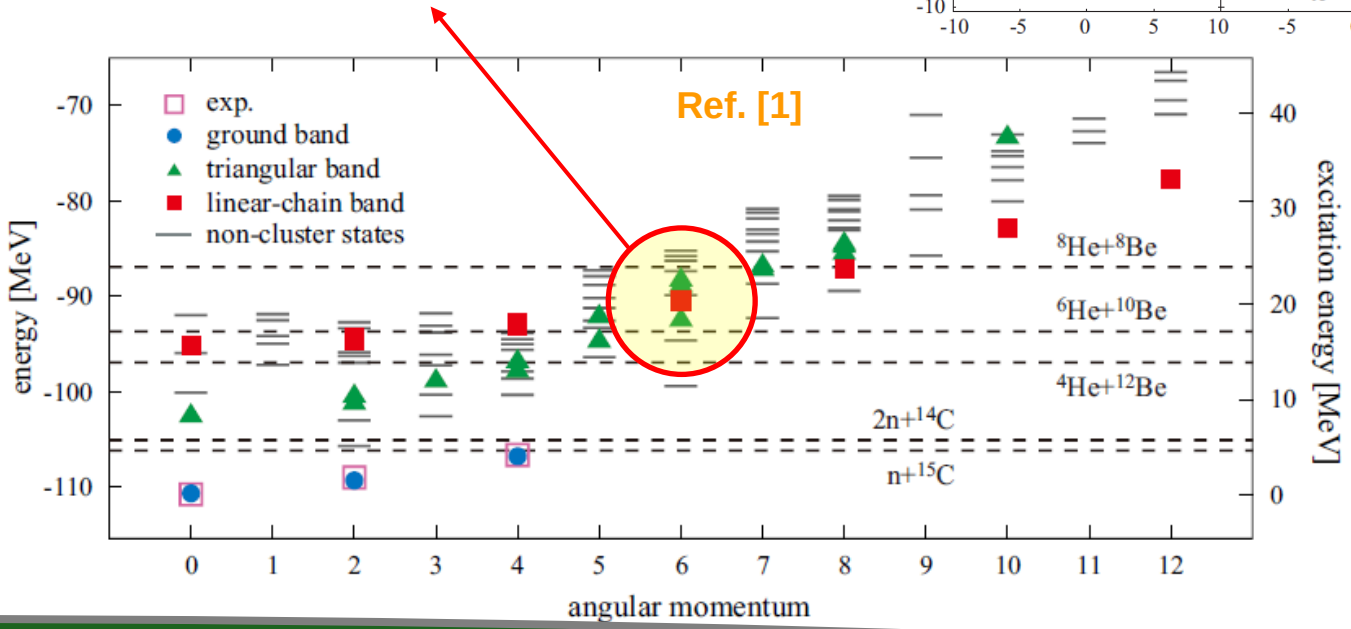


possible **cluster configurations**→**AMD** calculations **Ref. [1]**

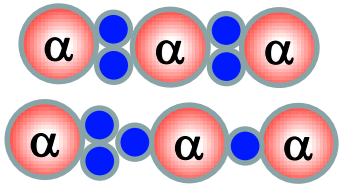


[1] T. Baba, Y. Chiba and M. Kimura , Phys. Rev. **C 90**, 064319 (2014)
[2] N. I. Ashwood et al., Phys. Rev. **C 70**, 0644607 (2004)
[3] P.J. Leask et al., Jour. Phys. G: Nucl. Part. Phys. **27**, B9 (2001)

molecular states **predicted** → possible **rotational bands** → **^{6}He+^{10}Be** powerful disintegration channel to explore this region → **confirmations needed.**

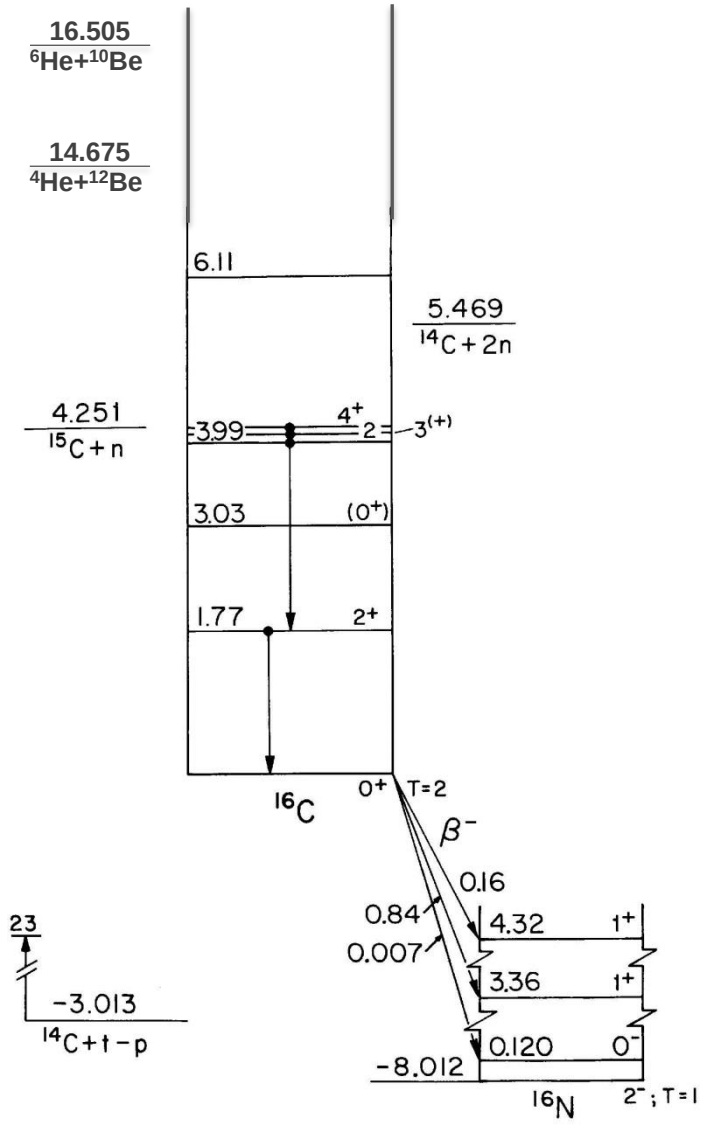


Many theoretical predictions



[1] T. Baba, Y. Chiba and M. Kimura , Phys. Rev. **C 90**, 064319 (2014)
[2] N. I. Ashwood et al., Phys. Rev. **C 70**, 0644607 (2004)
[3] P.J. Leask et al., Jour. Phys. G: Nucl. Part. Phys. **27**, B9 (2001)

no experimental evidence on ^{16}C molecular nature still provided **[2,3]** → very **low statistic** measurements



Experimental evidence still missing!

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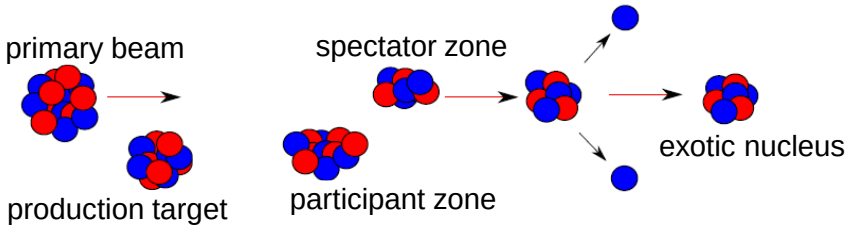
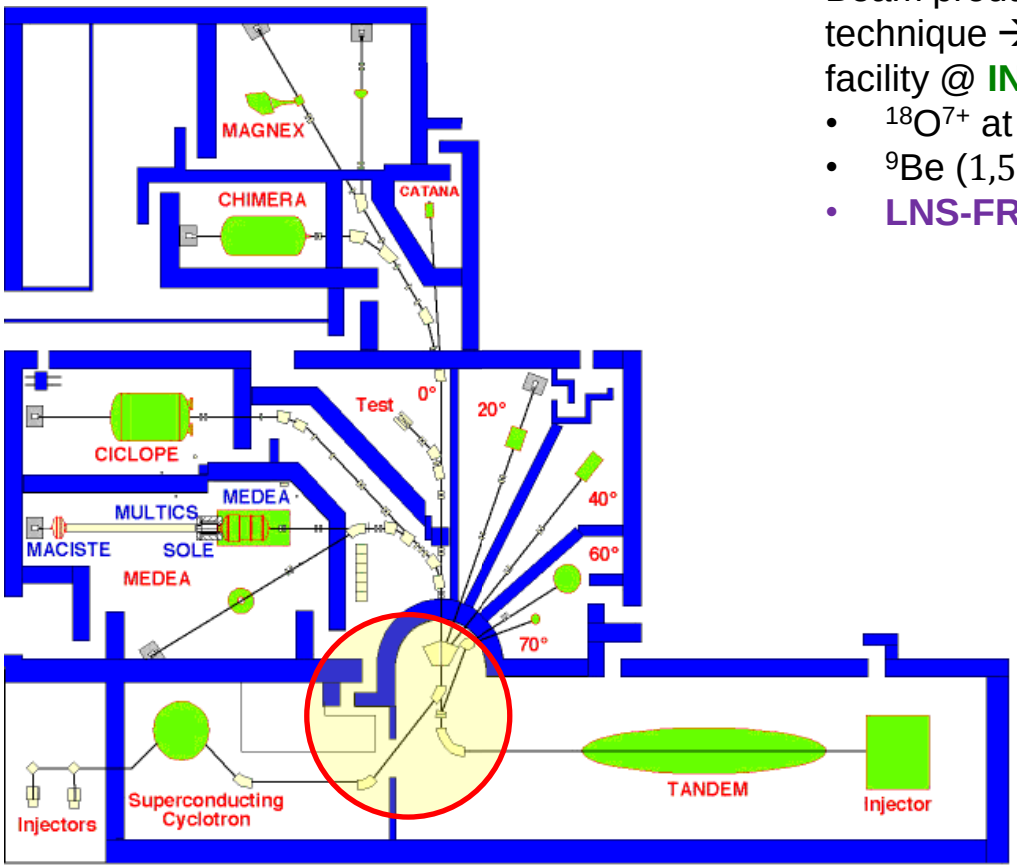


[1] I. Lombardo et al., Nuc. Phys. **B 215**, 272 (2011).



Beam production→**IFF** (**I**n **F**light **F**ragmentation) technique → **FRIBs** (**F**light **R**adioactive **I**on **B**eams) facility @ **INFN-LNS**:

- $^{18}O^{7+}$ at $56\ MeV/u$ (superconducting cyclotron K800);
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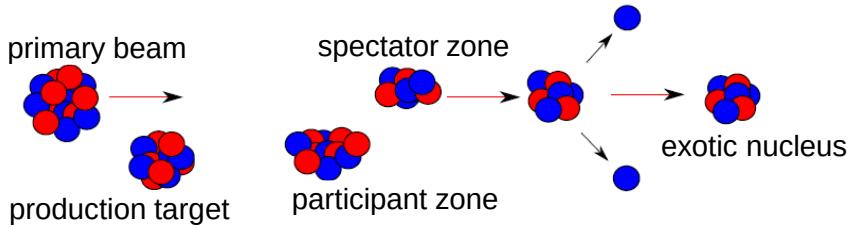
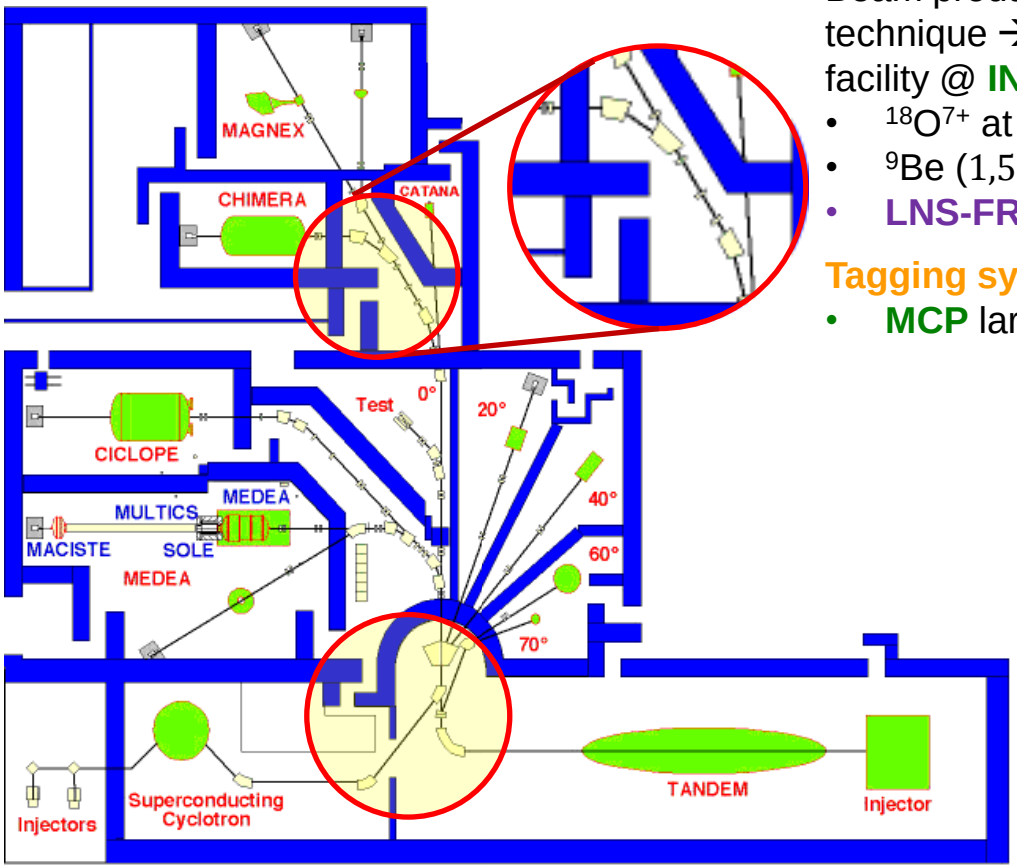


[1] I. Lombardo et al., Nuc. Phys. **B 215**, 272 (2011).



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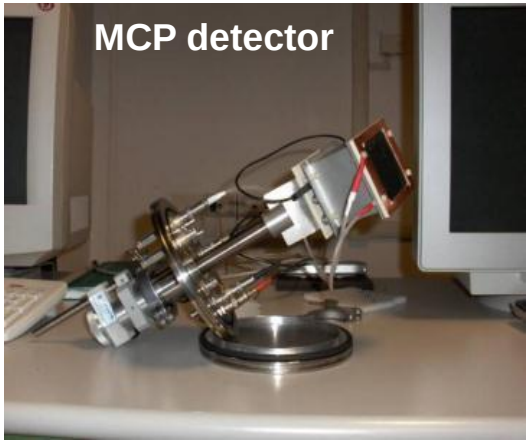

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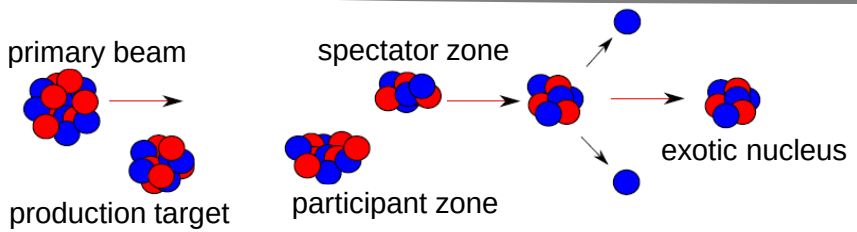
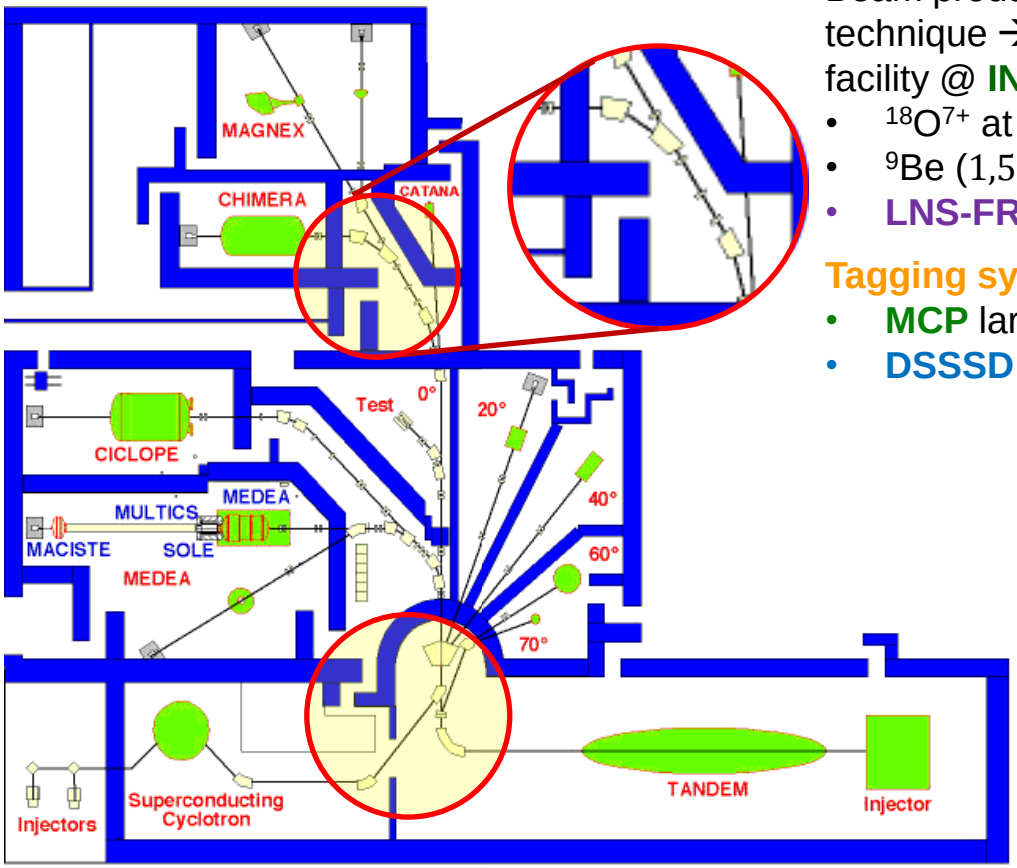


[1] I. Lombardo et al., Nuc. Phys. **B 215**, 272 (2011).



