



Clustering in light nuclei with light and heavy ion reactions

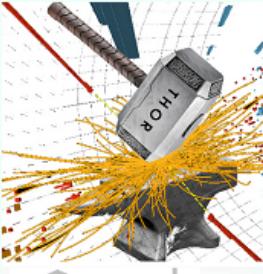
I. Lombardo

Istituto Nazionale di Fisica Nucleare – Sezione di Catania

D. Dell'Aquila, G. Verde, M. Vigilante

Univ. Napoli Federico II, INFN Napoli & Catania, IPN Orsay

ZIMÁNYI SCHOOL'17



Zimányi-COST
WINTER SCHOOL ON
HEAVY ION PHYSICS

Dec. 4. - Dec. 8.,
Budapest, Hungary

cost
COST Action CA15213

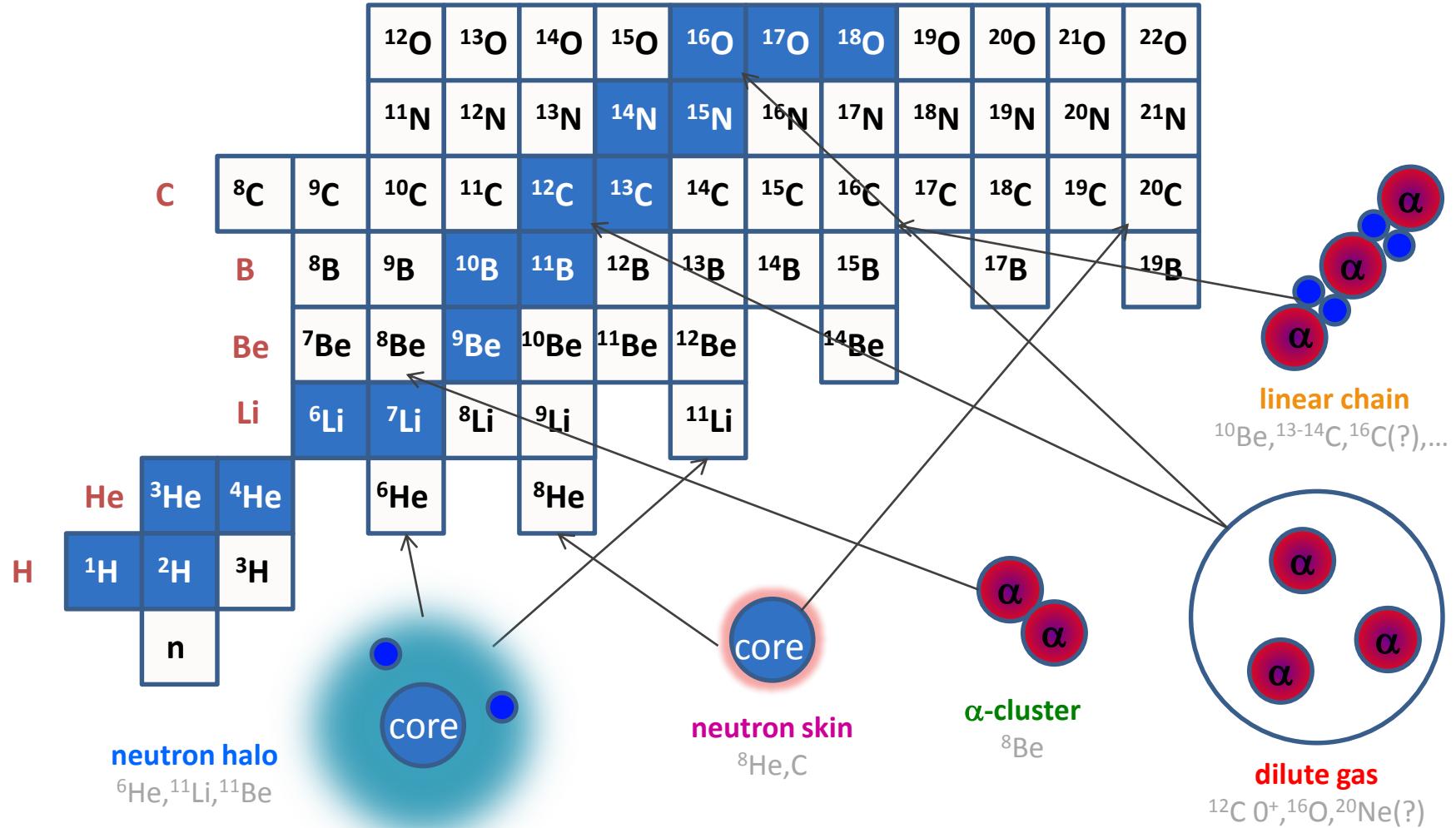
József Zimányi (1931 - 2006)

ivano.lombardo@ct.infn.it



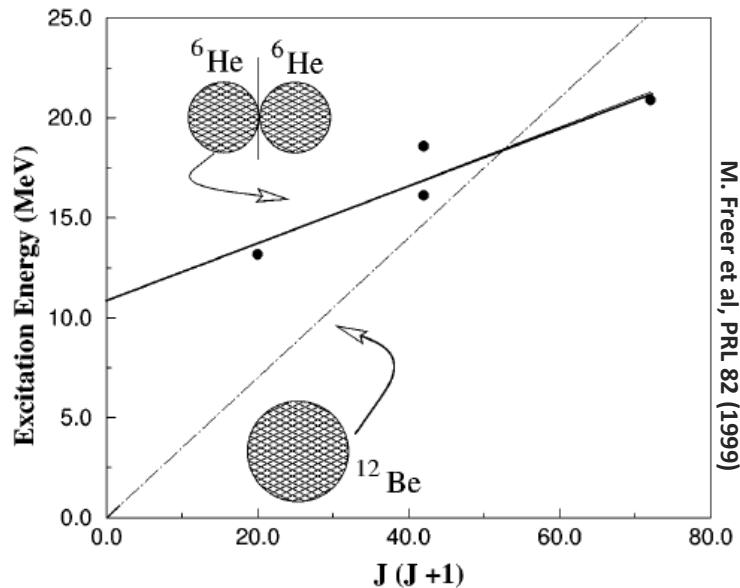
The unusual behavior of Lilliput nuclei

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

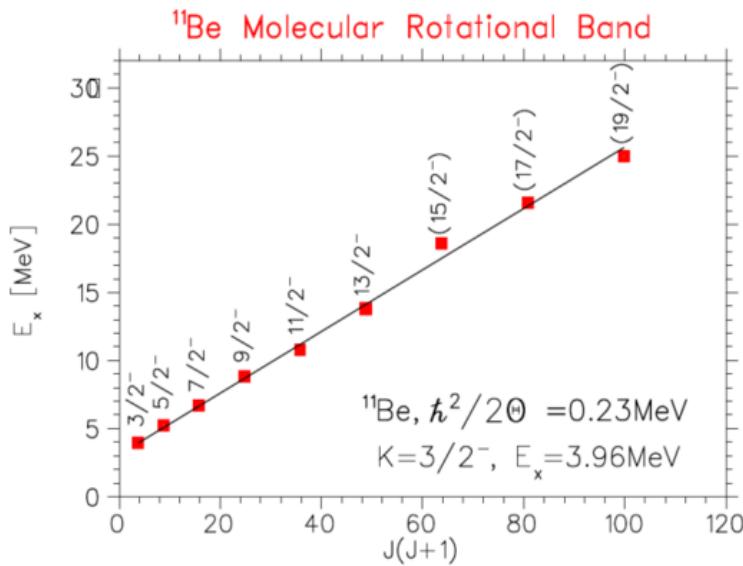


Some signatures that α -cluster structure appears in *nuclei*:

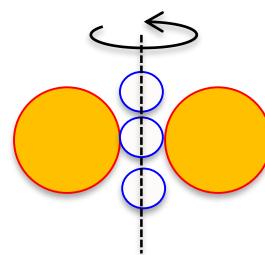
1. Strong deformation \rightarrow “abnormal” shape due to α -clustering \rightarrow Rotational bands with anomalously large moment of inertia [E_x vs $J(J+1)$]



M. Freer et al, PRL 82 (1999)

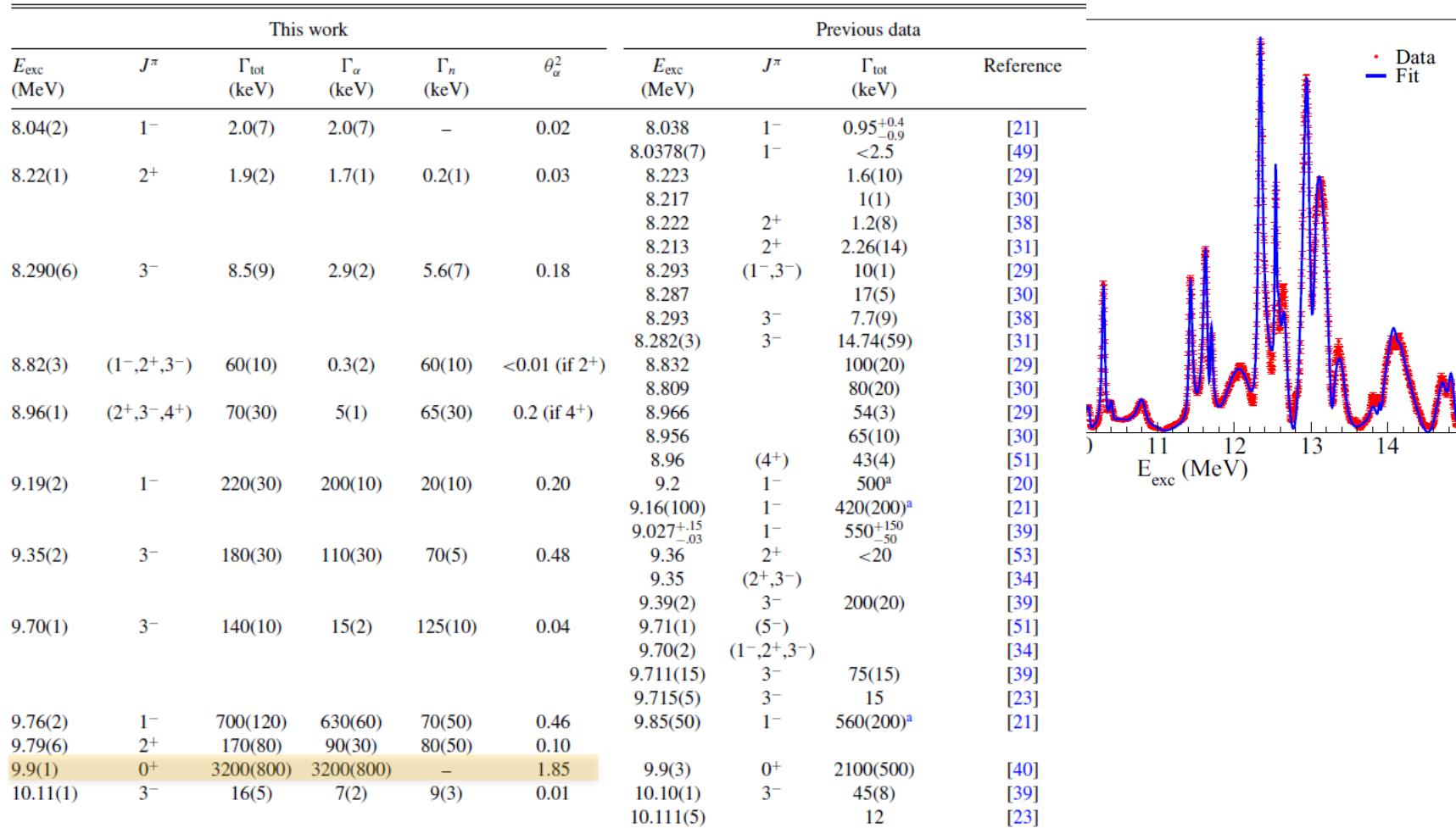


wonGertzen and Milin, Lect. Not. Phys. 875 (2012)

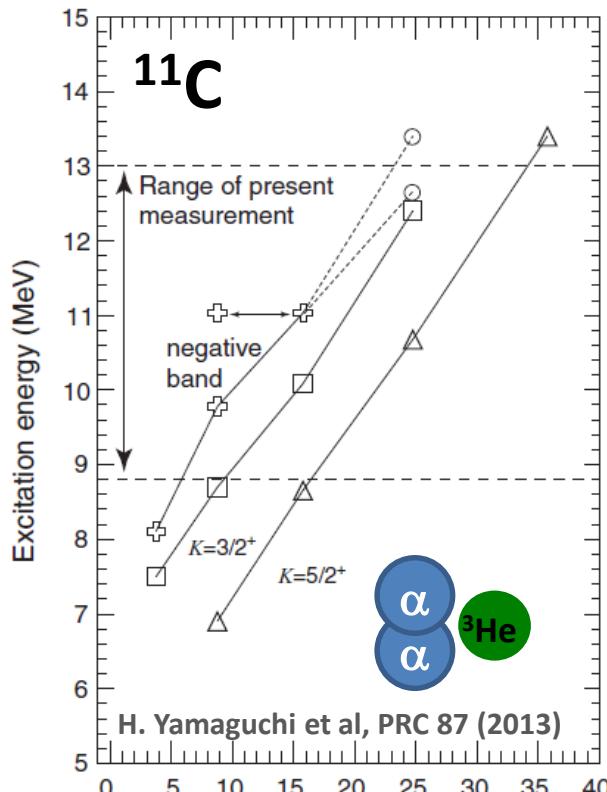


Some signatures that α -cluster structure appears in *nuclei*:

2. Obs. of states with Γ_α close or larger respect to the *Single Particle (Wigner) Limit*

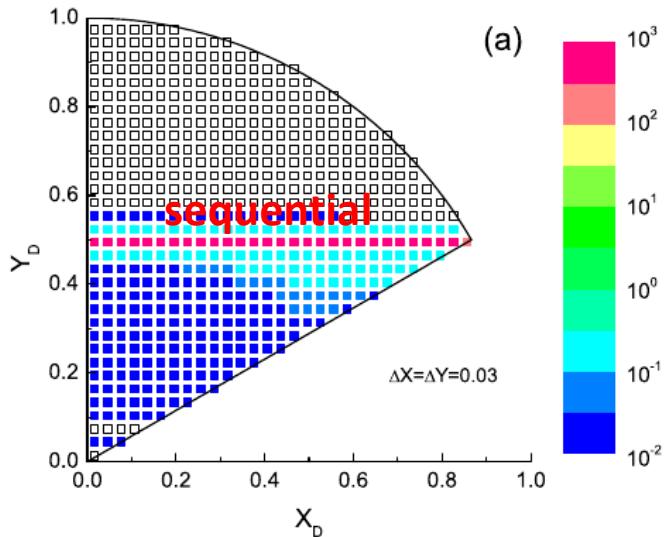
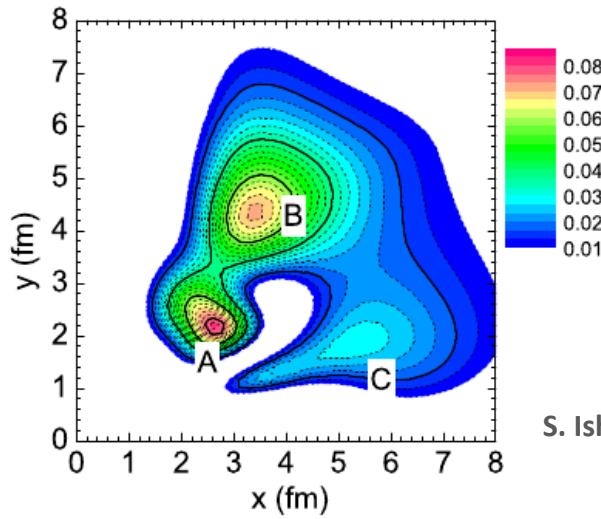
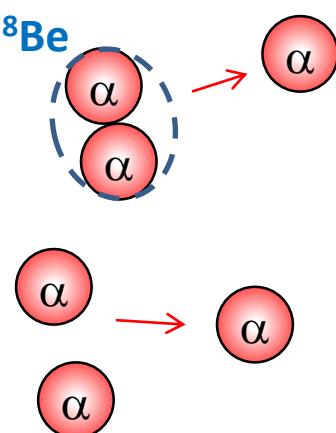


