UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

INFN NAPOLI

The Hoyle State in ^{12}C

Daniele Dell'Aquila

Dipartimento di Fisica "Ettore Pancini", Università degli Studi di Napoli "Federico II", Napoli, Italy

INFN-Sezione di Napoli, Napoli, Italy

- **Physics background**
  - Phenomenology of light nuclei → clustered states;
  - The Discovery of the Hoyle State in ^{12}C;
  - Astrophysical implications;
  - The Structure of the Hoyle State;

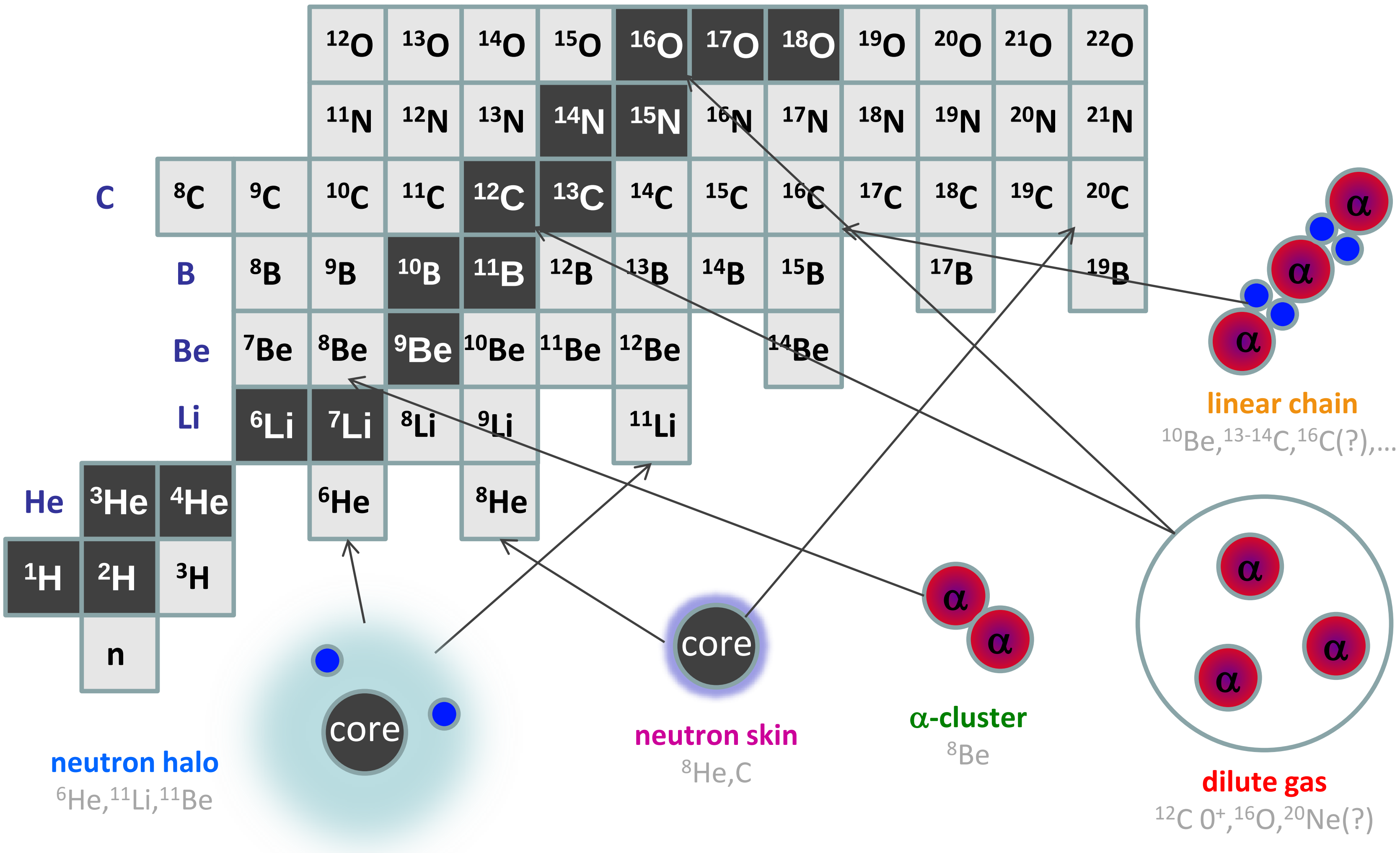
- **Alpha-decay of the Hoyle State**
  - Direct vs Sequential decay;
  - Recent high-precision experiments;
  - Theoretical interpretations;

- **Radiative decay of the Hoyle State**
  - State-of-the-art;
  - New perspectives: the MORALIS experiment at INFN-LNL;

- **Conclusions**

Università degli Studi di Napoli "Federico II" & INFN-Napoli

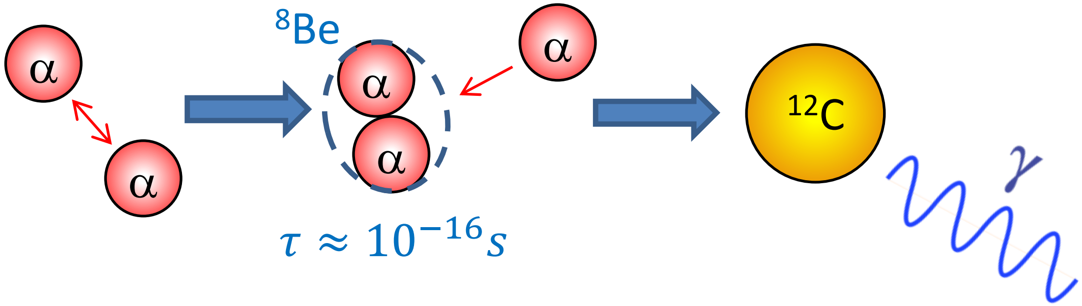
Complexity of nuclear force → deviation from the ***sphericity***: axial deformation (collective behaviours), spatial re-organization of nucleons in bounded **sub-units** (***cluster model***).



Helium burning in stars → the discovery of the Hoyle state in ^{12}C

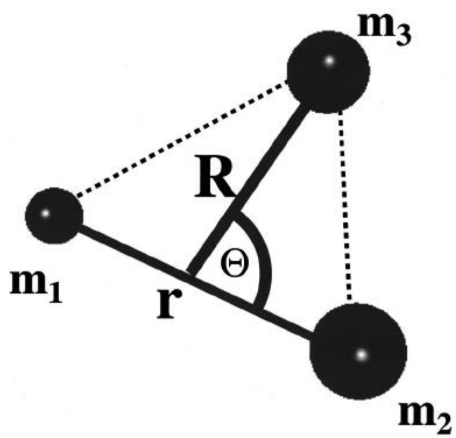
1939, Bethe → formation of ^{12}C from the collisions of three α-particles improbable → temperatures 50 times higher than the Sun required;
1951, Öpik → the nucleosynthesis of carbon occours in the Red Giant phase;
1952, Salpeter → the nucleosynthesis of carbon is a *sequential* two-steps process;

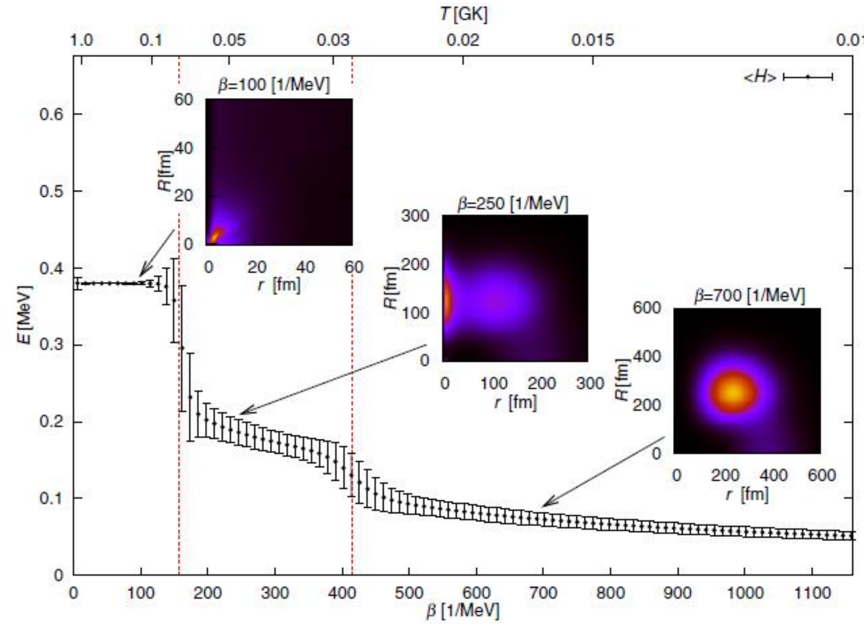
$$^{4}He + {}^{4}He \rightarrow {}^{8}Be$$
$$^{8}Be + {}^{4}He \rightarrow {}^{12}C + \gamma$$



1953, Hoyle → to reproduce the observed C/O abudance → the 3α process occours via an s-wave resonance → The Hoyle state (7.654 MeV, 0^+);
1957, Cook → experimental confirmation of the existence of the Hoyle state.