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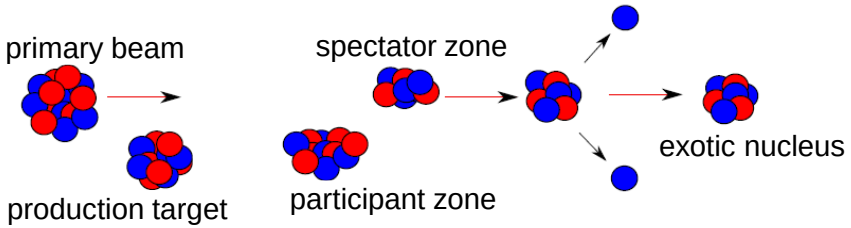

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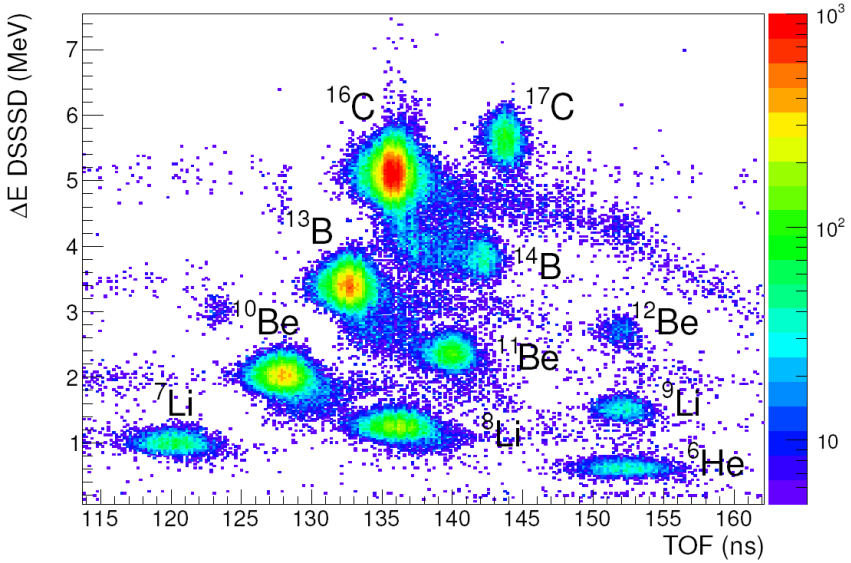

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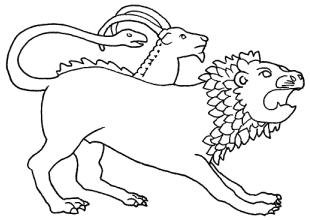
Identification (ΔE-ToF) plot FRIBs **cocktail beam** → good performances.
High **exotic beams** intensity:

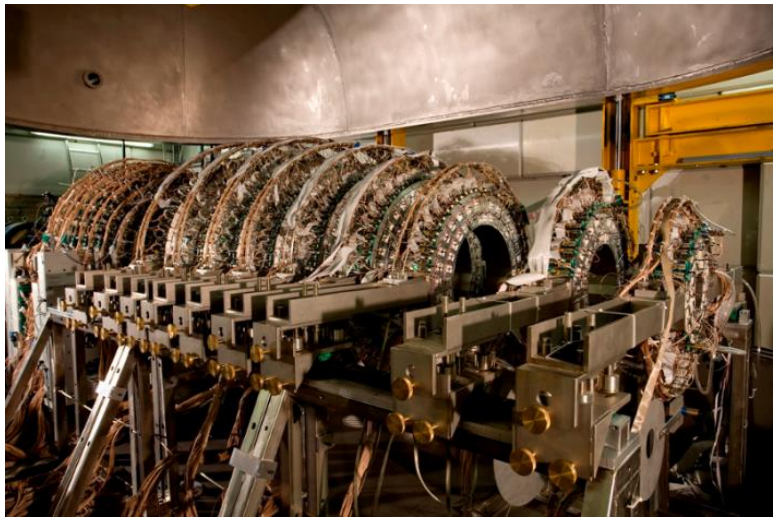
- ^{16}C $(49{,}5\ MeV/u)$ $10^5\ pps$;
- ^{13}B $(49{,}5\ MeV/u)$ $5 \cdot 10^4\ pps$;
- ^{10}Be $(56{,}0\ MeV/u)$ $4 \cdot 10^4\ pps$;

Complete cocktail beam identification

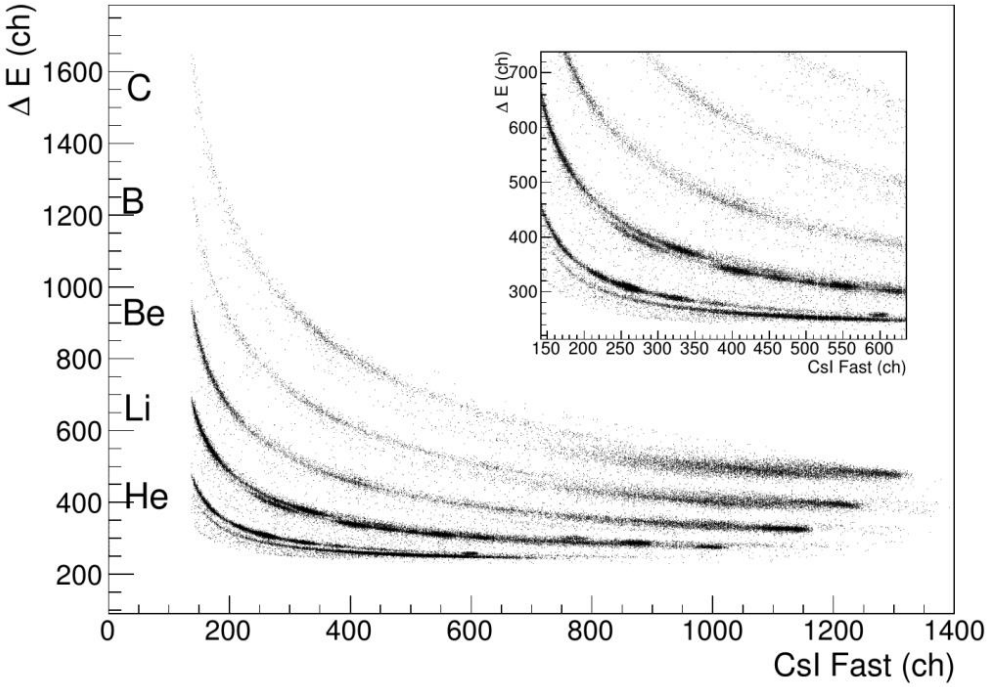


CHIMERA (**C**harged **H**eavy **I**on **M**ass **E**nergy **R**esolving **A**rray) **[1,2]**

[1] A. Pagano, Nucl. Phys. News **22**, 25 (2012)
[2] A. Pagano et al., Nucl. Phys. **A 734**, 504 (2004)



- 1192 **ΔE-E telescopes** ($\sim 300\mu m$ Si + CsI(Tl) scintillator);
- 9 **forward rings** ($1^{\circ} \leq \theta \leq 30^{\circ}$);
- 17 **rings sphere** ($30^{\circ} < \theta \leq 176^{\circ}$);



ΔE-E identification technique → **particles** and **fragments** identification.

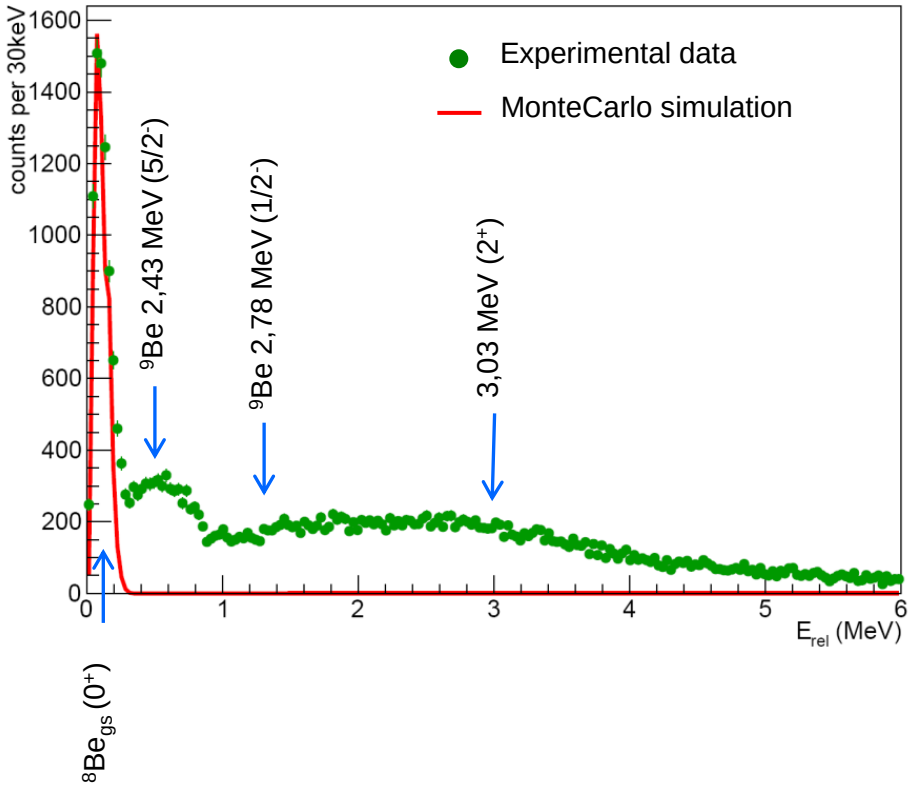
ΔE-E identification → good isotopic separation

As a **starting check** → **correlations** between **helium break-up** fragments from self-conjugated nuclei

- **2α correlations** → the **^{8}Be** spectroscopy:

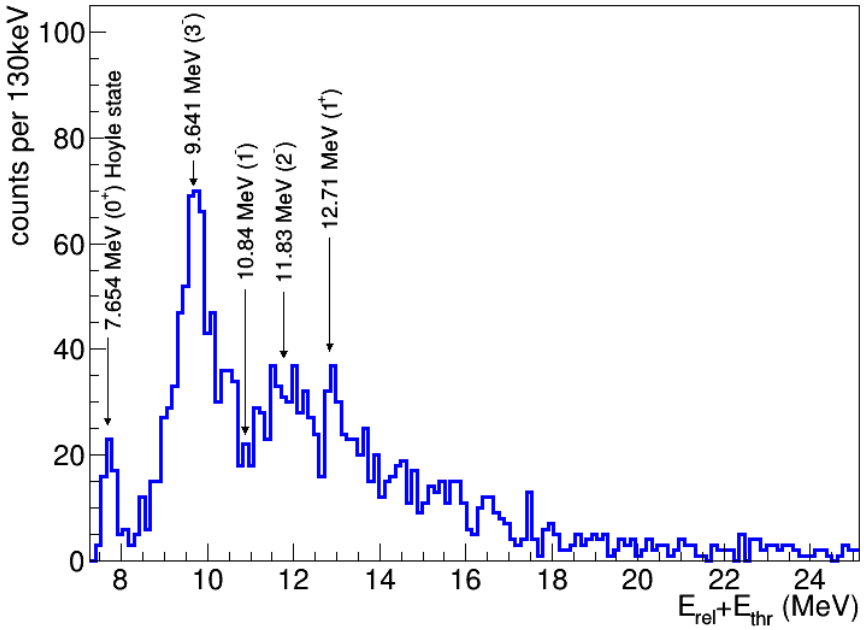
MonteCarlo simulation → good **agreement** with the experimental data for the **91,8 keV peak** (**$^{8}Be_{gs}$**) → good consistency of the procedure.

Possible contaminations of **^{9}Be** neutron decay → **ghost peaks**?



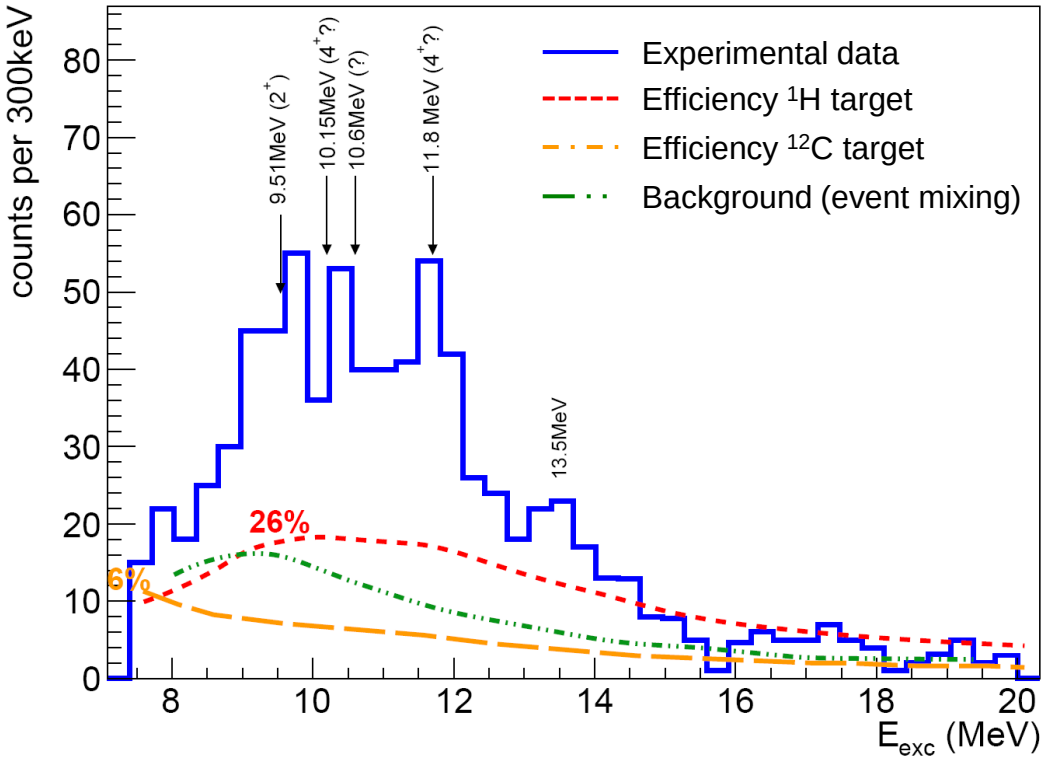
As a **starting check** → **correlations** between **helium break-up** fragments from self-conjugated nuclei

- **3α correlations** → the ^{12}C spectroscopy:



3 body correlations → good agreement with the literature → **^{12}C Hoyle state**.

