Analysis of states in ^{13}C and their cluster structure

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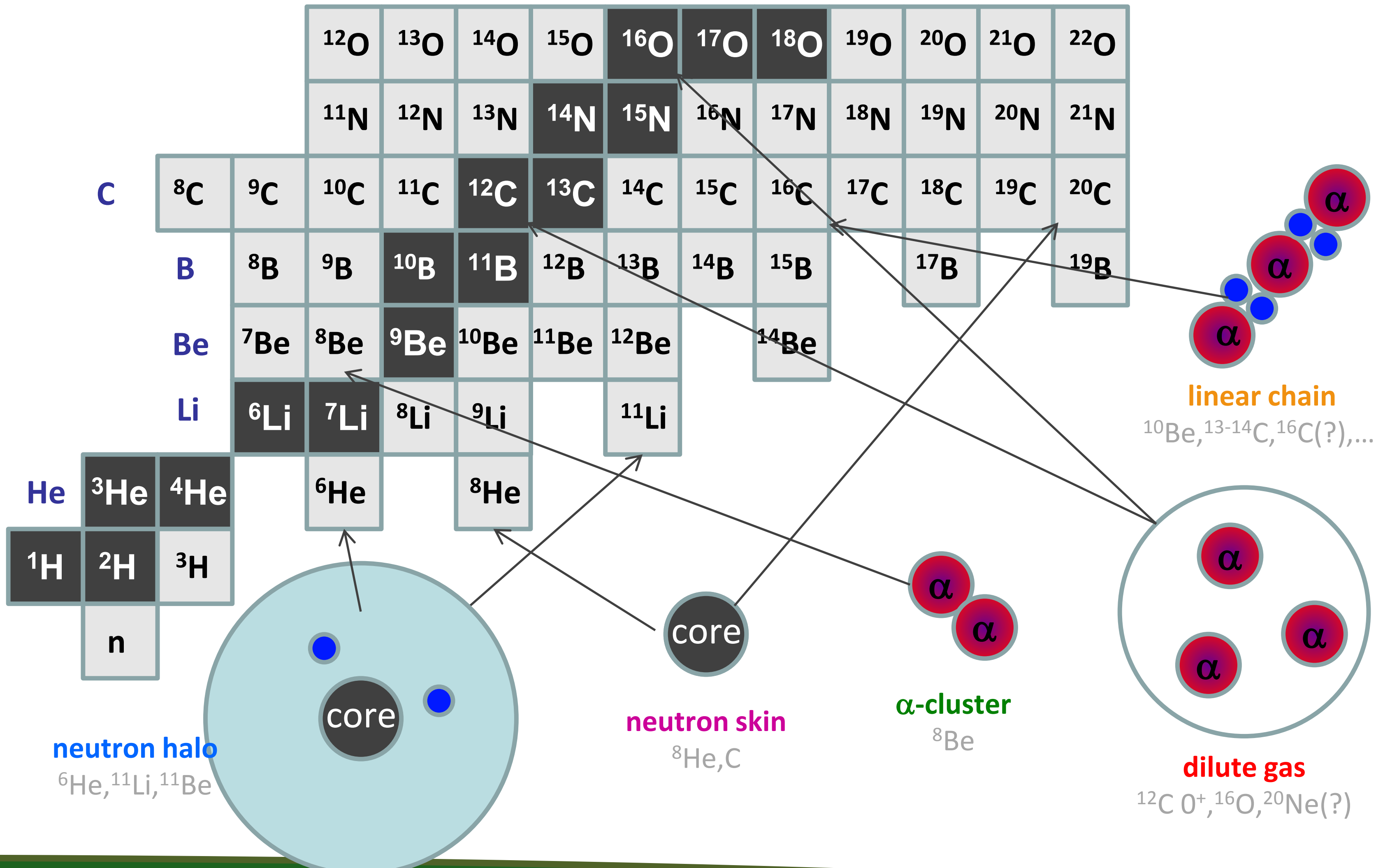
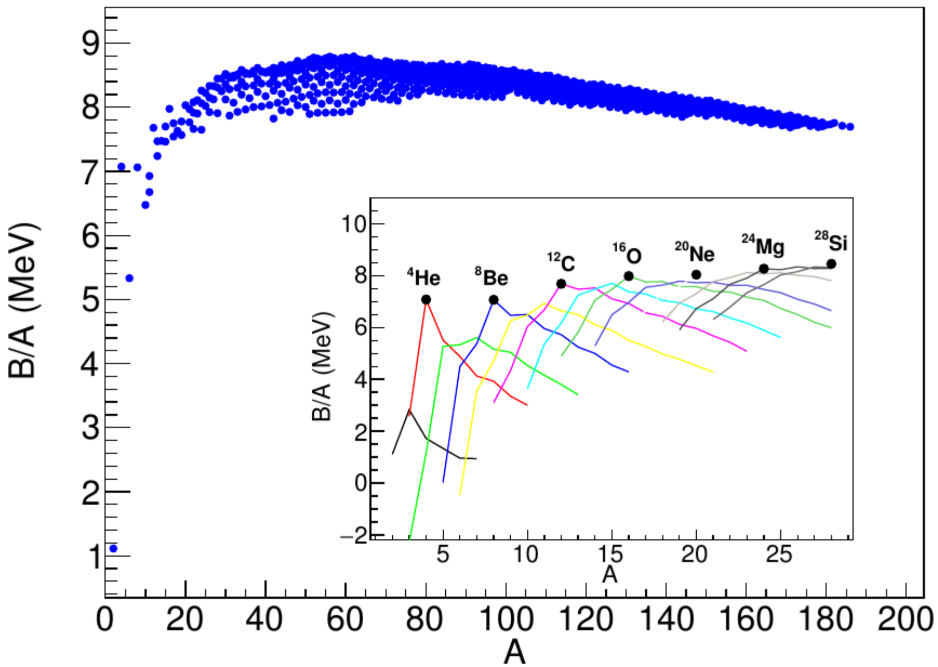
Complexity of nuclear force → long-range ***correlations***: spatial re-organization of nucleons in bounded **sub-units** (***cluster model***).



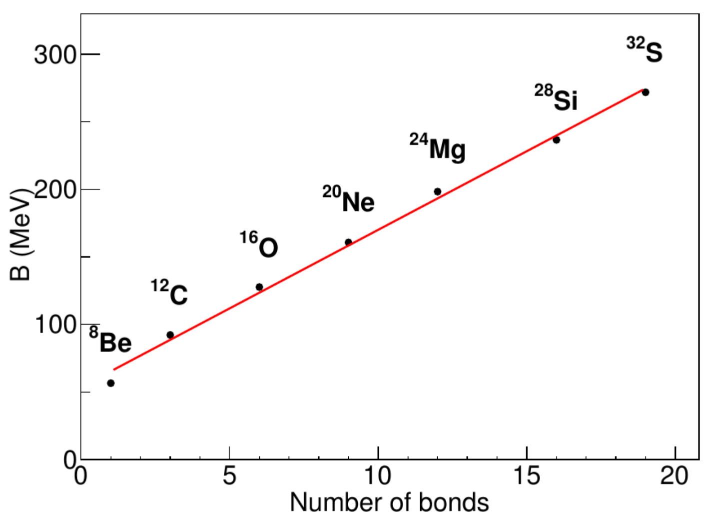


Binding energy of nuclei → self-conjugated nuclei are exceptionally bound → ***long range*** correlations → **clustering phenomena**.

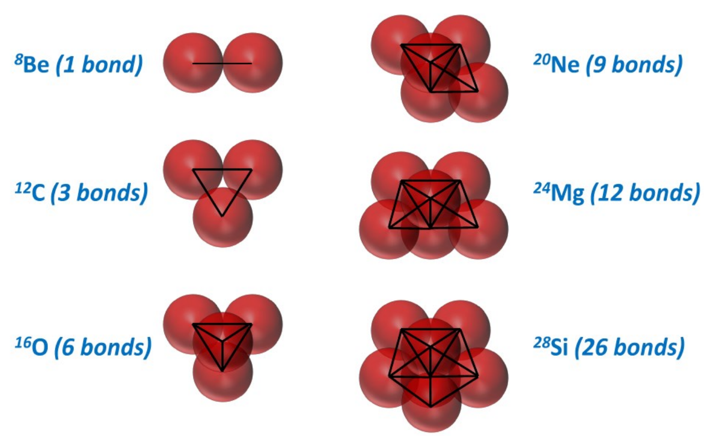
1930's : *Hasfstad and Teller* point out the existence of a linear correlation between the number of α-α bonds and the binding energy of self-conjugated nuclei:

L. Hafstad and E. Teller, Phys. Rev. 54, 681 (1938)

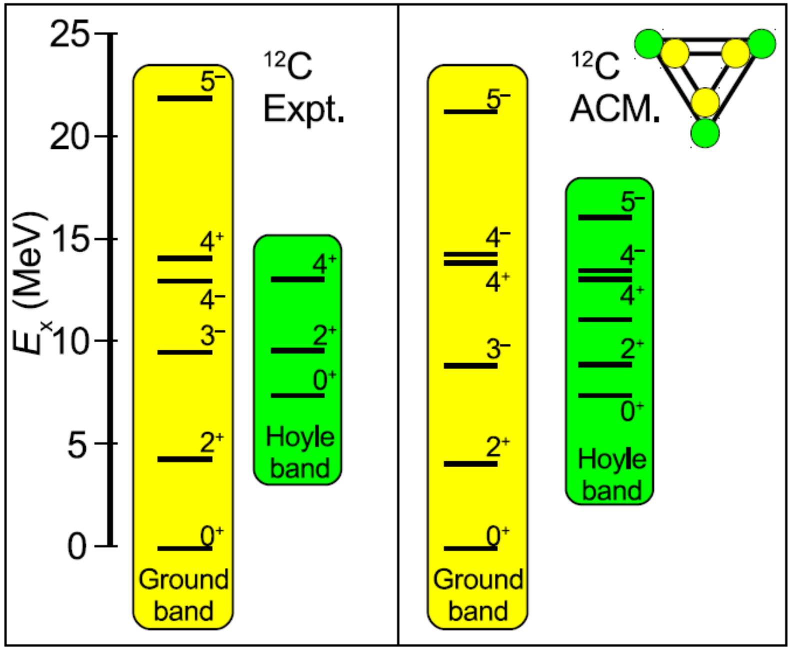
Adapted from:
L. Hafstad and E. Teller, Phys. Rev. 54, 681 (1938)



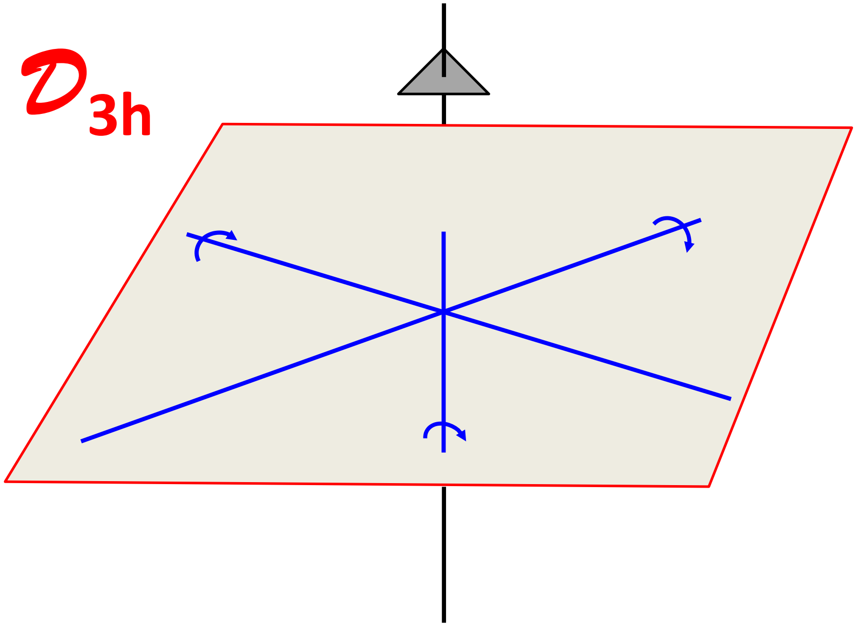
The beginning of the α-cluster model.