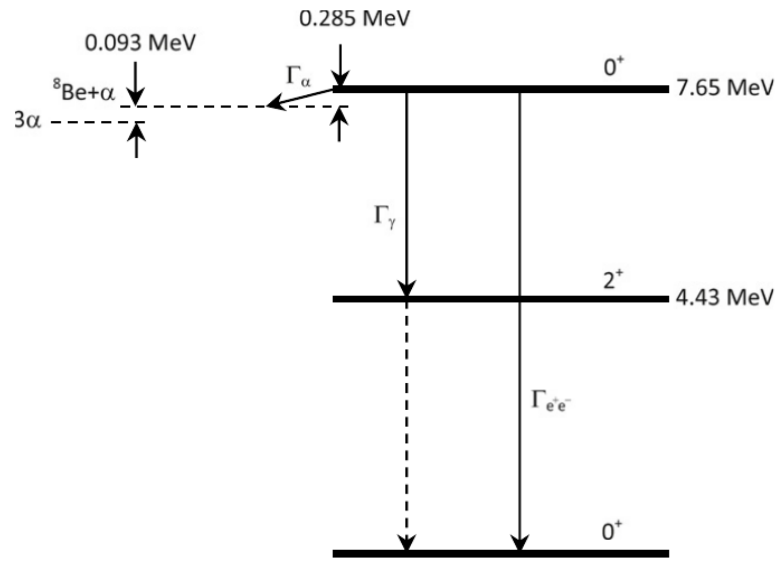
The Hoyle state in the triple-alpha process





$1/k_B T$

from Akahori et al., Phys. Rev. C ***92*** *(2015) 022801(R)*



At stellar temperatures T>10^8 K

The energy needed to form a ^{8}Be (92 keV) is extremely close to the *Gamow window* → ex: T=10^8 K → Gamow peak E_G=85 keV, Γ_G = 60 keV → the process is *resonant and proceeds through the Hoyle state in ^{12}C.*

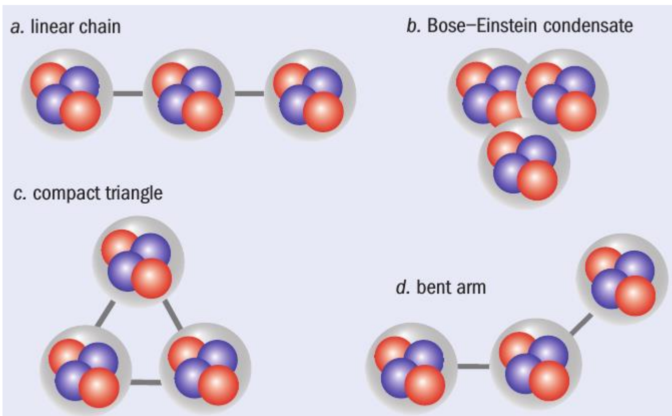
the 3α reaction rate is related to the properties of the Hoyle state via:

$$<\sigma v> \propto \frac{\Gamma_\alpha \Gamma_{rad}}{\Gamma} e^{-\frac{E_R}{k_B T}}$$

The Structure of the Hoyle State in ^{12}C

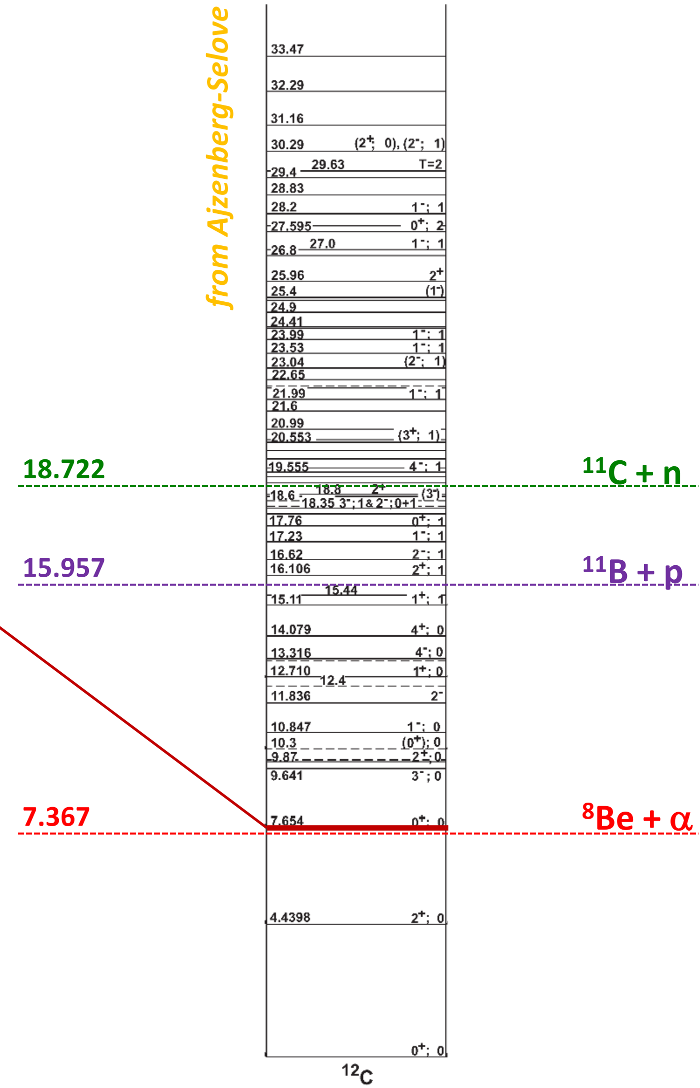
Cluster state of ^{12}C located at 7.654 MeV (0^+) → characterized by a pronounced cluster nature → quite unusual and not well understood properties → challenging open question in nuclear physics.

E_x = 7.654 MeV
$J^\pi = 0^+$



D. Jenkins and O. Kirsebom, The Secret of Life, Physics World Feb. 2013

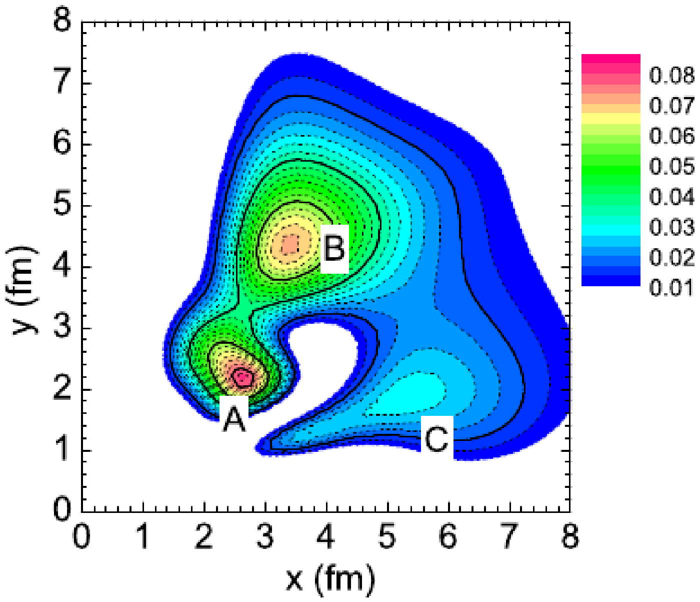
(a) linear chain: α-cluster model
(b) Bose-Einstein condensate: microscopic models (GCM, RGM)
(c) compact triangle: ACM
(d) bent-arm: microscopic models (Faddeev three-body formalism)



Dynamical symmetries and rotational bands

H. Morinaga, Phys. Rev. 101 (1956) 254 → suggested that the Hoyle state in ^{12}C could be highly deformed → linear chain structure.

Modern microscopic calculations → density distribution $\rho(x,y)$ of the Hoyle state from microscopic calculations based on the Faddeev three-body formalism → three distinct peaks whcih correspond to an equilateral triangle configuration (A), or a bent-arm configuration (B), (C).