Good test for the experimental technique



Found **bumps** corresponding to **excited states** known in literature (vertical arrows) → interesting peak at about **13.5 MeV**.

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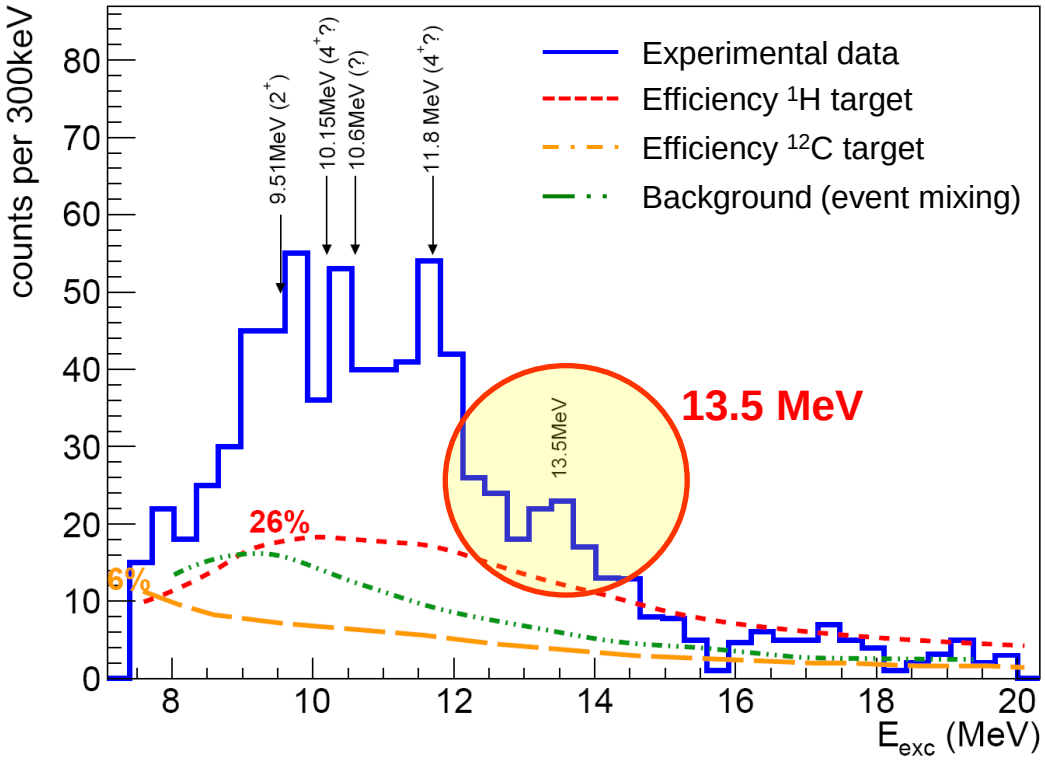


Found **bumps** corresponding to **excited states** known in literature (vertical arrows) → interesting peak at about **13.5 MeV**.

Smooth efficiency for both the possible target nuclei (^{12}C and ^{1}H from the polyethylene CH_2 target used) → **MonteCarlo simulation** with exponential angular distribution in the **anelastic scattering** center of mass frame:

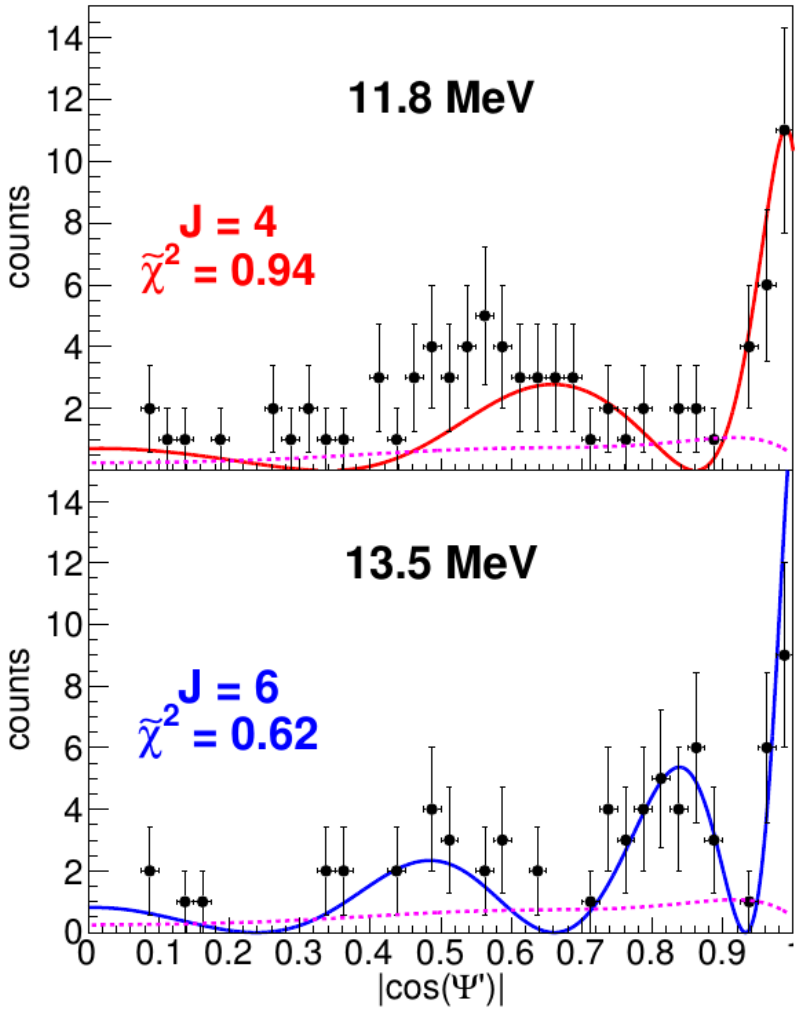
$$\frac{d\sigma}{d\Omega_{cm}} \propto e^{\frac{\theta_{cm}}{\alpha}}$$

α fall-of factor 12°-16°

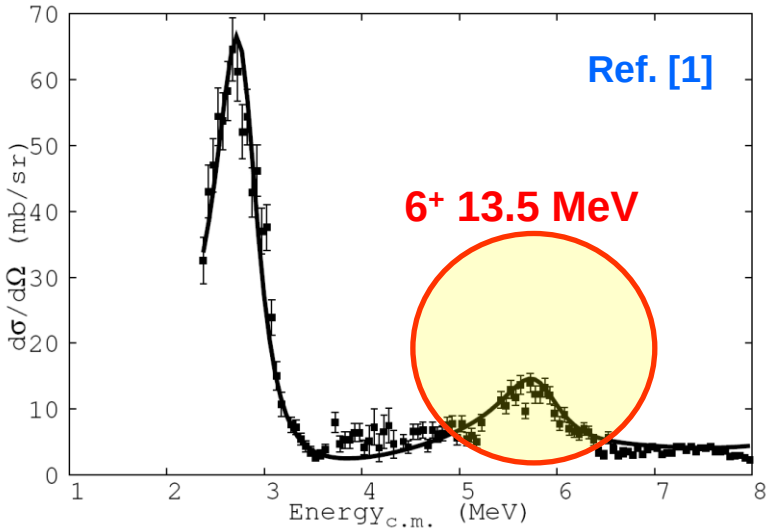
Flat **spurious background** contribution → **event mixing** procedure.

Possible **evidence** of a new excited state at about **13.5 MeV** not reported in literature.

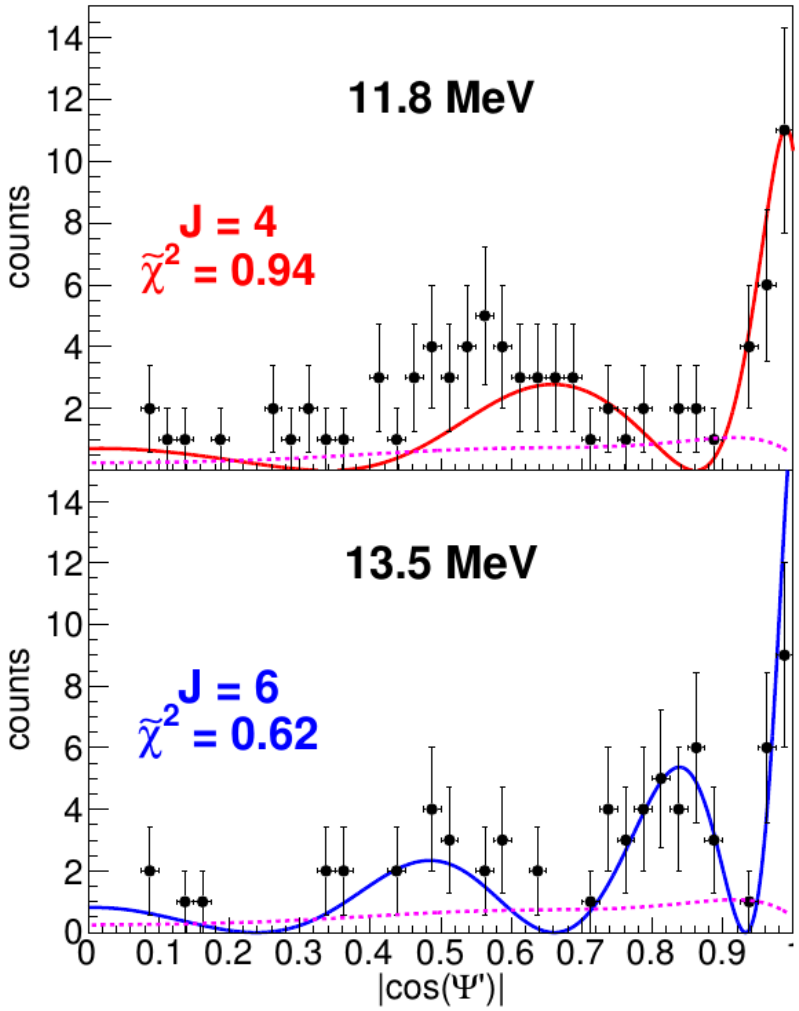
^{6}He+^{4}He channel: the ^{10}Be structure



Angular correlation analysis on **13.5 MeV** state→ **high spin** contributions → possible **6$^+$** assignement → **agreement** with the recent R-matrix calculation in resonant elastic scattering **^{6}He+^{4}He** experiment **[1]**



[1] G. Rogachev et al., J. Phys.: Conf. Ser. **569**, 012004 (2014)



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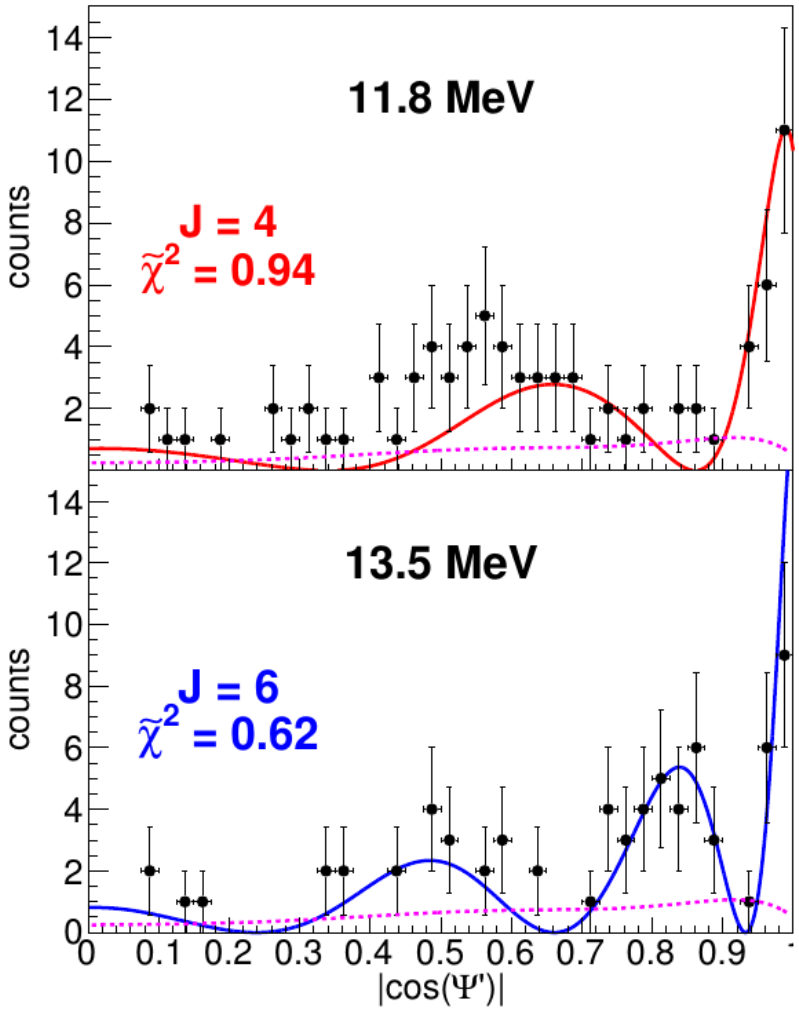

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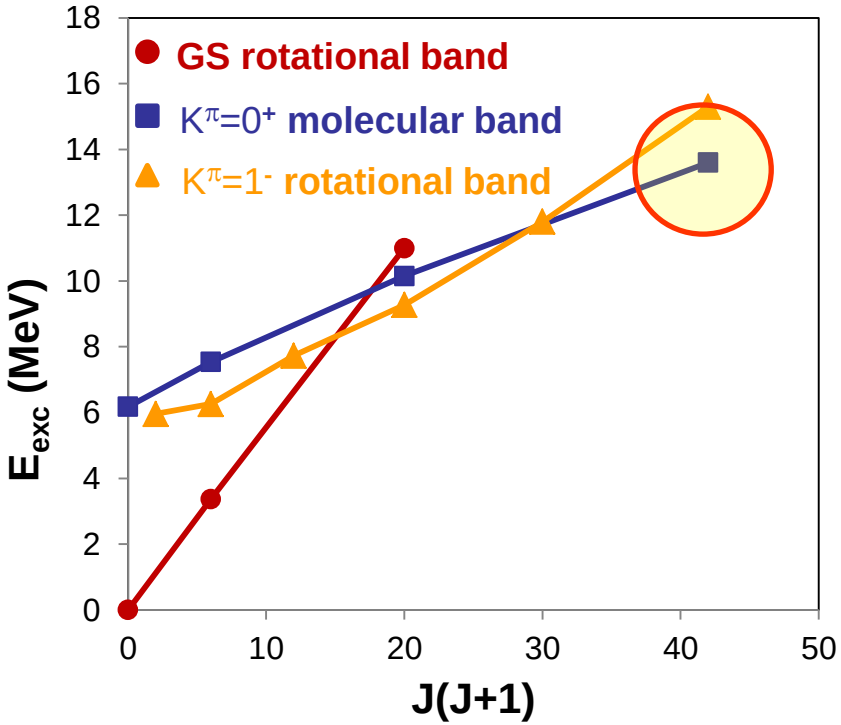
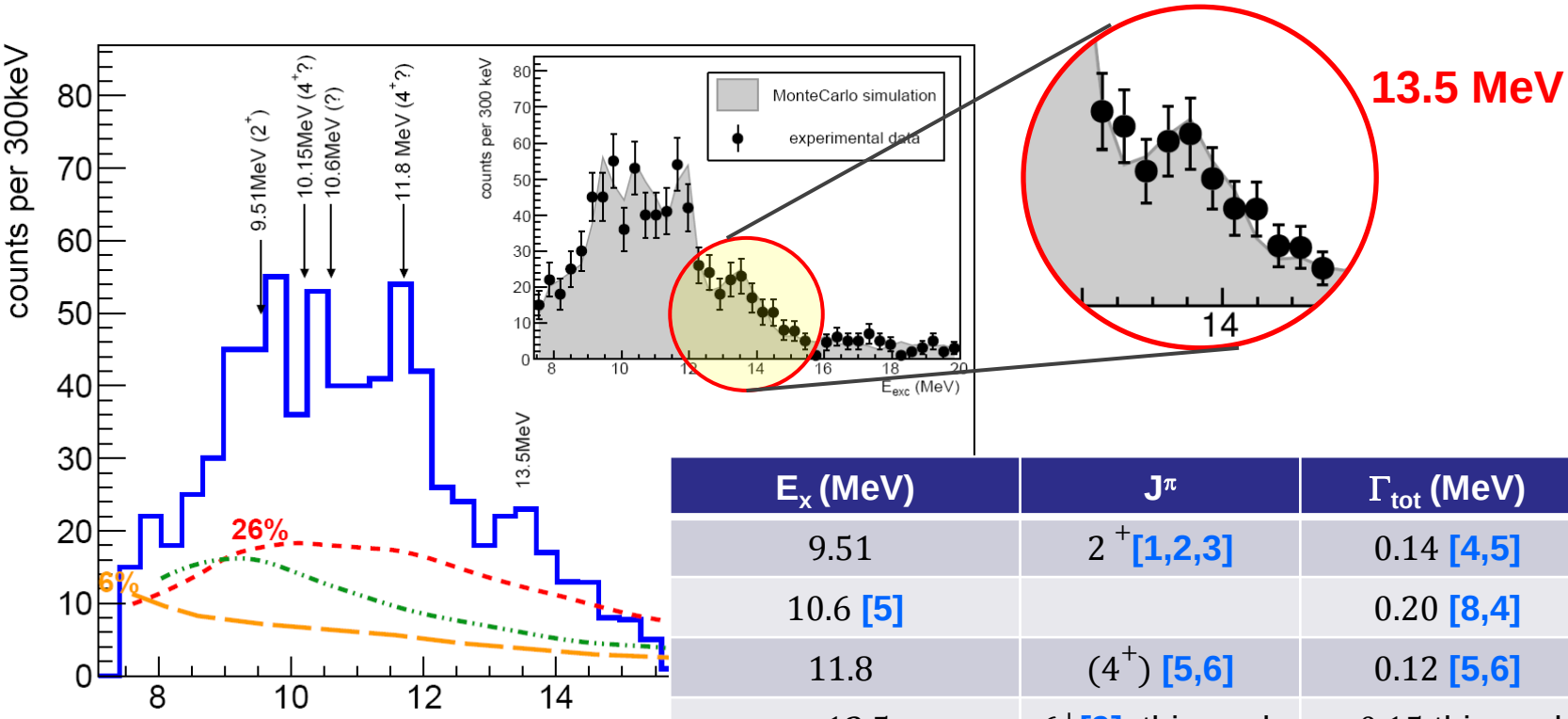


Possible **6$^+$** further **member** of the **K=0$^+$ molecular band** → **low statistics** → new experiments are needed.