Recently → applications of *point group symmetries* to clusterized nuclei, as ^{12}C



R. Bijker & F. Iachello, Phys. Rev. C 61, 067305 (2000).
D. M. Lambarri et al, Phys. Rev. Lett. 113 (2014) 012502



P. Atkins, *Physical Chemistry* (3rd ed.), OUP (1988) p. 409

- 3-fold *principal* symmetry axis ($\mathcal{C}_3$)
- 3 two-fold axes *perpendicular* to $\mathcal{C}_3$
- Horizontal mirror plane

Symmetry considerations → important benchmarck for *microscopic calculations*

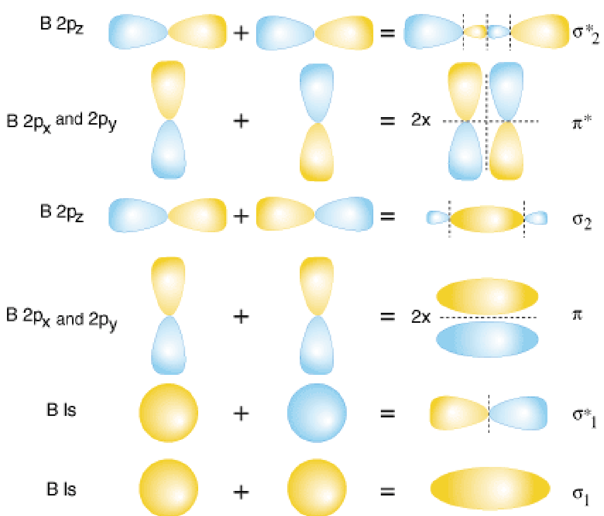
Probe of the geometry of ^{12}C → *nuclear fluorescence* experiments with linearly polarized γ beams, see e.g. L. Fortunato, PRC 99 (2019) 031302(R)

Symmetry considerations apply for *other self-conjugate* nuclei! e.g. ^{8}Be with Z_2 symmetry, see next talk by M. Gai

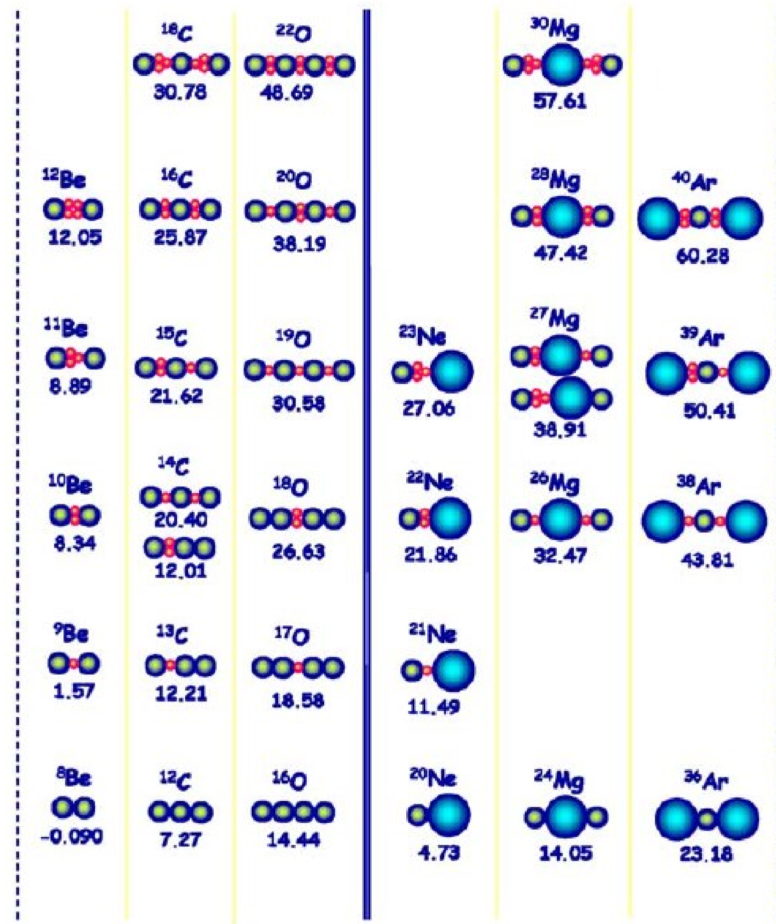
And for *non self-conjugate* nuclei?

Even if the occurrence of *clustering* in non-self-conjugated nuclei has been reported many decades ago (see, e.g. Rosenfeld & Blatt-Weisskopf) → renewed interest in more recent times

Some ideas taken from *physical chemistry* → extra neutrons acting as *covalence particles*



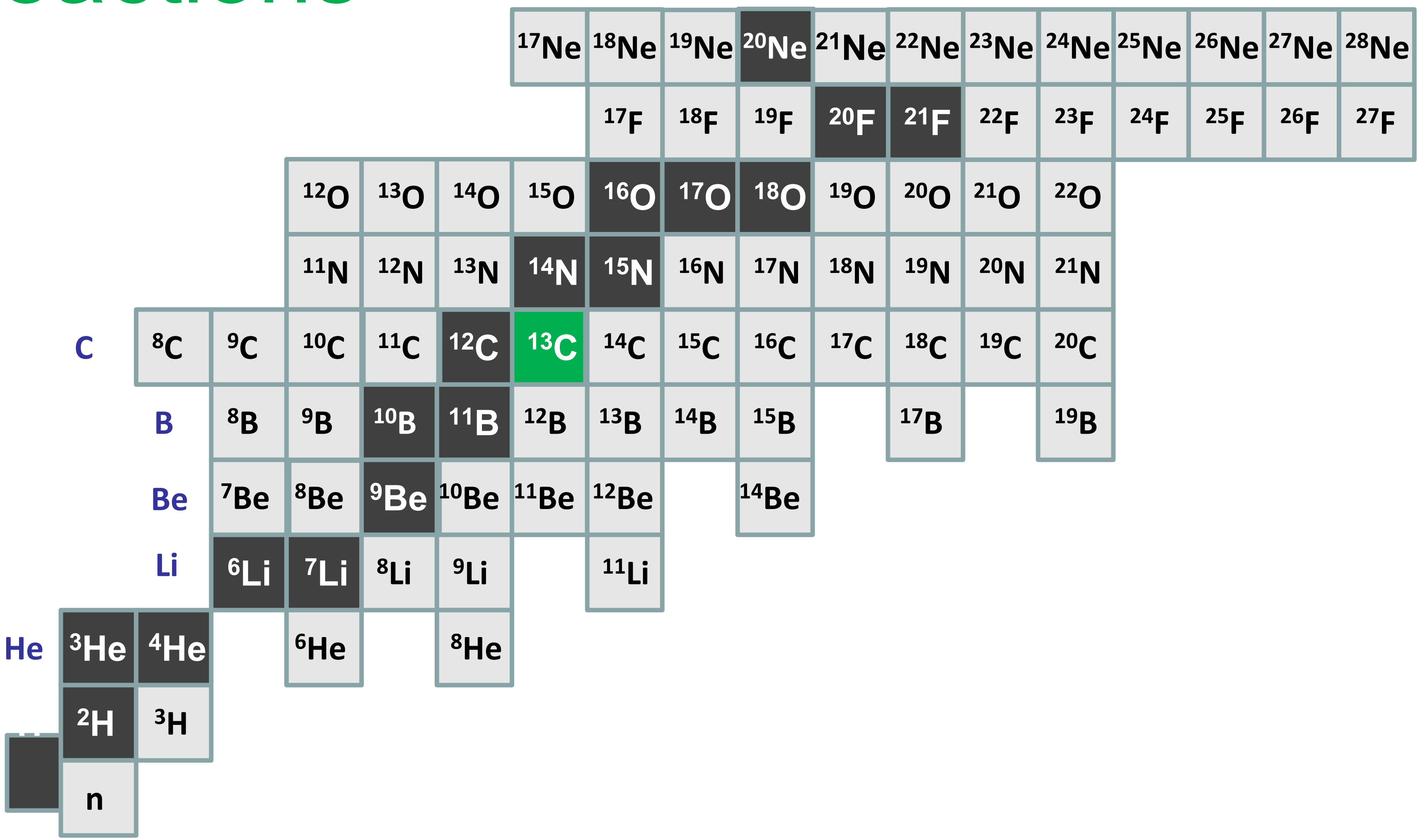
Energy considerations → molecular states close to Nα+n disintegration thresholds



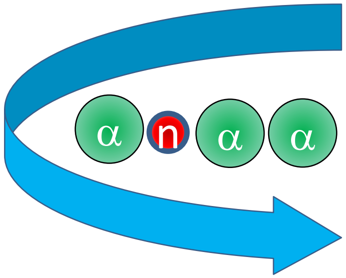
Signals of clusterization also in *p-rich* nuclei

«*Modified* Ikeda Diagram»