S. Ishikawa, Phys. Rev. C 90, 061604(R) (2014)

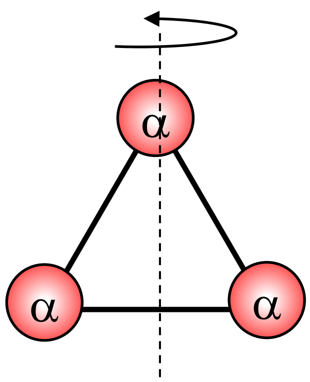
Università degli Studi di Napoli "Federico II" & INFN-Napoli

Dynamical symmetries and rotational bands

L.R. Hafstad, E. Teller, Phys. Rev. 54 (1938) 681 → suggested the role of dynamical symmetries in the 3-alpha cluster system → a simple picture can describe this system as a classical rotational top with a triangular symmetry → quantal rotational properties are given by the equation:

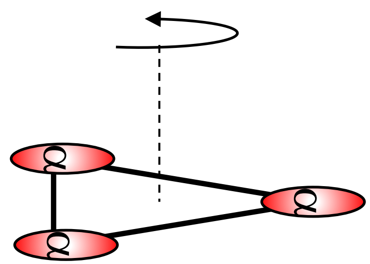
$$E_{J,K} = \frac{\hbar^2 J(J+1)}{2\mathcal{I}_{\mathrm{Be}}} - \frac{\hbar^2 K^2}{4\mathcal{I}_{\mathrm{Be}}}$$

K: projection of the angular momentum onto the 3-fold symmetry axis.
One generates a number of rotational bands with different values of K.



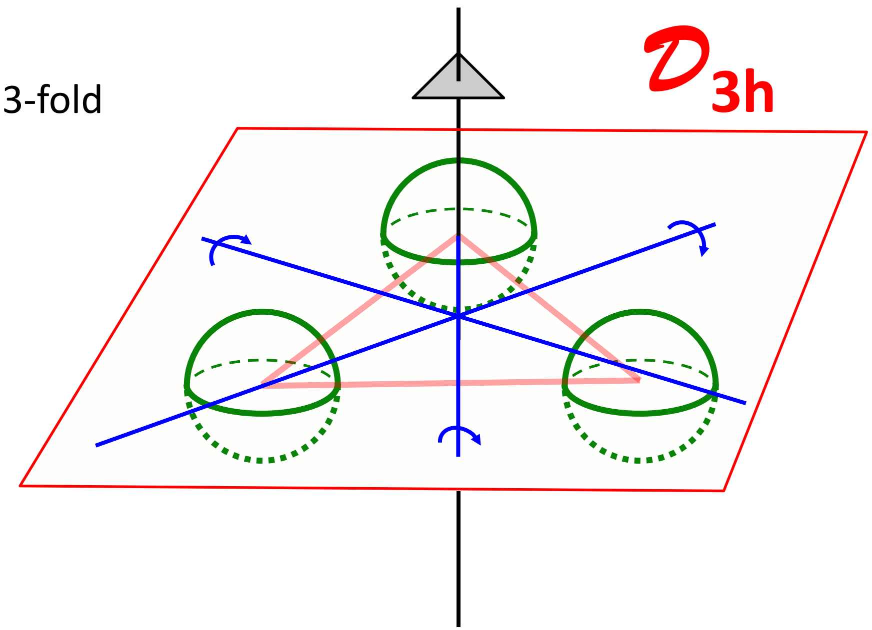
$K^\pi=0^+$

$0^+, 2^+, 4^+, \ldots$



$K^\pi=3^-, 6^+$

$3^-, 4^-, 5^-, \ldots$



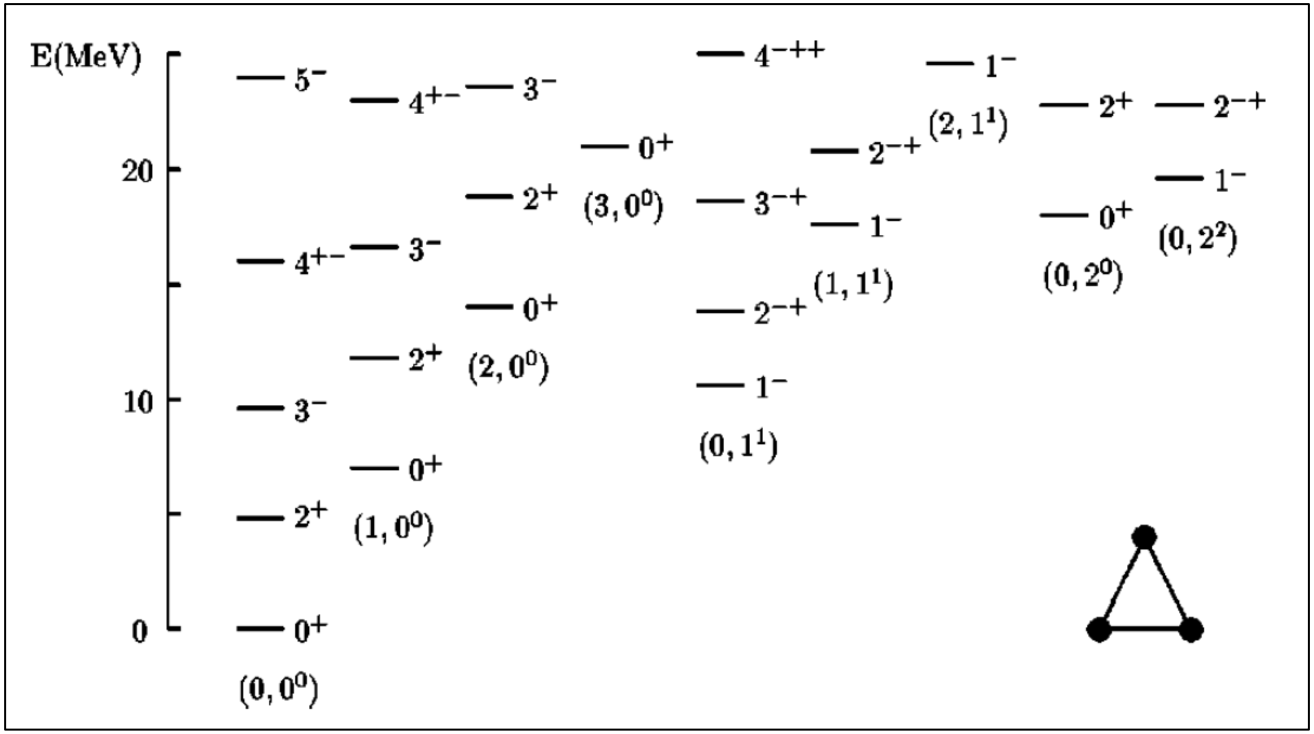
P. Atkins, *Physical Chemistry* (3rd ed.), OUP (1988) p. 409

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

Dynamical symmetries and rotational bands

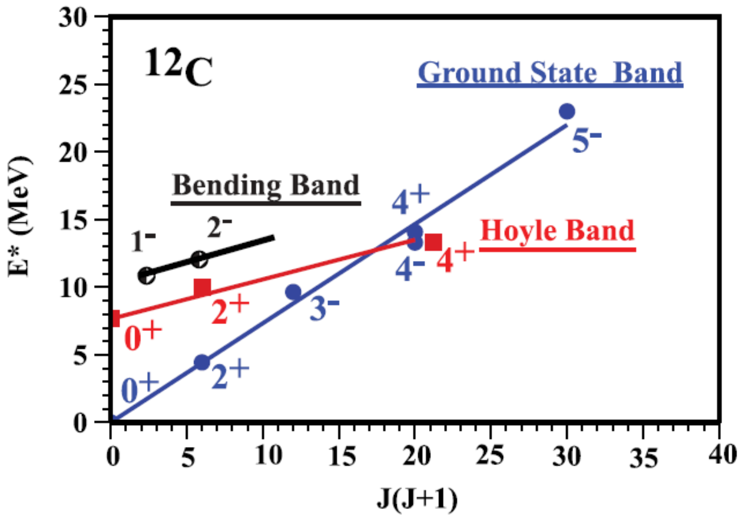
$\mathcal{D}_{3h}$ point group symmetry → can describe such rotations. The corresponding rotational-vibrational spectrum can be reproduced by the equation (*see R. Bijker and F. Iachello, Phys. Rev. C* ***61*** *(2000) 067305*):