Continuation of the ^{10}Be molecular band

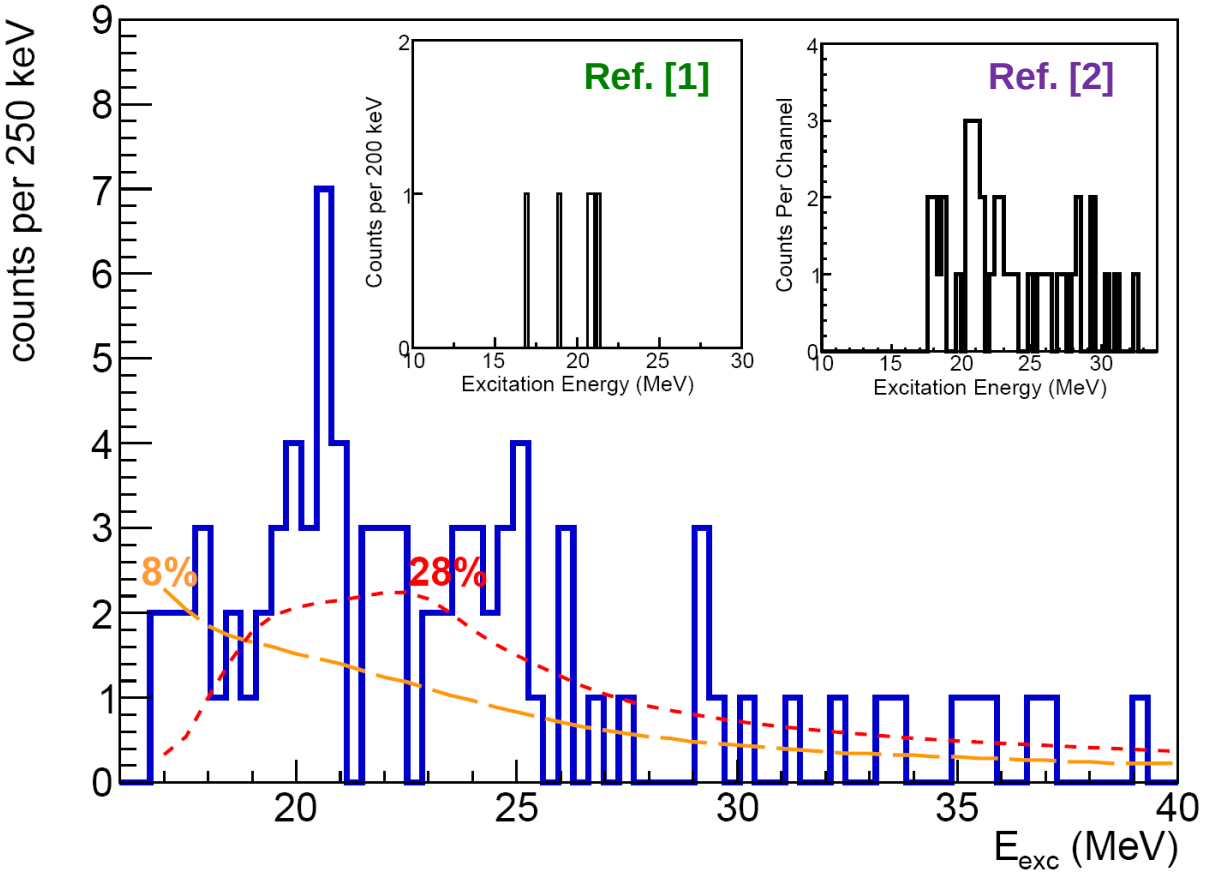
As a **final test** → complete **MonteCarlo simulation** with the **13.5 MeV** state (shadowed histogram) → nice **agreement** with the experimental data (black points)



E_x (MeV)	J^{π}	Γ_{tot} (MeV)
9.51	2^{+} [1,2,3]	0.14 [4,5]
10.6 [5]		0.20 [8,4]
11.8	(4^{+}) [5,6]	0.12 [5,6]
≈ 13.5	6^{+} [9], this work	≈ 0.15 this work

[1] M. Freer et al., Phys. Rev. **C 63**, 034301 (2001)
[2] S. Ahmed et al., Phys. Rev. **C 69**, 024303 (2004)
[3] N. Curtis et al. Phys. Rev. **C 73**, 057301 (2006)
[4] N. Curtis et al, Phys. Rev. **C 64**, 044604 (2001)
[5] Brookhaven National Laboratory, National Nuclear Data Center
[6] D.R. Tilley et al., Nucl. Phys. **A 745**, 155 (2004)
[7] M. Freer et al., Phys. Rev. Lett. **96**, 042501 (2006)
[8] N. Soic et al., Europhys Lett. **34**, 7 (1996)
[9] G.V. Rogachev et al., J. Phys.: Conf. Ser. **569**, 012004 (2014)

^{16}C 2 body disintegration → ^{6}He+^{10}Be break-up channel → **low statistics** data.



Experimental data
Efficiency ^{1}H target
Efficiency ^{12}C target

[1] N. I. Ashwood et al., Phys. Rev. **C 70**, 0644607 (2004)
[2] P.J. Leask et al., Jour. Phys. G: Nucl. Part. Phys. **27**, B9 (2001)

Low statistics results → 20,6 MeV bump

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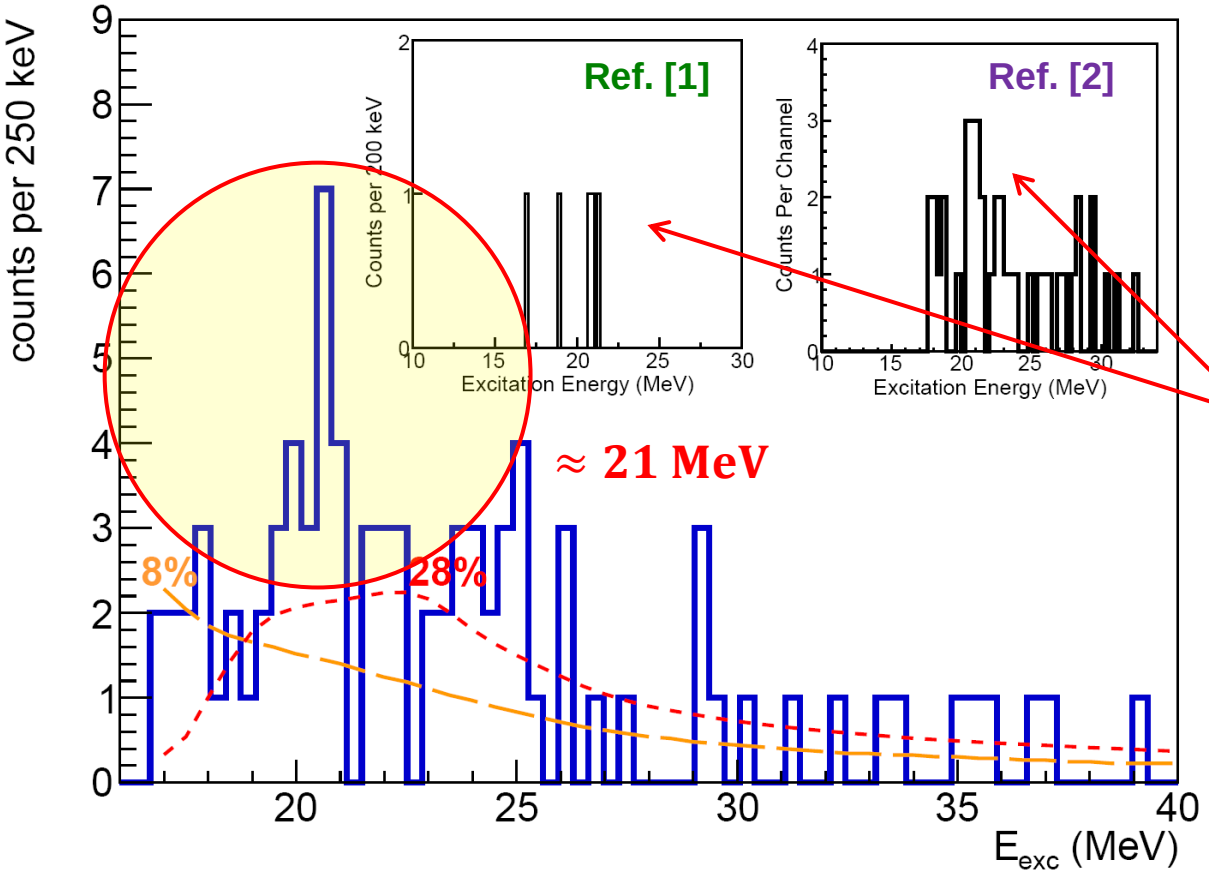

Experimental data
Efficiency ^{1}H target
Efficiency ^{12}C target

Enhancement at about **20.6 MeV** → possible **agreement** with the previous low statistics measurement s **[1][2]**→ **more statistics** required to confirm the suggestion.

[1] N. I. Ashwood et al., Phys. Rev. **C 70**, 0644607 (2004)
[2] P.J. Leask et al., Jour. Phys. G: Nucl. Part. Phys. **27**, B9 (2001)

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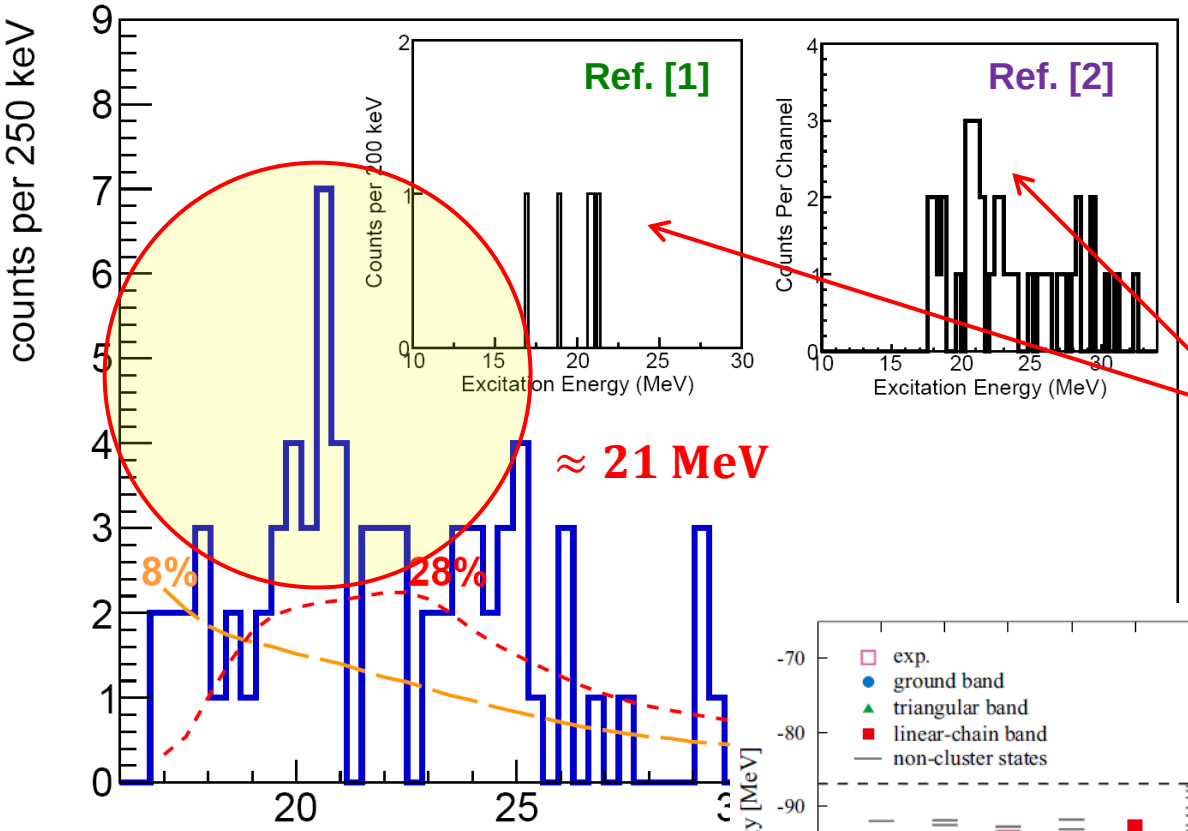

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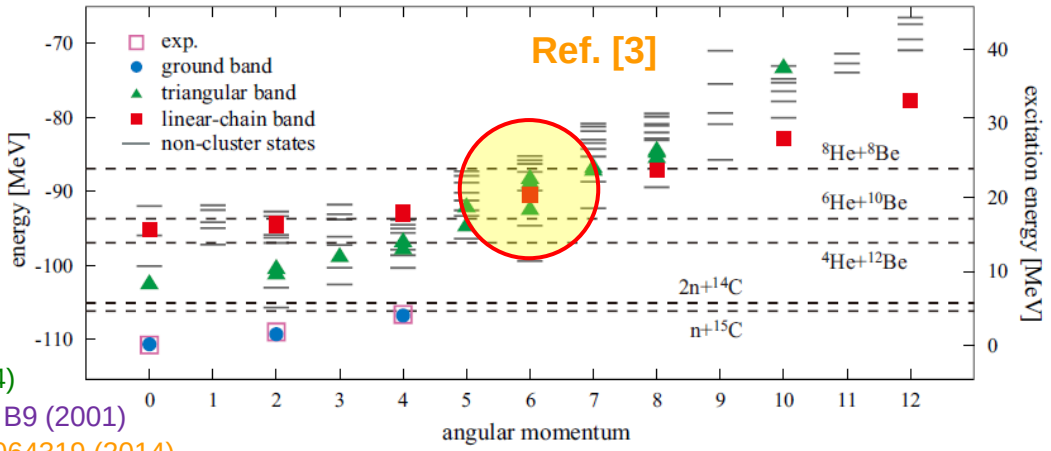
Efficiency ^{12}C target

Enhancement at about **20.6 MeV** → possible **agreement** with the previous low statistics measurement s **[1][2]**→ **more statistics** required to confirm the suggestion.