Clustering in ^{13}C with α + ^{9}Be reactions



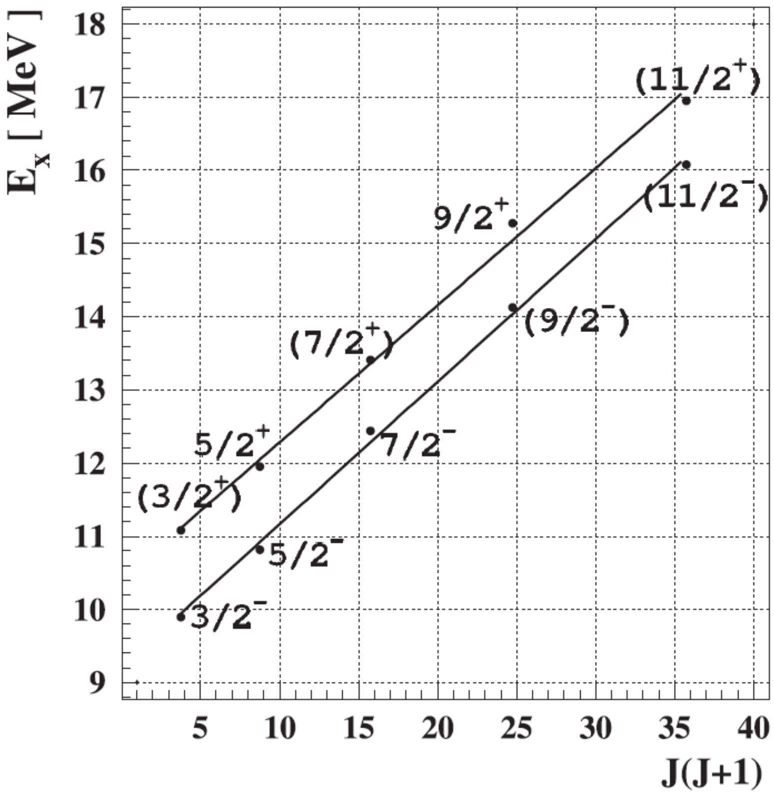
^{13}C structure: *hints* from theory

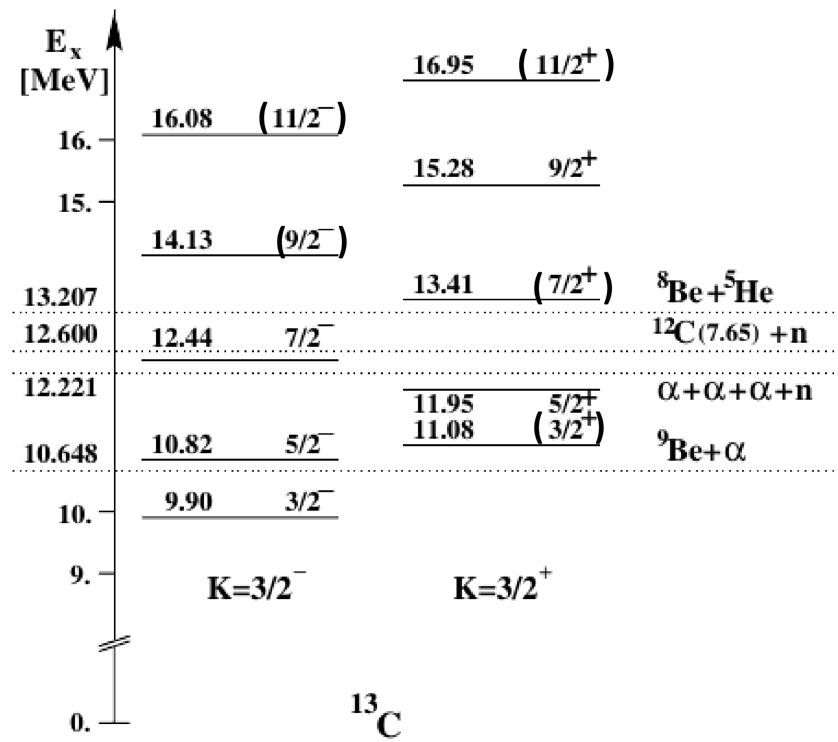


rotating deformed structures → rotational bands.

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 $^{9}Be_{gs}$ + α cluster prolate configuration → J^{π} assigments based on the rotational bands ($K=3/2^{\pm}$).





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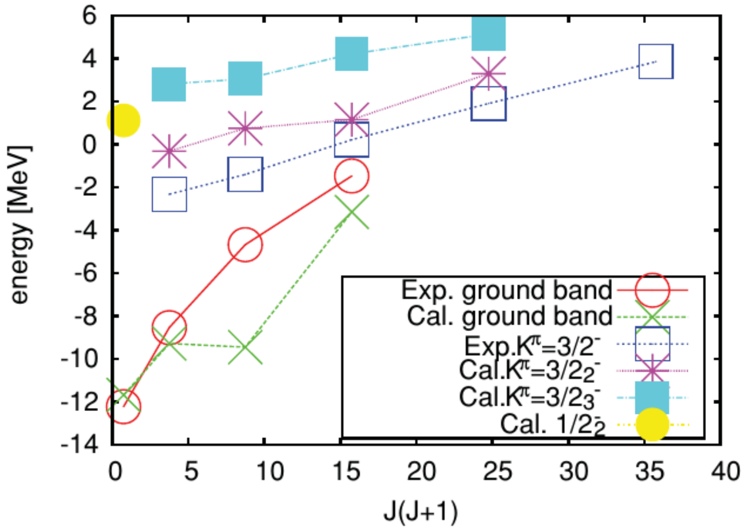
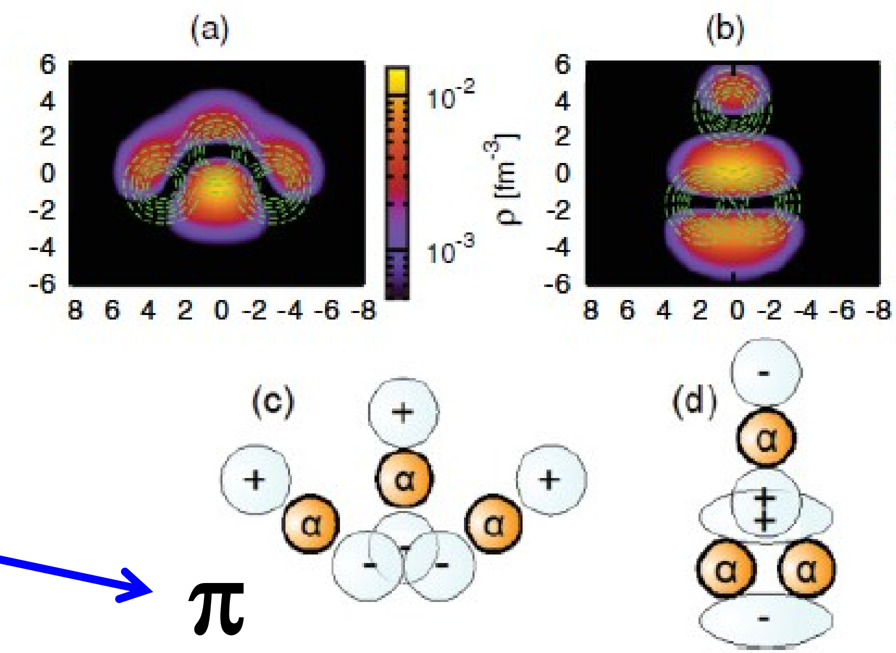
Near and above the α-threshold → different α-cluster configurations proposed for ^{13}C



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

Microscopic GCM 3α+n model → proposed two new rotational bands (K=3/2$^-_2$ and K=3/2$^-_3$).

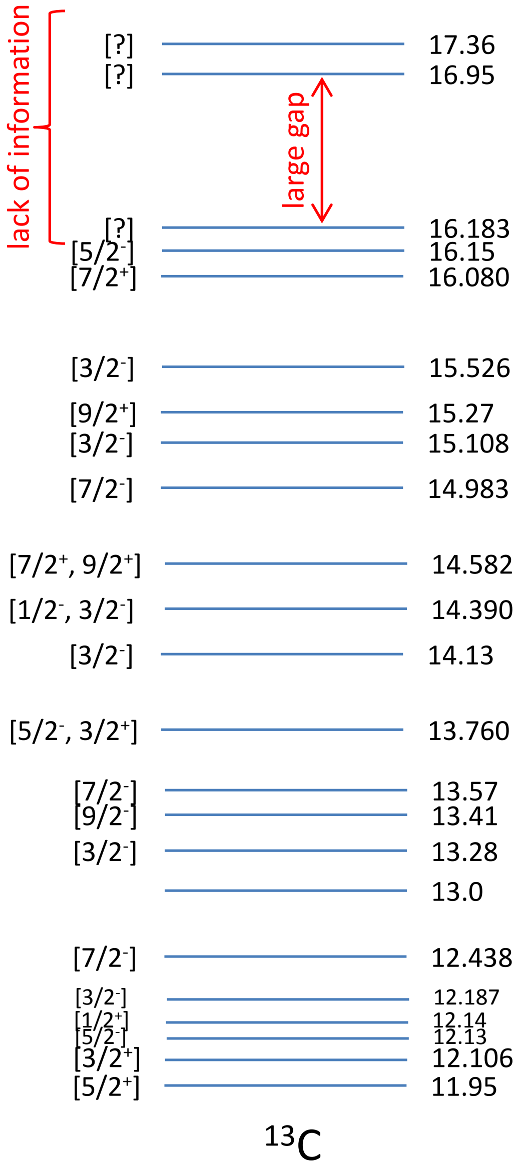
$3/2_2^-$ **$3/2_3^-$**



π ***Spur.***

"By adding the valence neutron in this (π) orbital, the ***α-α distance shrinks*** and the **binding energy** of the system **increases**. As a consequence, the **stability** of the **bent linear-chain** configuration is **achieved.**"

The spectroscopy of ^{13}C: *experimental* techniques



from Ajzemberg-Selove compilation

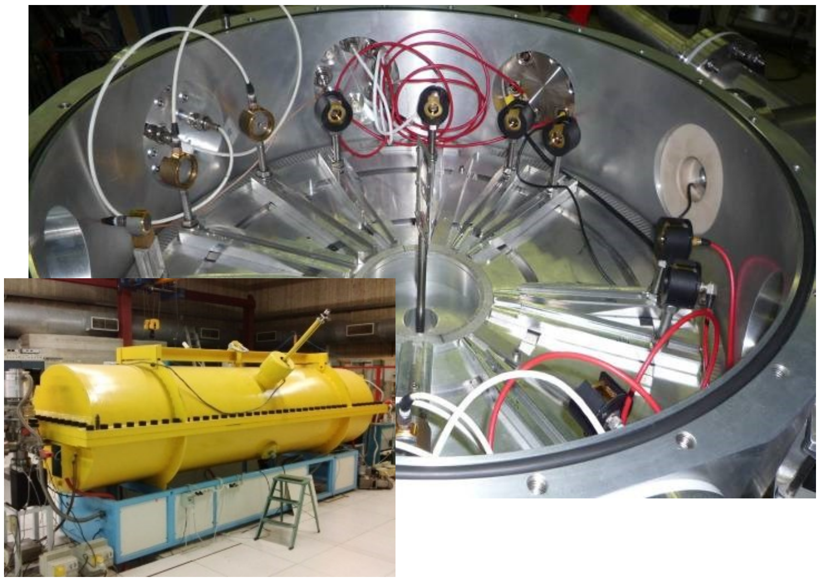
To investigate the structure of ^{13}C above the α-threshold (10.651 MeV) → ^{9}Be(α,n), ^{9}Be(^{6}Li,d), ^{13}C(α,α'), ^{9}Be(α,α) etc.