$$E = E_0 + Av_1 + Bv_2 + CL(L+1) + D(K \pm 2l)^2$$



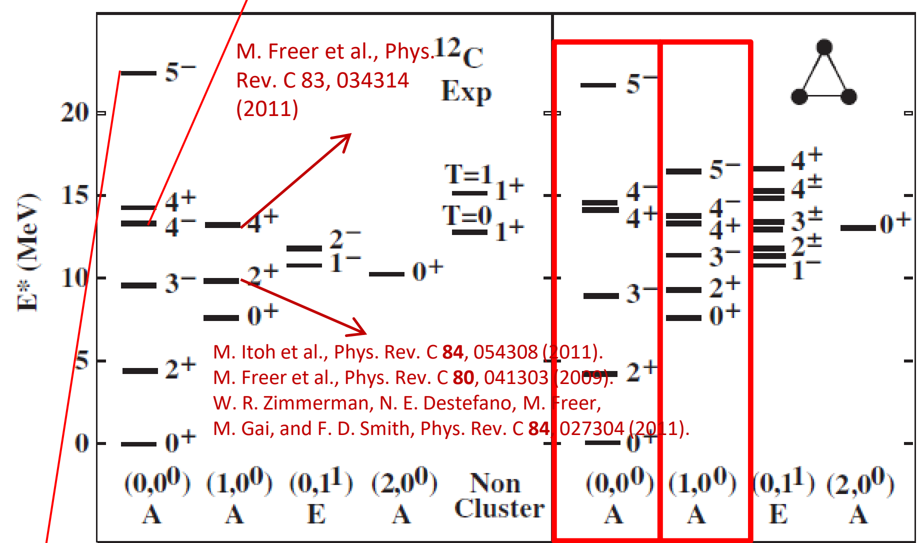
Dynamical symmetries and rotational bands

Marin-Lambarri, PRL (2014) → first experimental evidence for $\mathcal{D}_{3h}$ symmetry in nuclei.



M. Freer, et al., Phys. Rev. C 76 (2007) 034320.
O.S. Kirsebom, et al., Phys. Rev. C 81 (2010) 064313.

exp **ACM**



M. Freer et al., Phys. Rev. C 83, 034314 (2011)

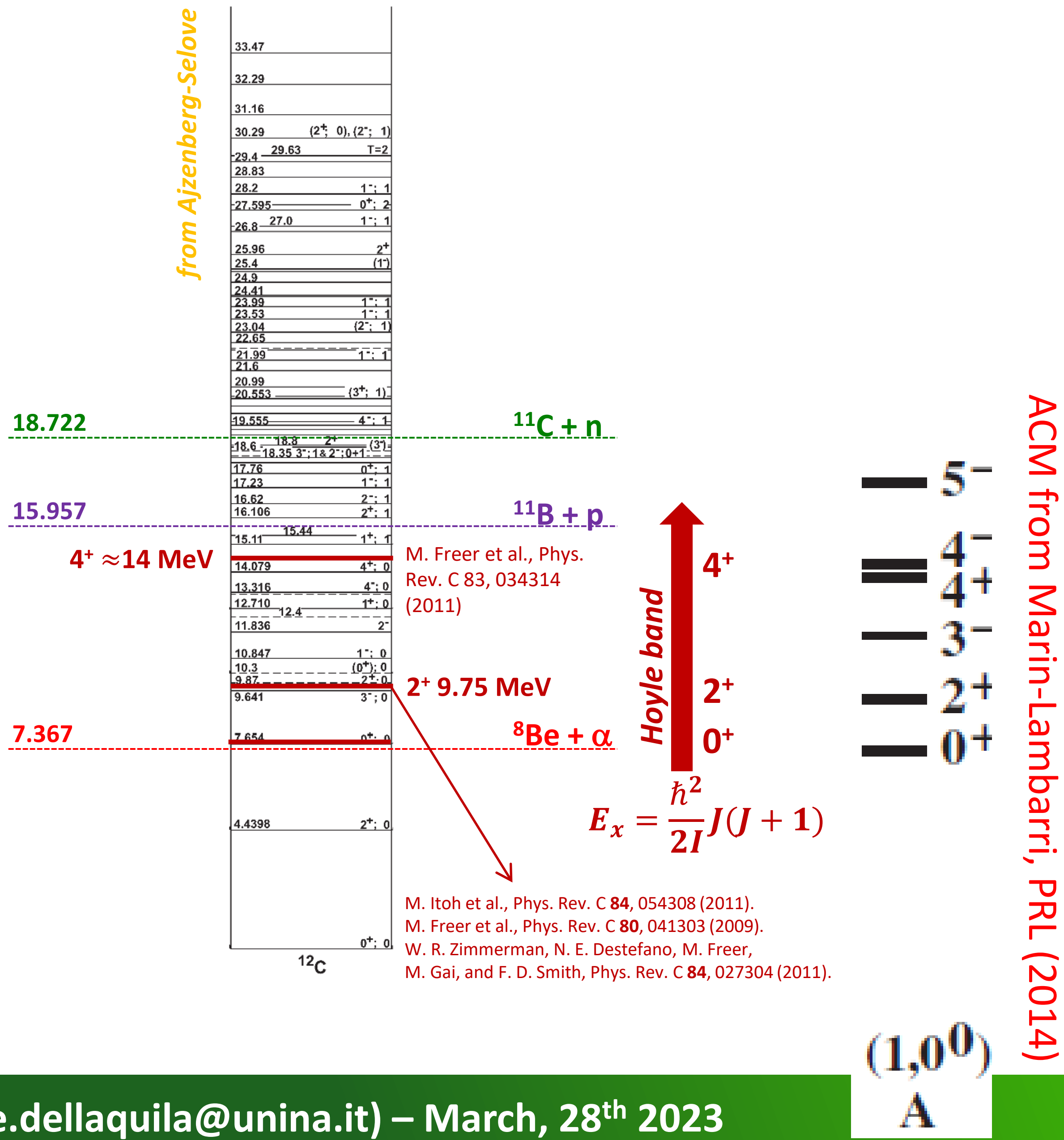
M. Itoh et al., Phys. Rev. C **84**, 054308 (2011).
M. Freer et al., Phys. Rev. C **80**, 041303 (2009).
W. R. Zimmerman, N. E. Destefano, M. Freer, M. Gai, and F. D. Smith, Phys. Rev. C **84**, 027304 (2011).

D.J. Marín-Lámbarri et al., Phys. Rev. Lett. 113 (2014) 012502.

Hoyle band

GS band

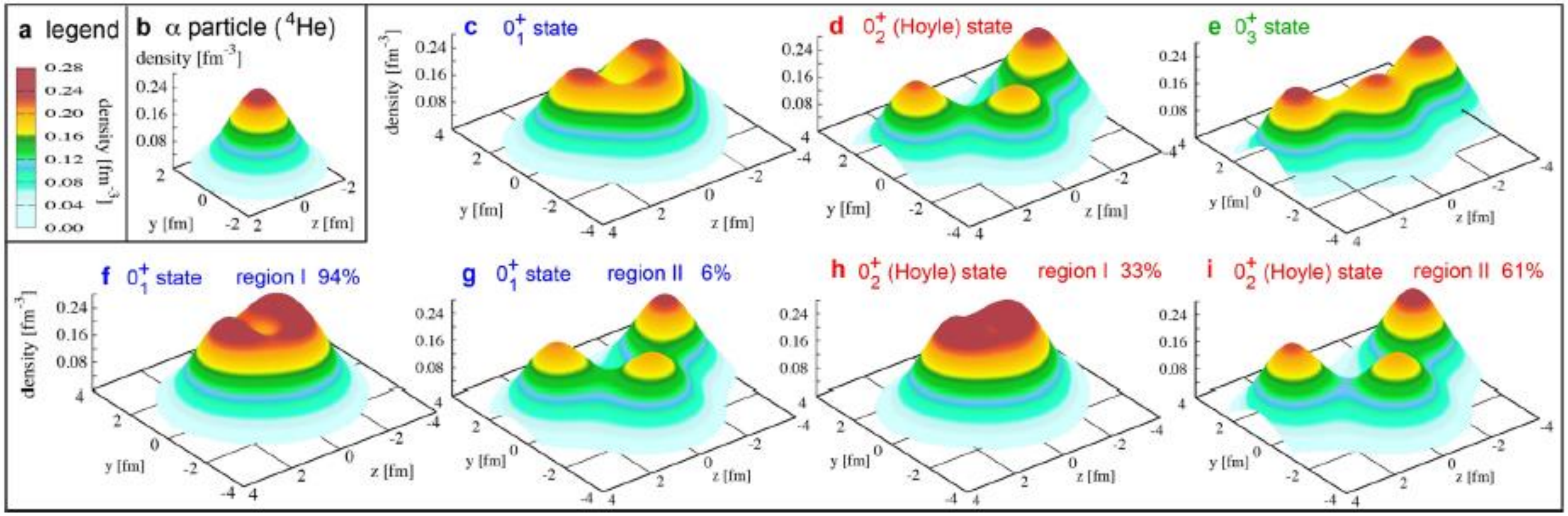
Università degli Studi di Napoli "Federico II" & INFN-Napoli