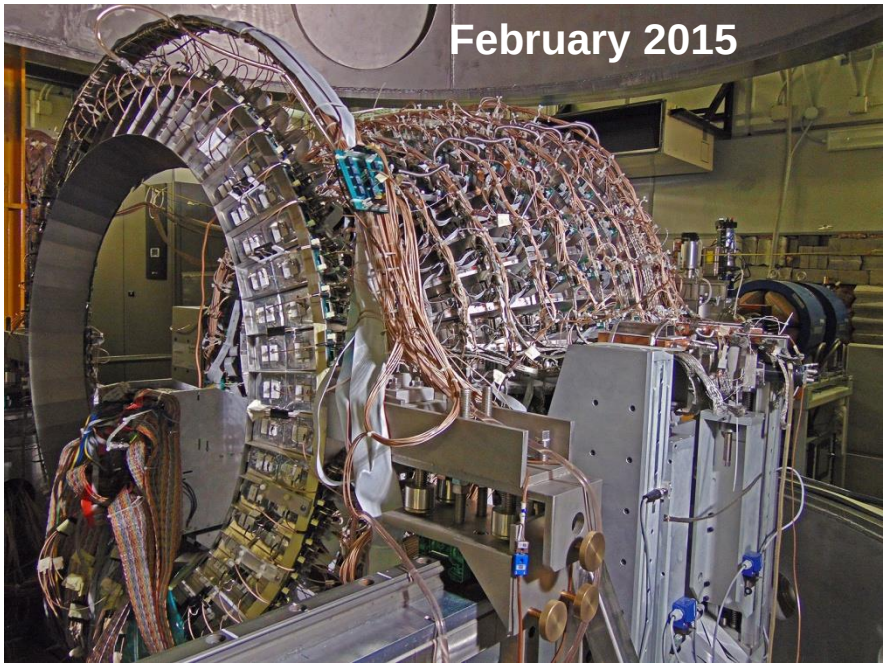
[1] N. I. Ashwood et al., Phys. Rev. **C 70**, 0644607 (2004)
[2] P.J. Leask et al., Jour. Phys. G: Nucl. Part. Phys. **27**, B9 (2001)
[3] T. Baba, Y. Chiba and M. Kimura , Phys. Rev. **C 90**, 064319 (2014)

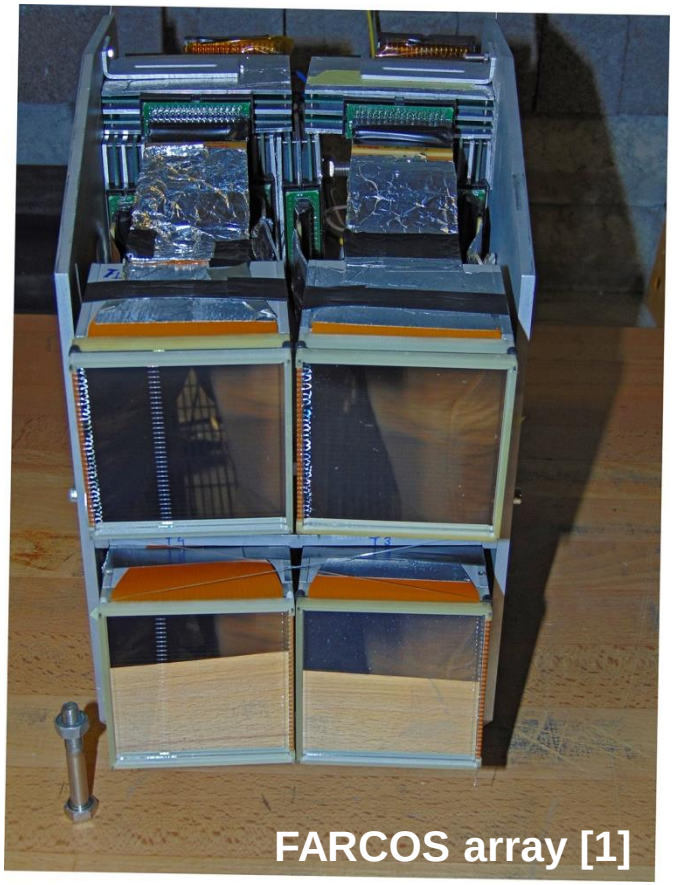
Low statistics results → 20,6 MeV bump

Future perspectives: the CLIR experiment @ LNS

CLIR (**C**lustering in **L**ight **I**on **R**eactions) February– June 2015 → new investigation of cluster structures in nuclear reactions induced by FRIBs beams at INFN-LNS

FARCOS array **[2]** coupled to **CHIMERA** device → **improved** energy and angular resolution → **Double Sided Silicon Strip Detectors (DSSSD)+CsI** detectors.





[1] G. Verde et al., J. Phys. Conf. Ser. **420**, 0112158 (2013)

CLIR (**C**lustering in **L**ight **I**on **R**eactions) February– June 2015 → new investigation of cluster structures in nuclear reactions induced by FRIBs beams at INFN-LNS

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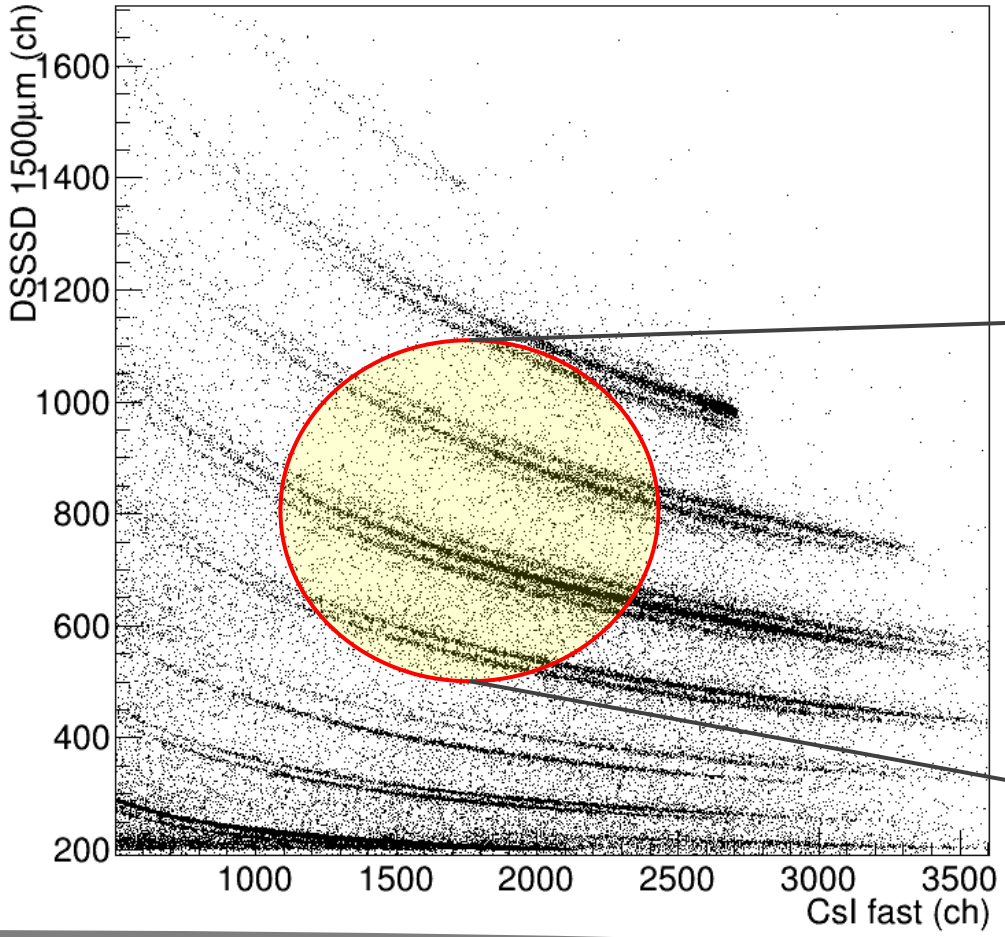
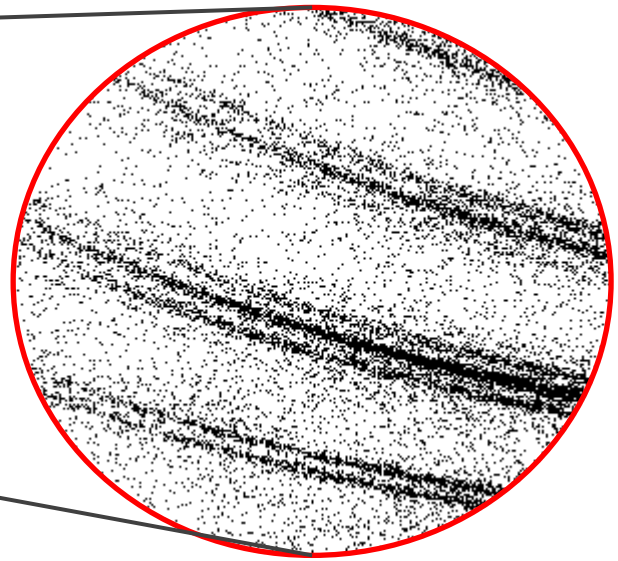


ΔE-E identification plot with FARCOS DSSSD (1500 μm) vs CsI fast
^{16}O+C @ 55 MeV/u



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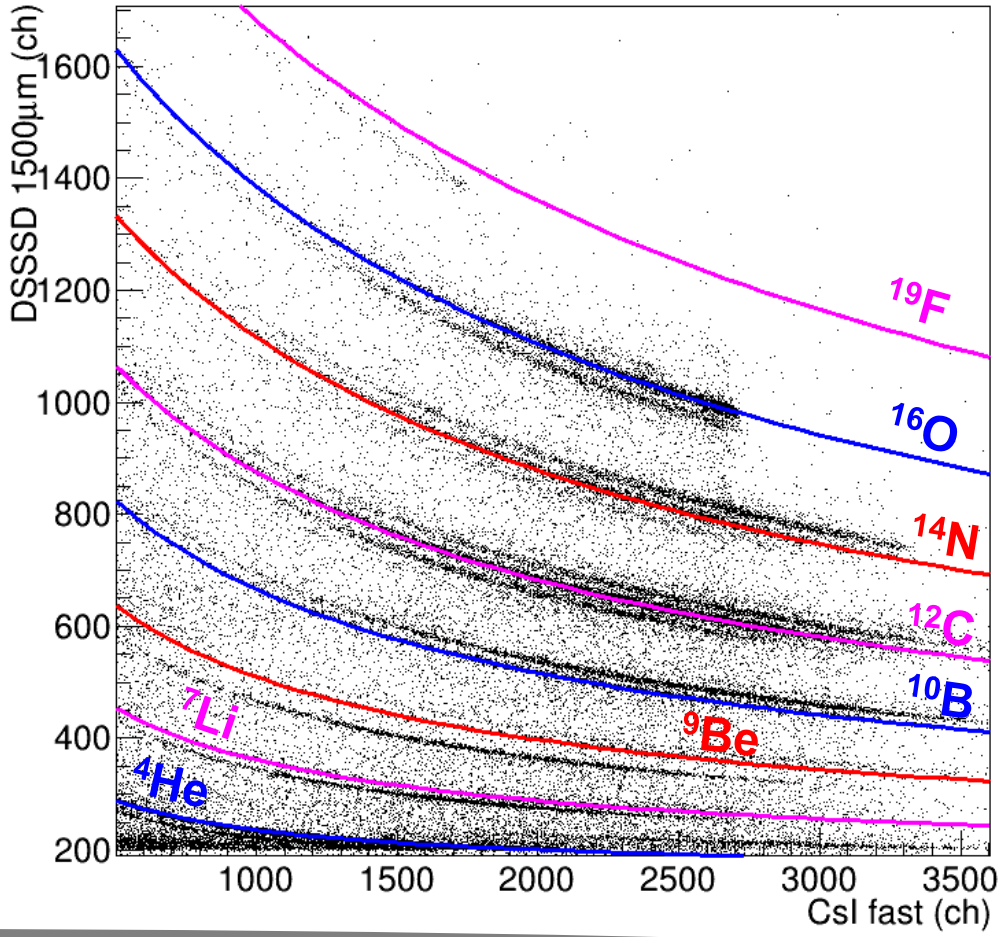

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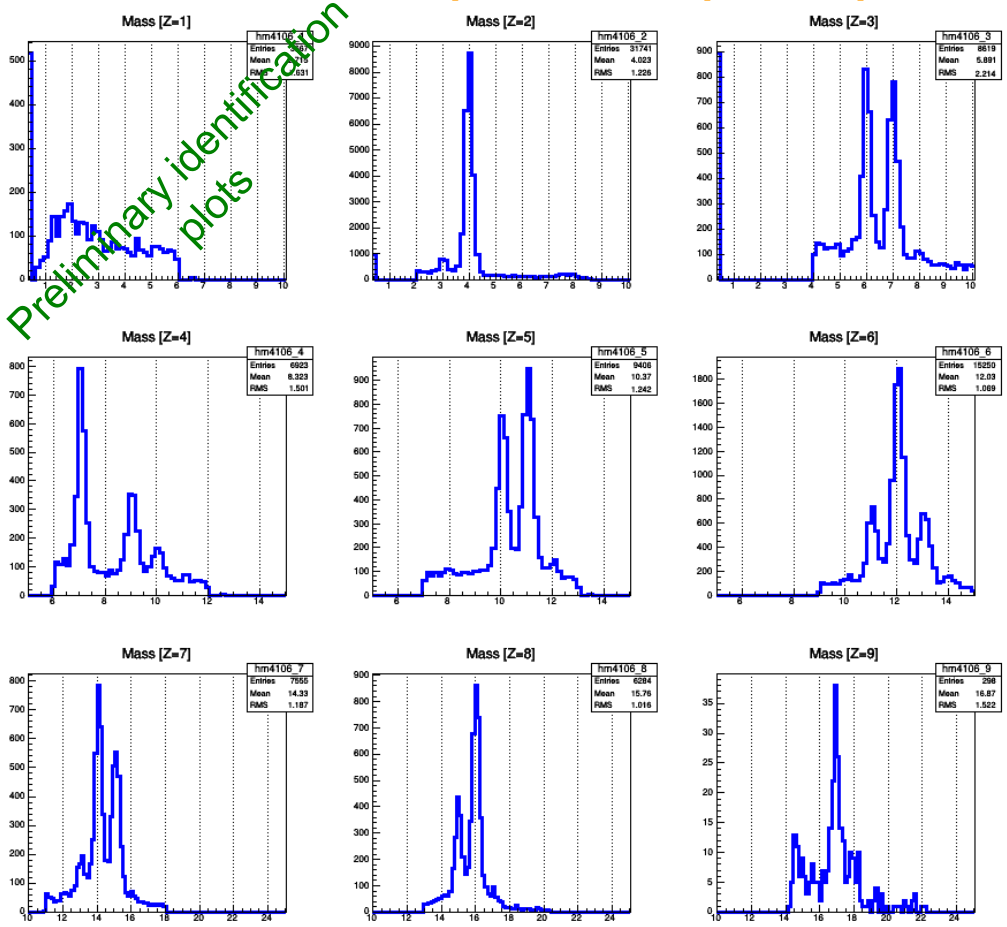


- We have performed a **spectroscopic investigation** of **^{10}Be** and **^{16}C** via **cluster break-up** reactions at intermediate energies at **INFN-LNS**.

- The cocktail beam was provided by the **FRIBs facility** → particle by particle identification → **tagging system** coupled to **CHIMERA 4π** multi-detector.

- **^{6}He-^{4}He correlations** → structure of **^{10}Be** → **new possible 6^{+} state** at about **13.5 MeV** excitation energy → possible agreement with a recent R-matrix calculation **[1]** (resonant elastic scattering data) → energetic compatibility with a 6^{+} further member of the **^{10}Be molecular band**.

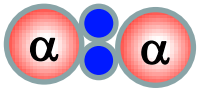
- **^{6}He-^{10}Be correlations** → structure of **^{16}C** → very **low statistics** data → agreement with previous experiment enhancement at about **21 MeV** excitation energy.

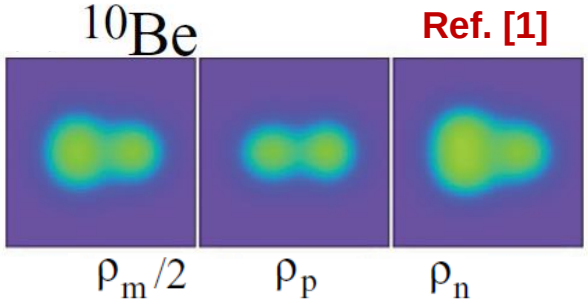
Future Perspectives:
CLIR experiment INFN-LNS February 2015 – June 2015
Data Analysis still in progress…

[1] G. Rogachev et al., J. Phys.: Conf. Ser. **569**, 012004 (2014)

Thank you for your attention.