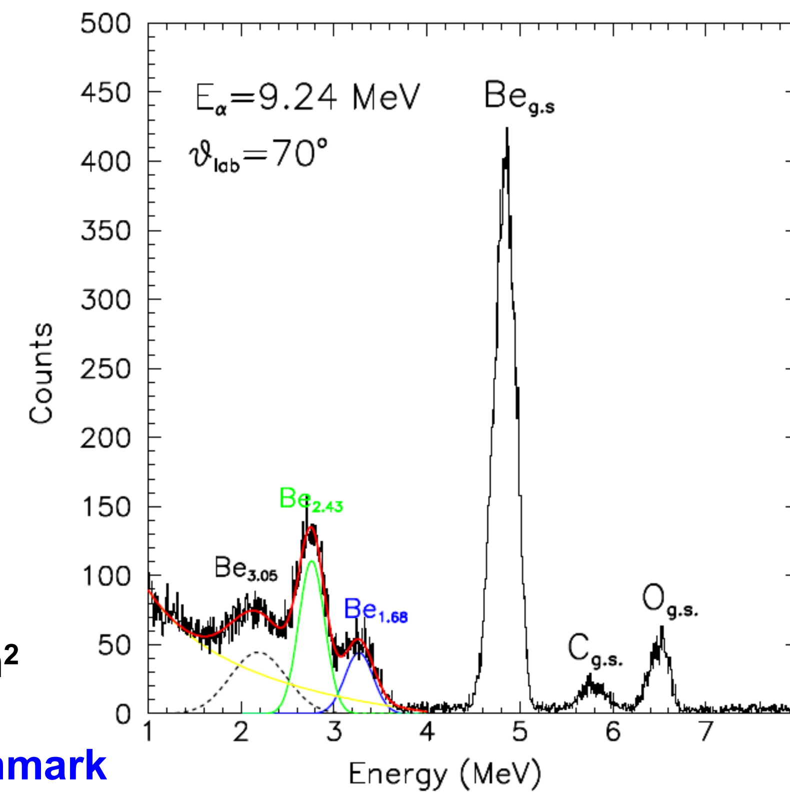
The *Resonant Elastic Scattering* is particularly suited for investigating states in the compound ^{13}C with α-cluster nature since the ^{9}Be presents a well developed *molecular nature*.

• R.B. Taylor et al, NPA 65 (1965) 318	DK	$6.3 < E_{lab} < 19.7$
• J.D. Goss et al, PRC 7 (1973)	DK	$1.7 < E_{lab} < 5.6$
• Z.A. Saleh et al, Ann. Phys. 7 (1974) 76	DK	$1.4 < E_{lab} < 2.5$
• J. Leavitt et al, NIM B 85 (1994) 37	DK	$0.6 < E_{lab} < 4.2$
• J. Liu et al, NIM B 108 (1996) 247	DK	$0.9 < E_{lab} < 5.3$
• M. Zadro et al, NIM B 259 (2007) 836	IK	$2.0 < E_{cm} < 4.3$
• M. Freer et al, PRC 84 (2011) 034317	IK	$1.6 < E_{cm} < 6.0$

LAB. ACC.
UNI. NA.
TTT-3

Beam: $^4He^{++}$ → E_{Lab}: 3.6 – 10 MeV
(60keV step, 110 energy changes, energy spread ≤ 3 keV) TTT-3MV of Lab. Acceleratore – Naples, Italy
Silicon detectors: energy resolution ≈ 5.0 ‰



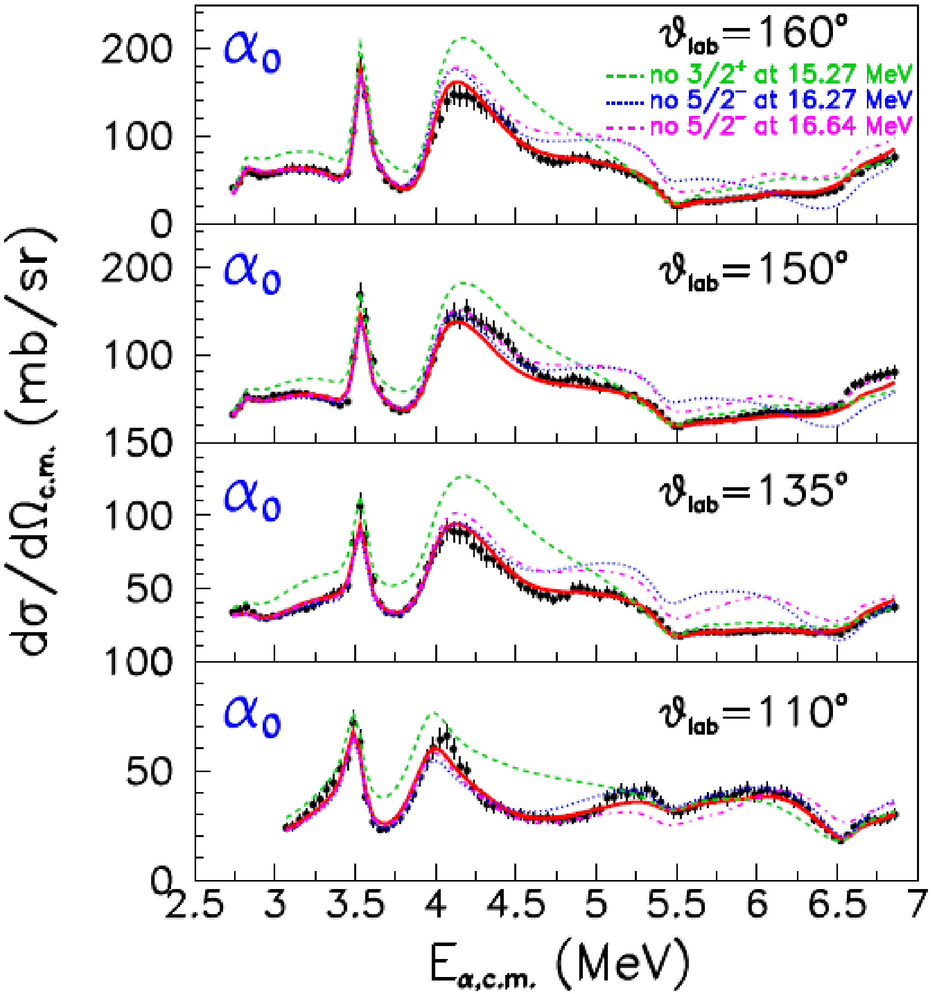


Thin ^{9}Be target → self supporting, 122 μg/cm^2
C and O contamination
Thin target absolute cross sections → benchmark with a dedicated thick target experiment

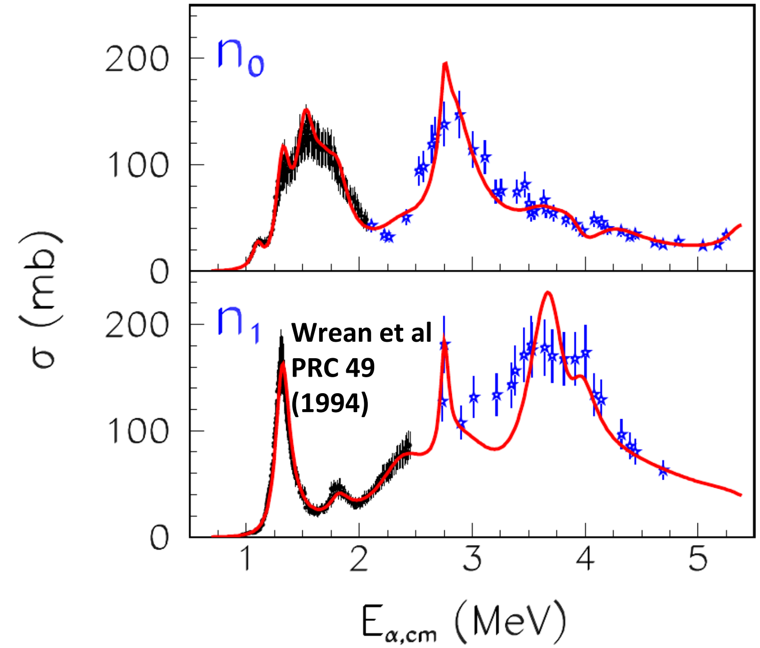
I. Lombardo et al, NIM B 302 (2013) 19-23

^{13}C structure via α + ^{9}Be: *R*-matrix calculations

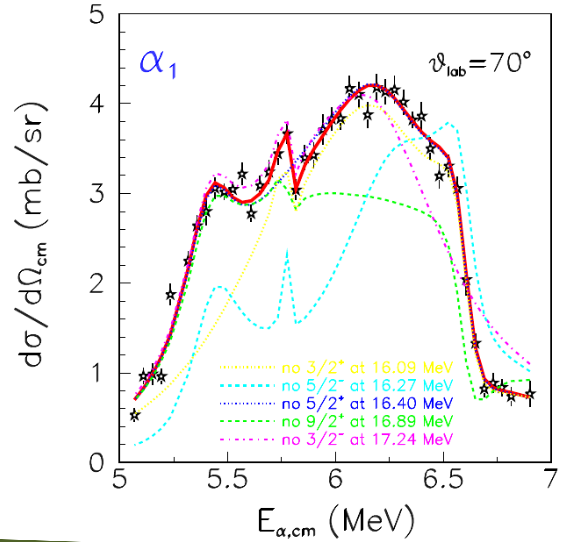
^{9}Be(α,α_0)



^{9}Be(α,n_0,n_1)



L. van der Zwan and K.W. Geiger, Nucl. Phys. A 152 (1970) 481



^{9}Be(α,α_1)

