^{10}Be and ^{16}C structures investigated by means of break-up reactions at INFN-LNS

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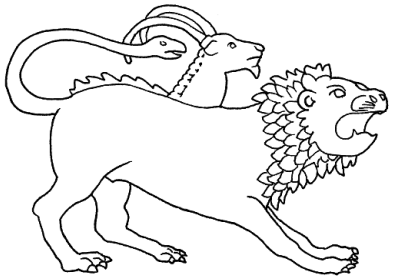
for the CHIMERA Collaboration



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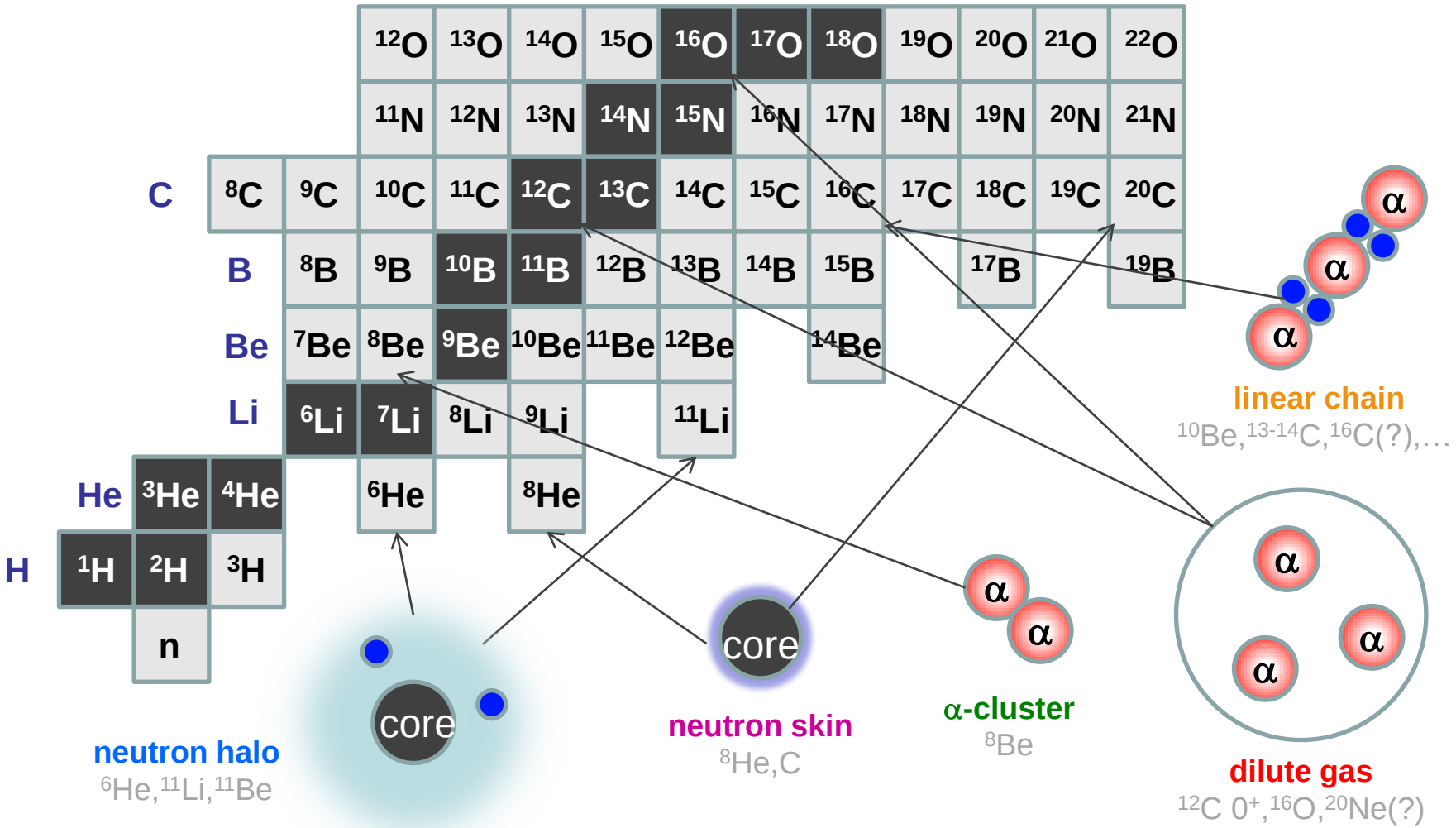
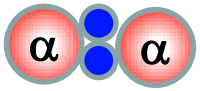
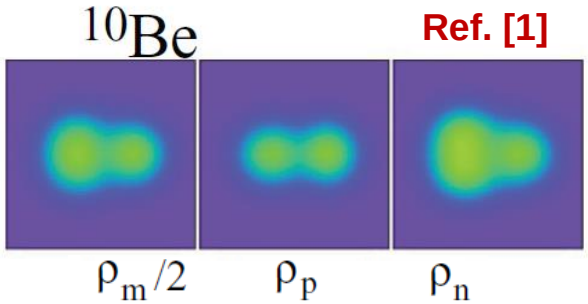
Complexity of nuclear force → **dominant** phenomena of nucleon-nucleon ***correlations*** which determine a spatial re-organization of the nucleons in bounded **sub-units** → the ***constituent clusters***.



Very big variety of physical phenomena that need investigations

The ^{10}Be case

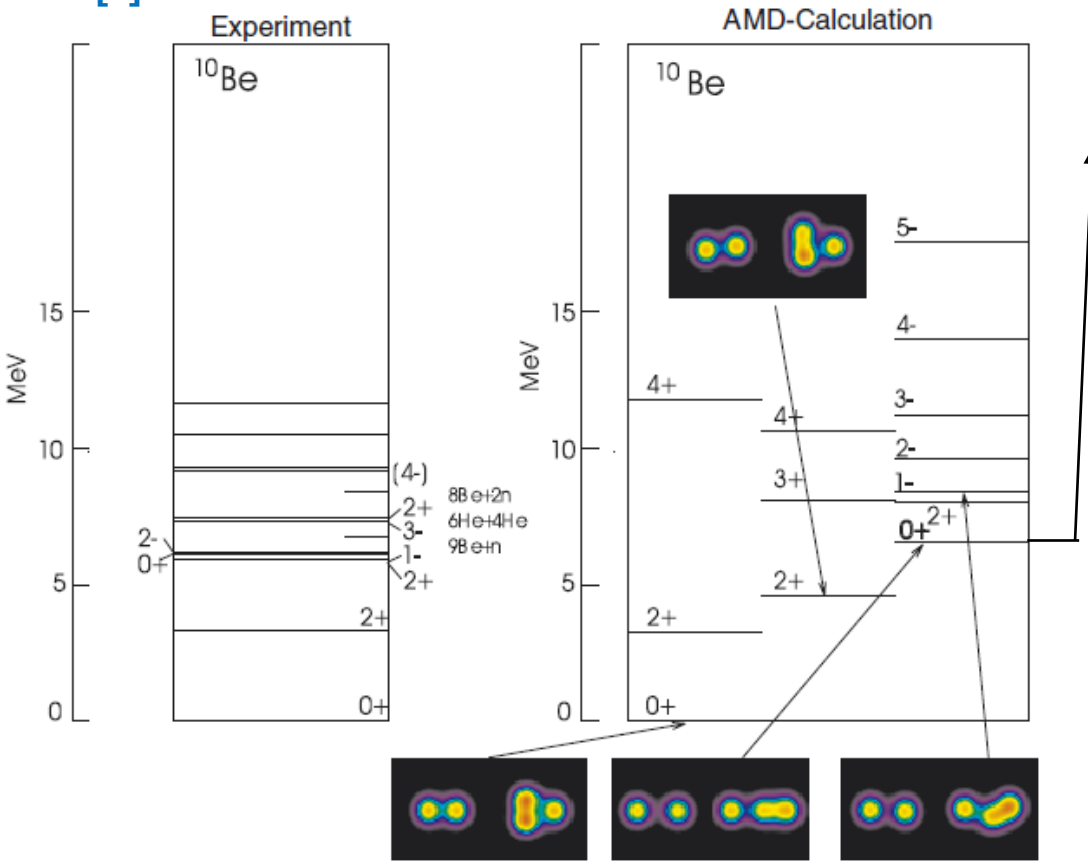




Ref. [1]