Further Slides

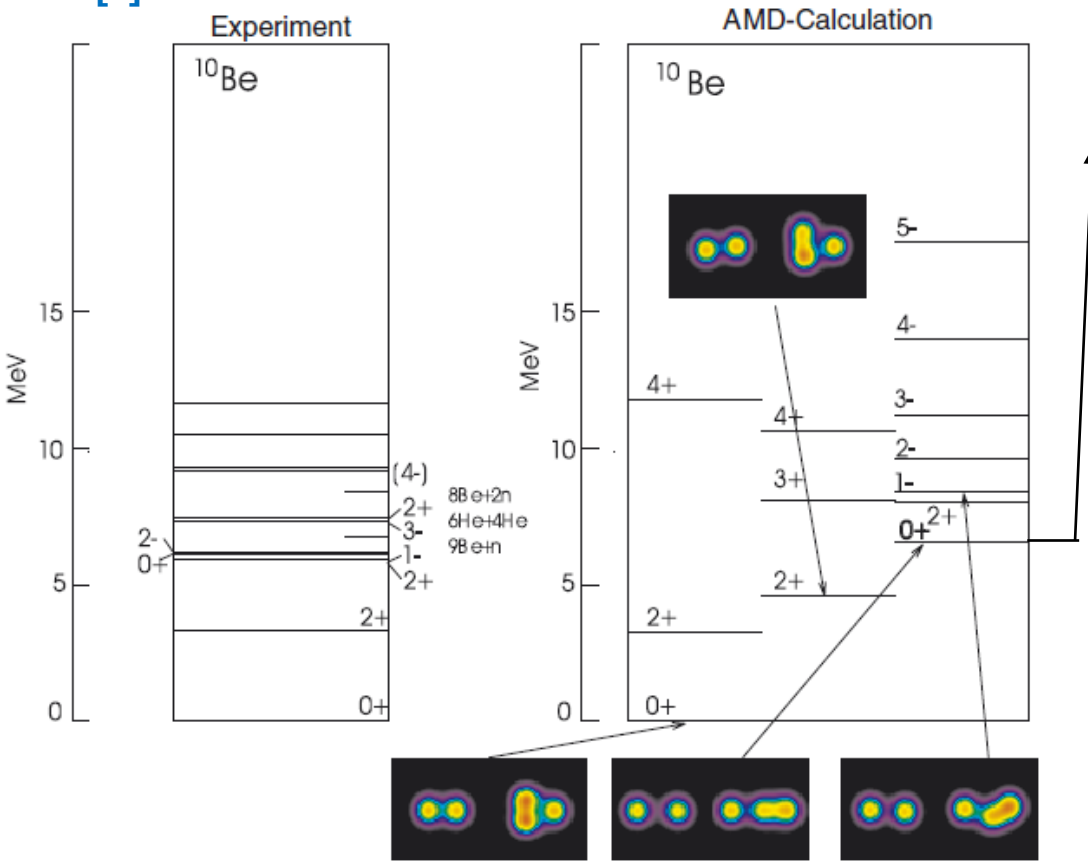




Ref. [1]

AMD+VAP calculations → high deformation in GS→ **[1]** → $K^{\pi}=0^{+}$ rotational band **[2]**

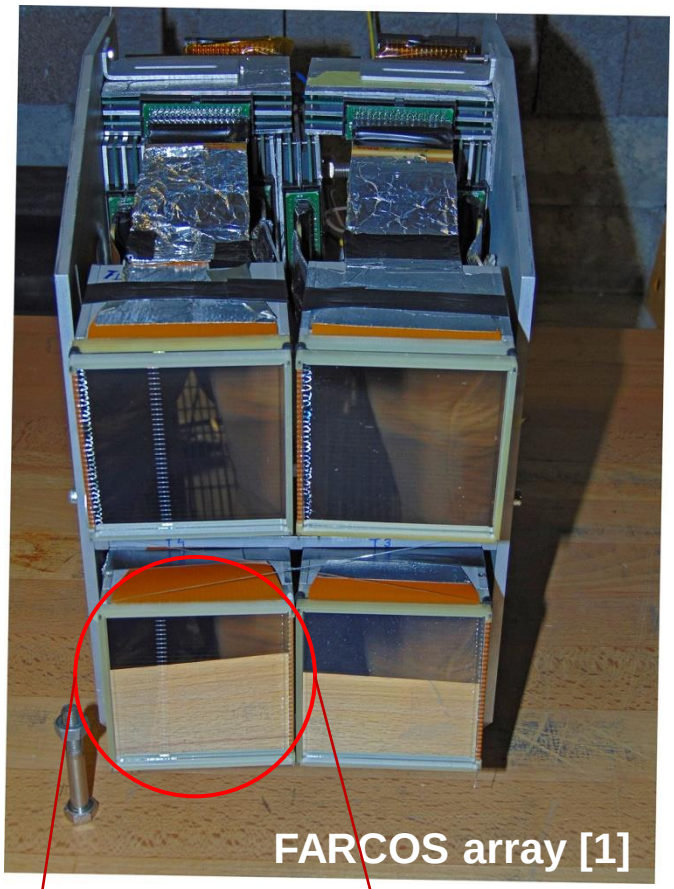
Ref. [3]

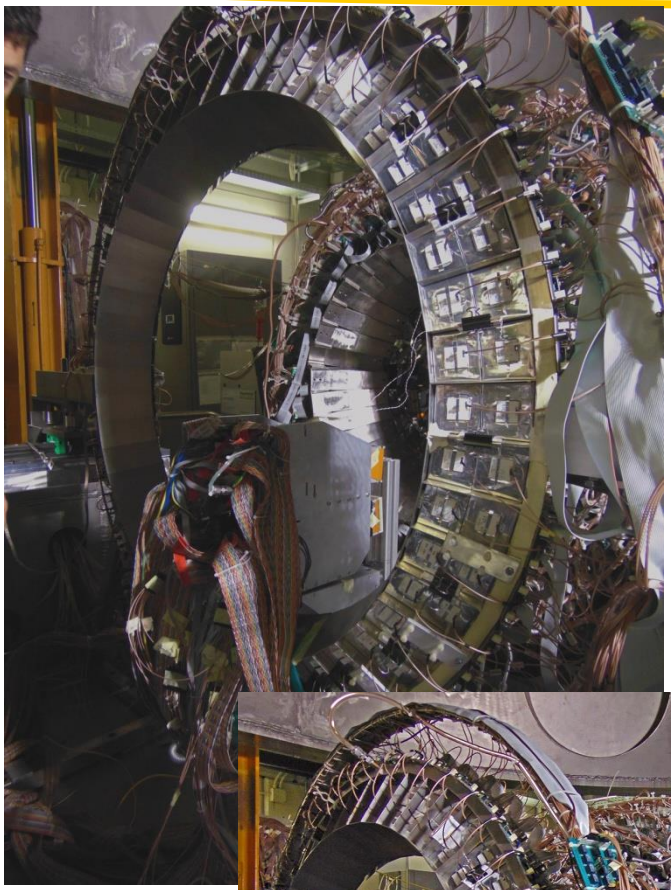


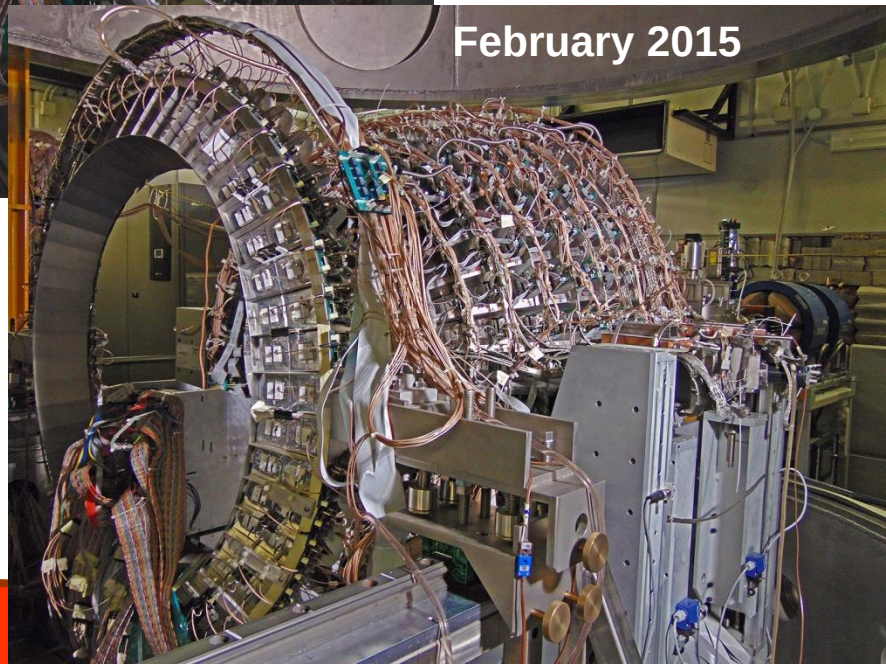
High α-α cluster distance **[3]** → strong **molecular structure** → $K^{\pi}=0^{+}$ **molecular band** built on the 6.1793 MeV **[4]** state

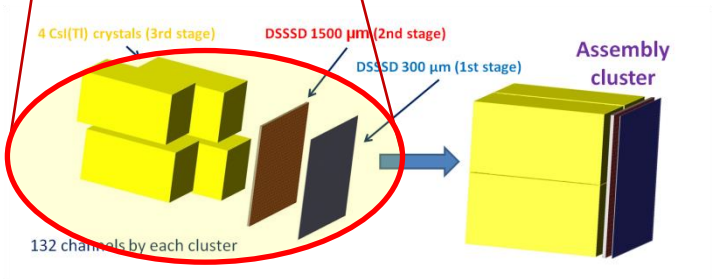
[1] Y. Kanada-En'yo, Phys. Rev. **C 91**, 014315 (2015)
[2] D. Suzuki et al., Phys. Rev. **C 87**, 054301 (2013)
[3] Y. Kanada-En'yo, J. Phys. G **24**, 1499 (1998)
[4] M. Freer et al., Phys. Rev. Lett. **96**, 042501 (2006)

Future Perspectives: the CLIR experiment @ INFN-LNS



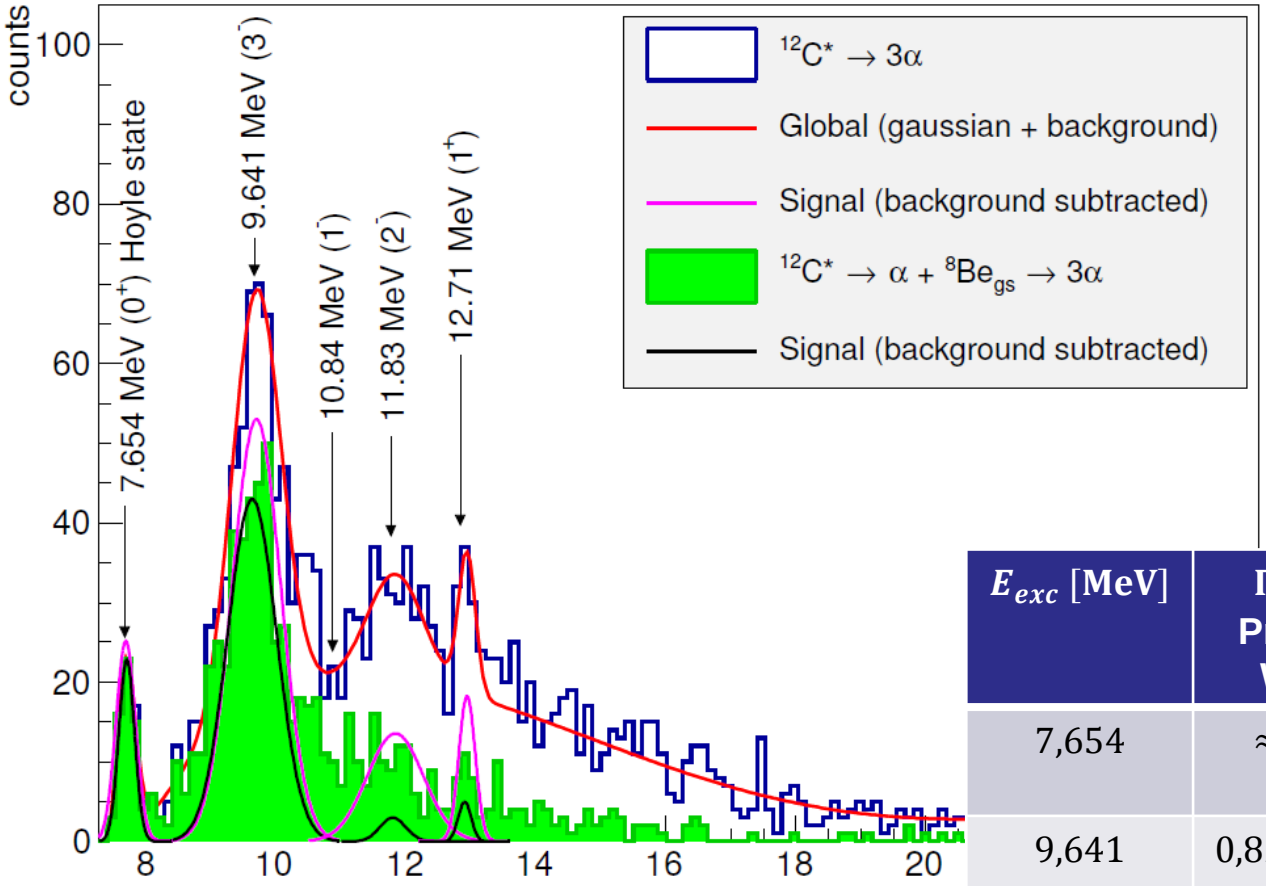






[2] G. Verde et al., J. Phys. Conf. Ser. **420**, 0112158 (2013)

^{12}C → study of branching ratios for cluster disintegration → $^{12}C^* \rightarrow {}^{8}Be_{gs}{}^{*} + \alpha \rightarrow 3\alpha$



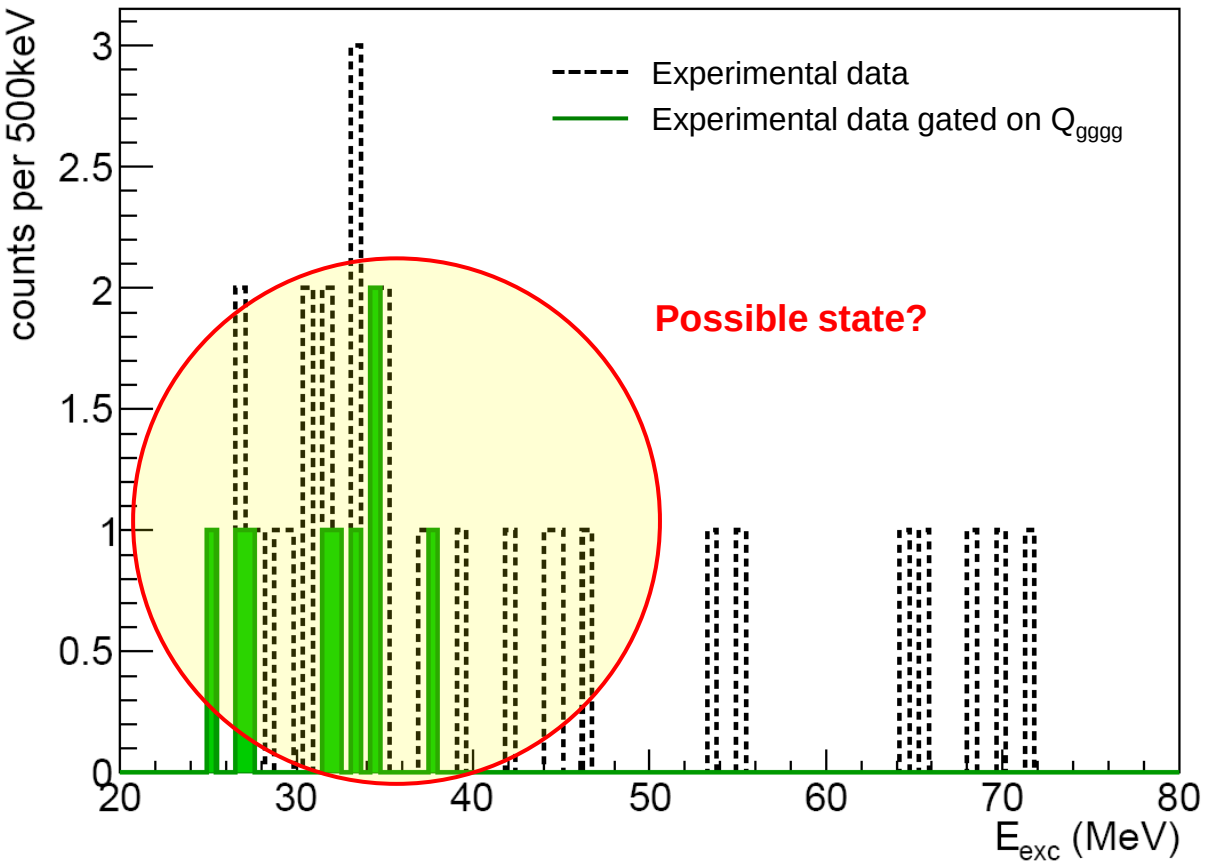
No evidence of Equal Energy Sharing (**EES**) for the **Hoyle state**

E_{exc} [MeV]	$\Gamma_{\alpha_0}/\Gamma_{\alpha}$ Present Work	$\Gamma_{\alpha_0}/\Gamma_{\alpha}$ Refs
7,654	$\approx 1{,}00$	$> 0{,}995$ [1,2]; $0{,}83 \pm 0{,}05$ [3]
9,641	$0{,}82 \pm 0{,}09$	0,972 [4]
11,83	$0{,}10 \pm 0{,}21$	≈ 0 [4]
12,71	$0{,}22 \pm 0{,}24$	≈ 0 [4]

[1] O.S. Kirsebom et al., Phys. Rev. Lett. **108**, 202501 (2012).
[2] J. Manfredi et al., Phys. Rev. **C 85**, 037603 (2012).
[3] Ad.R. Raduta et al., Phys. Lett. B **705**, 65 (2011).
[4] M. Freer et al., Phys. Rev. **C 76**, 034320 (2007).