AZURE R-Matrix Program

AZURE2

R. Azuma et al, Phys. Rev. C 81, 045805 (2010)

I. Lombardo et al, Phys. Rev. C 97 (2018)

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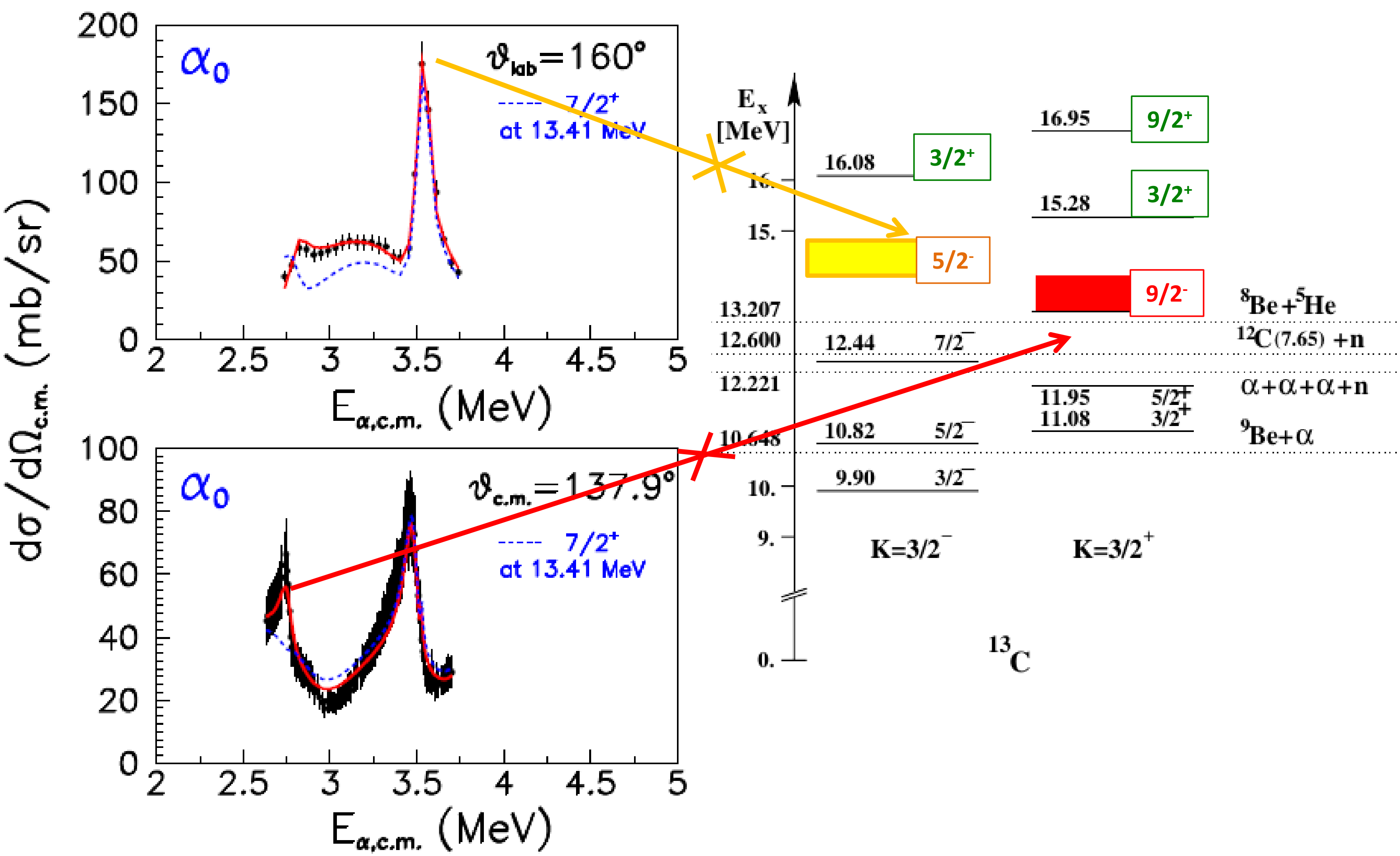
«*Differential diagnosis*» on some «*critical*» J^{π} assignments



Many *angles* and *channels* → solve ambiguities

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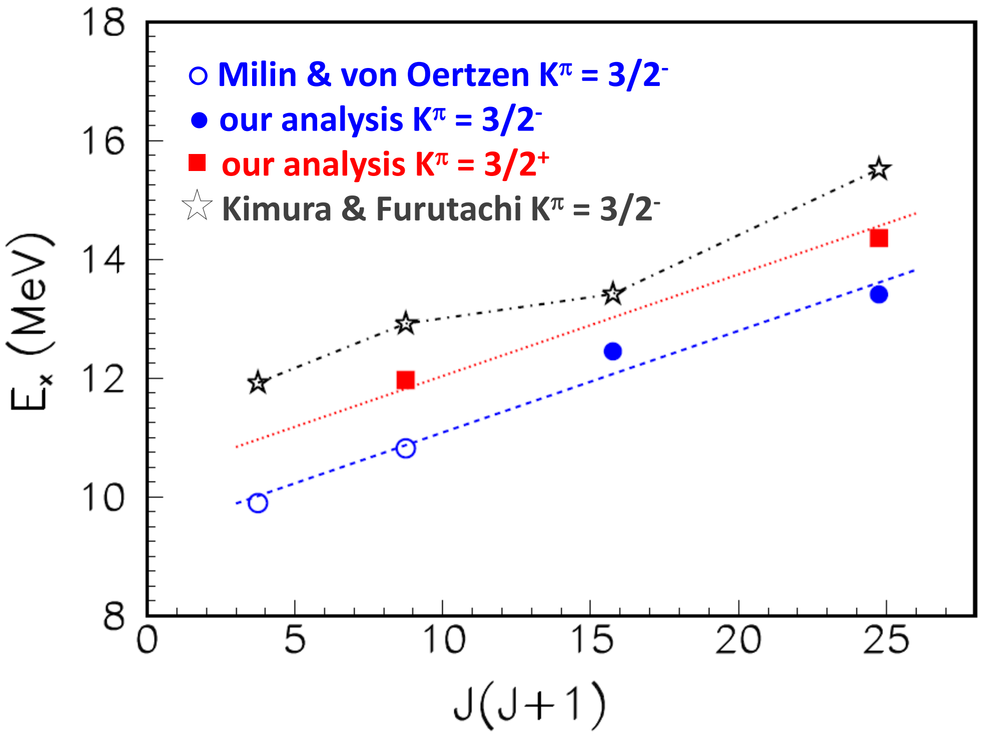
literature | **our data from the Napoli exp.**

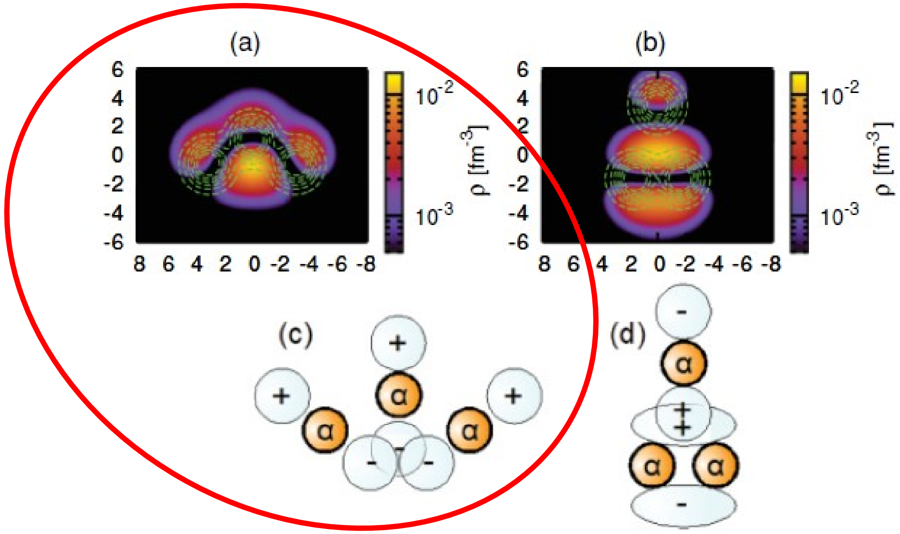
E_x^{lit}	J^{π}_{lit}	E_x	J^{π}	Γ	Γ_{α_0}	Γ_{α_1}	Γ_n
11.75	$3/2^-$	11.75	$3/2^-$	116(27)	3(1)	—	113(26)
11.97	$5/2^+$						
12.13	$5/2^-$	12.17	$5/2^-$	199(28)	28(7)	—	171(21)
12.14	$1/2^+$	12.33	$1/2^+$	230(37)	40(7)	—	190(30)
12.44	$7/2^-$						
13.28	$3/2^-$	13.05	$3/2^-$	546(112)	153(29)	—	393(83)
13.41	$9/2^-$						
13.57	$7/2^-$	13.49	$7/2^-$	417(116)	114(51)	—	303(65)
13.76	$(3/2,5/2)^+$	13.63	$5/2^+$	743(51)	623(30)	—	120(21)
14.13	$3/2^-$	14.13	$5/2^-$	94(12)	94(12)	—	—
		14.17	$7/2^+$	6(1)	6(1)	—	—
14.39	$(1/2,5/2)^-$	14.28	$7/2^-$	392(93)	185(51)	—	207(42)
14.58	$(7/2^+,9/2^+)$						
14.98	$(7/2^-)$	14.64	$7/2^-$	361(47)	279(28)	—	82(19)
		15.04	$5/2^+$	965(377)	831(355)	—	134(22)
15.27	$9/2^+$	15.27	$3/2^+$	1201(280)	1061(260)	—	140(20)
16.08	$(7/2^+)$	16.09	$3/2^+$	365(55)	233(29)	55(14)	77(12)
		16.27	$5/2^-$	1596(142)	1503(130)	87(10)	6(2)
16.18		16.40	$5/2^+$	17(4)	2(1)	14(2)	1(1)
		16.64	$5/2^-$	1502(156)	1294(110)	10(6)	153(40)
		16.67	$7/2^+$	904(100)	633(100)	2(1)	—
16.95		16.89	$9/2^+$	635(60)	501(40)	86(10)	4(2)
		16.91	$3/2^-$	1079(200)	702(100)	257(50)	120(50)
		17.23	$3/2^+$	393(120)	280(80)	—	113(40)
17.36		17.24	$3/2^-$	216(75)	185(60)	20(9)	11(6)
		17.52	$5/2^+$	2153(290)	1834(170)	86(50)	233(70)
17.92		17.86	$7/2^-$	477(210)	457(200)	—	20(10)

At high energies → broad resonances → OM oscillations?