Carbon isotopes: trimeric structure → triangular or linear shapes



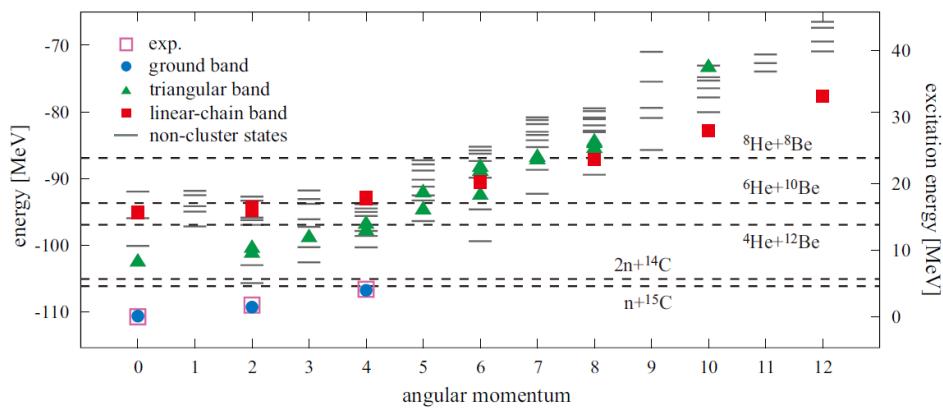
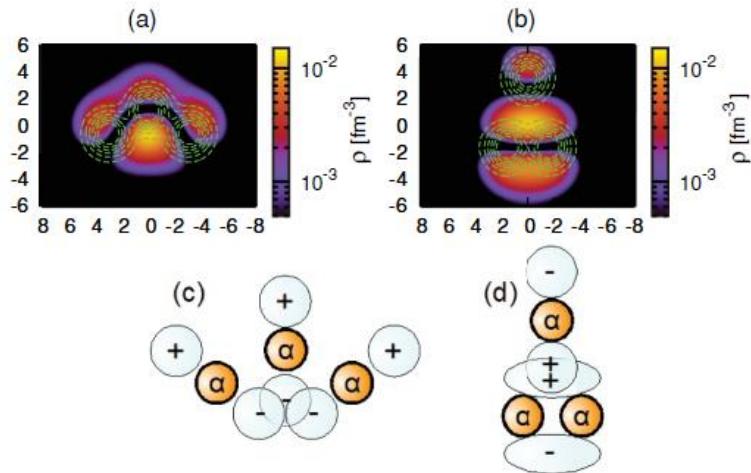
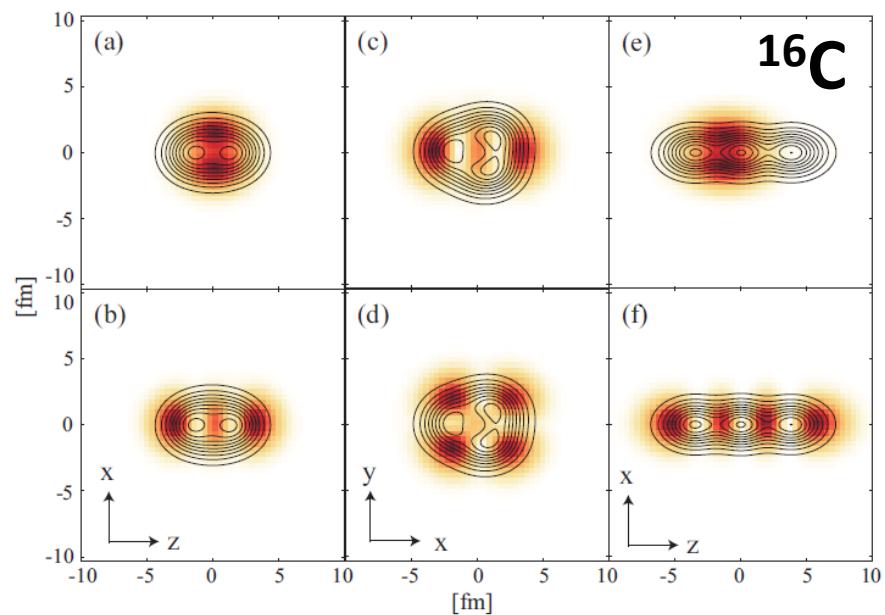
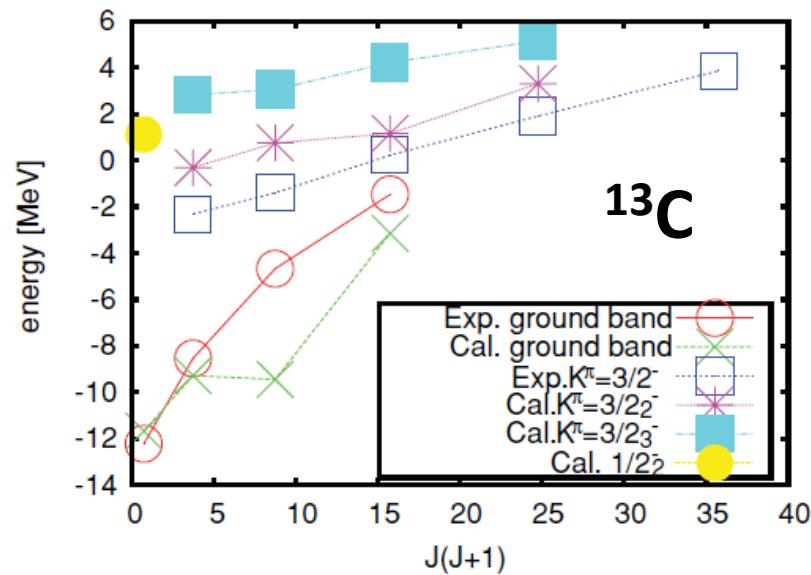
12C* Hoyle

$J(J+1)$

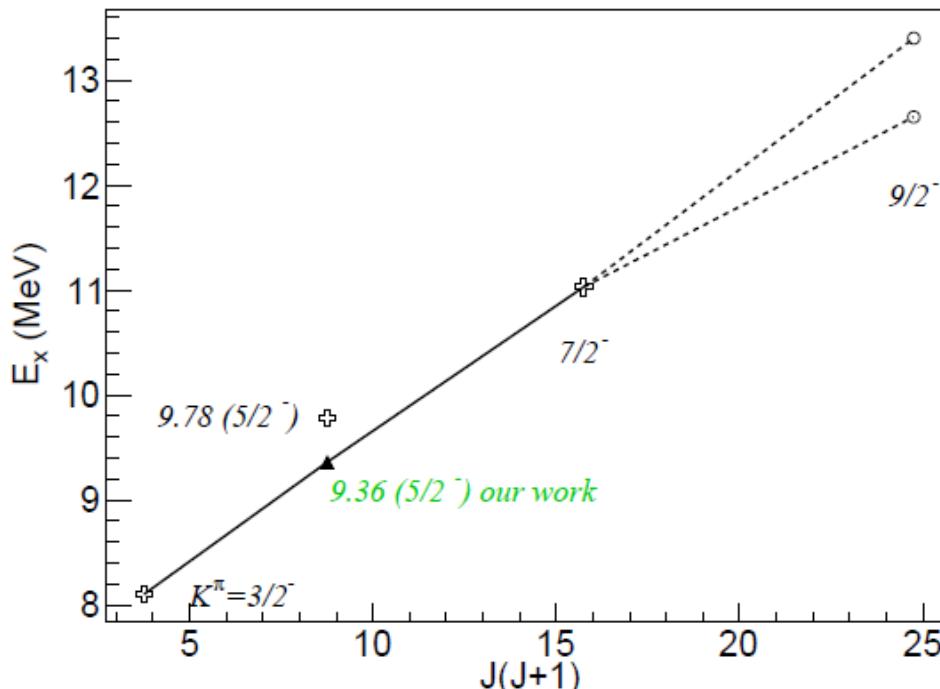


Hoyle → from fermions to bosons in nuclei?

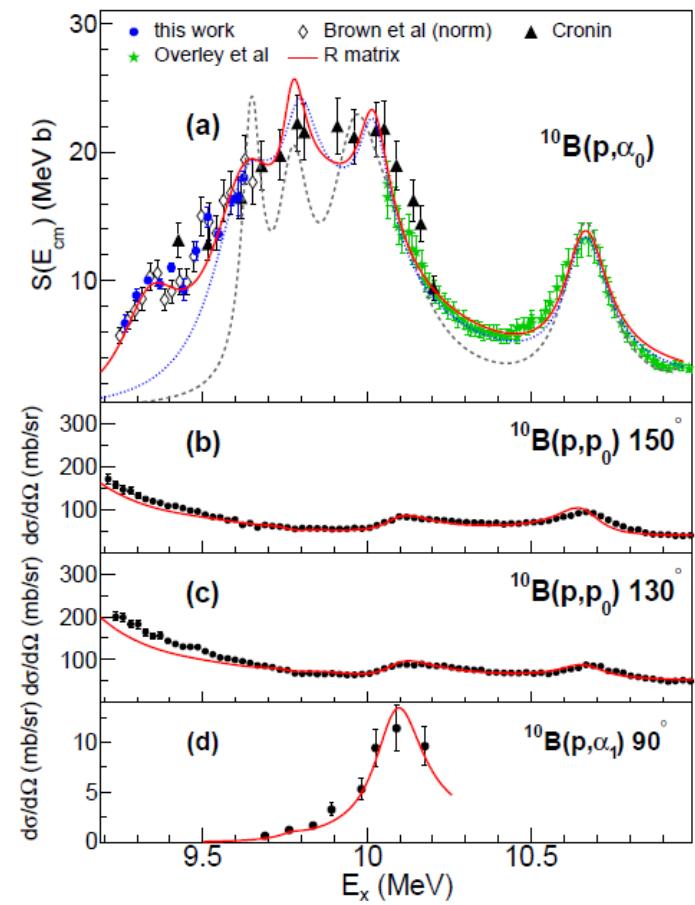
Carbon isotopes: trimeric structure → triangular or linear shapes



$^{11}\text{C} \rightarrow \text{formation}$ reaction involving an α -decay channel: $\text{p} + ^{10}\text{B} \rightarrow ^{11}\text{C}^* \rightarrow \alpha + ^7\text{Be}$



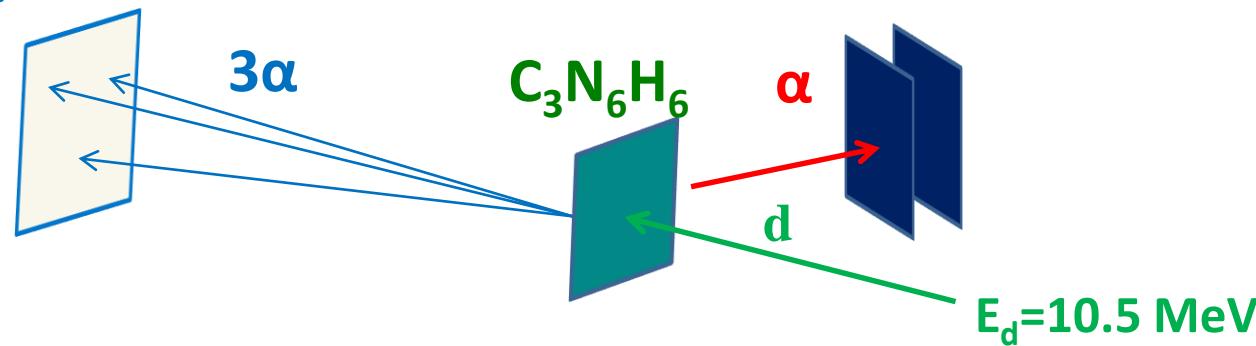
E_x (MeV)	J^π_{lit}	Γ_{tot}^{lit}	E_x (MeV)	J^π	ℓ_{α_0}	Γ_{p_0}	Γ_{α_0}	Γ_{α_1}	Γ_{tot}
9.20	$5/2^+$	500 ± 90							
9.65 ($3/2^-$)	210 ± 40		9.36 ($5/2^-$)	2	4	235			239
9.78 ($5/2^-$)	240 ± 50		9.65 ($3/2^-$)	0	45	223			268
9.97 ($7/2^-$)	120 ± 20		9.80 $5/2^-$	2	12	116	4	132	
10.08 $7/2^+$	≈ 230		9.98 $7/2^-$	2	498	66	4	568	
			10.02 $7/2^+$	3	13	105	1	119	
			10.10 ($5/2^+$)		147		36	183	
10.68 $9/2^+$	200 ± 30		10.67 $9/2^+$	3	126	37			163



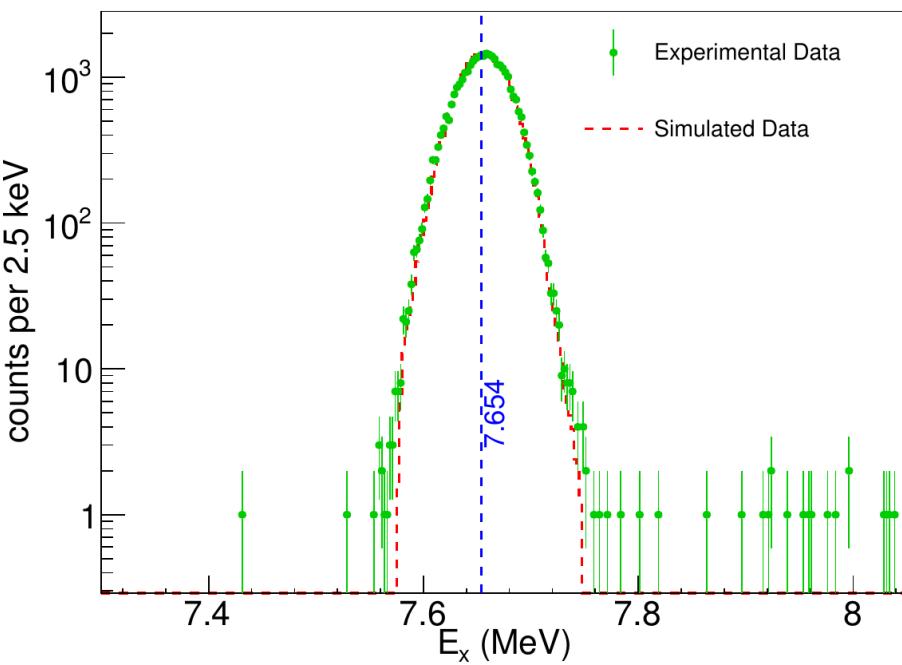
- State at **9.36 MeV** → large alpha structure (70% W.L.)
- **Sophisticated technique** (inverse absorber)
- Confirmed in **successive works** (M. Wiescher et al PRC 2017)