Superior limit for EES decay < 2%!!!

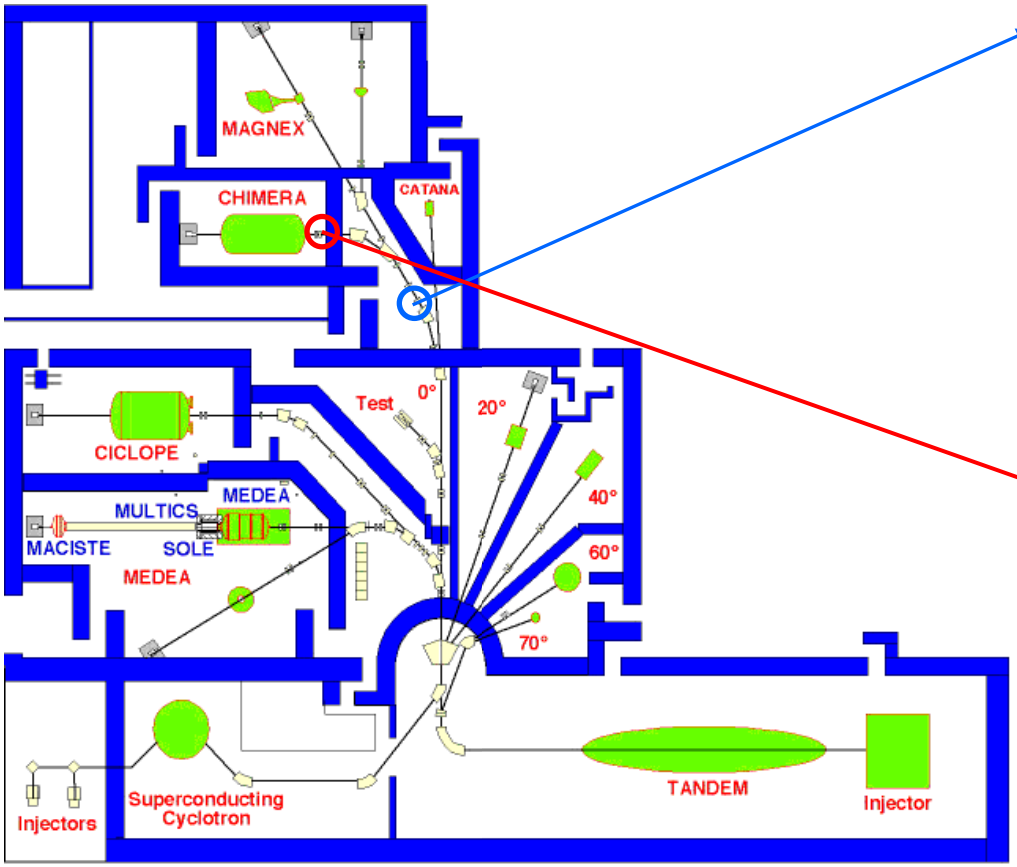
^{16}C 3 body disintegration → ^{6}He+^{6}He+^{4}He break-up channel → **low statistics** data → **no data** present in literature .

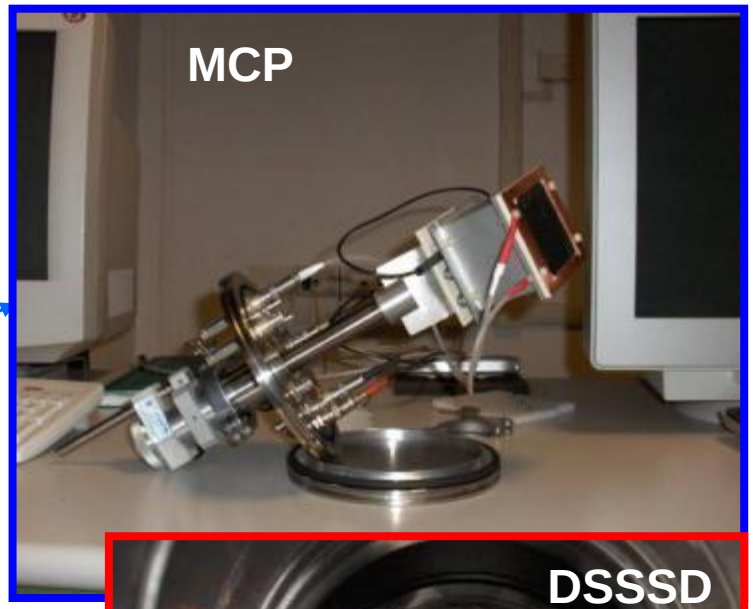


Very low statistics → no data in literature

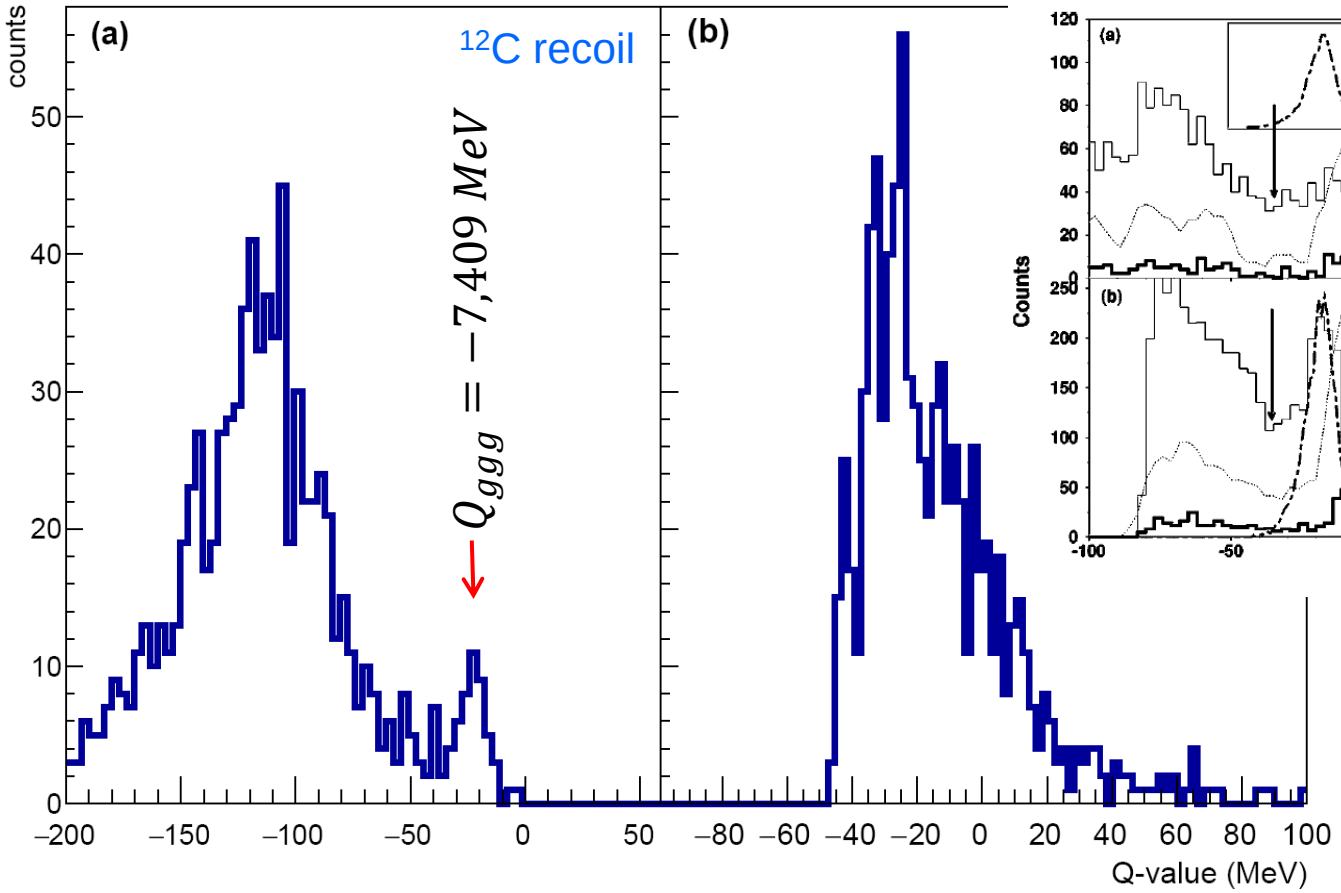
Univ. degli Studi di Napoli Federico II & INFN - Napoli

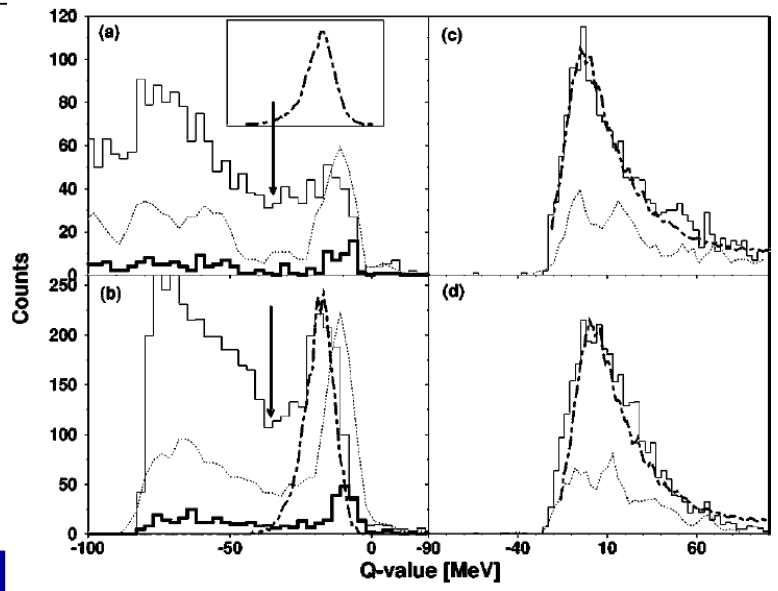
Istituto Nazionale di Fisica Nucleare
LNS - Laboratori Nazionali del Sud





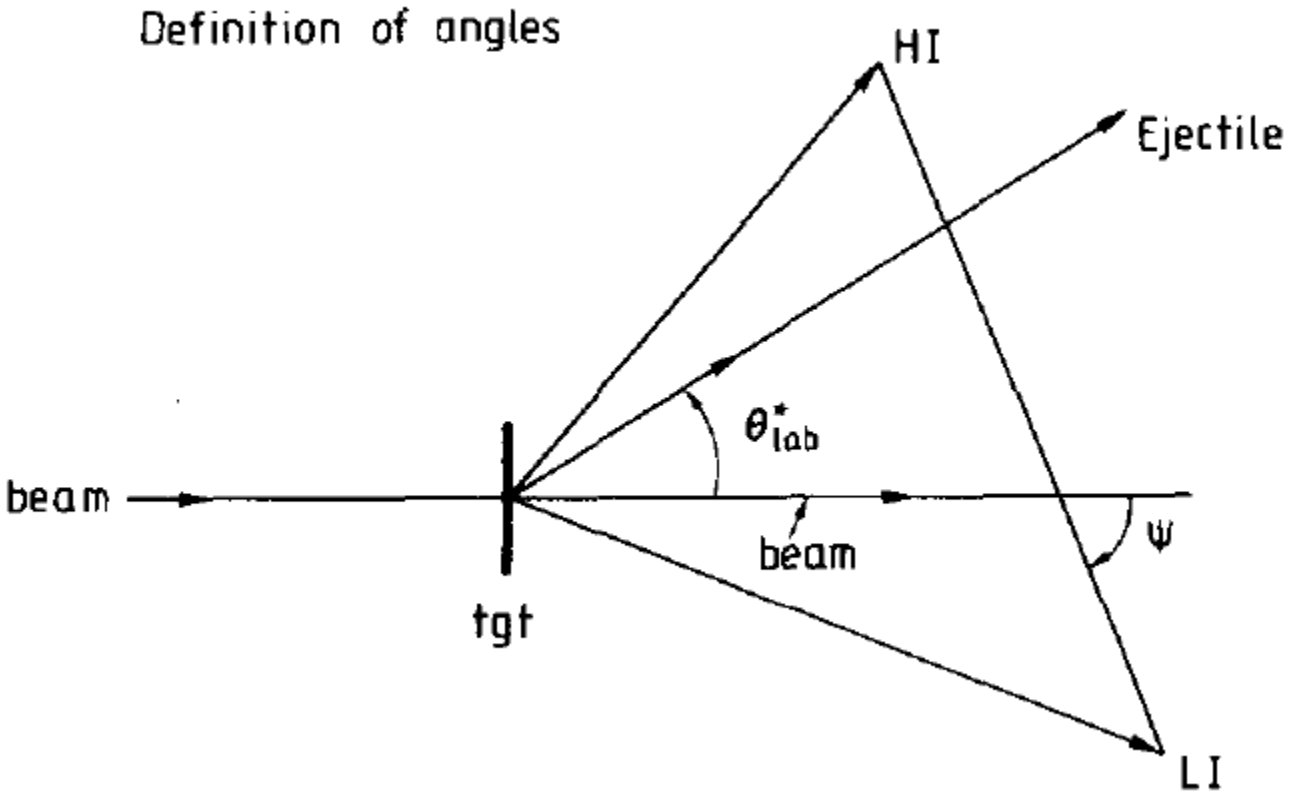
Q-value spectrum for ^{6}He+^{4}He decay





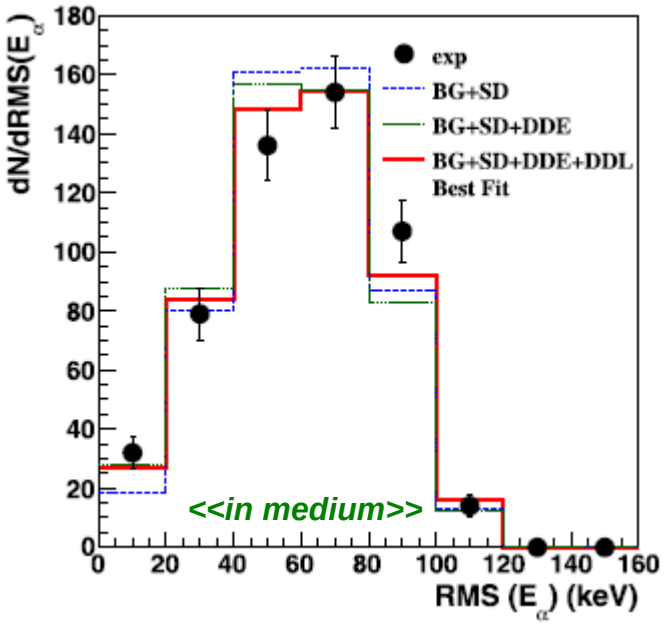
Ref. [1]

[1] M. Freer et al., Phys. Rev. **C 63**, 034301 (2001)

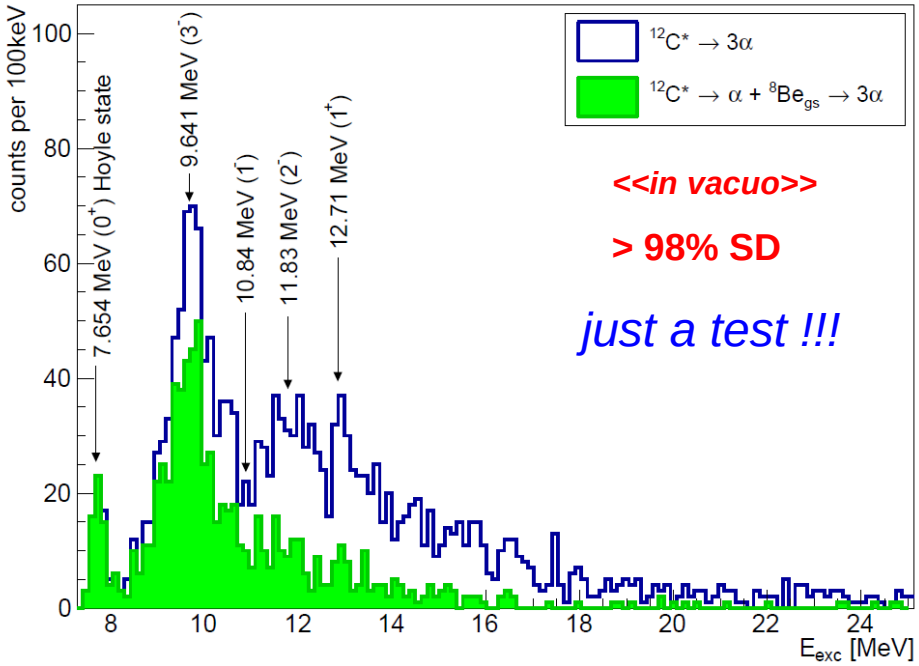


from ref. S. Marsh and W.D.M. Rae, Phys. Lett. B 153, 21 (1985)

^{12}C case: structure of the Hoyle State (*sequential* vs direct emission) *in vacuo* and *in medium* → signature of BEC ???