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

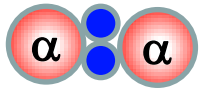
Ref. [3]

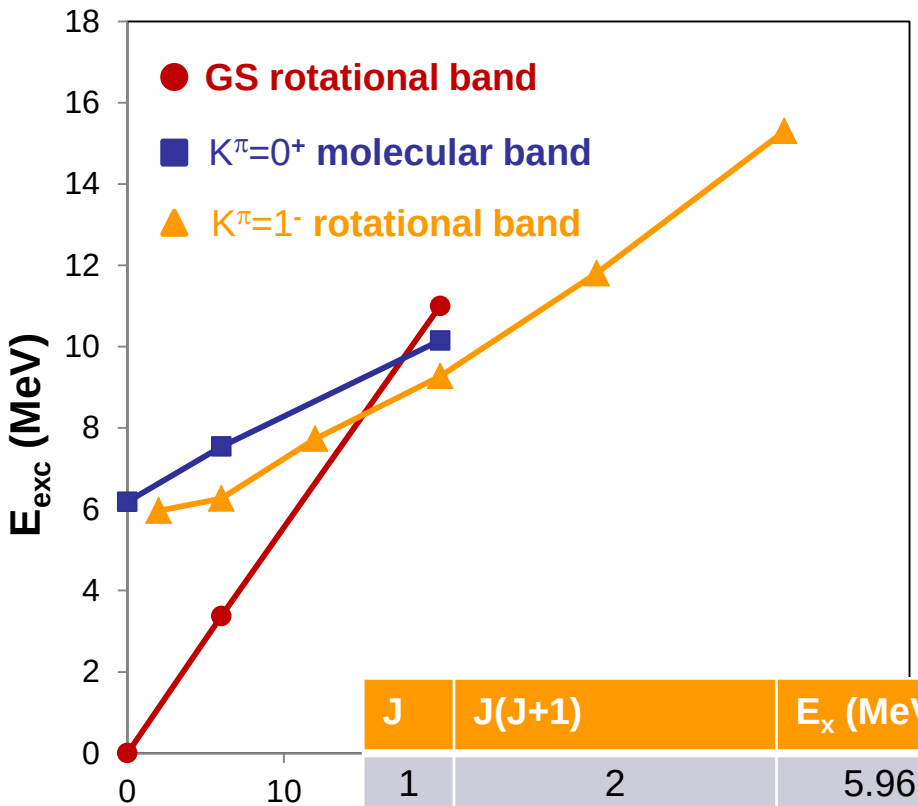


High α-α cluster distance **[3]** → strong **molecular structure** → $K^{\pi}=0^{+}$ **molecular band** built on the 6.1793 MeV **[4]** state

[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)

The ^{10}Be case





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

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

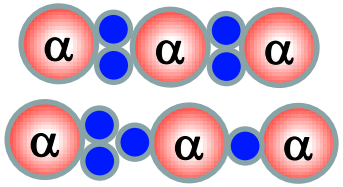
J	J(J+1)	E_x (MeV)
0	0	0
2	6	3.37
4	20	11.78 [14]→11 [2] (?)

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

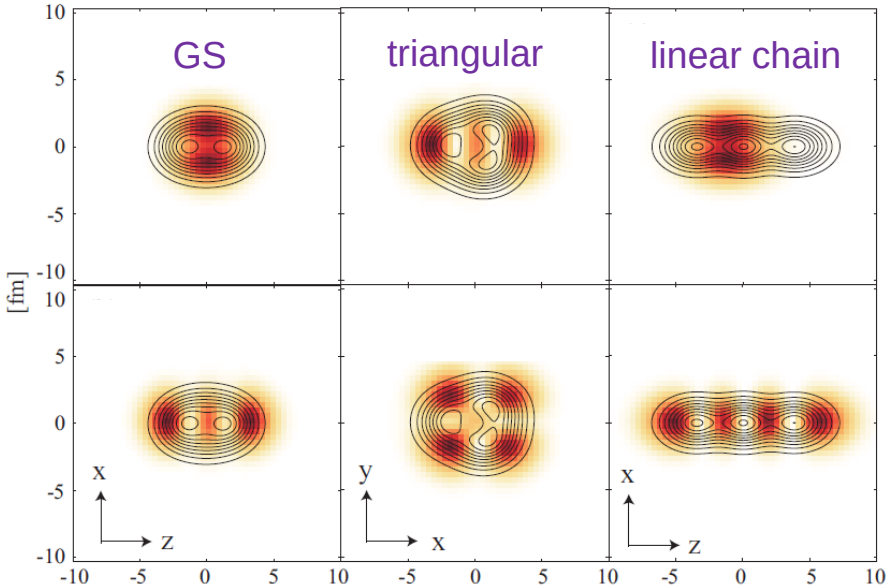
[1] Y. Kanada-En'yo, Phys. Rev. **C 91**, 014315 (2015)
[2] D. Suzuki et al., Phys. Rev. **C 87**, 054301 (2013)
[3] Y. Kanada-En'yo, J. Phys. G **24**, 1499 (1998)
[4] M. Freer et al., Phys. Rev. Lett. **96**, 042501 (2006)
[5] N. Soic et al., Europhys Lett. **34**, 7 (1996)
[6] M. Freer et al., Phys. 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

The ^{16}C case

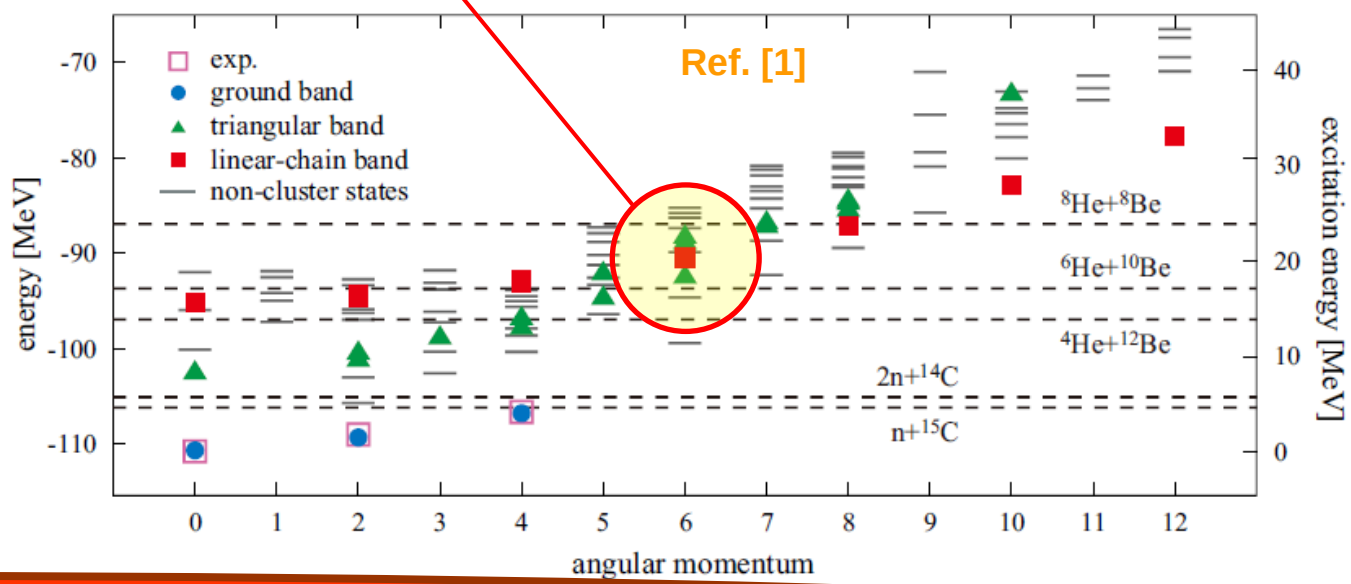


possible **cluster configurations**→**AMD** calculations **Ref. [1]**



[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.**



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

Experimental evidence still missing!