Some (naive) speculations:

- *2 opposite parity* *group of* states could match the rule of *rotational band*; for some of them, γ_α^2 is a sizable fraction of the WL.
- *Large separation* between the two opposite parity bands (≈1 MeV);
- Almost *parallel* bands;
- *Short bands* (*J*<9/2): centrifugal stress?
- *Very large* values of *moment of inertia*: similar to the ones calculated with the GCM by Kimura & Furutachi





New experiments at E_α = 1.0-3.5 MeV

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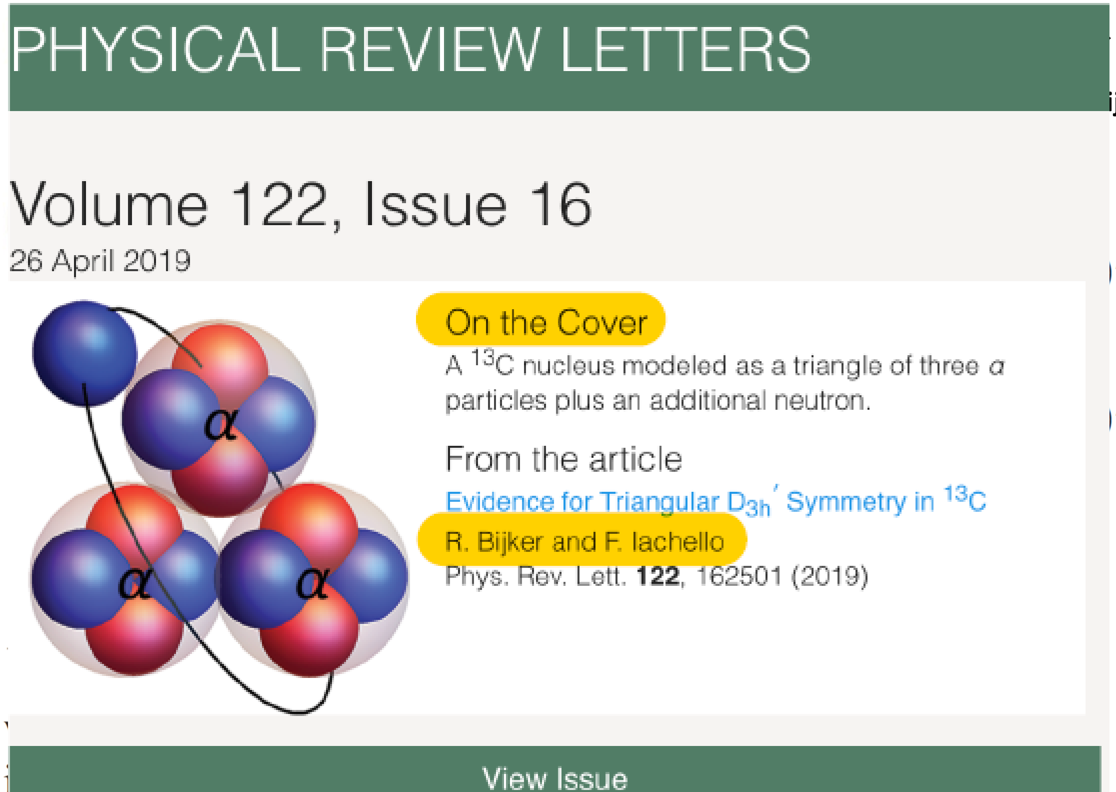

PHYSICAL REVIEW LETTERS

Volume 122, Issue 16

26 April 2019

On the Cover

A ^{13}C nucleus modeled as a triangle of three α particles plus an additional neutron.

From the article

Evidence for Triangular D_{3h}' Symmetry in ^{13}C

R. Bijker and F. Iachello

Phys. Rev. Lett. **122**, 162501 (2019)

View Issue

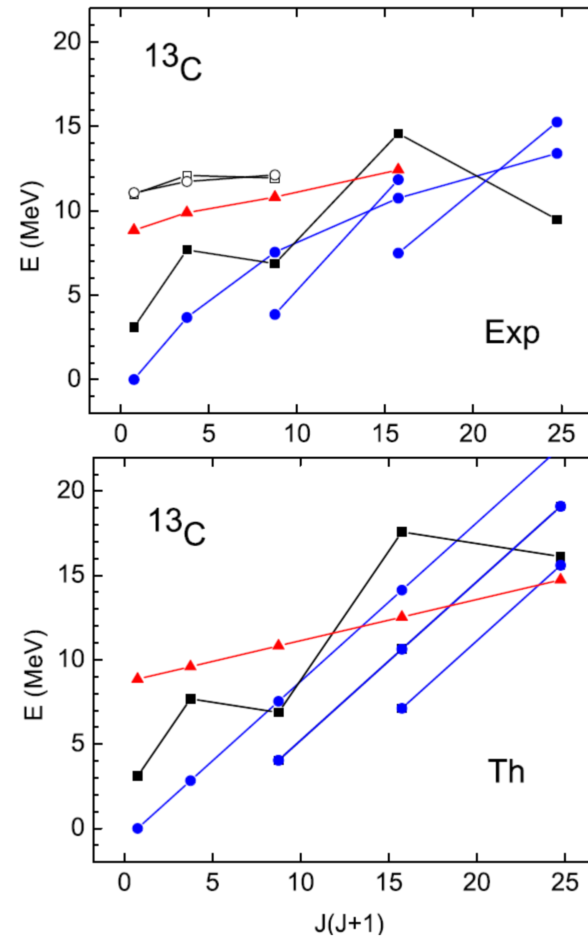
description of ^{13}C spectrum

ijker & F. Iachello, Phys. Rev. Lett. 122 (2019) 162501

3…

the so-called decoupling parameter with $g_\Omega(J) = \delta_{K,1/2}(-1)^{J+1/2}(J+1/2)$. The latter term applies only to representations $\Omega \equiv E_{1/2}^{(\pm)}$ and $K^P = 1/2^\pm$.

$\mathcal{D}'_{3h}$ double group



Symmetry → *recurrences* in the rotational bands

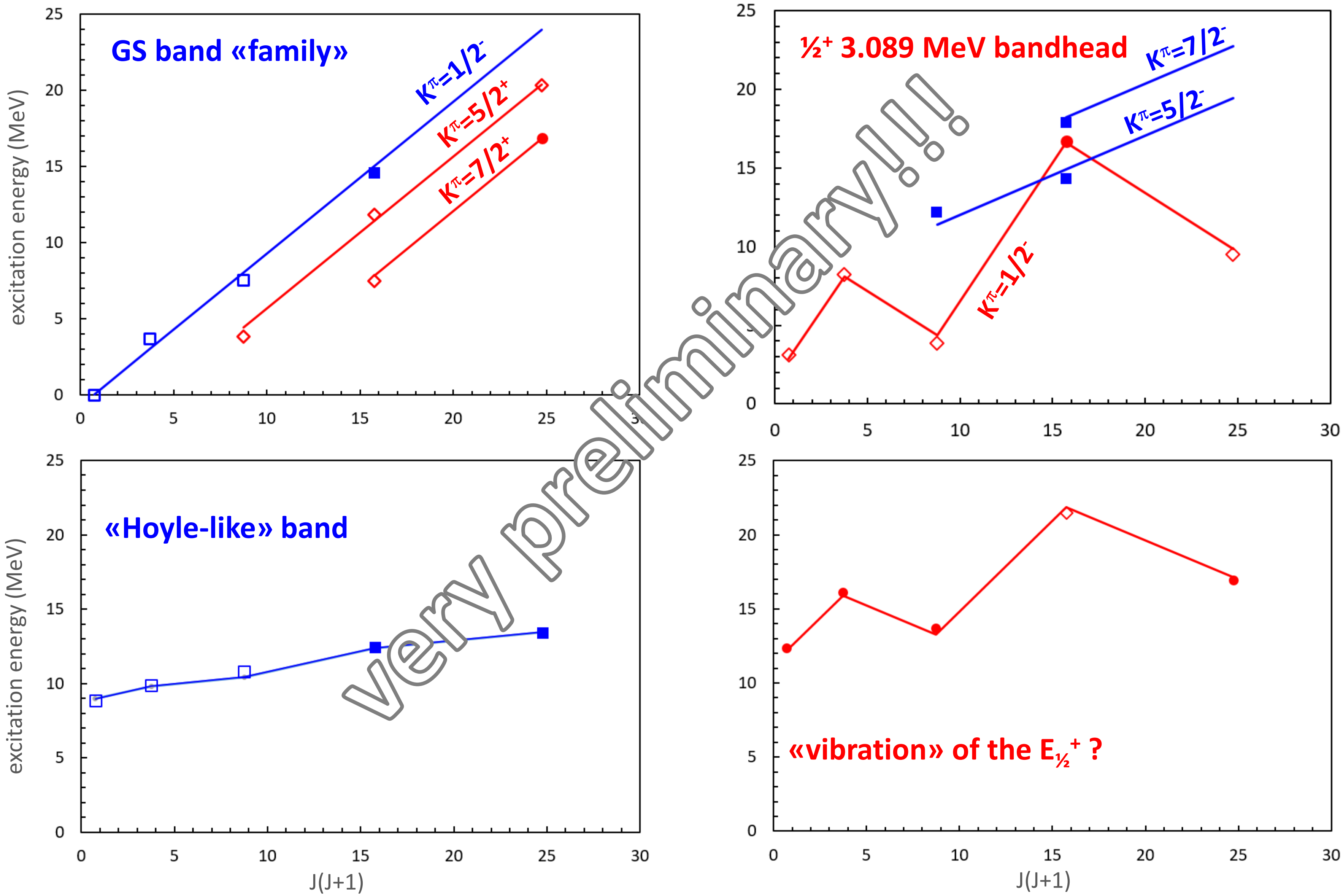
e.g. ½$^-$ coupled to 5/2$^+$ and 7/2$^+$, etc…

e.g. ½$^+$ coupled to 5/2$^-$ and 7/2$^-$, etc…

^{13}C: new data vs. $\mathcal{D}'_{3h}$ symmetry

Open symbols: Ajzenberg-Selove A 523 (1991) **Full symbols:** *present work*

Blue symbols: *negative parity* states **Red symbols:** *positive parity* states



New experiments at E_α > 10 MeV important!

- Investigations of ^{13}C **spectroscopy** at E_x larger than the *α emission threshold* → useful method to unveil *cluster structures* in *non self-conjugated nuclei.*

- A possible reaction → $^{9}Be(\alpha,\alpha)$ RES→ *few data* available in the literature (many uncertainties in J^{π} assignments)

- A new experiment carried out at Laboratorio dell'Acceleratore (TTT-3MV) of the University of Naples "Federico II" → direct kinematics → excitation functions of $^{9}Be(\alpha,\alpha_0)$ EBS at ϑ_{lab} = 110°, 135°, 150°, 160°in E_{α} = 3.6 – 10 MeV energy range → inelastic α_1 at ϑ_{lab} = 70°

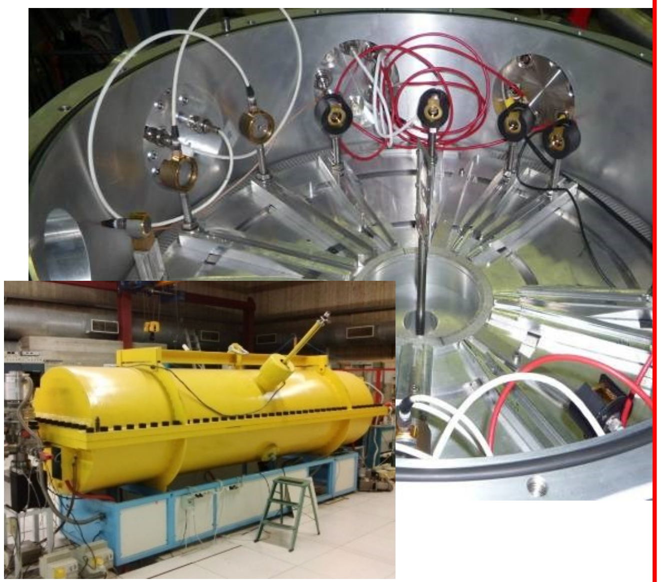
- Comprehensive *R-matrix fit* of the data with the AZURE2 code by including the $^{9}Be(\alpha,\alpha_0)$ data (160°, 150°, 135° and 110°), the $^{9}Be(\alpha,\alpha_1)$ data (70°), the low energy points from *Saleh et al*. and *Goss et al* and the *neutron* channels.