^{12}C in the Hoyle state \rightarrow production reaction: $d + ^{14}\text{N} \rightarrow \alpha + ^{12}\text{C}^* \rightarrow \alpha + (\alpha + \alpha + \alpha)$

Si Hodoscope



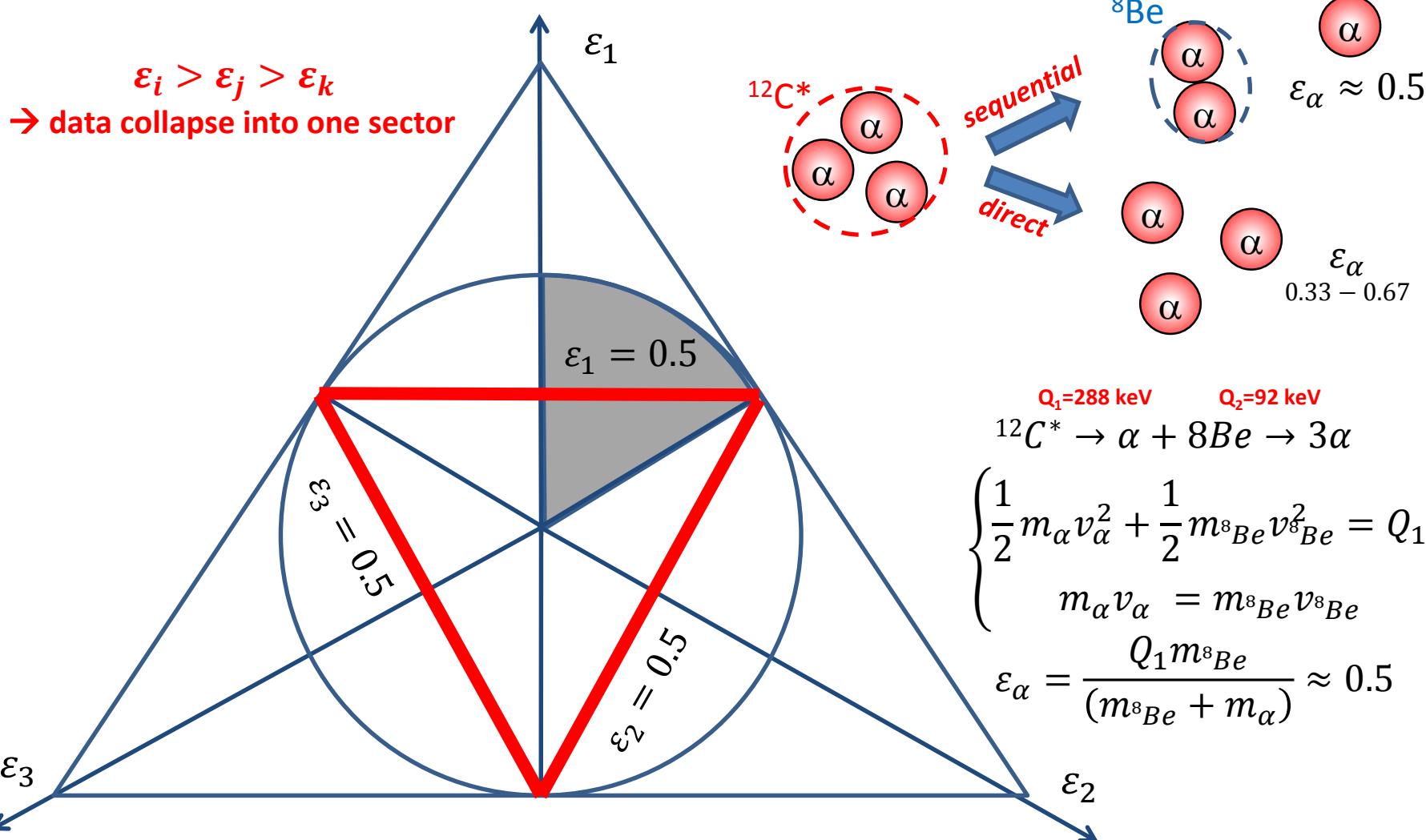
Invariant mass spectrum: $E_x = \sqrt{s} - m_{gs}$



Study of *sequential* vs *direct* mechanism: symmetric Dalitz Plot

$$\varepsilon_{i,j,k} = E_{i,j,k}/(E_i + E_j + E_k)$$

Normalized energies in the ^{12}C emitting reference frame



Study of *sequential* vs *direct* mechanism

$$\varepsilon_{i,j,k} = E_{i,j,k}/(E_i + E_j + E_k)$$

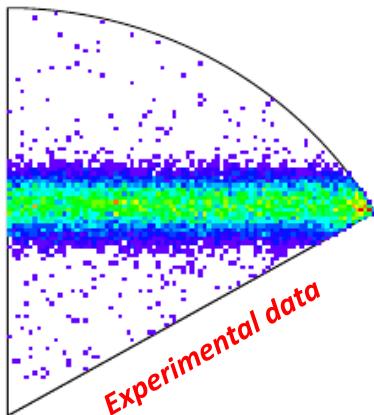
$$\varepsilon_i > \varepsilon_j > \varepsilon_k$$

$$x = \sqrt{3}(\varepsilon_j - \varepsilon_k)$$

$$y = 2\varepsilon_i - \varepsilon_j - \varepsilon_k$$

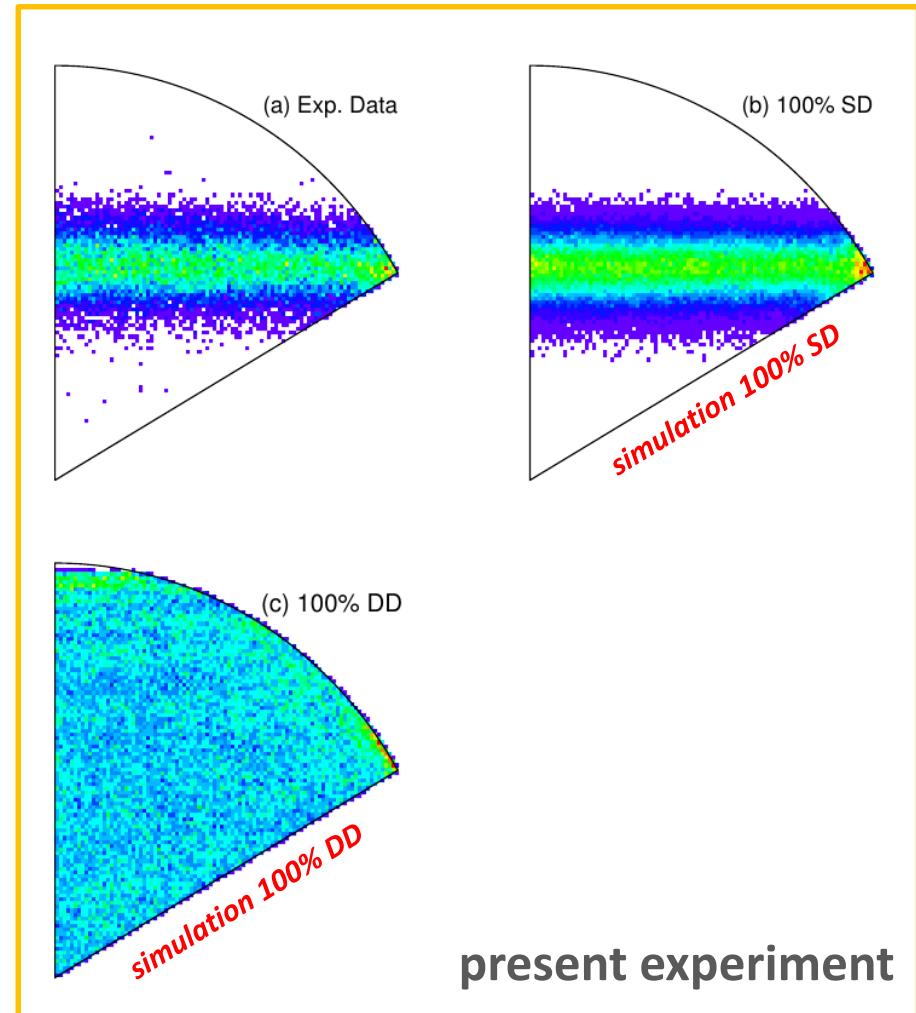
M. Itoh et al. PRL (2014)

(b) SD



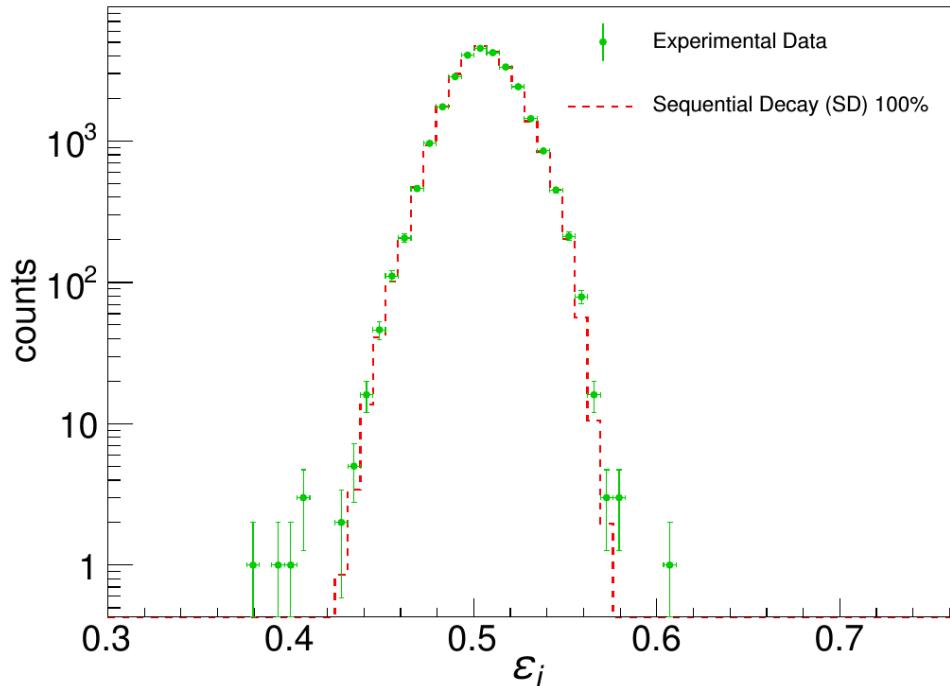
simulation 100% SD

Strip detectors → background due to ambiguities
in track reconstruction for M>1 events

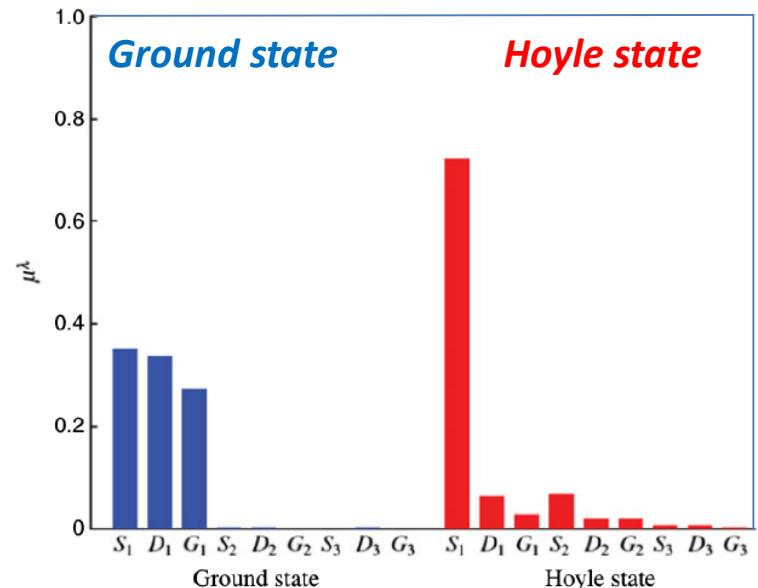


28000 counts under the sequential decay peak
→ compatible with **fully sequential process**