FRIBs Facility @ LNS

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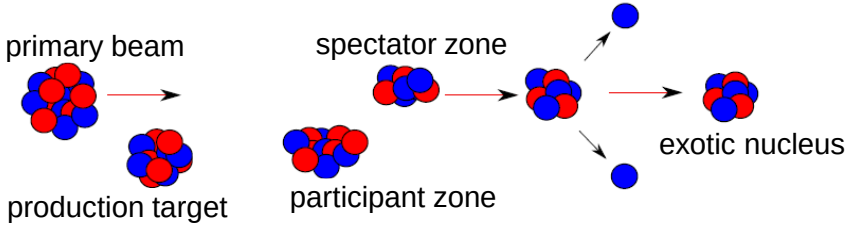
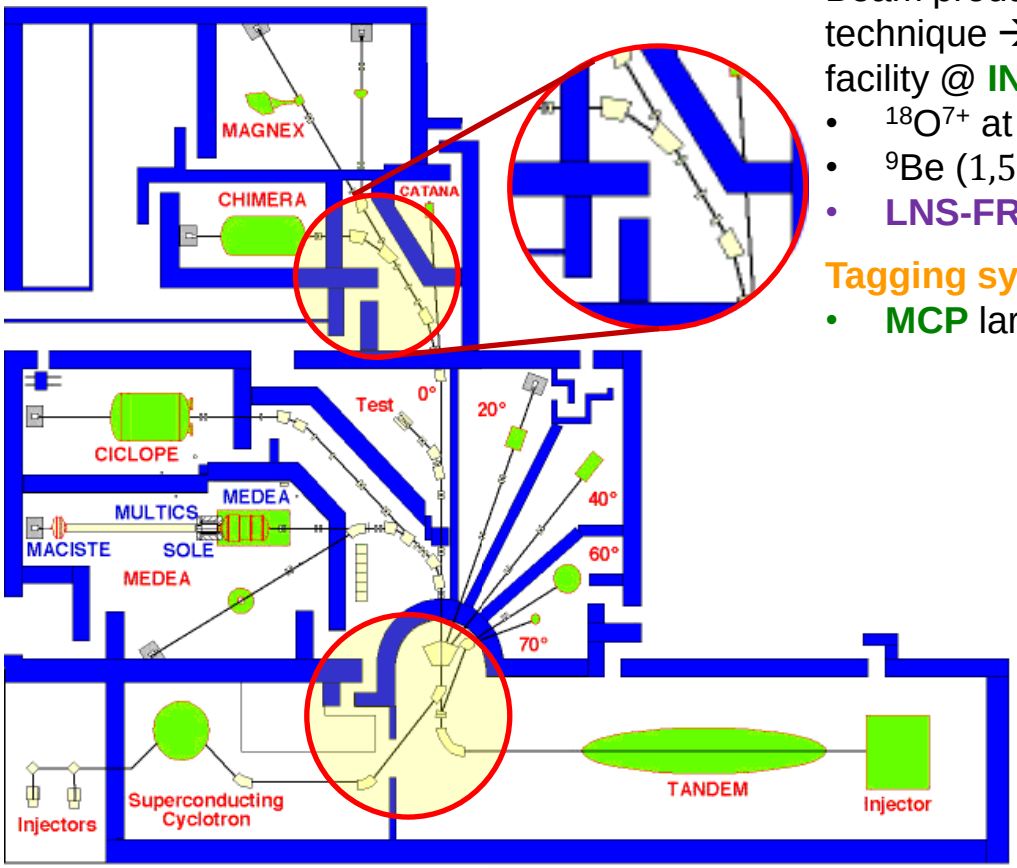
LNS - Laboratori Nazionali del Sud



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

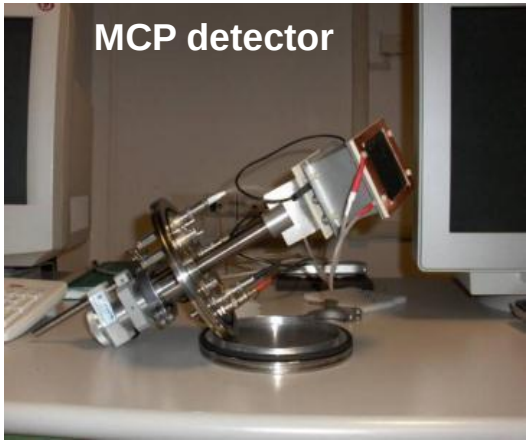


Beam production→**IFF** (**I**n **F**light **F**ragmentation) technique → **FRIBs** (**F**light **R**adioactive **I**on **B**eams) facility @ **INFN-LNS**:

- $^{18}O^{7+}$ at $56\ MeV/u$ (superconducting cyclotron K800);
- ^{9}Be ($1{,}5\ mm$ tickness) production target;
- **LNS-FRS** (**F**ragment-**R**ecoil **S**eparator) $B\rho \approx 2{,}8Tm$;

Tagging system **[1]** (particle by particle identification):

- **MCP** large area detector;



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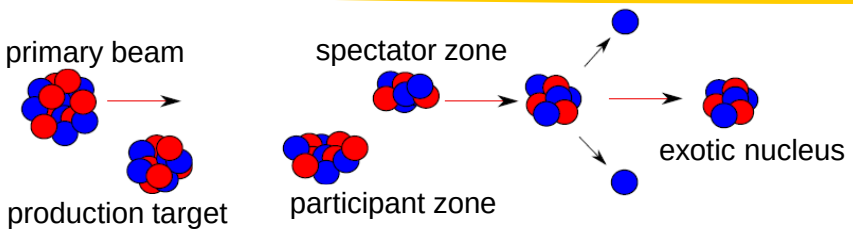
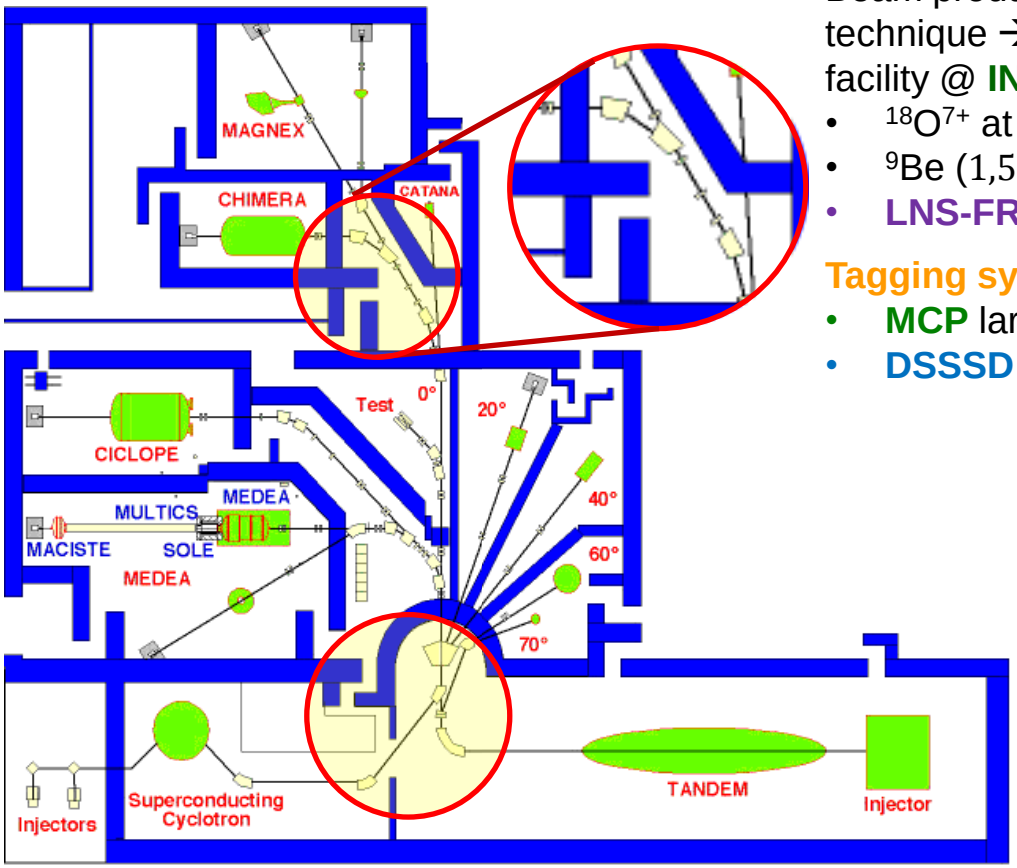


[1] I. Lombardo et al., Nuc. Phys. **B 215**, 272 (2011).