- Strong efforts to fit data at various angles → reproduction of data with a reasonable set of parameters in a wide energy range → revised *spectroscopy* in the region E_x = 12 MeV – 17 MeV (above the α+^{9}Be and α+α+α+n cluster thresholds)

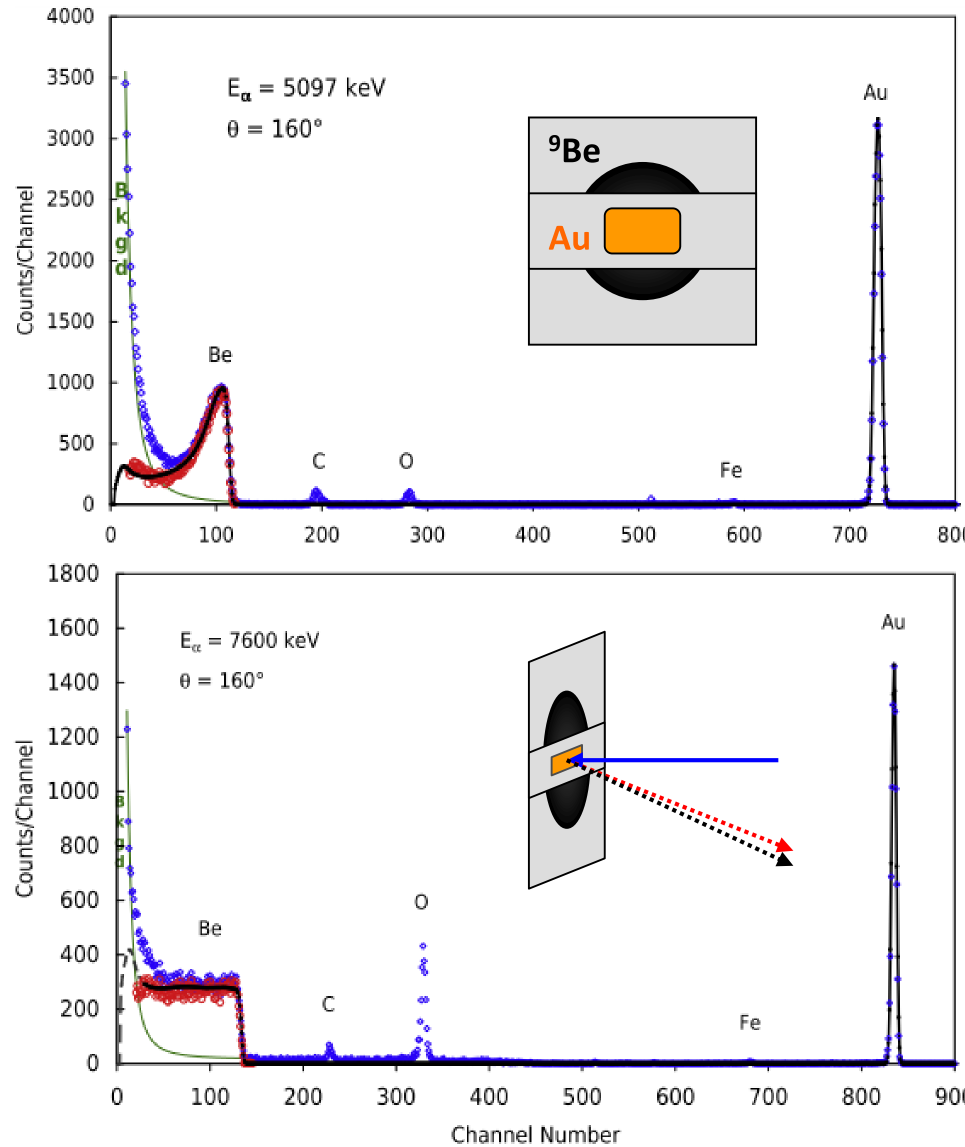
- *Hints* for the existence of *rotational bands* with molecular nature. Preliminary comparison with models seems to confirm this point.

Thanks for your attention!

Further Slides



cross section *check* with thick target method



Thin ^{9}Be target → self support
C and O contamination
Thin target absolute cross sec
with a dedicated thick target e
I. Lombardo et al, NIM B 302 (2013) 19-23

Reliable cross sections → spectroscopy

Data from Resonant Elastic Scattering experiments

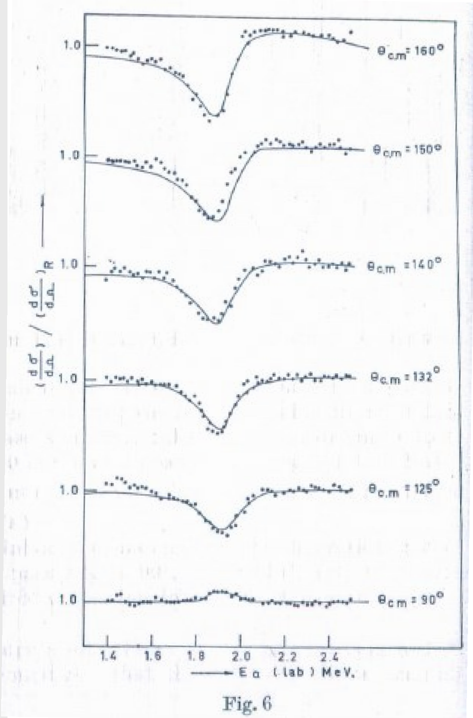
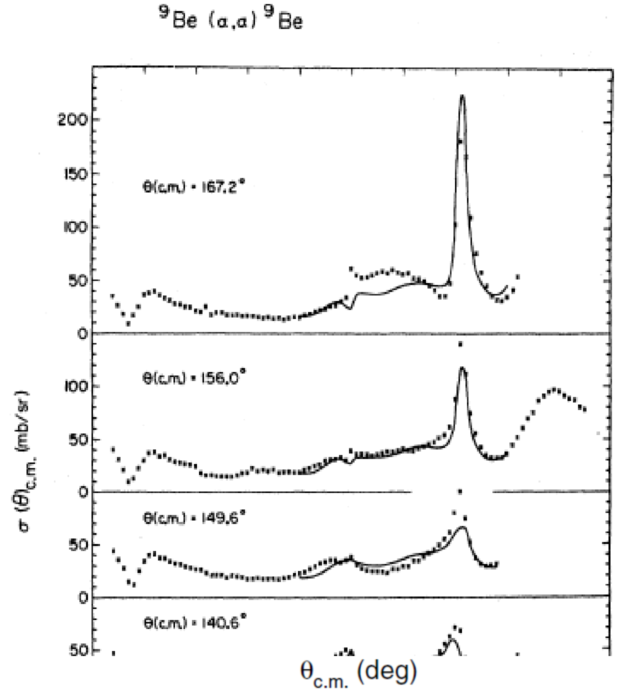
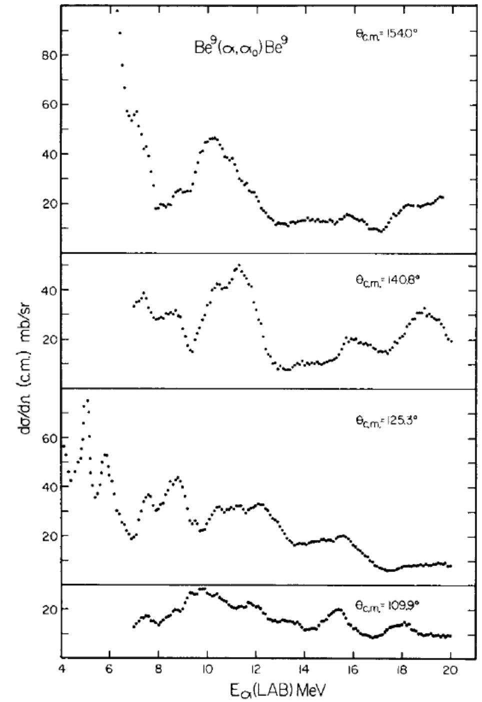


Fig. 6

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

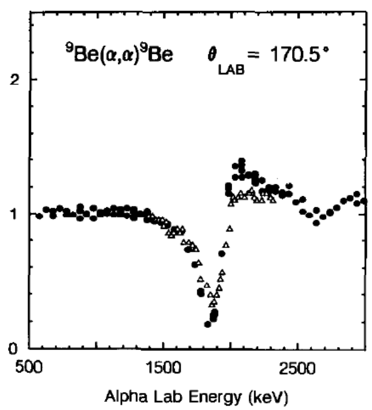


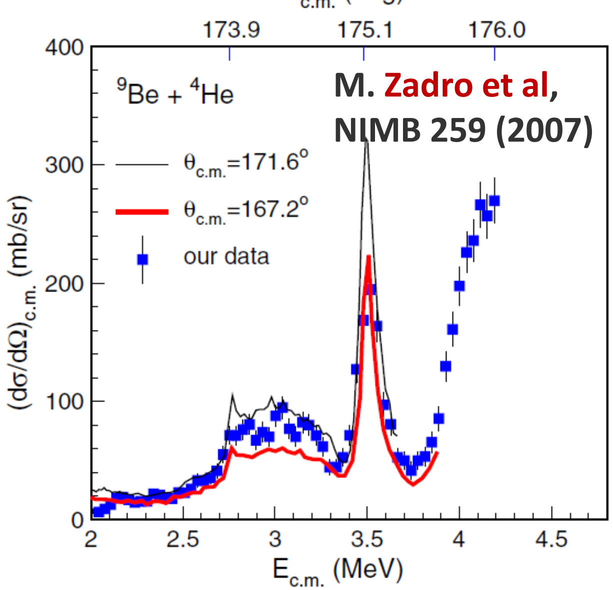
J.D. Goss et al, PRC 7 (1973)



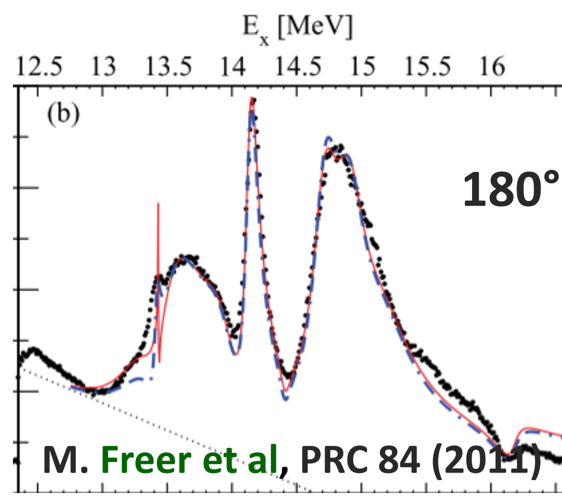
R.B. Taylor et al, Nucl. Phys. 65 (1965)