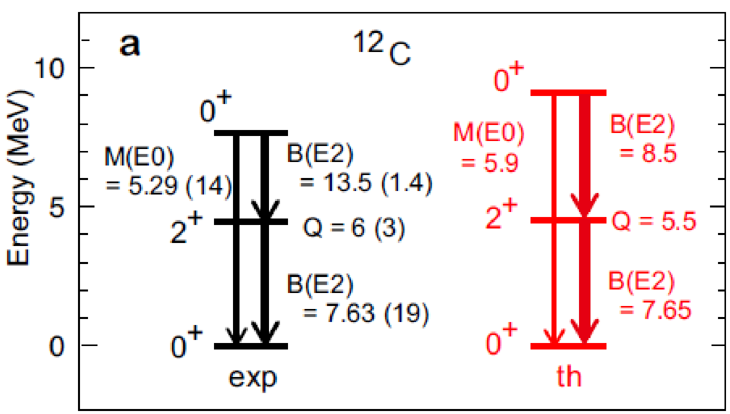
$$E_x = \frac{\hbar^2}{2I} J(J+1)$$

M. Itoh et al., Phys. Rev. C **84**, 054308 (2011).
M. Freer et al., Phys. Rev. C **80**, 041303 (2009).
W. R. Zimmerman, N. E. Destefano, M. Freer, M. Gai, and F. D. Smith, Phys. Rev. C **84**, 027304 (2011).

Otsuka et al., Nature Comm. 2021; MCSM with statistical learning.



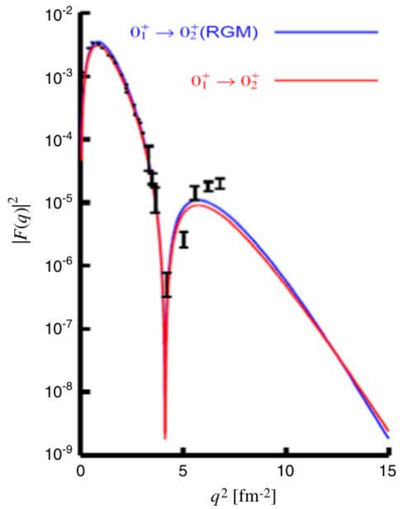
Reasonable reproduction of *transition strengths* and *quadrupole* momenta



The Structure of the Hoyle State in ^{12}C

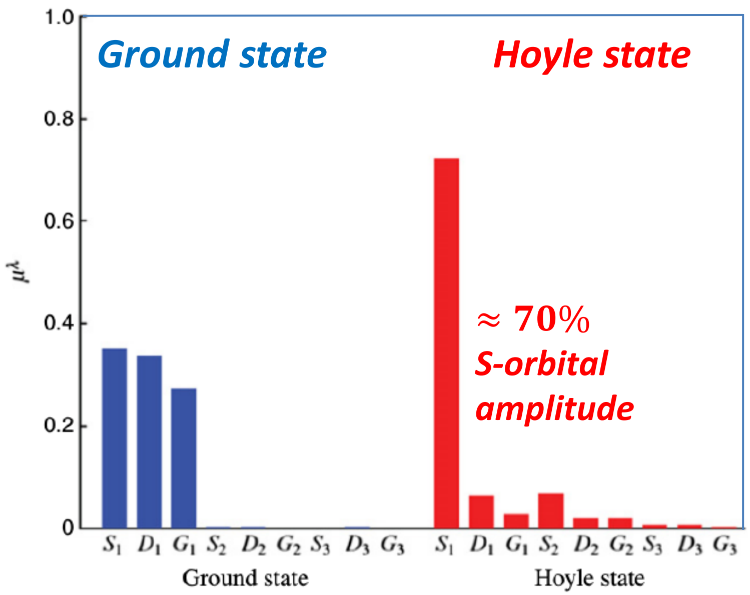
electron inelastic scattering

I. Sick, J.S. McCarthy, Nuclear Phys. A 150 (1970) 631
A. Nakada et al., Phys. Rev. Lett. 27 (1971) 745
P. Strehl, Th.H. Schucan, Phys. Lett. B 27 (1968) 641



Bose-Einstein condensation phenomena in nuclei

Weakly bound system → an α may tunnel significantly into the barrier → increasing of the volume → the internal structure of a-particles is no longer important (antisymmetrization properties negligible) → the bosonic system may condensate → *Bose Einstein Condensate* (BEC).



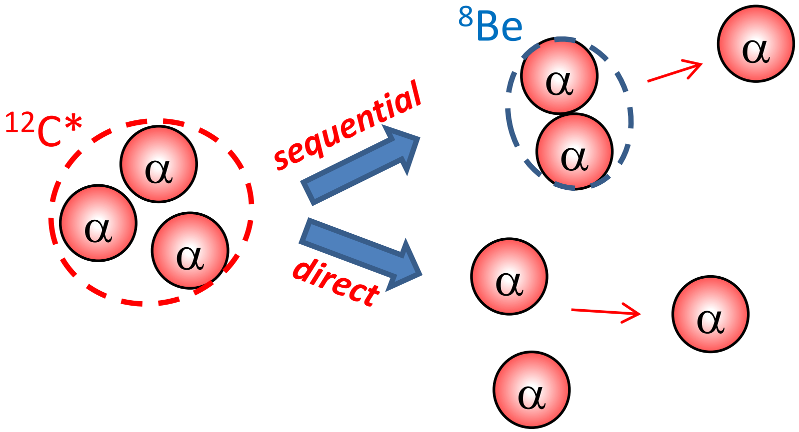
Tohsaki, Horiuchi, Schuck and Röpke (THSR) wave-function method→ fit of the electron inelastic scattering $0^+ \to 0^+_2$ → Hoyle state radius 1.35 – 1.60 times the ground state one.

$$|\Psi_{THSR}\rangle = S_1|\Psi_{S_1}\rangle + D_1|\Psi_{D_1}\rangle + \cdots$$

Dominant amplitude → BEC

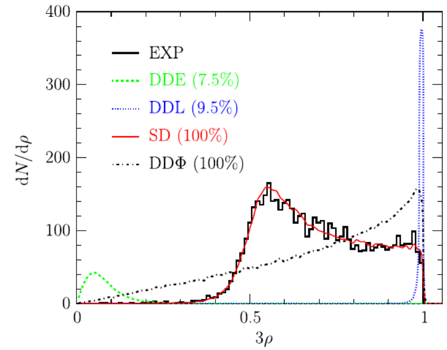
- Taiichi Yamada and Peter Schuck, Eur. Phys. J. A26, 185 (2005)
- Y. Funaki, H. Horiuchi, W. von Oertzen, G. Röpke, P. Schuck, A. Tohsaki, and T. Yamada, Phys. Rev. C 80, 064326 (2009)

Alpha-decay of the Hoyle state



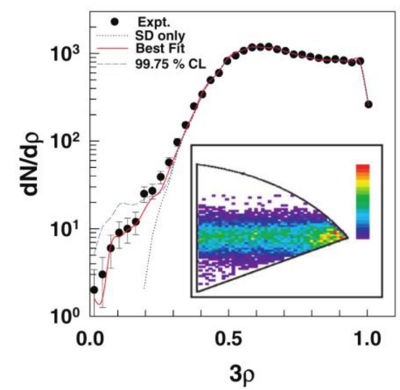
Experiment	$\Gamma_{3\alpha}/\Gamma$ (%)
[1] M. Freer *et al.*	< 4
[2] Ad.R. Raduta *et al.*	17.0 ± 5.0
[3] J. Manfredi *et al.*	< 3.9
[4] O.S. Kirsebom *et al.*	< 0.5
[5] T.K. Rana *et al.*	0.91 ± 0.14
[6] M. Itoh *et al.*	< 0.2
[7] L. Morelli *et al.*	1.1 ± 0.8

[1] M. Freer et al., Phys. Rev. C 49, R1751 (1994). [2] Ad. R. Raduta et al., Phys. Lett. B 705, 65 (2011). [3] J. Manfredi et al., Phys. Rev. C 85, 037603 (2012). [4] O. S. Kirsebom et al., Phys. Rev. Lett. 108, 202501 (2012). [5] T. K. Rana et al., Phys. Rev. C 88, 021601(R) (2013). [6] M. Itoh et al., Phys. Rev. Lett 113, 102501 (2014). [7] L. Morelli et al., J. Phys. G: Nucl. Part. Phys. 43, 045110 (2016).