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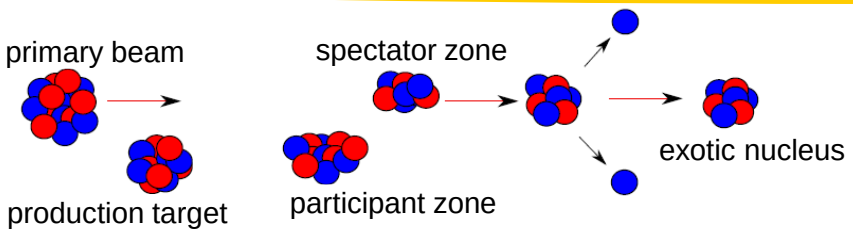
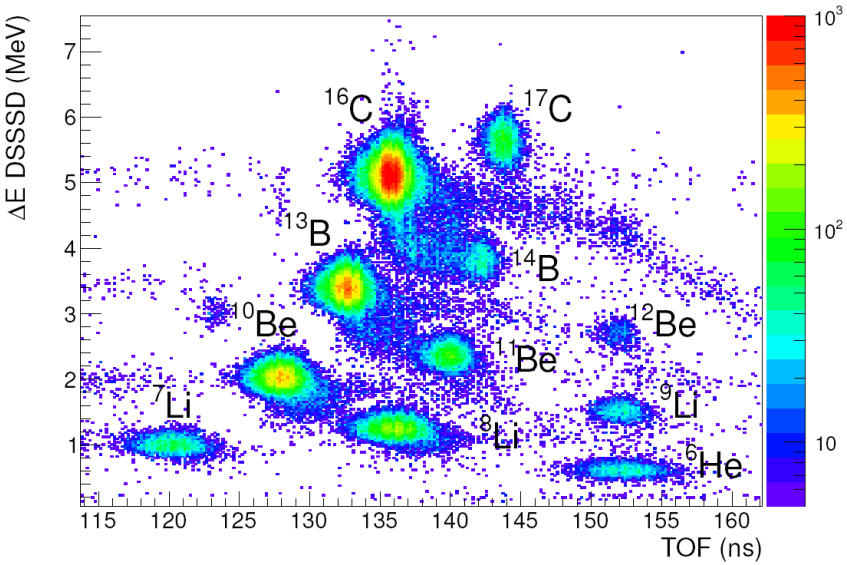


[1] I. Lombardo et al., Nuc. Phys. **B 215**, 272 (2011).



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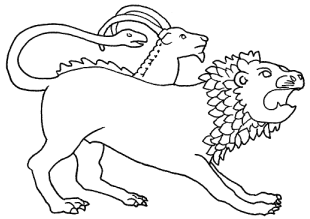
Identification (ΔE-ToF) plot FRIBs **cocktail beam** → good performances.
High **exotic beams** intensity:

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

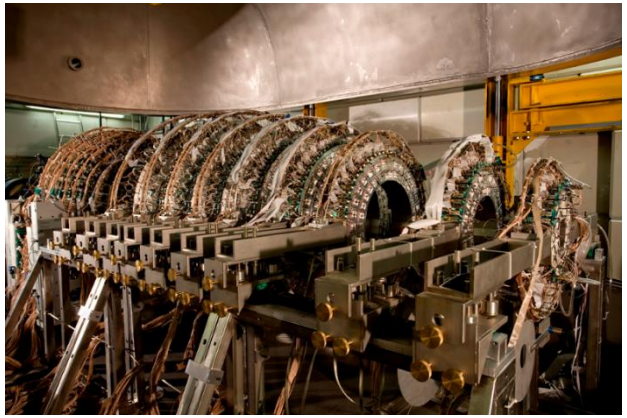
Complete cocktail beam identification

The CHIMERA 4π multi-detector



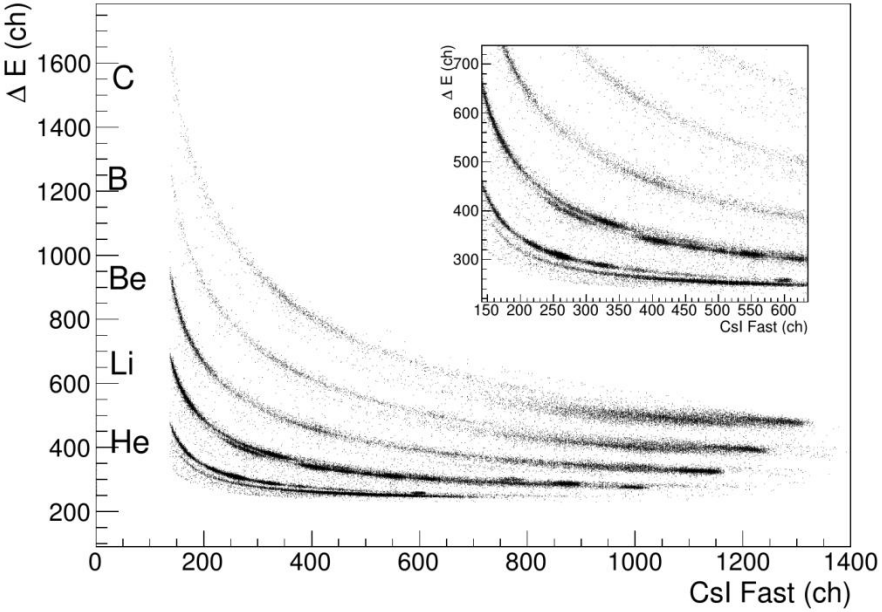
CHIMERA (**C**harged **H**eavy **I**on **M**ass **E**nergy **R**esolving **A**rray) **[1,2]**

[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** ($30^{\circ} < \theta \leq 176^{\circ}$);

First **3 forward rings**→144 telescopes ($1^{\circ} \leq \theta \leq 7^{\circ}$) complete azimuthal coverage→ **ΔE-E identification** technique.



Good **^{4}He – ^{6}He** separation → beryllium line mainly dominated by **^{10}Be**