Study of *sequential* vs *direct* mechanism: ε_i plot



D. Dell'Aquila et al., PRL 119 (2017)
see also the viewpoint in Physics by OS Kirsebom

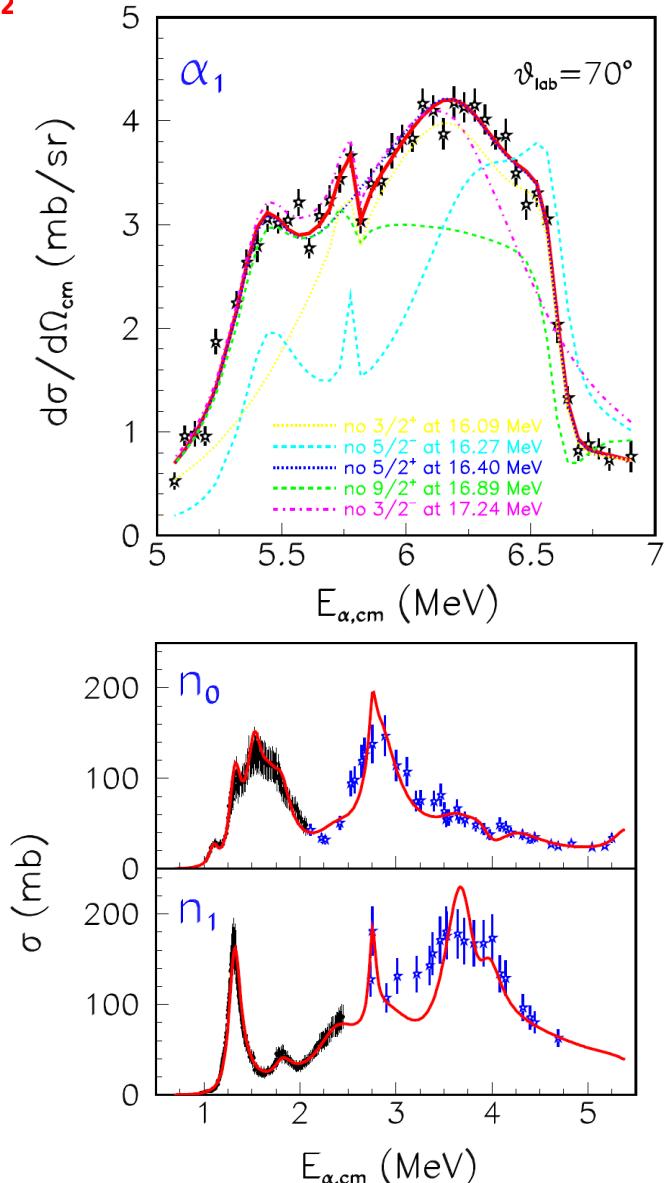
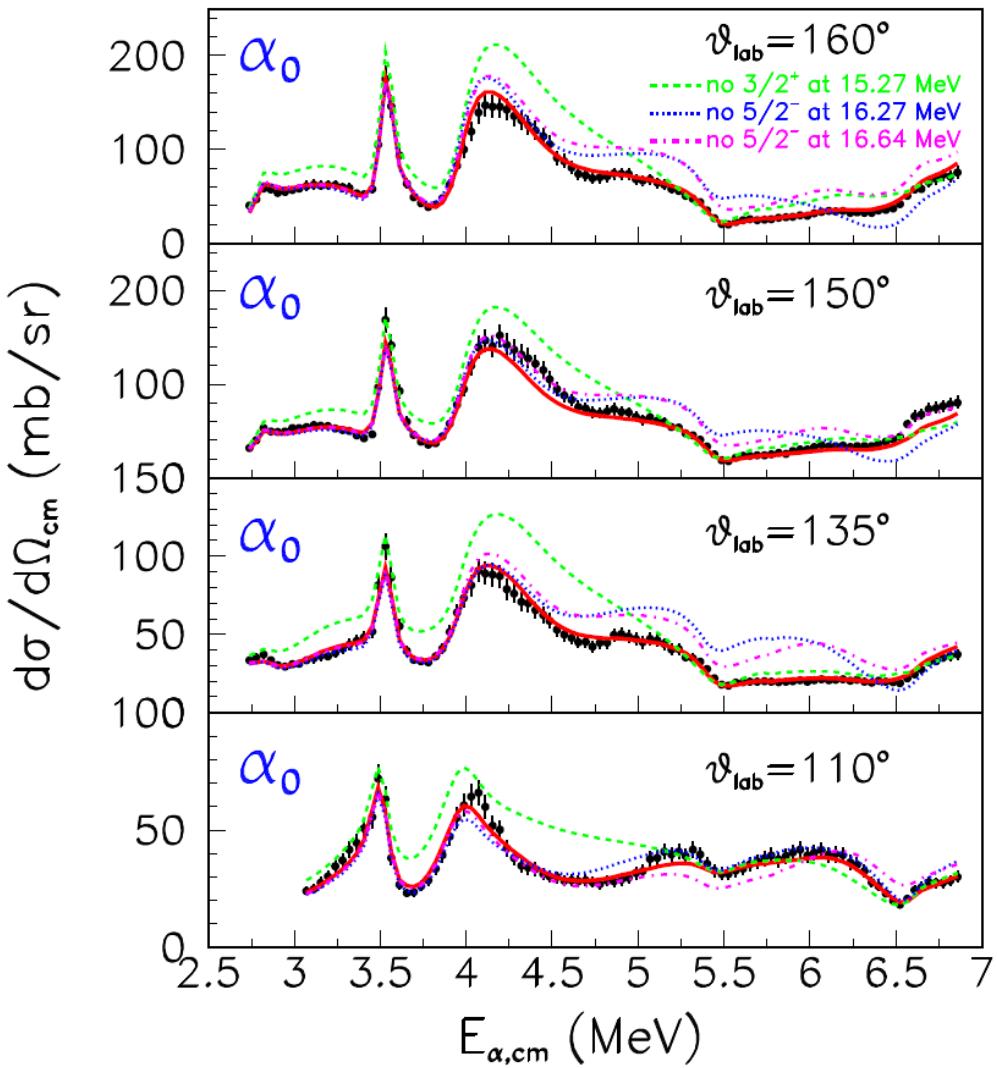


T. Yamada and P. Schuck, Eur. Phys. J. A26, 185 (2005)
Y. Funaki, H. Horiuchi, W. von Oertzen, G. Röpke, P. Schuck, A. Tohsaki, and T. Yamada, Phys. Rev. C 80, 064326 (2009)

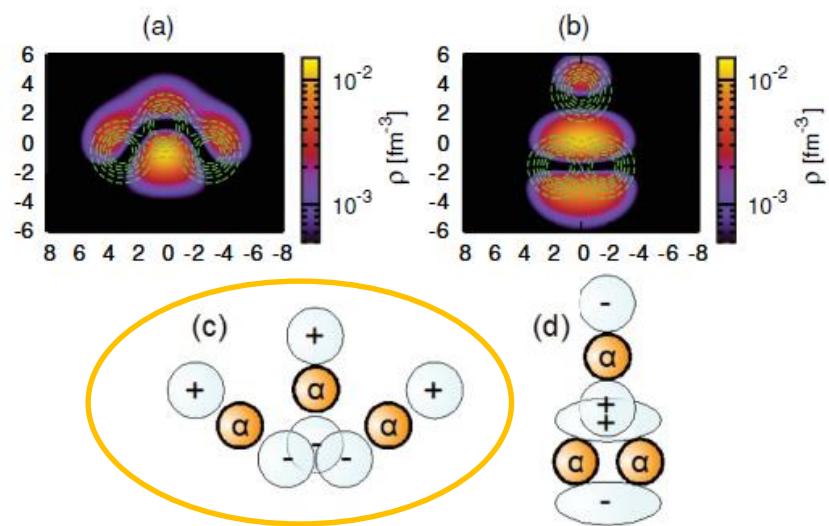
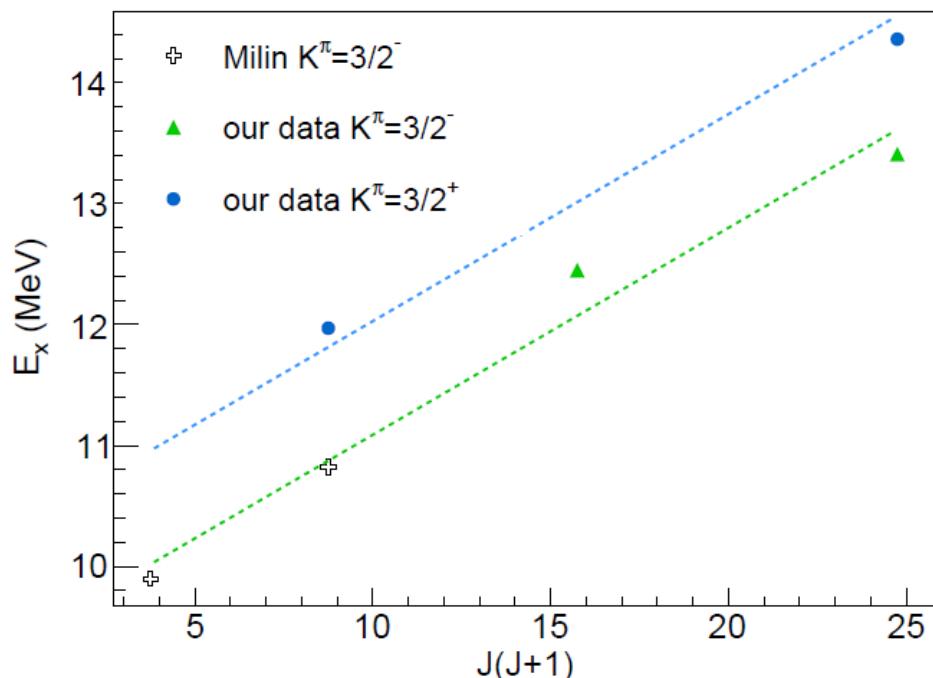
Signals of BEC in nuclei → linked to the appearance of DD of the Hoyle state

Direct 3 alpha decay < - > ^{12}C nucleosynthesis in low T environment (WD, NS)

Resonant elastic scattering $\alpha + {}^9\text{Be} \rightarrow {}^{13}\text{C}^$ structure (**formation**)
various de-excitation channels open! $\rightarrow \alpha_0, \alpha_1, n_0, n_1, n_2$*



E_x^{lit}	J_x^{π}	E_x	J_x^{π}	Γ	Γ_{α_0}	Γ_{α_1}	Γ_n
11.75	$3/2^-$	11.75	$3/2^-$	116	3	-	113
11.97	$5/2^+$	11.97	$5/2^+$	152	65	-	87
12.13	$5/2^-$	12.17	$5/2^-$	199	28	-	171
12.14	$1/2^+$	12.33	$1/2^+$	230	40	-	190
12.44	$7/2^-$	12.45	$7/2^-$	222	16	-	206
13.28	$3/2^-$	13.05	$3/2^-$	546	153	-	393
13.41	$9/2^-$	13.41	$9/2^-$	84	21	-	63
13.57	$7/2^-$	13.49	$7/2^-$	417	114	-	303
13.76	$(3/2, 5/2)^+$	13.63	$5/2^+$	743	623	-	120
14.13	$3/2^-$	14.13	$5/2^-$	94	94	-	-
			$7/2^+$	6	6	-	-
14.39	$(1/2, 5/2)^-$	14.28	$7/2^-$	392	185	-	207
14.58	$(7/2^+, 9/2^+)$	14.36	$9/2^+$	322	70	-	252
14.98	$(7/2^-)$	14.64	$7/2^-$	361	279	-	82
			$5/2^+$	965	831	-	134
15.27	$9/2^+$	15.27	$3/2^+$	1201	1061	-	140
16.08	$(7/2^+)$	16.10	$3/2^+$	365	233	55	77
			$5/2^-$	1596	1503	87	6
16.18		16.40	$5/2^+$	17	2	14	1
		16.64	$5/2^-$	1502	1294	10	153
		16.67	$7/2^+$	904	633	2	-
16.95		16.89	$9/2^+$	635	501	86	4
		16.91	$3/2^-$	1079	702	257	120
		17.23	$3/2^+$	393	280	-	113
17.36		17.24	$3/2^-$	216	185	20	11
		17.52	$5/2^+$	2153	1834	86	233
17.92		17.86	$7/2^-$	477	457	-	20



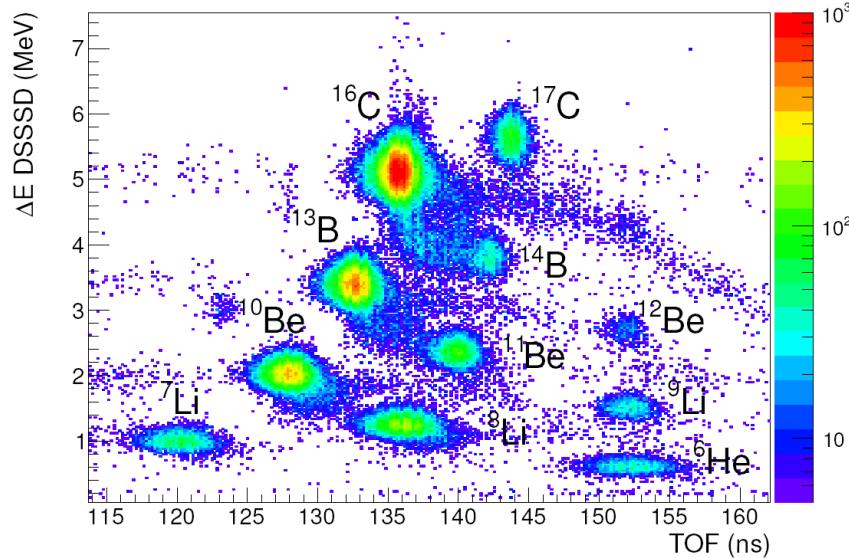
Hint -> obtuse triangle configuration

- Light nuclei → **effective** nuclear force → correlations and **clusters**
- Good candidates: carbon isotopes → nuclear **trimers**
- Present analysis: **^{11,12,13}C**
- Complexity of nuclear forces → several (**different**) approaches
 - **¹¹C** → compound nucleus reaction & *R*-matrix analysis
 - **¹²C** → direct reaction → analysis of decay via Dalitz plot
 - **¹³C** → resonant elastic scattering → *R*-matrix
- **Clustering** is ubiquitous in all these cases
- Perspective: signal of **clusterization** in **hot nuclear matter** produced with **intermediate** and **relativistic** energy collisions?
- True in-medium correlations and **new mechanisms** of **resonances** formation (“**stellar-like**” formation of **⁸Be***, see G. Verde talk & D. Dell’Aquila thesis).

Further Slides



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



Identification (DE-ToF) plot FRIBs **cocktail beam** → good performances.

High **exotic beams** intensity:

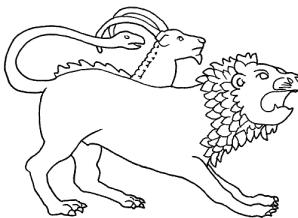
- ^{16}C ($49,5 \text{ MeV/u}$) 10^5 pps ;
- ^{13}B ($49,5 \text{ MeV/u}$) $5 \cdot 10^4 \text{ pps}$;
- ^{10}Be ($56,0 \text{ MeV/u}$) $4 \cdot 10^4 \text{ pps}$;

Beam production → **IFF** (In Flight Fragmentation) technique → **FRIBs** (Flight Radioactive Ion Beams) facility @ **INFN-LNS**:

- $^{18}\text{O}^{7+}$ at 56 MeV/u (superconducting cyclotron K800);
- ^9Be ($1,5 \text{ mm}$ thickness) production target;
- **LNS-FRS** (Fragment-Recoil Separator) $B\rho \approx 2,8Tm$;

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

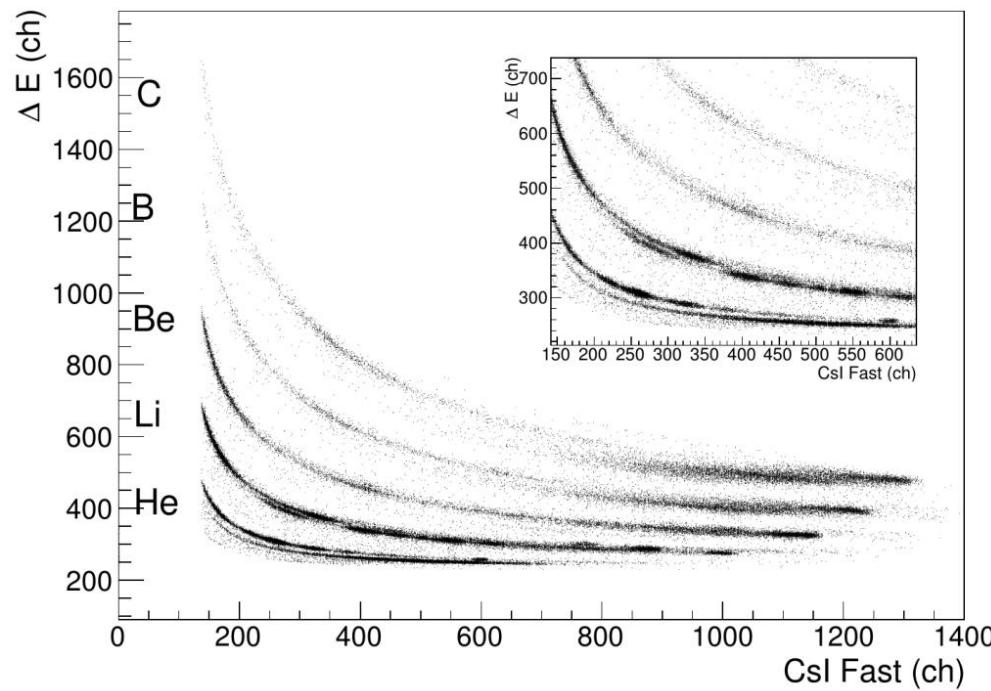
- **MCP** large area detector;
- **DSSSD** position sensitive detector ($\approx 13m$ after);