O.S. Kirsebom et al.

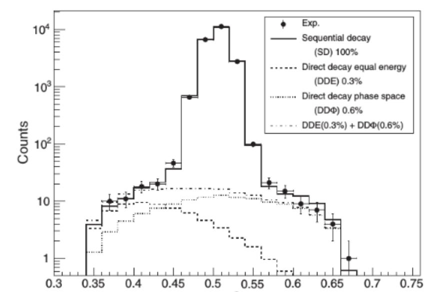
≈ 5000 events → no evidence of direct decays → upper limit of 0.5% to direct branching ratios.



T.K. Rana et al.

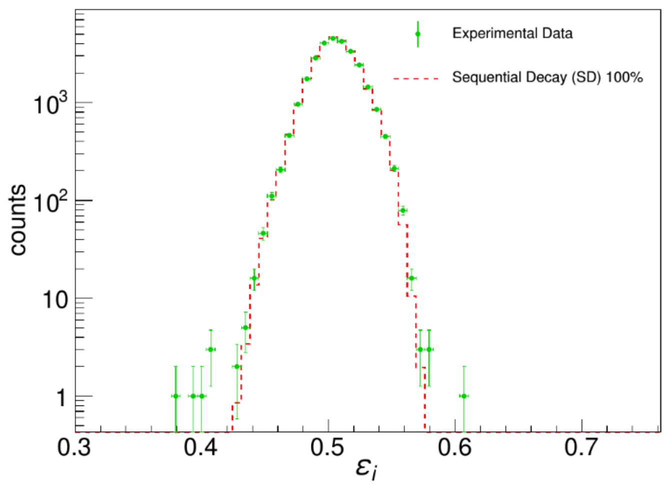
≈ 20000 events → non-vanishing direct decay branching ratio

$$\frac{\Gamma_{3\alpha}}{\Gamma} = 0.91 \pm 0.14$$



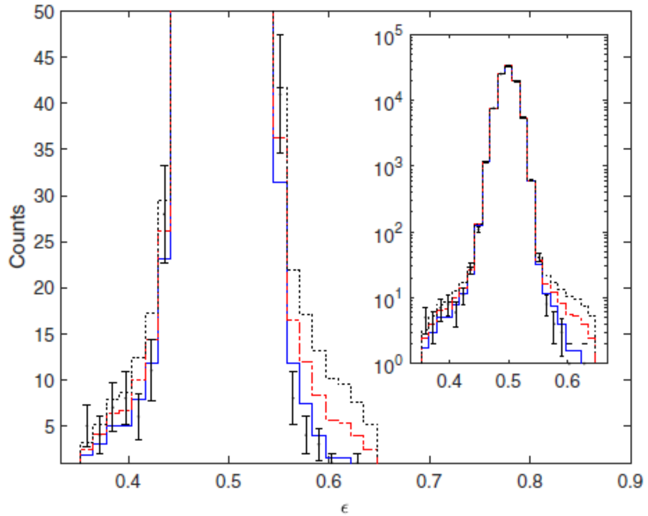
M. Itoh et al.

≈ 20000 events → direct decay under the sensitivity of the experimental sensitivity → <0.2%



D. Dell'Aquila et al., Phys. Rev. Lett. (2017)
14N(d,a)12C with multi-particle coincidence techniques and a high-resolution hodoscope of silicon detectors.

$$\frac{\Gamma_{3\alpha}}{\Gamma} < 4.3 \cdot 10^{-4}$$

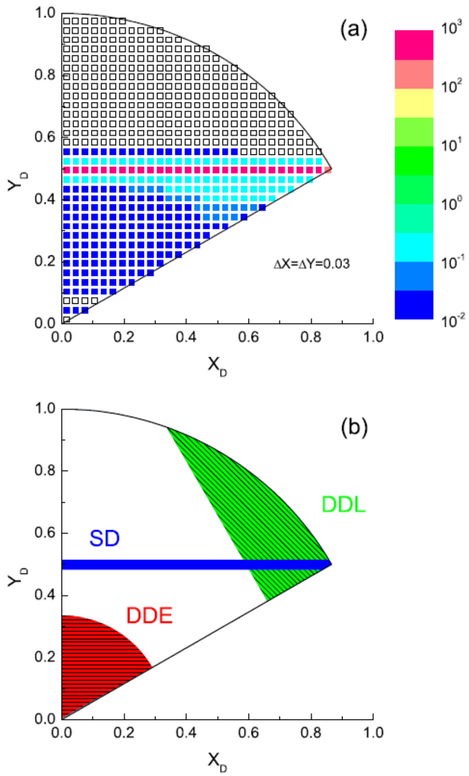


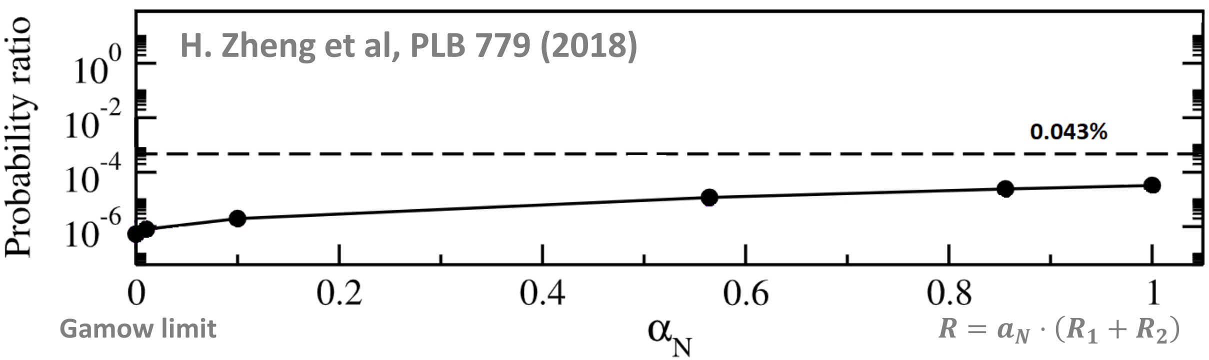
R. Smith et al., Phys. Rev. Lett. (2017)
Alpha-inelastic scattering: 12C(4He, 3α)α using an array of silicon strip detectors.

$$\frac{\Gamma_{3\alpha}}{\Gamma} < 4.7 \cdot 10^{-4}$$

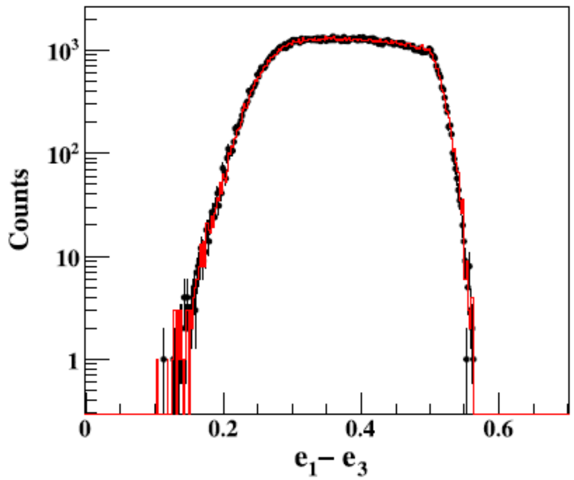
Alpha-decay of the Hoyle state

S. Ishikawa, PRC 90 (2014)



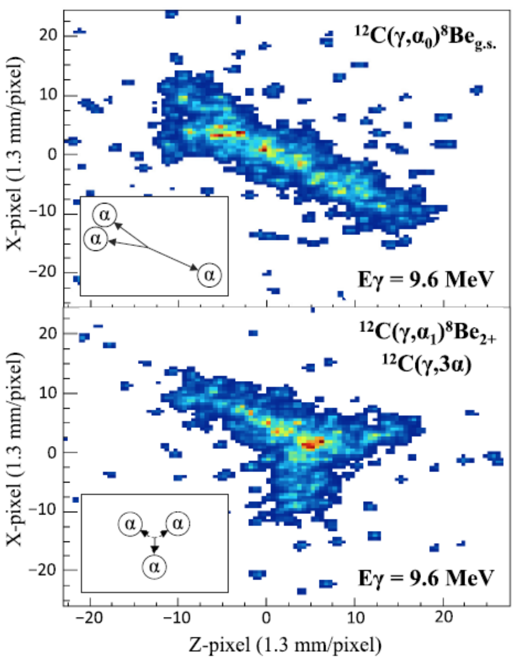


Alpha-decay of the Hoyle state



T.K. Rana et al., Phys. Lett. B (2017)
Alpha-inelastic scattering: $^{12}C(^4He, {}^3\alpha)\alpha$ using an array of silicon strip detectors.