ΔE-E identification → good isotopic separation

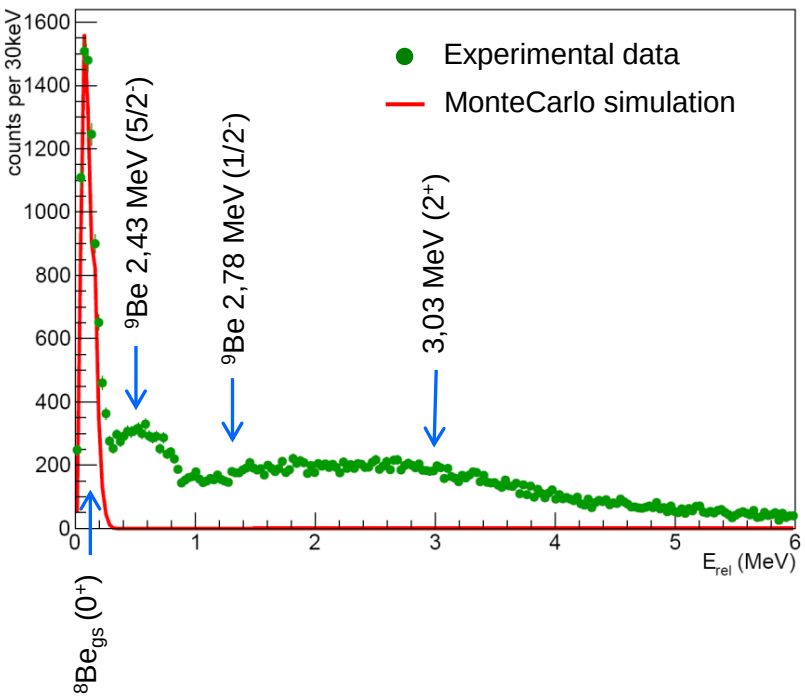
Check on self-conjugated nuclei

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

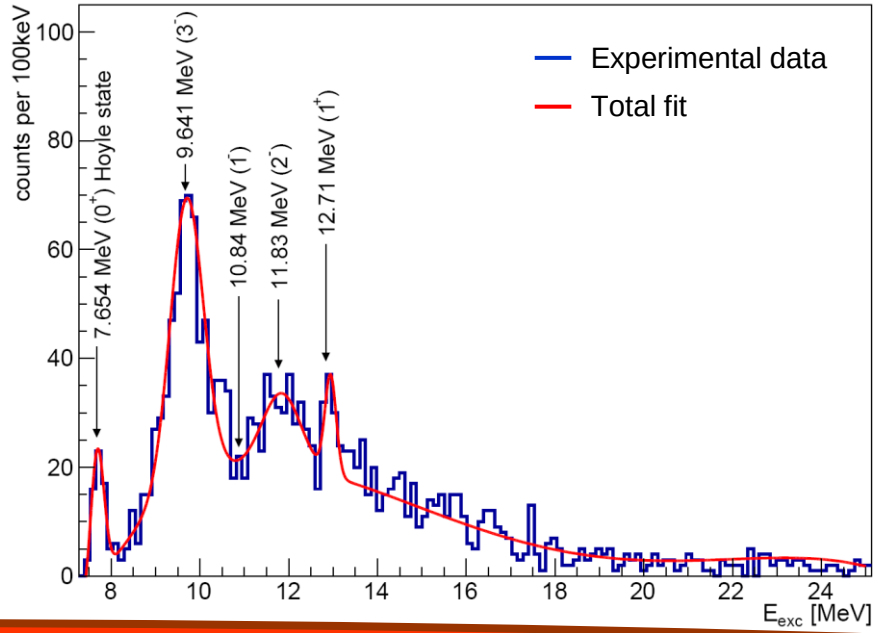
- **2α correlations** → the **^{8}Be** spectroscopy:

  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**?



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



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

Check on self-conjugated nuclei

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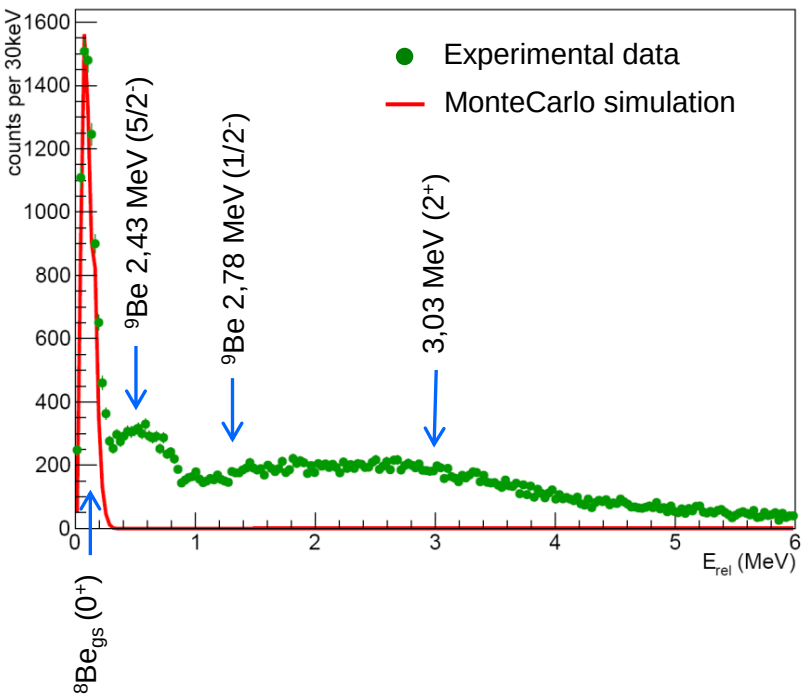

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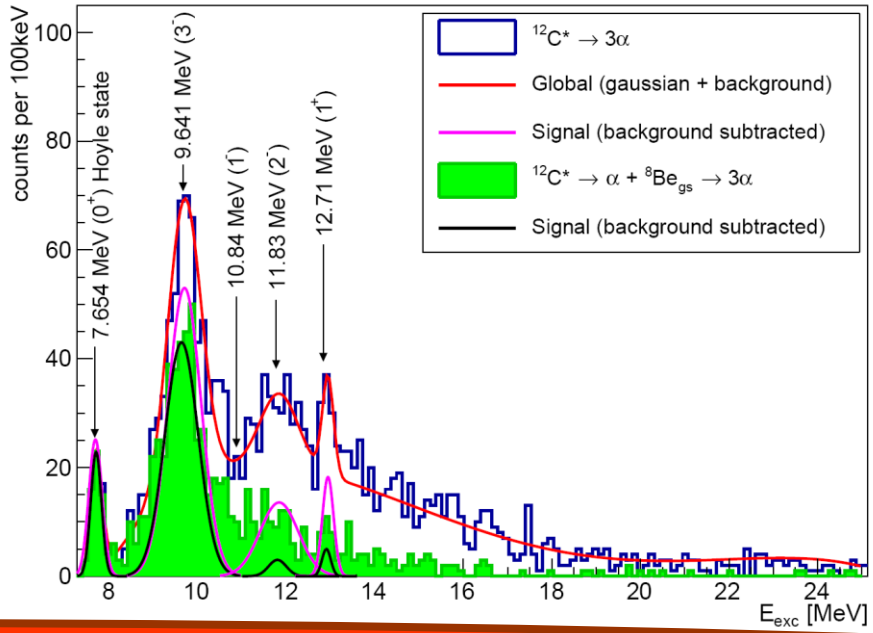
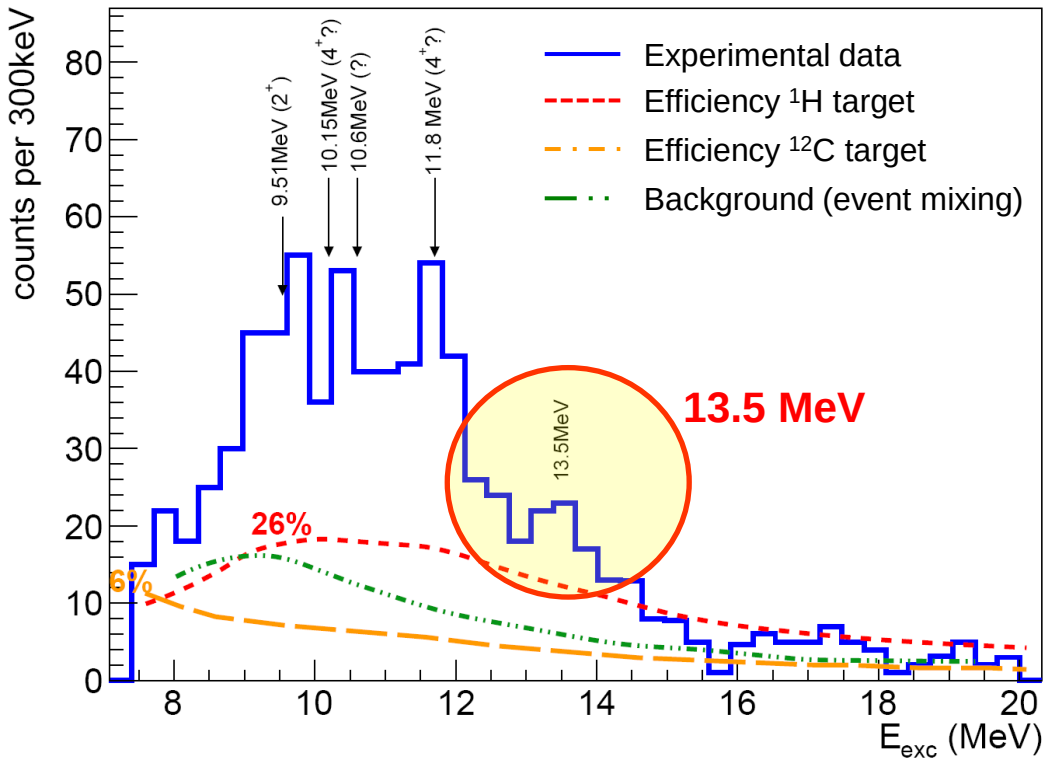


3 body correlations → good agreement with the literature → **^{12}C Hoyle state**.