AdR. Raduta et al, PLB 705 (2011)



	Experiment	DDE (%)	DDΦ (%)	DDL (%)	DD (%)	C.L. (%)
v	Freer et al	...	...	...	< 4	99.5
m	Raduta et al	7.5 ± 4.0	...	9.5 ± 4.0	17.0 ± 5.0	...
v	Manfredi et al	< 0.45	1.3 ± 0.9 (< 3.9)	...	...	99.75
v	Kirsebom et al	< 0.09	< 0.5	< 0.09	< 0.5	95
v	Rana et al	0.3 ± 0.1	0.60 ± 0.09	< 0.1	0.91 ± 0.14	99.75
v	Itoh et al	< 0.08	< 0.2	...	< 0.2	95

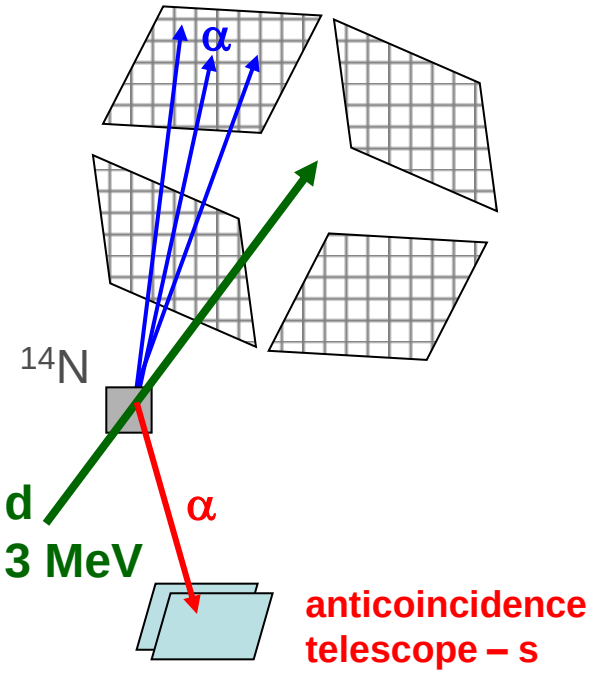
from Itoh et al, PRL 113 (2014)

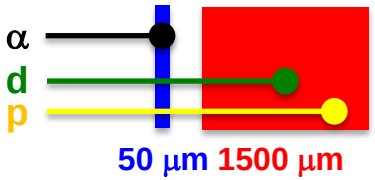
Could we shed light on this situation?

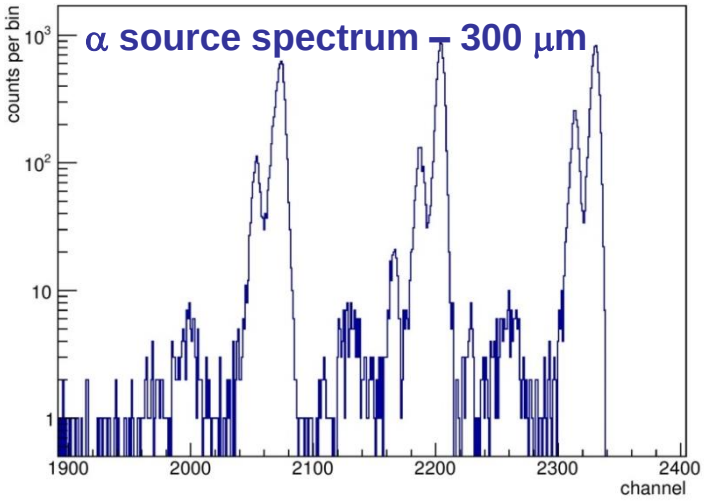
^{12}C case: idea on a *high resolution* new measurement at *low energy*

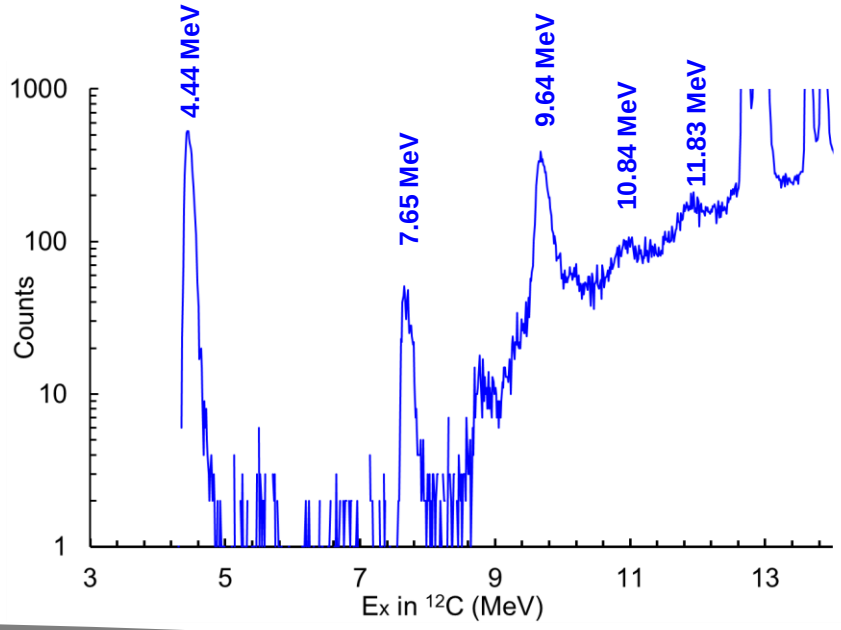
^{14}N(d,α)^{12}C @ CN accelerator, LNL Italy

4 high resolution Si pad wall (OSCAR)

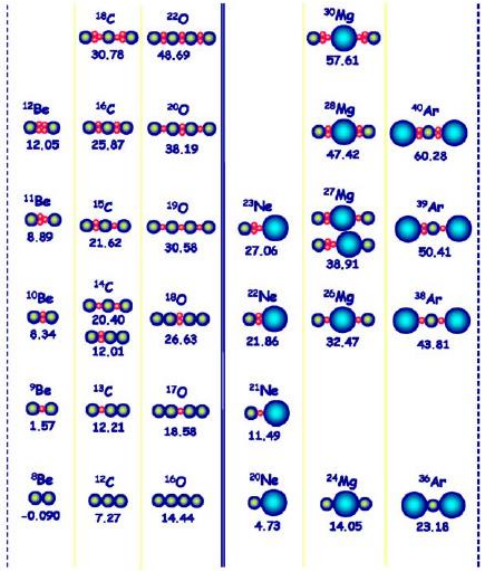






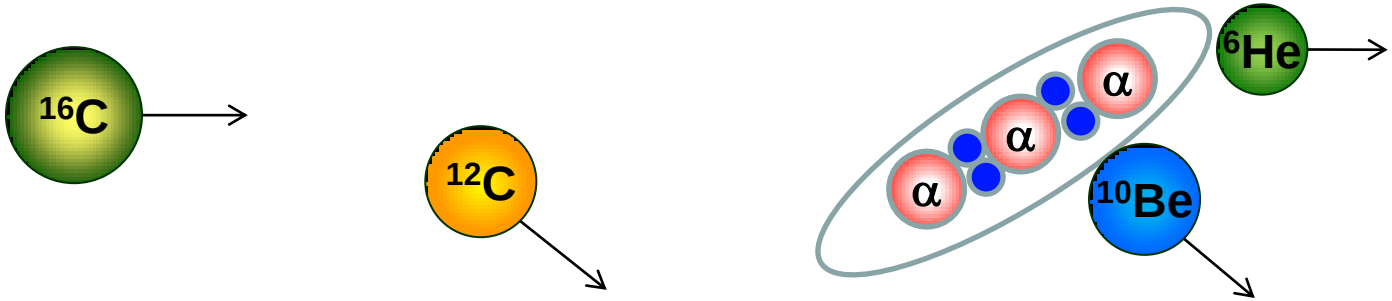


Branching ratios of other ^{12}C* states



molecular structures suggested near the **disintegration thresholds** → **Ikeda scheme** → Basic Idea:
projectile sequential **break-up reactions** to explore ^{10}**Be** and ^{16}**C** cluster structure.

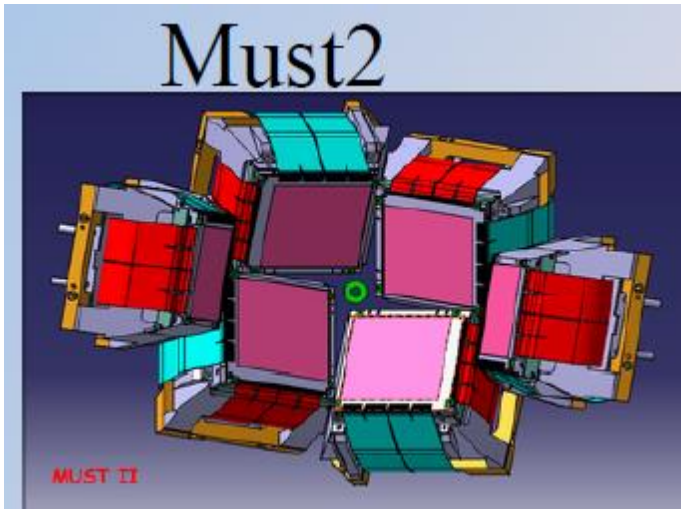
Sequential break-up reaction: **anelastic excitation** of projectile nucleus above the particle emission threshold → **sequential disintegration** of projectile nucleus

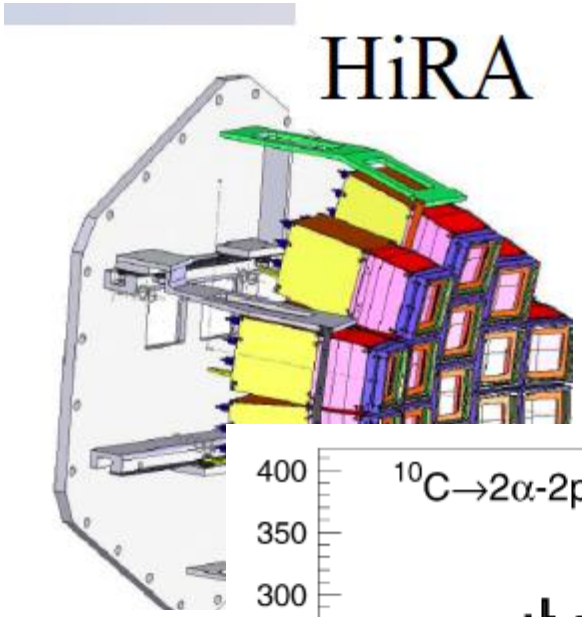


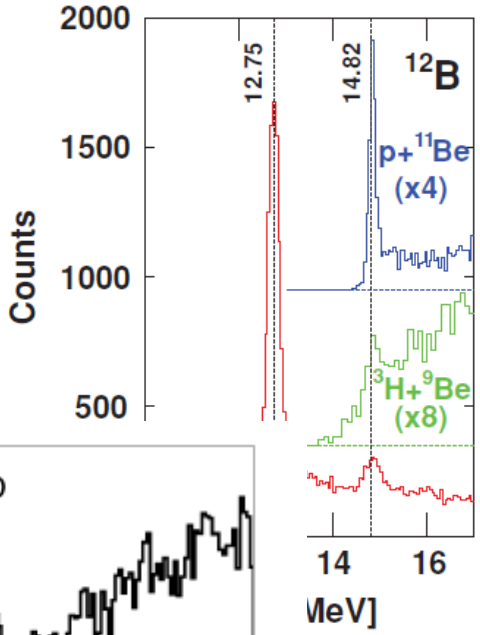
To obtain the **spectroscopy** of break-up nucleus→**relative energy** analisys:

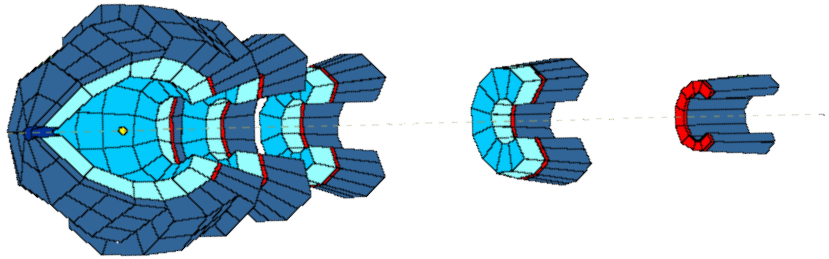
$$E_{exc} = E_{rel} + E_{thr}$$

In Flight beams → short living **RI** → ***inelastic scattering*** or ***reactions*** on targets followed by ***break-up*** → **cluster decay** of nuclei → ***correlations*** (high ***energy*** and ***angular*** resolution)

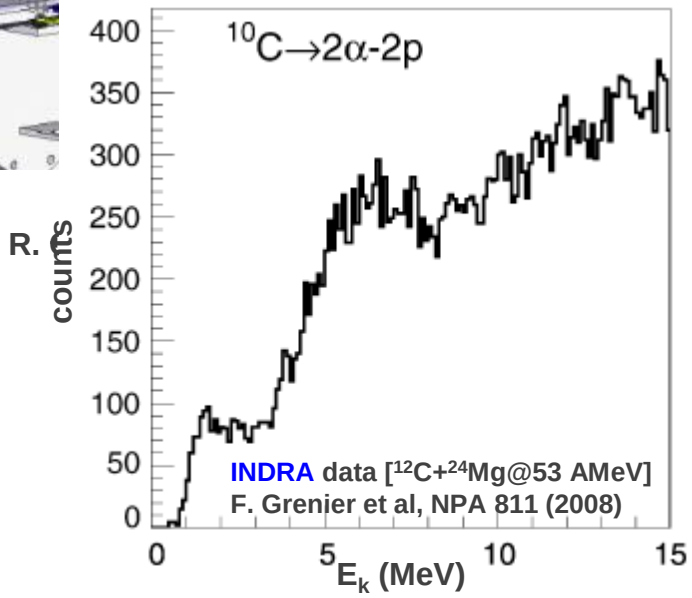








Indra



Correlations → ^{10}Be and ^{16}C structure