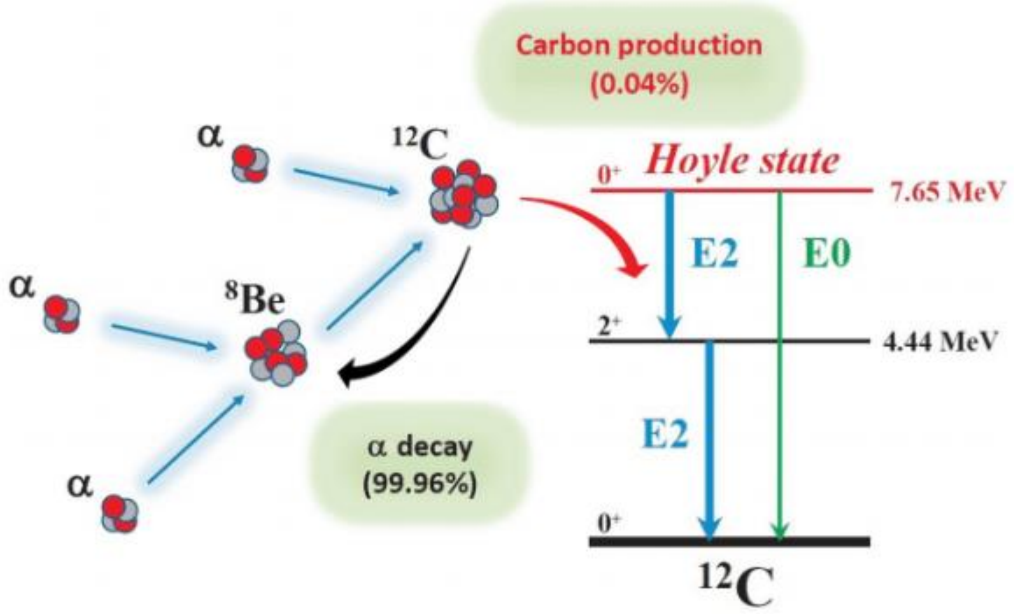
$$\frac{\Gamma_{3\alpha}}{\Gamma} < 1.9 \cdot 10^{-4}$$



R. Smith et al., Phys. Rev. C (2020)
Gamma-induced dissociation of ^{12}C → $\Gamma_{3\alpha}$ for the 2+ collective excitation of the Hoyle state investigated with a TPC → decay penetrabilities are used to determine a stringent upper limit to the direct 3-alpha decay of the Hoyle state.

$$\frac{\Gamma_{3\alpha}}{\Gamma} < 5.7 \cdot 10^{-6}$$

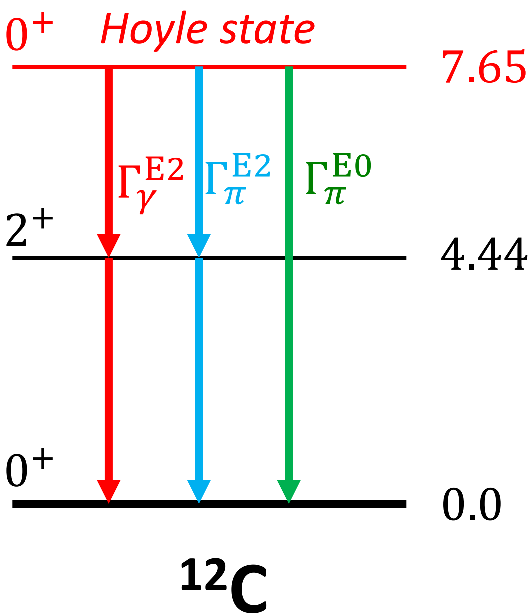
Experiment	Γ_{DD}/Γ (%)	type	year
M. Freer et al.	< 4	L.I.	1994
Ad.R. Raduta *et al.*	17.0 ± 5.0	H.I.	2011
J. Manfredi et al.	< 3.9	H.I.	2012
O.S. Kirsebom et al.	< 0.5	L.I.	2012
T.K. Rana et al.	0.91 ± 0.14	L.I.	2013
M. Itoh et al.	< 0.2	L.I.	2014
L. Morelli et al.	1.1 ± 0.8	H.I.	2016
D. Dell'Aquila et al.	<0.043	L.I.	2017
R. Smith et al.	<0.047	L.I.	2017
T.K. Rana et al.	<0.019	L.I.	2019
J. Bishop et al.	<0.043	beta	2020
R. Smith et al.	$< 5.7 \cdot 10^{-4}$	ind.	2020


Carbon production
(0.04%)
α
12C
Hoyle state
0+
7.65 MeV
α
8Be
E2
E0
2+
4.44 MeV
α decay
(99.96%)
α
E2
0+
12C

Reaction rate of the three-alpha process in stars

→ *spectroscopic properties of the Hoyle state in ^{12}C:*

$$< \sigma v > \propto \frac{1}{T^3} \Gamma_{rad} e^{-\frac{E_R}{k_B T}}$$



$$\Gamma_{rad} = \Gamma_{\pi}^{E0} + \Gamma_{\pi}^{E2} + \Gamma_{\gamma}^{E2}$$

$$\Gamma_{rad} = \Gamma_{\pi}^{E0} \left[\frac{\Gamma}{\Gamma_{\pi}^{E0}}\right] \left[\frac{\Gamma_{rad}}{\Gamma}\right]$$

$$\Gamma_{\pi}^{E0} = 63.3(20)\ \mu eV$$

M. Freer and H. O. U. Fynbo, Prog. Part. Nucl. Phys.78, 1(2014).

$$\Gamma_{\pi}^{E0}/\Gamma = 7.6(4) \cdot 10^{-6}$$

T. K. Eriksen et al., Phys. Rev. C102, 024320 (2020).

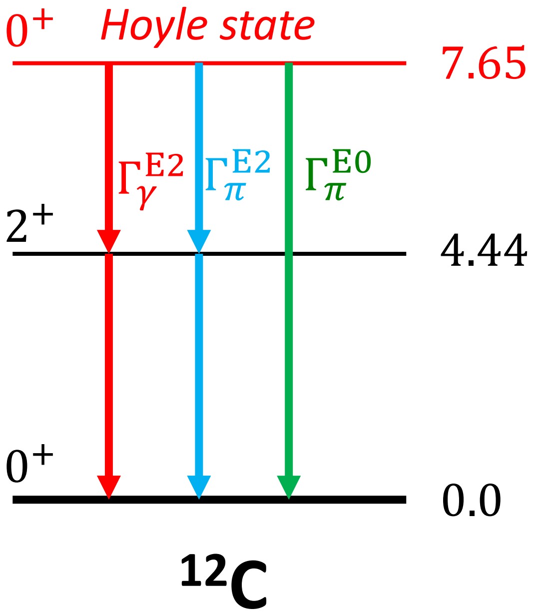
$$\Gamma_{rad}/\Gamma = 4.19(11) \cdot 10^{-4}$$

D. E. Alburger,Phys. Rev.124, 193 (1961).
P. A. Seeger and R. W. Kavanagh,Nucl. Phys.46, 577 (1963).
I. Hall and N. W. Tanner,Nucl. Phys.53, 673 (1964).
D. Chamberlin et al., Phys. Rev. C9, 69 (1974).
C. N. Davids, et al., Phys. Rev. C11,2063 (1975).
H.-B. Mak et al., Phys. Rev. C12, 1158 (1975).
R. G. Markham et al., Nucl. Phys. A270, 489 (1976).
A. W. Obst and W. J. Braithwaite, Phys. Rev. C13, 2033(1976)

Reaction rate of the three-alpha process in stars

→ *spectroscopic properties of the Hoyle state in ^{12}C:*

$$< \sigma v > \propto \frac{1}{T^3} \Gamma_{rad} e^{-\frac{E_R}{k_B T}}$$



state-of-the-art

$$\Gamma_{rad}/\Gamma = 4.19(11) \cdot 10^{-4}$$

D. E. Alburger,Phys. Rev.124, 193 (1961).
P. A. Seeger and R. W. Kavanagh,Nucl. Phys.46, 577 (1963).
I. Hall and N. W. Tanner,Nucl. Phys.53, 673 (1964).
D. Chamberlin et al., Phys. Rev. C9, 69 (1974).
C. N. Davids, et al., Phys. Rev. C11,2063 (1975).
H.-B. Mak et al., Phys. Rev. C12, 1158 (1975).
R. G. Markham et al., Nucl. Phys. A270, 489 (1976).
A. W. Obst and W. J. Braithwaite, Phys. Rev. C13, 2033(1976).