Interesting study of **sequential de-excitation** for the **Hoyle state** → $^{12}C^{*} \rightarrow \alpha + {}^{8}Be_{gs}$ (green spectrum)

Good test for the experimental technique

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



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:

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

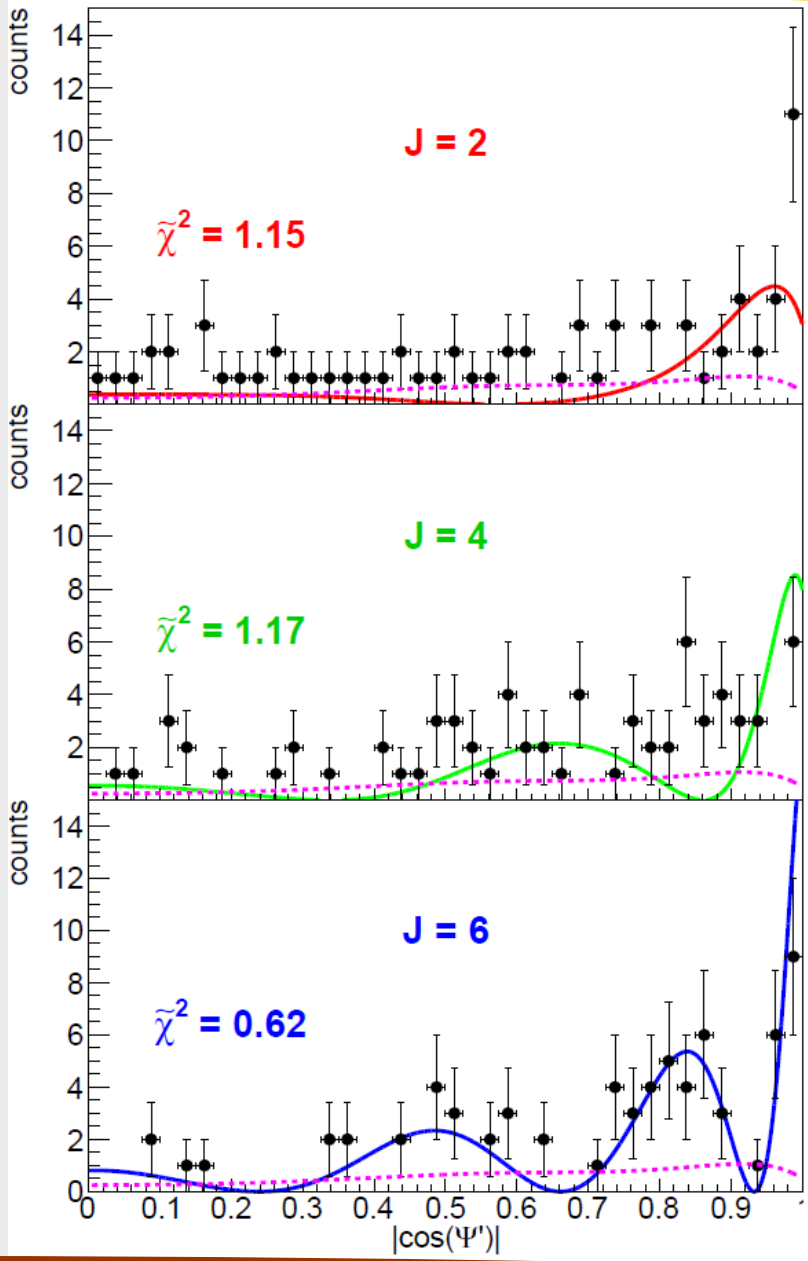
α fall-of factor 12°-16°

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

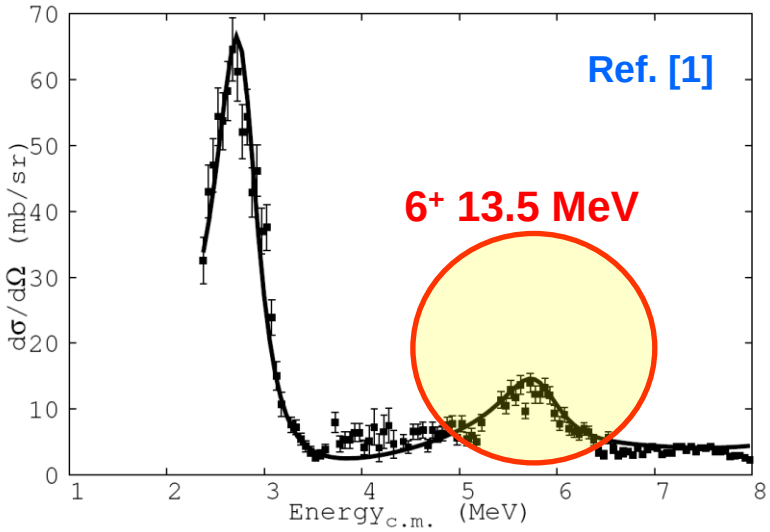
Possible **evidence** of a new excited state at about **13.5 MeV** not reported in literature.

Possible new state in ^{10}Be

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

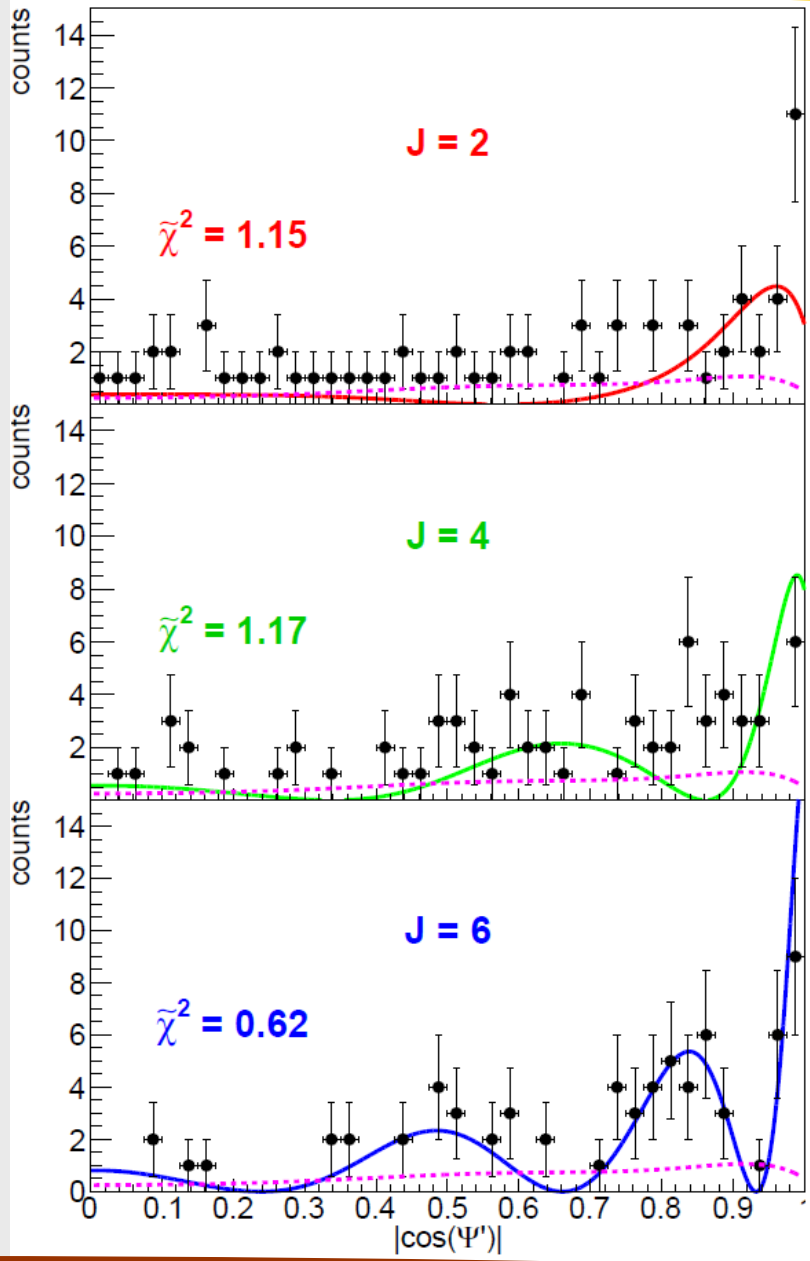


Angular correlation analysis on **13.5 MeV** state→ **high spin** contributions → possible **6^+** assignement → **agreement** with the recent R-matrix calculation in resonant elastic scattering **$^{6}He+^{4}He$** experiment **[1]**