Investigation of **cluster structures** in light unstable nuclei via **invariant mass spectroscopy** → the **Unstable** experiment @ **FRIBs Facility (LNS)**

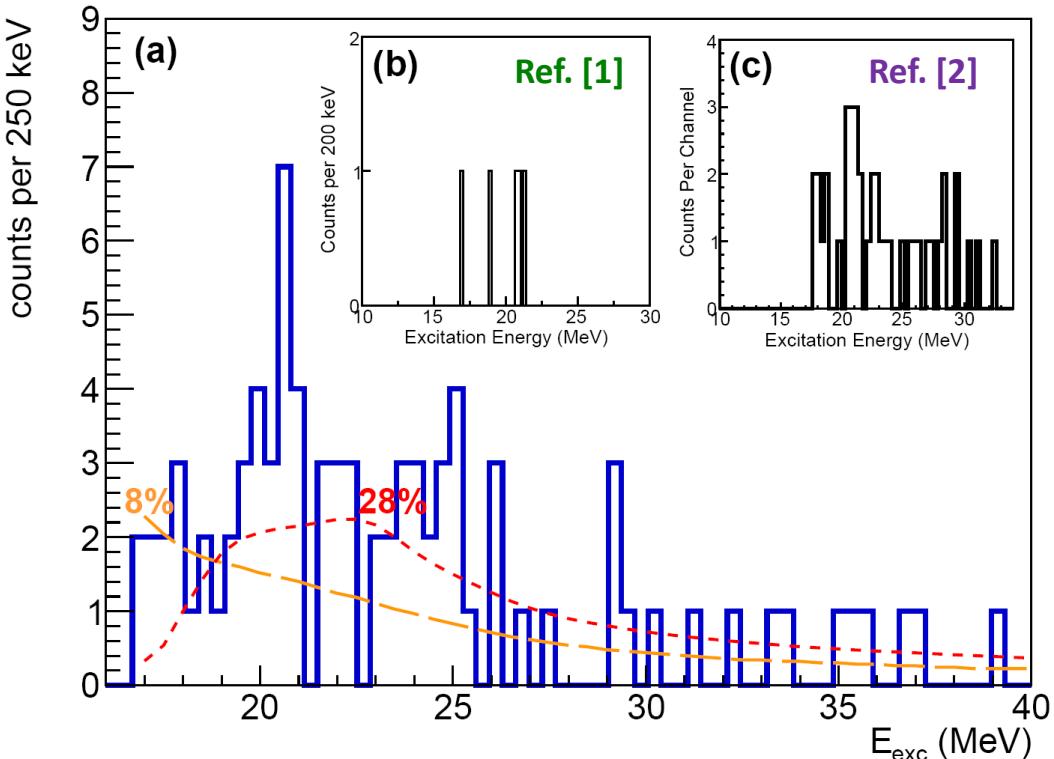
CHIMERA (Charged Heavy Ion Mass Energy Resolving Array) [1,2]

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



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

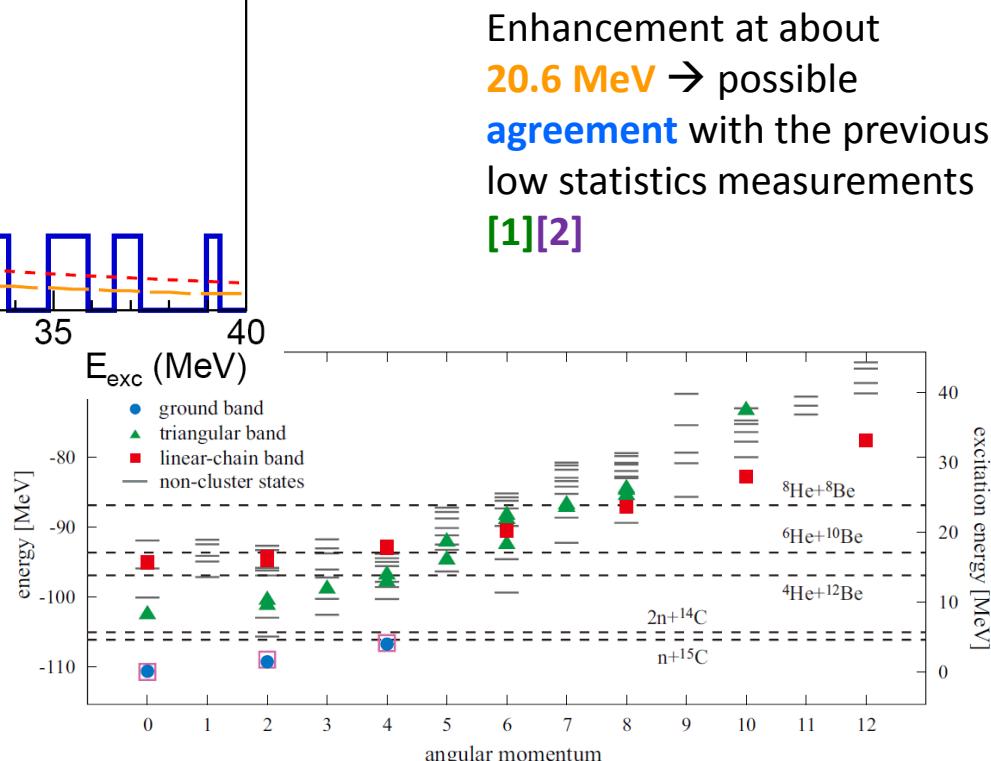
$^{10}\text{Be} + ^6\text{He}$ correlations → invariant mass of ^{16}C



- [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] D. Dell'Aquila et al., Phys. Rev. C **93**, 024611 (2016)

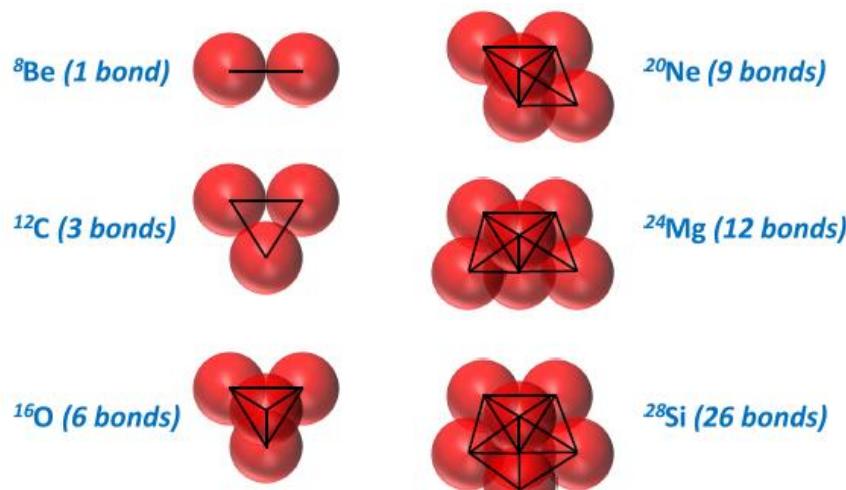
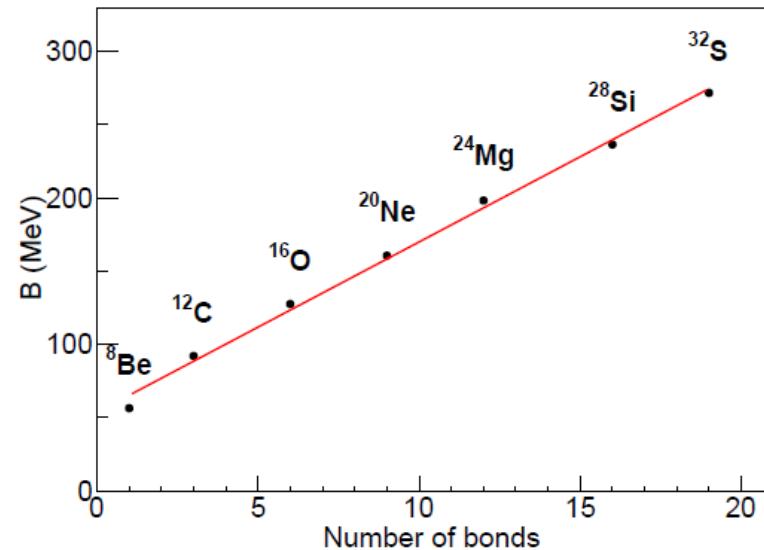
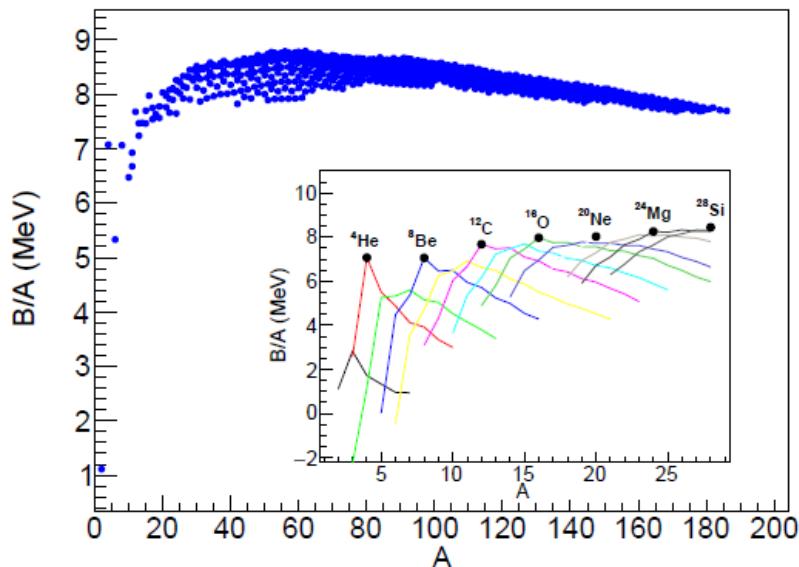
— Experimental data
- - - Efficiency ^1H target
- - - Efficiency ^{12}C target

^{16}C 2-body disintegration →
 $^6\text{He} + ^{10}\text{Be}$ break-up channel →
low statistics data [3].

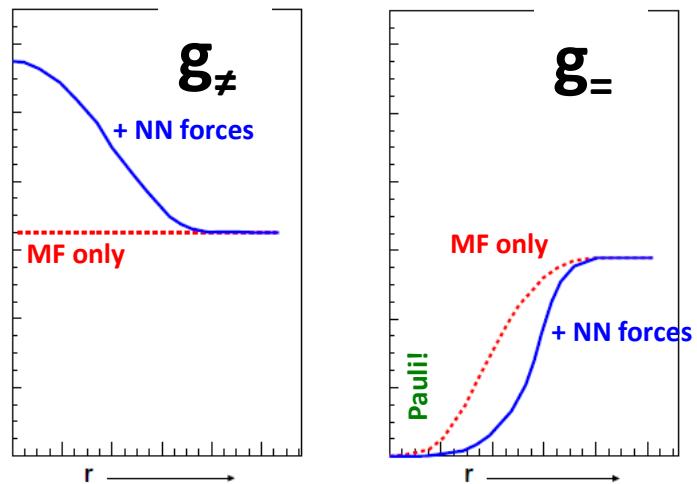


Low statistics results → 20.6 MeV bump

Masses of light nuclei → existence of *clusters* in nuclei!

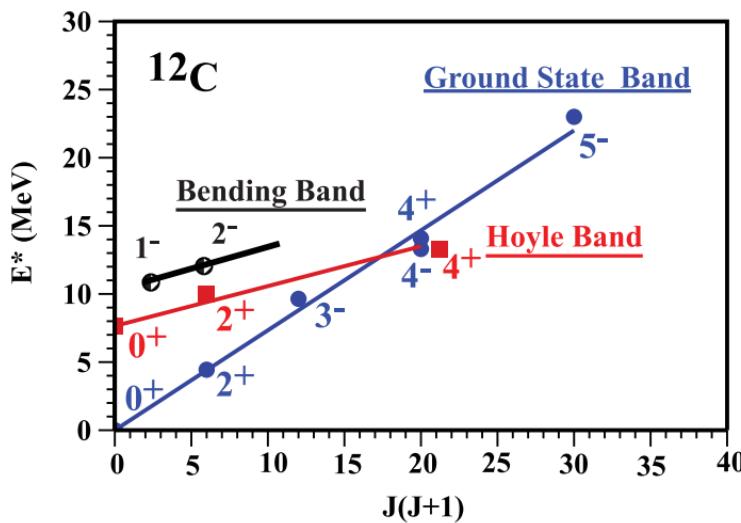


Spacial correlation function for uncorrelated (\neq) and correlated (=) nucleons

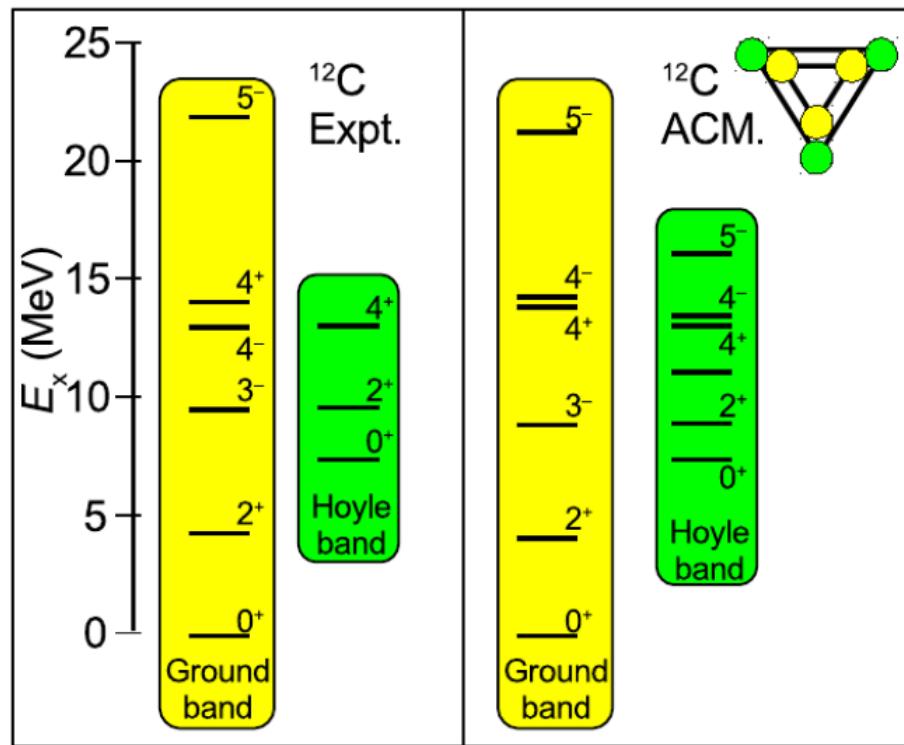


Some signatures that α -cluster structure appears in *nuclei*:

2. Appearance of sequences of levels (E_x , J^π) predicted by quantum-mechanical *rotation* and *vibration* of *triangular* or *tetrahedral* structures (ACM) → (new) SYMMETRIES

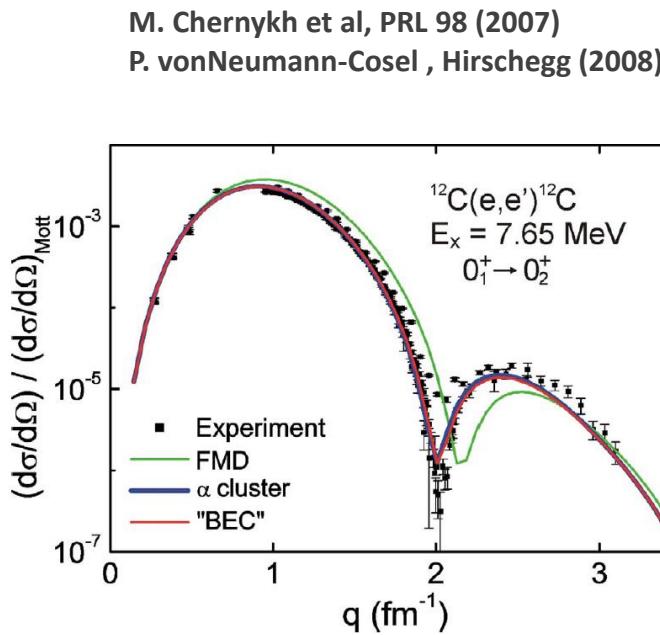
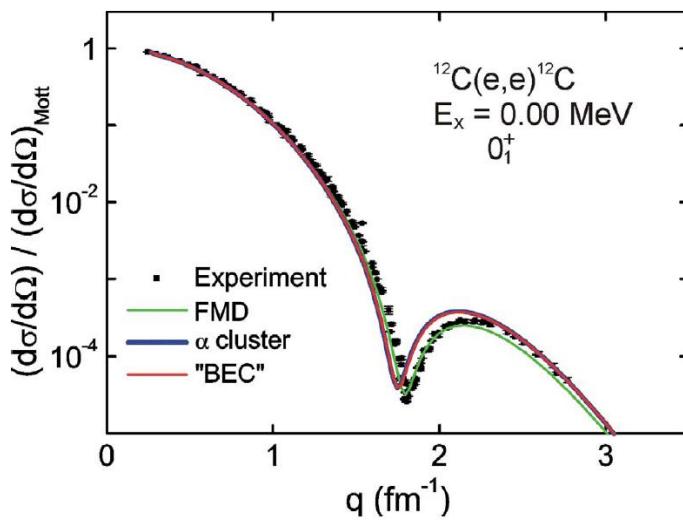


D.J. Marin-Lambarri et al, PRL 113 (2014)



Some signatures that α -cluster structure appears in nuclei:

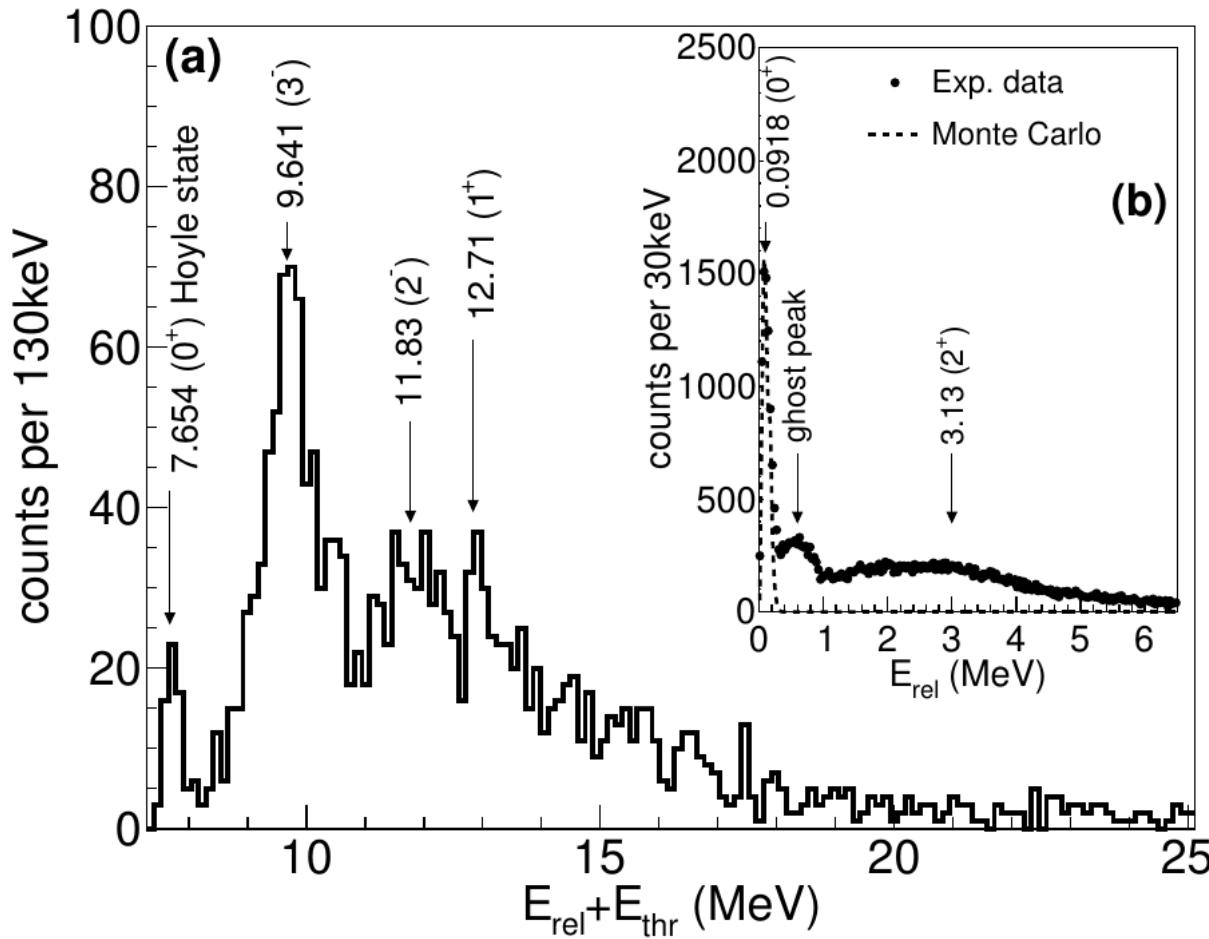
4. Direct *measurement of radii of GS and excited states of nuclei (e scattering)*
5. *Diffractive aspects of elastic scattering induced by protons*



6. Coulomb energy differences in *Mirror Nuclei* (Wildermuth – Tang)
7. Many other probes

Check on self-conjugated nuclei: 2α correlations

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

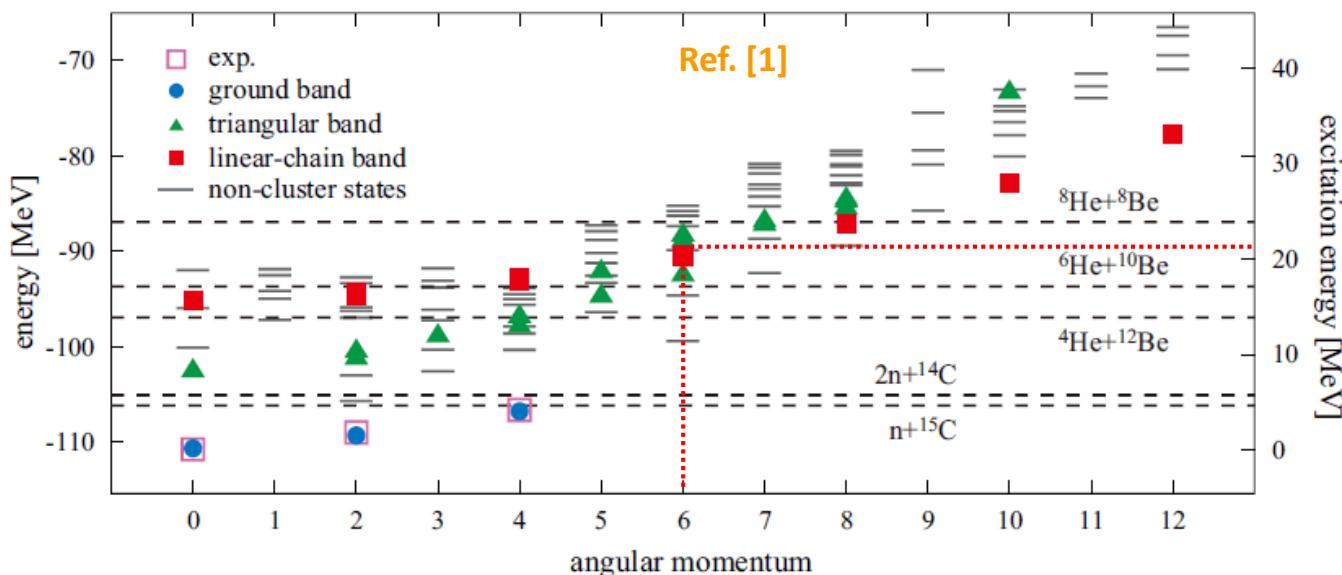


(b) 2α relative energy spectrum → the structure of ${}^8\text{Be}$.

Ground state of ${}^8\text{Be}$ → agreement with Monte Carlo calculations (dashed line).

(a) 3α relative energy spectrum → the structure of ${}^{12}\text{C}$.

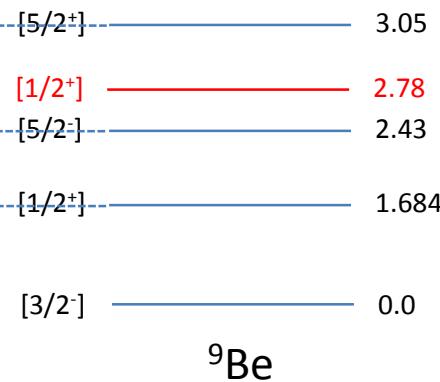
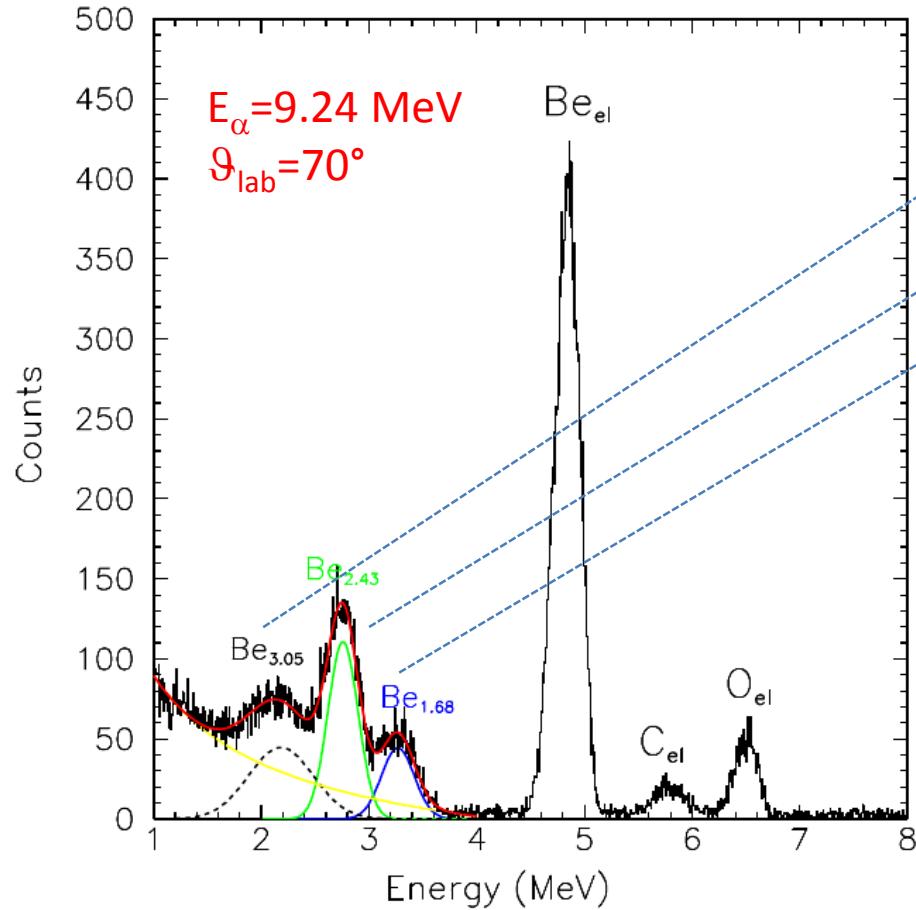
Evidence of the Hoyle state.

$^{10}\text{Be} + ^6\text{He}$ correlations

Molecular states predicted (AMD calculations) at these energies → need to improve statistics and invariant mass resolution.

S. Koyama et al., CLUSTER'16 Conference → yield enhancement in the $^{12}\text{B} + ^4\text{He}$ correlations observed at the same energy!

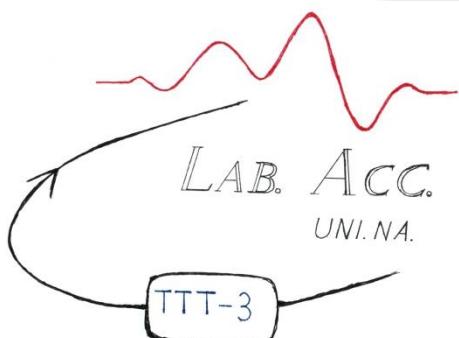
[1] T. Baba, Y. Chiba and M. Kimura , Phys. Rev. C **90**, 064319 (2014)



Identification of the α_1 and α_2 groups by means of a *multi-parametric fit* → continuus background (*exponential*) to reproduce the data.