J. Leavitt et al., NIMB 85 (1994)





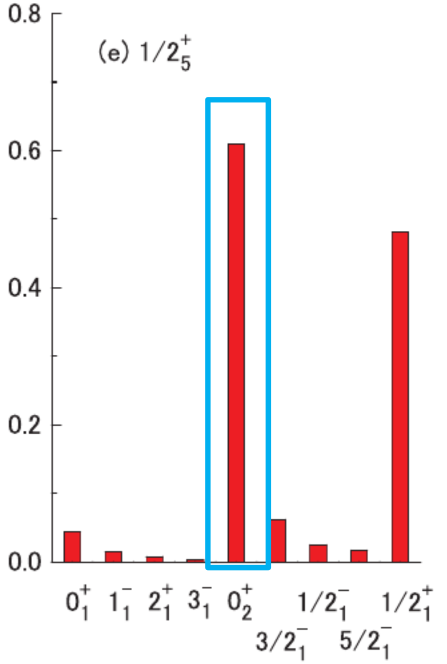
M. Zadro et al, NIMB 259 (2007)

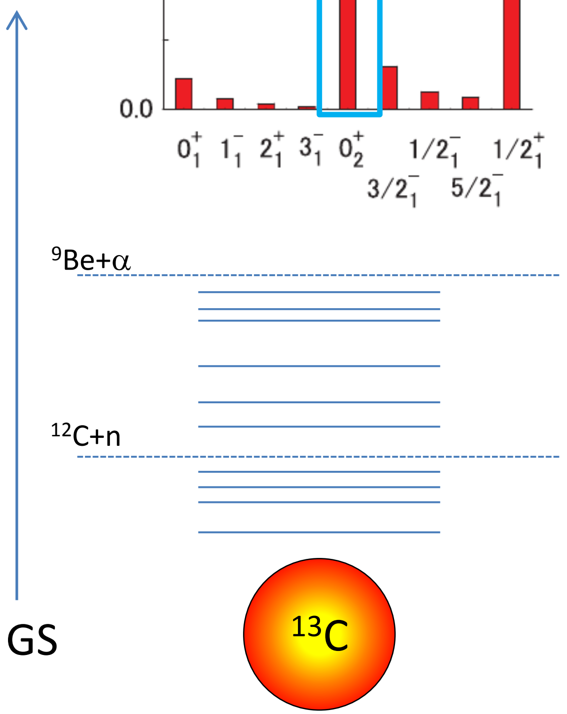


M. Freer et al, PRC 84 (2011)

Limited θ_{cm} and E_α ranges → new experiment

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





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 $^9Be_{gs}$ + α cluster prolate configuration → J^π assigments based on the rotational bands ($K=3/2^\pm$).

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

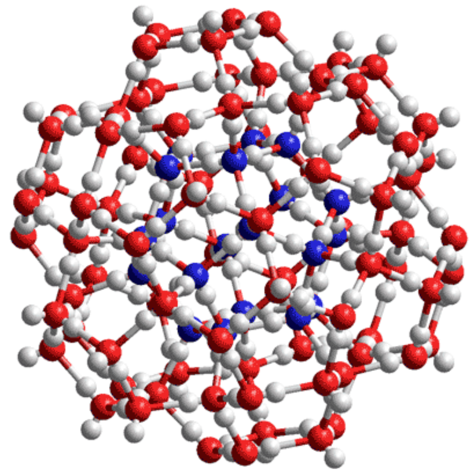
N. Furutachi and M. Kimura, Phys. Rev. C 83 (2011)
microscopic 3α+n model → proposed two new rotational bands ($K=3/2^-_2$ and $K=3/2^-_3$).

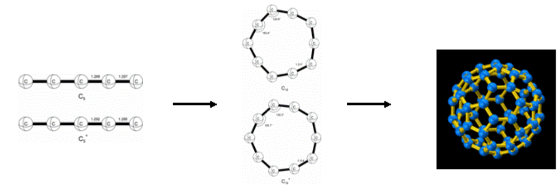
Coupling of one neutron with a ^{12}C* core → possible gas-like states analog of Hoyle state in ^{13}C:

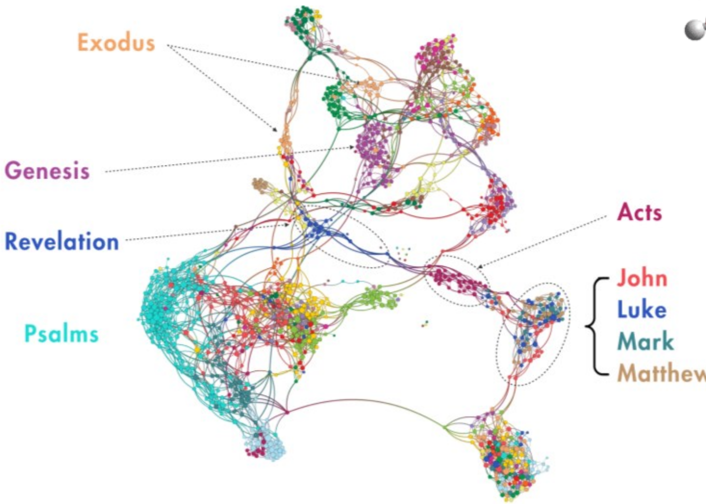
Y. Chiba and M. Kimura, J. Phys. Conf. Ser. 569 (2014) 012047
molecular bands ($K=1/2^\pm$).

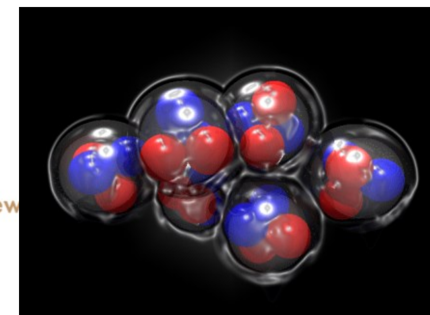
T. Yamada and Y. Funaki, Phys. Rev. C 92 (2015) 034326
$1/2^+_5$ state predicted at 14.9 MeV with a strong $^{12}C(0^+_2)$ + n spectroscopic factor → analog of Hoyle state in ^{13}C.

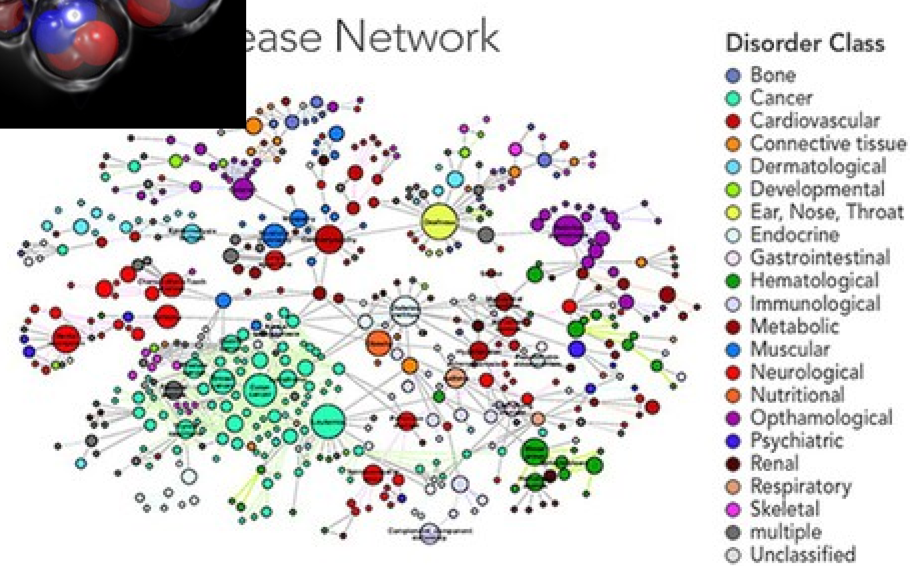
Clustering: an *ubiquitous* phenomenon

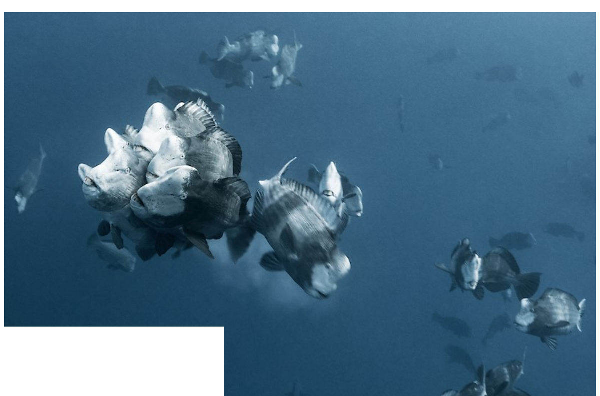




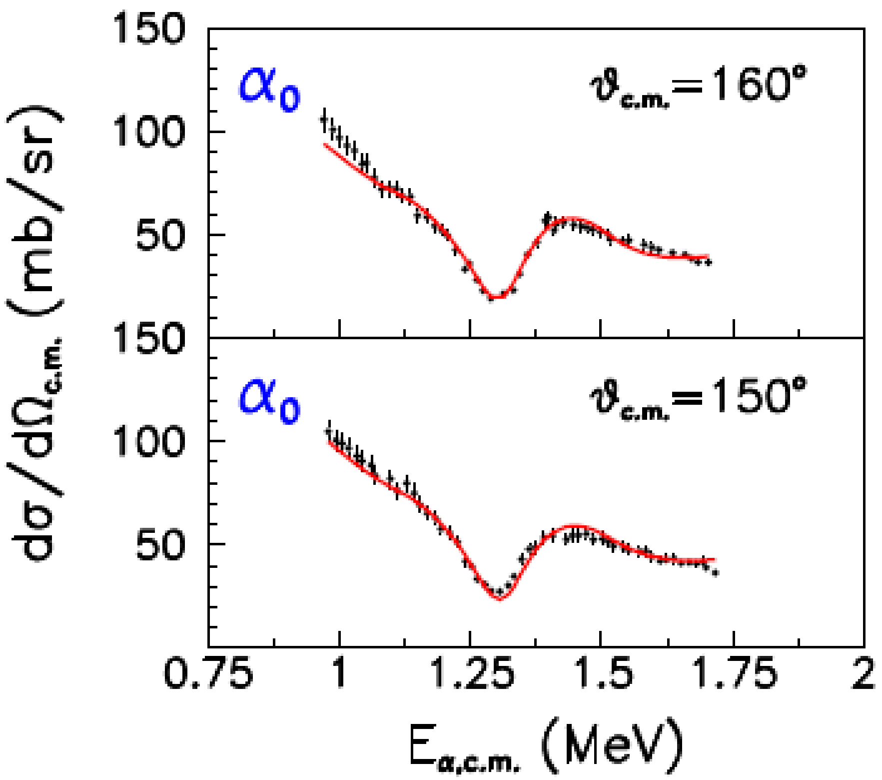








Correlations **between the fundamental components of a system**



Saleh et al (Ann. Phys. 7) to study the spectroscopy of states at lower energies

Lack of high accuracy data at Ecm = 1.75 – 2.5 MeV → Goss et al

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