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

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



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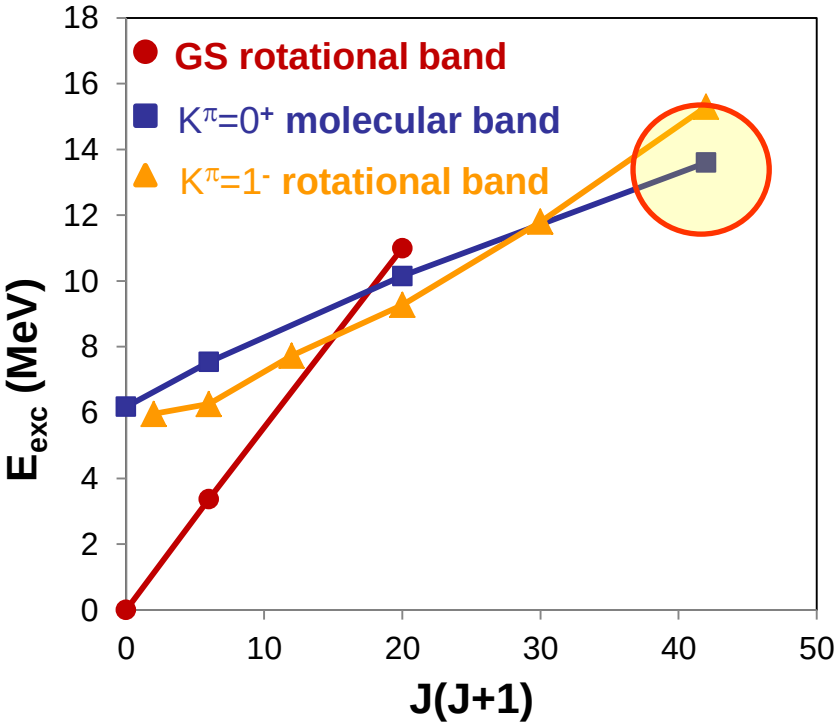
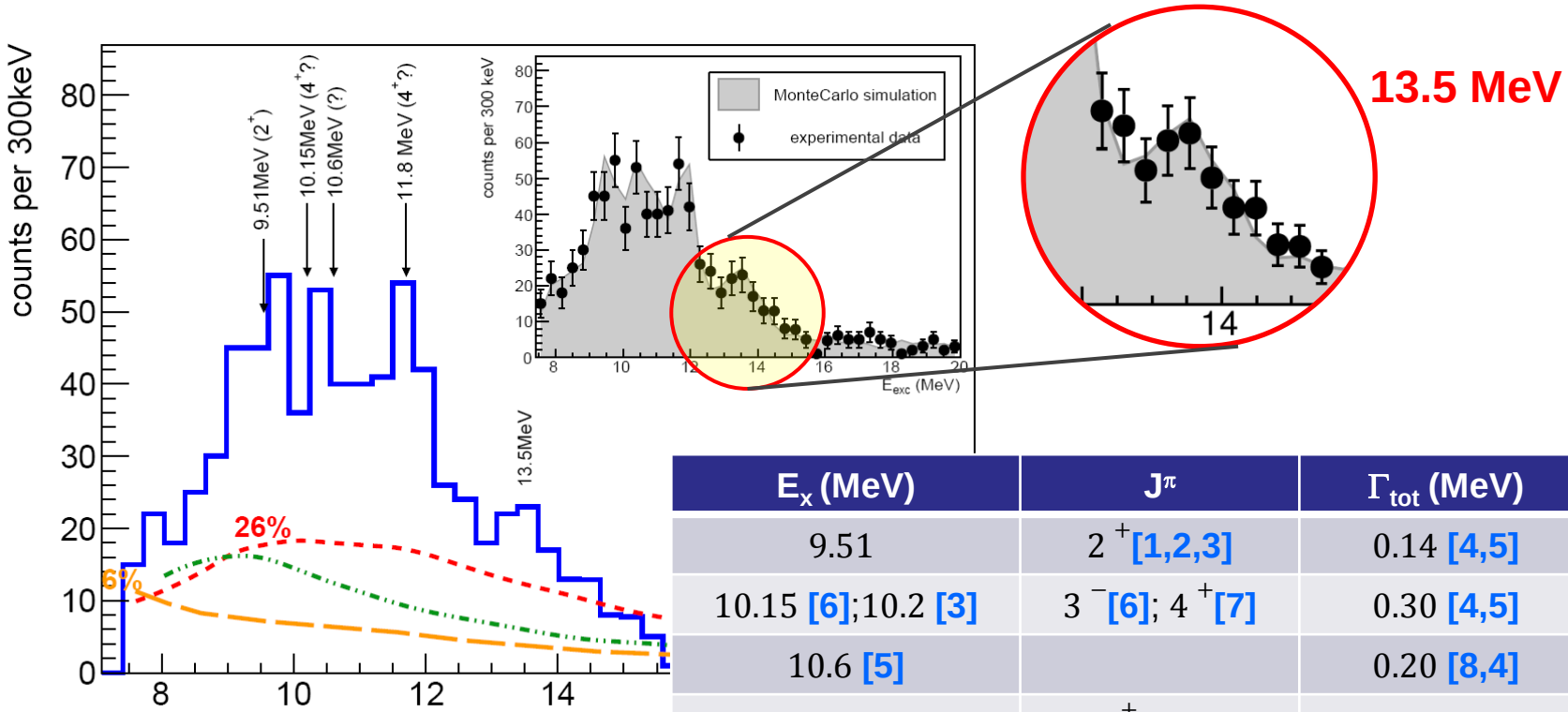


Possible **6$^+$** further **member** of the **K=0$^+$ molecular band** → **low statistics** → new experiments are needed.