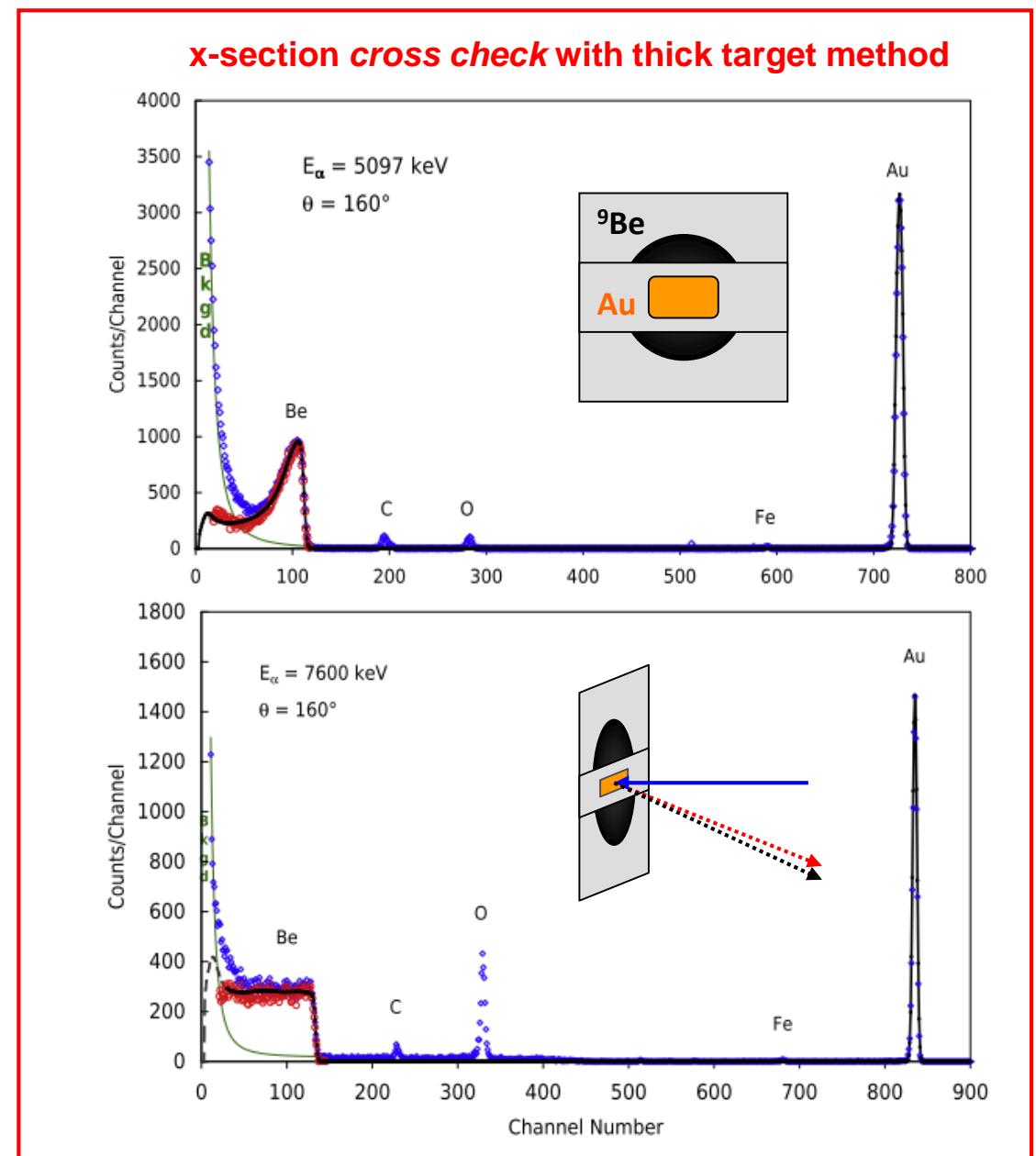
State at **2.78 MeV** (broad) not included in the fit → never observed in α inelastic scattering reactions.

Vanishing contribution of α particles from **${}^9\text{Be}$ break-up** → Monte Carlo calculation.

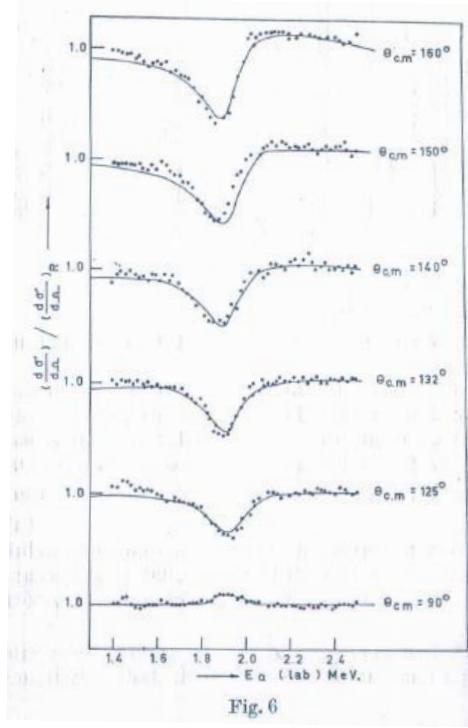


- *background*
- *exp. data*
- *exp. data (background sub)*
- *calculation*

Thick-target yield → nice benchmark of the cross sections.



$5/2^+$ 11.97 MeV

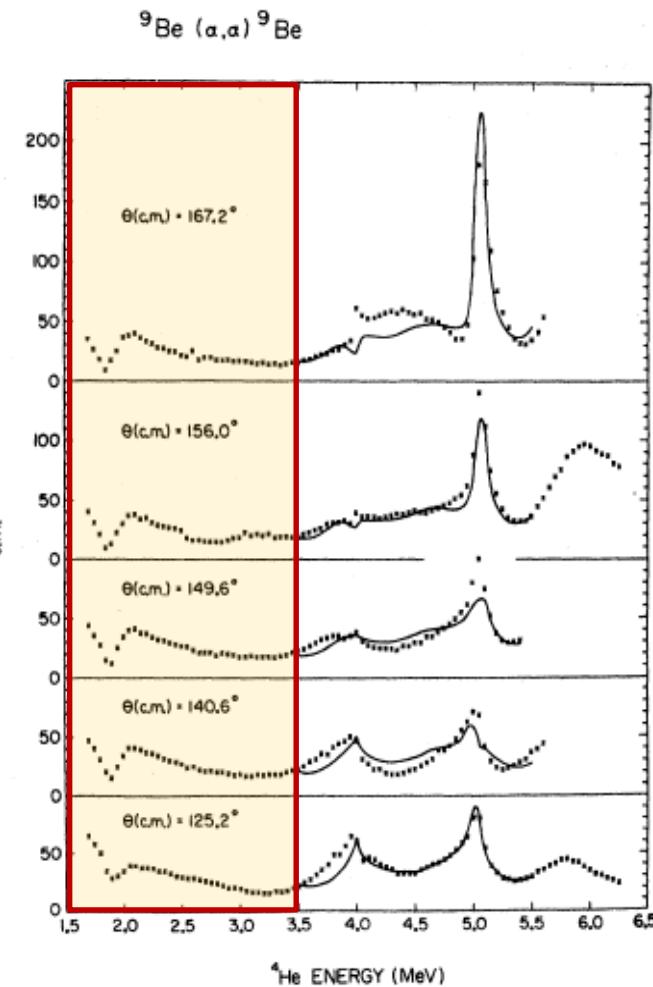


Z.A. Saleh et al., Ann. Phys. (1974)

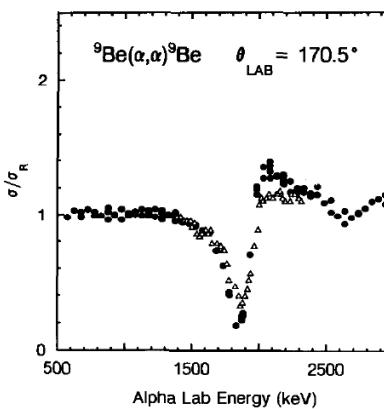
	13.0
[7/2]	12.438
[3/2]	12.187
[1/2 ⁺]	12.14
[5/2]	12.13
[3/2 ⁺]	12.106
[5/2 ⁺]	11.95

^{13}C

from Ajzemberg-Selove compilation

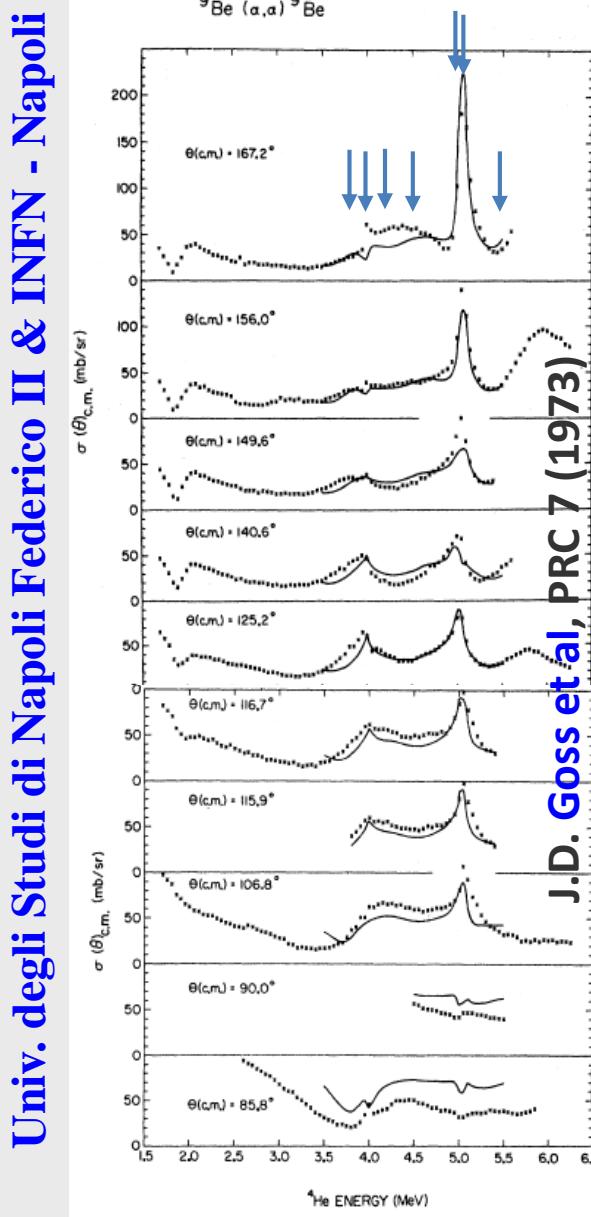


J.D. Goss et al., PRC 7 (1973)



J. Leavitt et al., NIMB (1994)

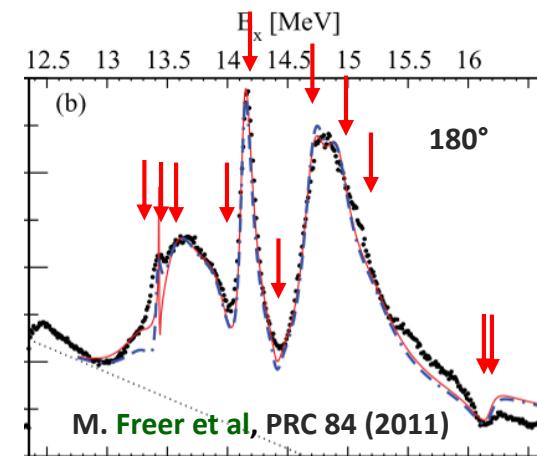
Data from RES experiments: $E_\alpha > 3.5$ MeV



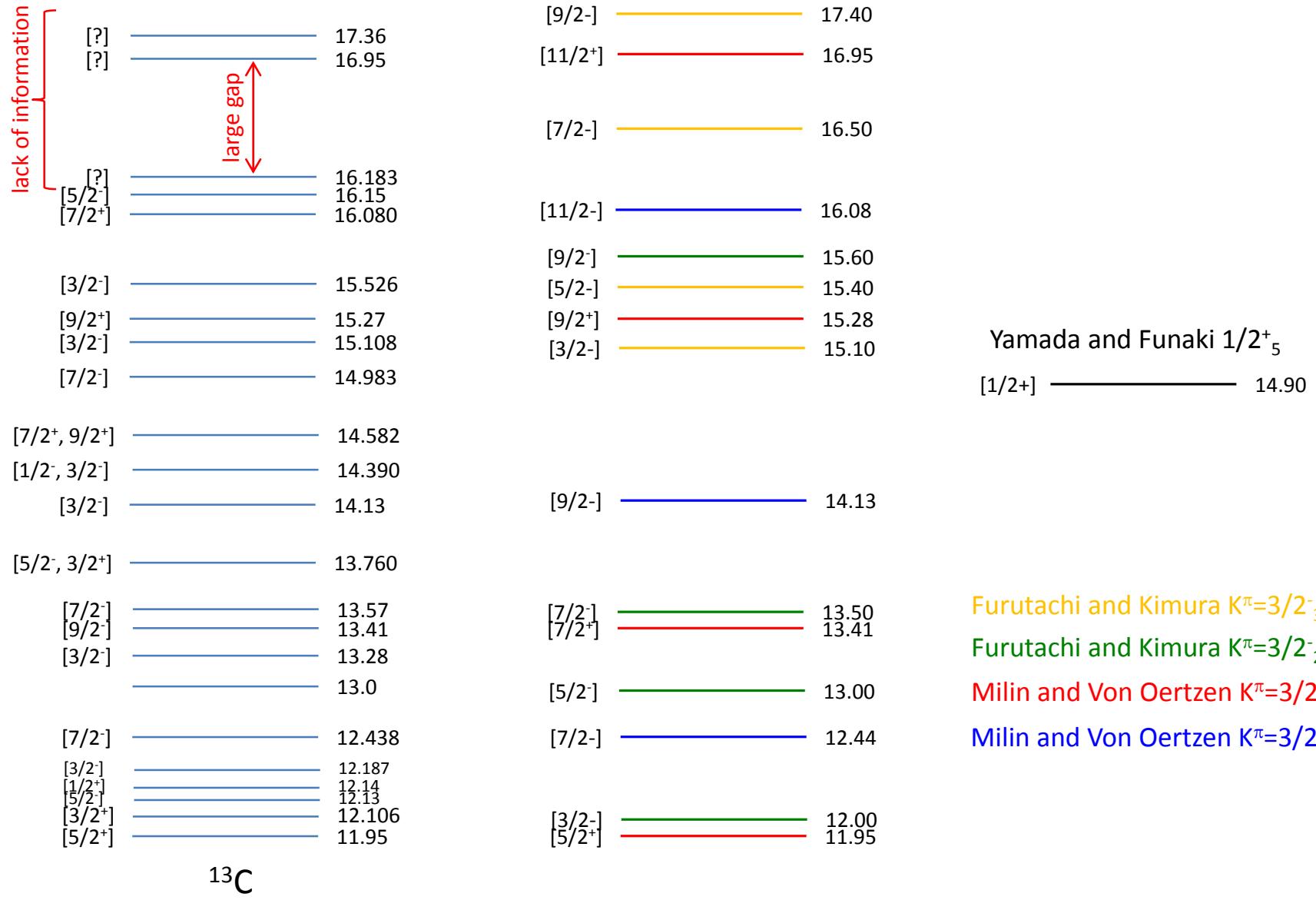
Goss et al.