Continuation of the ^{10}Be molecular band

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

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

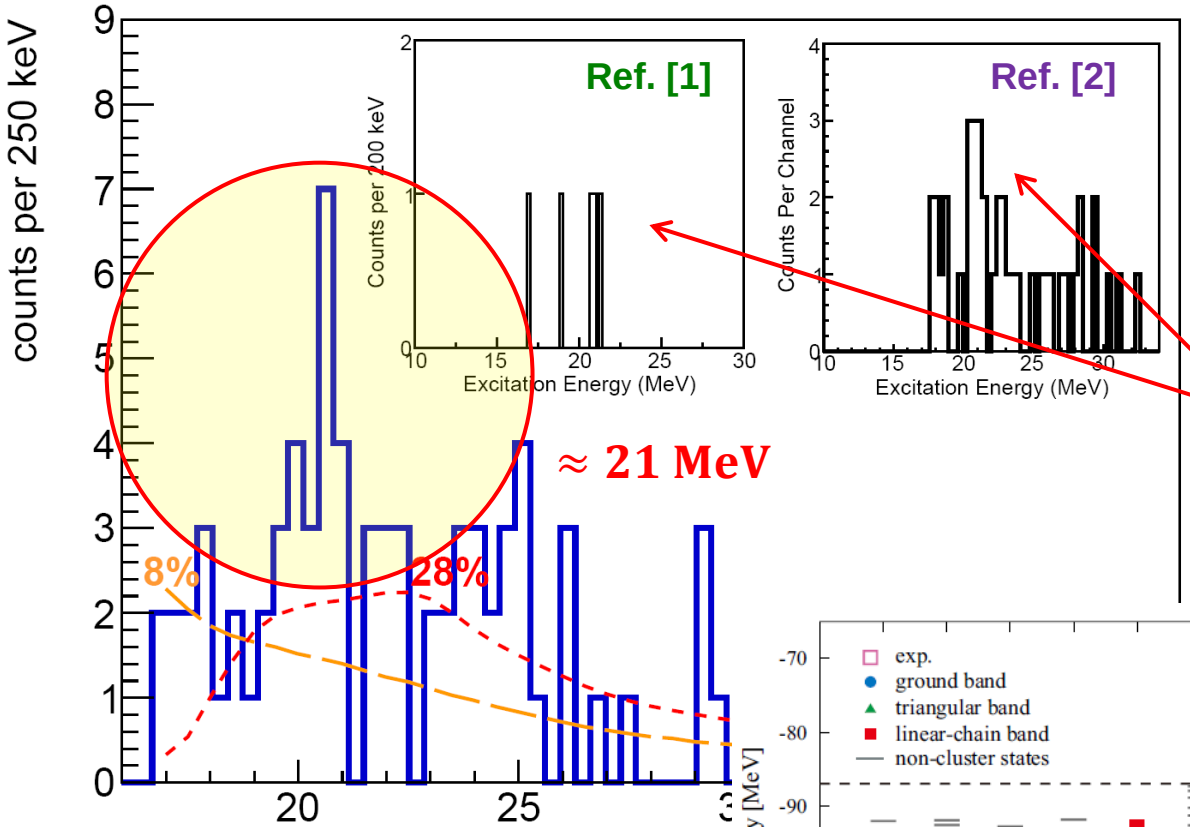


E_x (MeV)	J^{π}	Γ_{tot} (MeV)
9.51	2^{+} [1,2,3]	0.14 [4,5]
10.15 [6];10.2 [3]	3^{-} [6]; 4^{+} [7]	0.30 [4,5]
10.6 [5]		0.20 [8,4]
11.8	(4^{+}) [5,6]	0.12 [5,6]
≈ 13.5	6^{+} [9], this work	≈ 0.15 this work

[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)

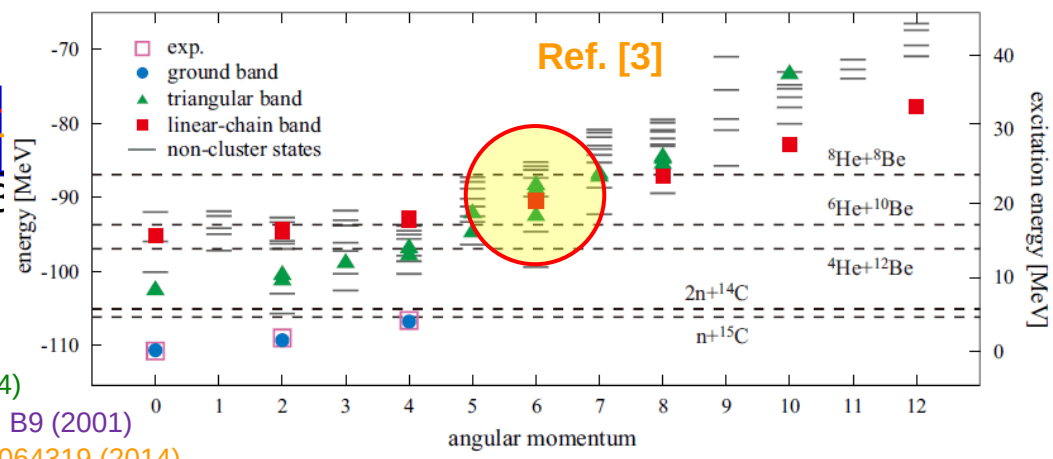
^{6}He-^{10}Be coincidences: the ^{16}C structure

^{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

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

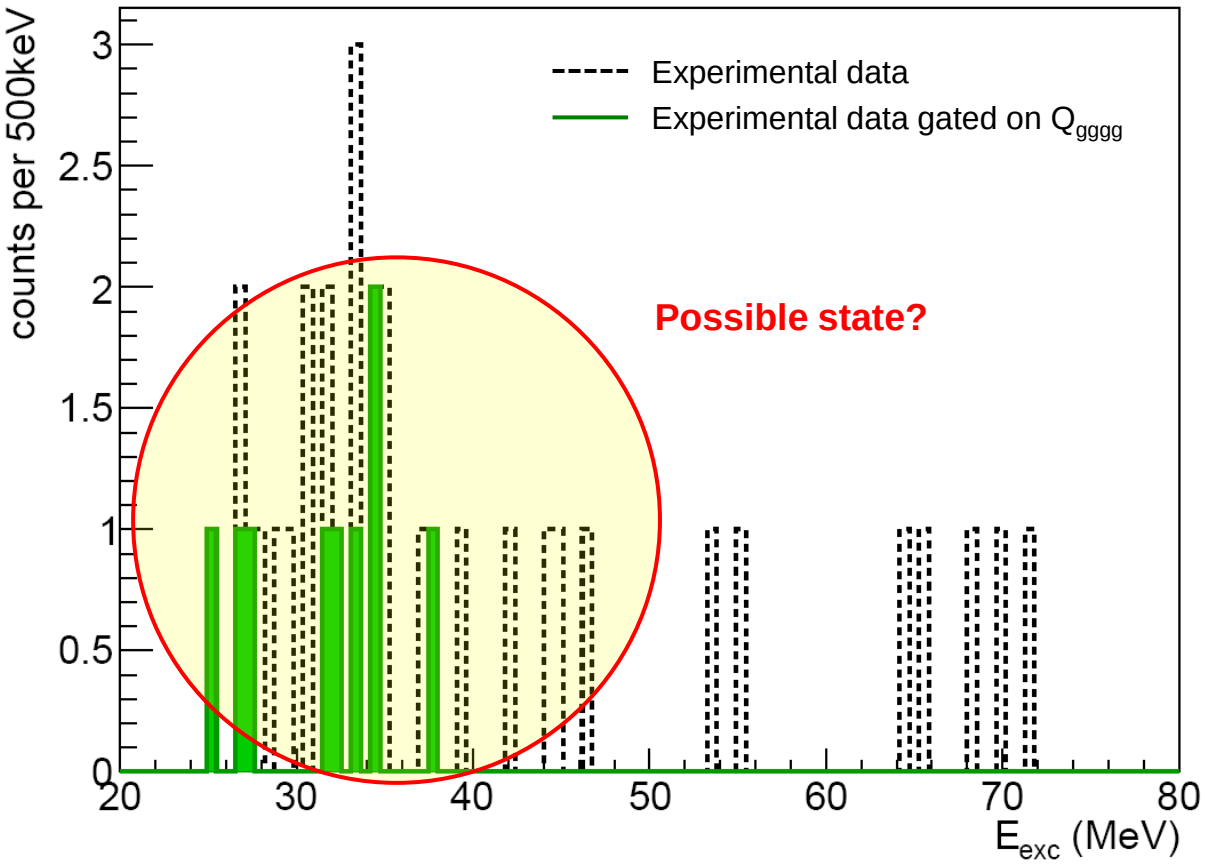


[1] N. I. Ashwood et al., Phys. Rev. **C 70**, 0644607 (2004)
[2] P.J. Leask et al., Jour. Phys. G: Nucl. Part. Phys. **27**, B9 (2001)
[3] T. Baba, Y. Chiba and M. Kimura , Phys. Rev. **C 90**, 064319 (2014)

Low statistics results → 20,6 MeV bump

^{16}C three body break-up: $^{6}He+^{6}He+^{4}He$

^{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

Conclusions and Perspectives

- 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.

- **^{16}C three body disintegrations** → **^{6}He-^{6}He-^{4}He** correlations → ve
→ enhancement at about **33 MeV** → **no data provided by literatu**

Future Perspectives: **FARCOS** array **[2]** coupled to **CHIMERA** devic
and angular resolution → **DSSSD+CsI** detectors.
(**CLIR experiment** INFN-LNS February 2015 – June 2015).

[1] G. Rogachev et al., J. Phys.: Conf. Ser. **569**, 012004 (2014)
[2] G. Verde et al., J. Phys. Conf. Ser. **420**, 0112158 (2013)

Thank you for your attention.