Freer et al.

E_x (MeV)	E_α (MeV)	J^π	Γ (keV)	E_x (MeV)	E_α (MeV)	J^π	Γ (keV)	J^π
13.28	3.80	$3/2^-$	343	13.38	3.94	$3/2^-$	340	
13.42	4.00	$(9/2^-)$	58	13.43	4.01	$9/2^-, 7/2^+$	2	$7/2^+$
13.56	4.20	$5/2^+$	685	13.53	4.16	$7/2^-$	596	$7/2^-$
13.77	4.51	$3/2^+$	247	13.93	4.74	$5/2^+$	337	
14.11	5.00	$5/2^-$	75	14.13	5.03	$5/2^-$	124	$9/2^-$
14.16	5.07	$7/2^+$	73	---	---	---	---	
14.46	5.50	$(5/2^+)$	400	14.41	5.43	$7/2^-$	111	
---	---	---	---	14.72	5.88	$9/2^+$	285	
---	---	---	---	14.96	6.22	$7/2^-$	406	$9/2+$
---	---	---	---	15.15	6.50	$5/2^-$	493	$3/2^-$
---	---	---	---	16.14	7.93	$7/2^+$	140	
---	---	---	---	16.16	7.96	$5/2^-$	253	



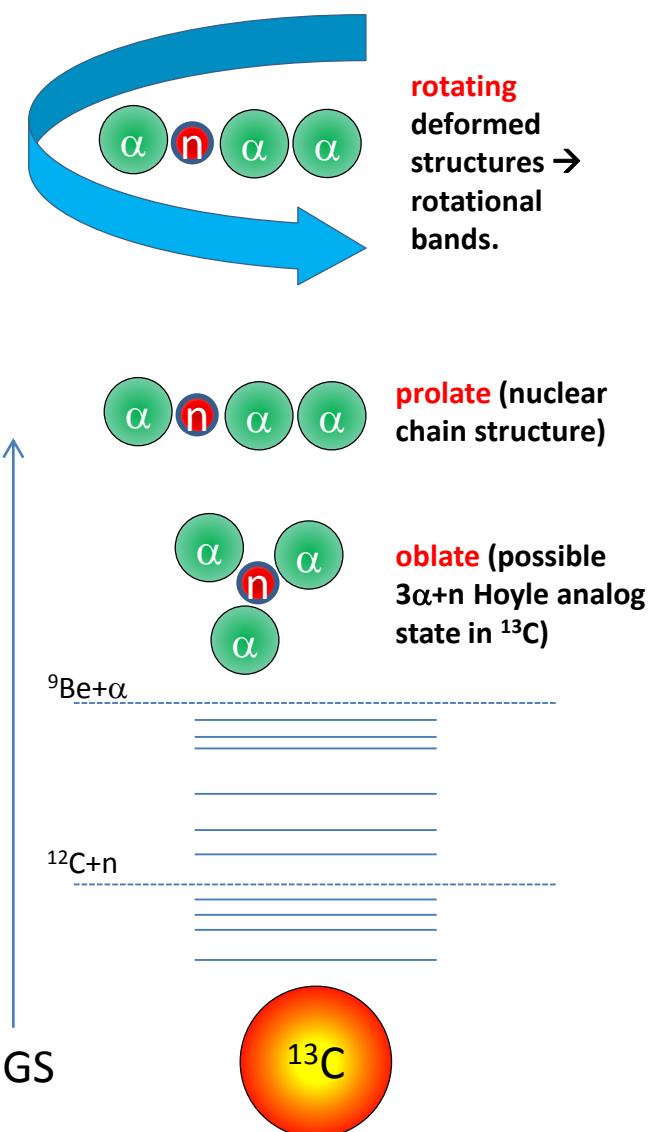
Proposed rotational bands



from Ajzenberg-Selove compilation

predicted rotational bands

 ^{13}C



Near and above the α -threshold → different α -cluster configurations proposed for ^{13}C → theoretical works:

M. Milin and W. Von Oertzen EPJ A 14 (2002) 295

proposed parity doublet band of $^{9}\text{Be}_{\text{gs}} + \alpha$ cluster prolate configuration → J^π assignments based on the rotational bands ($K=3/2^\pm$).

T. Yoshida, N. Itagaki and T. Otsuka, Phys. Rev. C 79 (2009)

N. Furutachi and M. Kimura, Phys. Rev. C 83 (2011)

microscopic $3\alpha + \text{n}$ model → proposed two new rotational bands ($K=3/2^-_2$ and $K=3/2^-_3$).

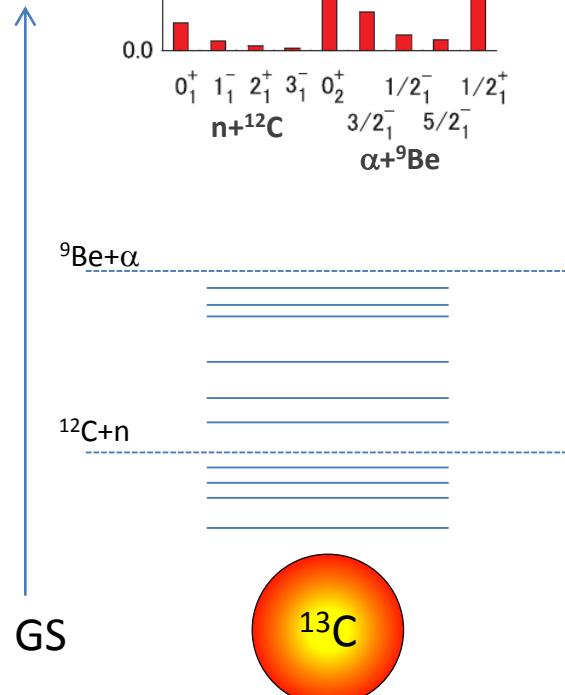
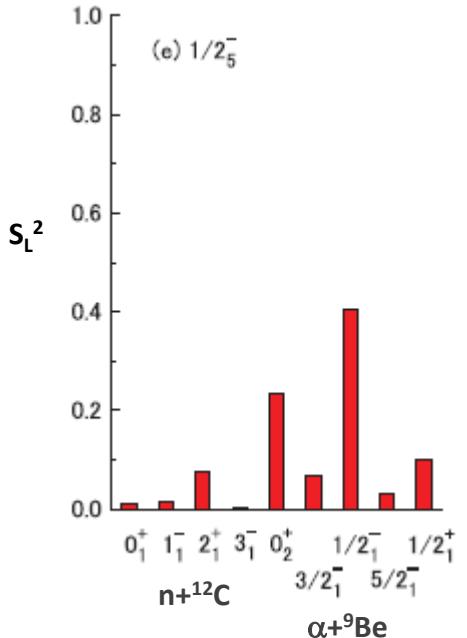
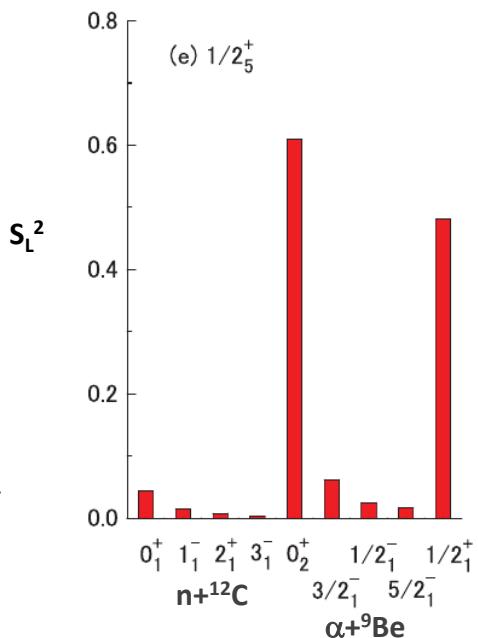
Coupling of one neutron with a $^{12}\text{C}^*$ core
→ possible gas-like states analog of Hoyle state in ^{13}C :

Y. Chiba and M. Kimura, J. Phys. Conf. Ser. 569 (2014) 012047
molecular bands ($K=1/2^\pm$).

T. Yamada and Y. Funaki, Phys. Rev. C 92 (2015) 034326

$1/2^+_5$ state predicted at 14.9 MeV with a strong $^{12}\text{C}(0^+_2) + \text{n}$ spectroscopic factor → analog of Hoyle state in ^{13}C .

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 spectroscopic factor → analog of Hoyle state in ^{13}C .

Analysis of α Scattering From ^{25}Mg at 12.5 MeV in Terms of the Coupled-Channel Calculation (*).

S. COSTA, R. GIORDANO, F. PORTO, S. SAMBATARO and A. SCALIA

*Istituto Nazionale di Fisica Nucleare - Sezione di Catania
Centro Siciliano di Fisica Nucleare e di Struttura della Materia - Catania*

L. ZUFFI

*Istituto di Fisica dell'Università - Milano
Istituto Nazionale di Fisica Nucleare - Sezione di Milano*

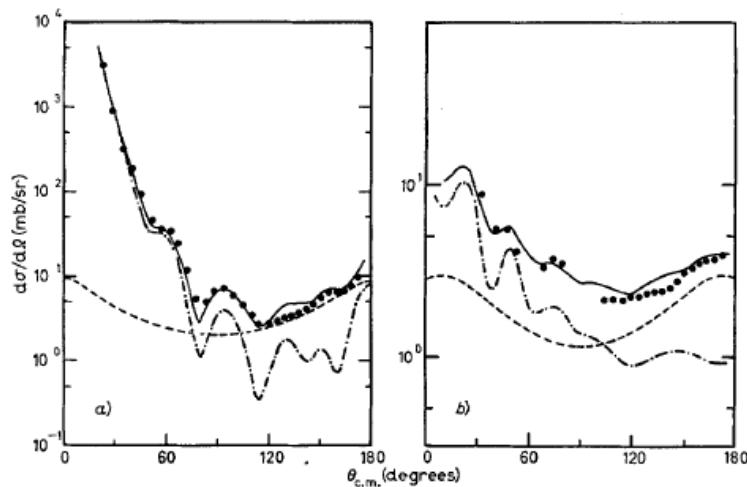


Fig. 9. -- Experimental averaged cross-sections of the $\frac{1}{2}^+$ (a) and $\frac{3}{2}^+$ (b) members of the g.s. band ($K\pi = \frac{1}{2}^+$), as compared with theoretical curves. The dashed lines are the Hauser-Feshbach calculations. The dot-dashed lines are the coupled-channel calculations. The solid lines are obtained by adding the compound contribution to the e.c. calculations. b) $E^* = 1.61$ MeV.

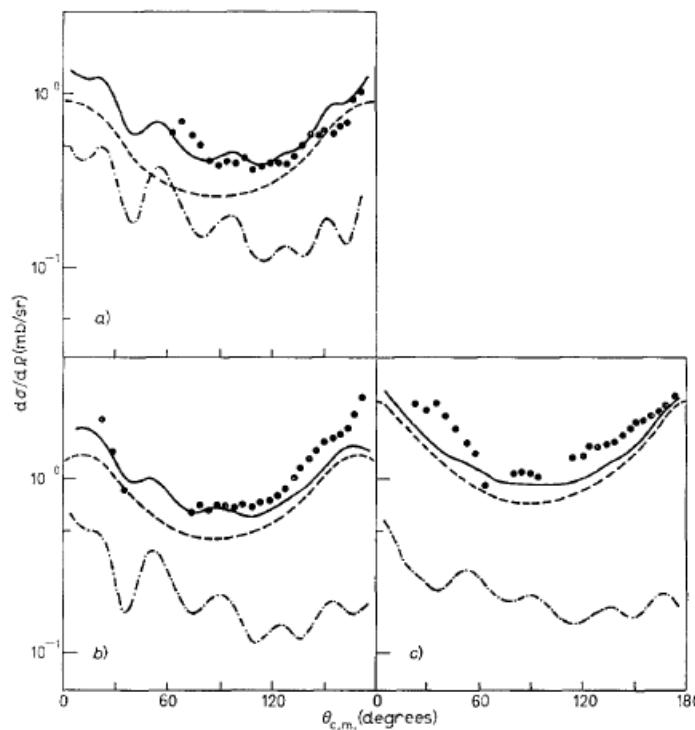
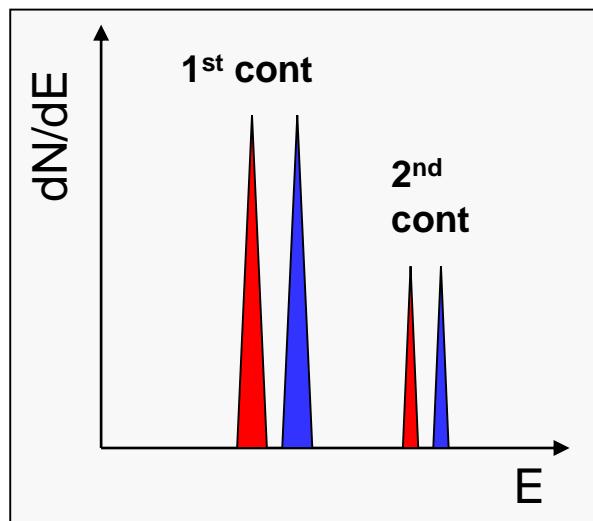
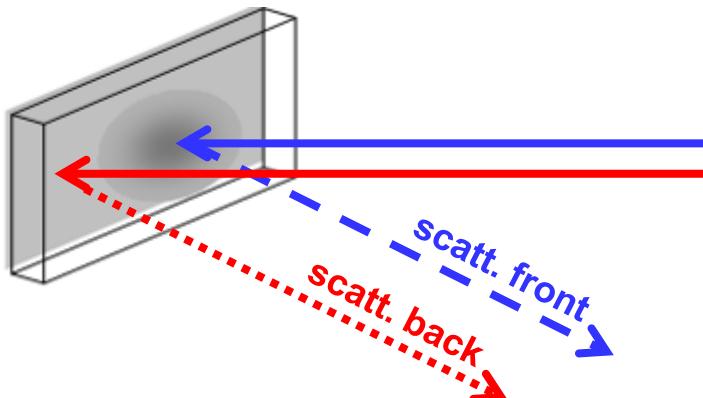


Fig. 10. -- Experimental averaged cross-sections of the $\frac{1}{2}^+$ (a), $\frac{3}{2}^+$ (b) and $\frac{5}{2}^+$ (c) members of the $K\pi = \frac{1}{2}^+$ band, as compared with theoretical curves. The dashed lines are the Hauser-Feshbach calculations. The dot-dashed lines are the coupled-channel calculations. The solid lines are obtained by adding the compound contribution to the e.c. calculations. a) $E^* = 0.59$ MeV, b) $E^* = 0.97$ MeV, c) $E^* = 1.96$ MeV.



- good *identification of scattering events*
→ *kinematics and target structure*
- very *low background*

Target ${}^9\text{Be}$ → $129 \mu\text{g}/\text{cm}^2$
 Formvar → $6 \mu\text{g}/\text{cm}^2$
Build-up (other experiments)

Manufactured by INFN
 Laboratori Nazionali del Sud - Catania