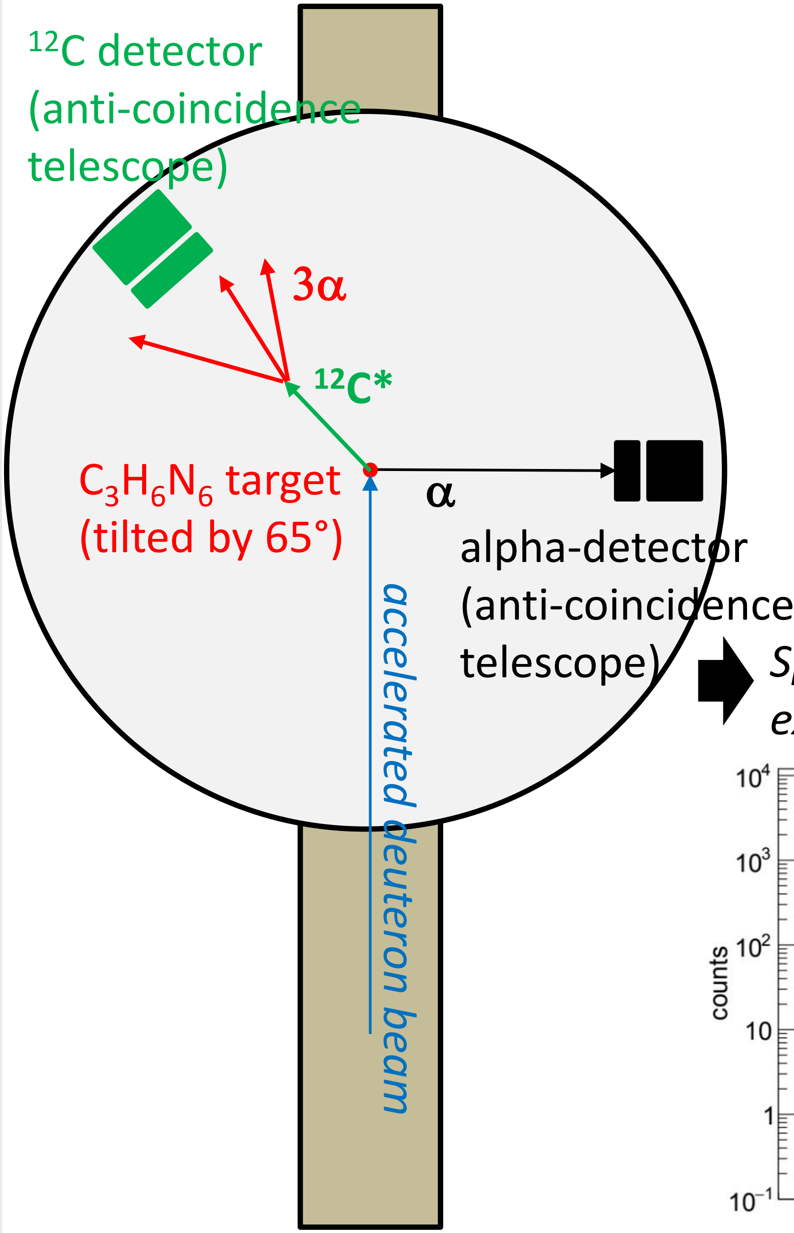
recent improved gamma-ray spectroscopy experiment

$$\Gamma_{rad}/\Gamma = 6.2(6) \cdot 10^{-4}$$

T. Kibédi et al., Phys. Rev. Lett. 125 (2020) 182701.

Tremendous impact on the three-alpha process in stars → about 34%!!!

Radiative decay of the Hoyle state



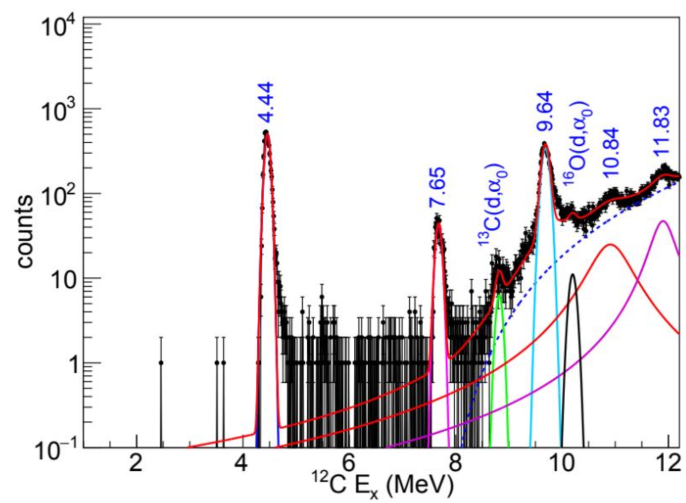
Use the $^{14}N(d,\alpha)^{12}C$ reaction to populate ^{12}C in its Hoyle state and then measure the fraction of its radiative decays by deducing the ^{12}C-α coincidence rate.

Beam: d @ 2.7 MeV (CN accelerator)

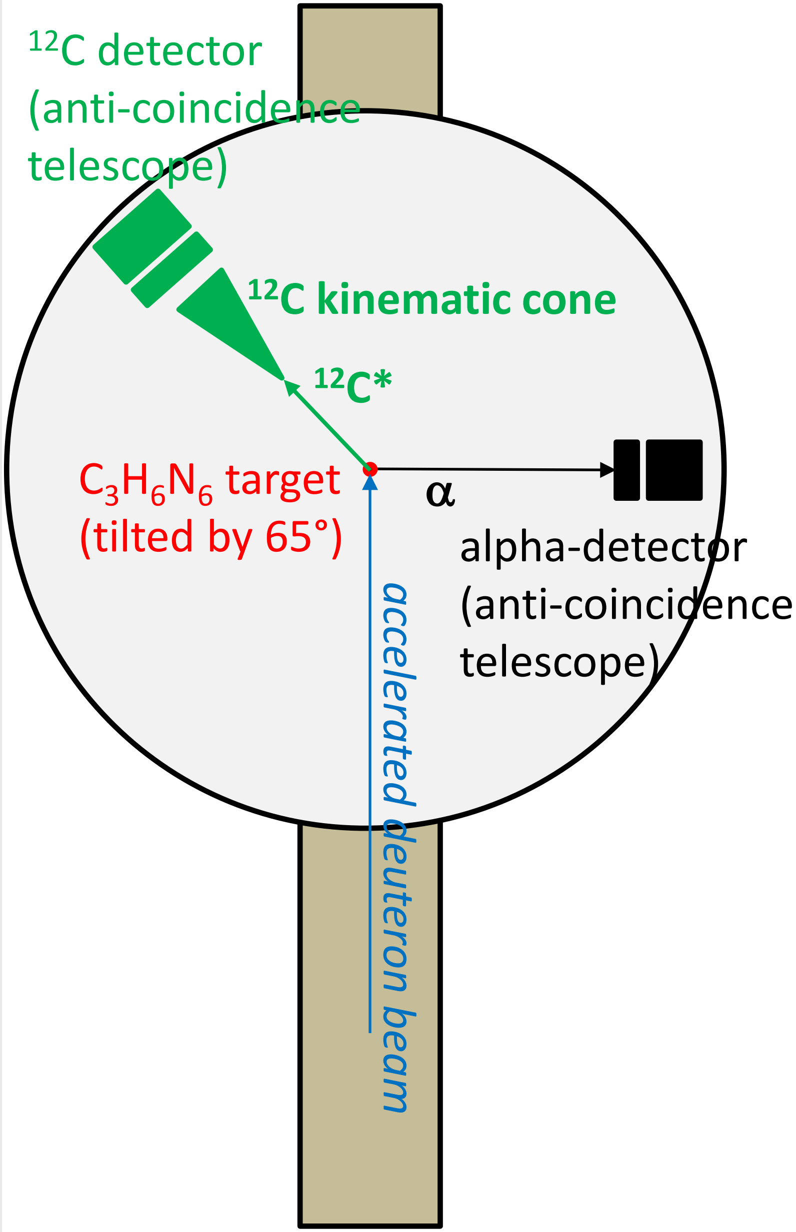
Target: $C_3H_6N_6$ + C backing

Detectors: Anti-coincidence telescope (90°) + Anti-coincidence telescope (64.8°).

Spectrum from the GHOST test experiment at the CN accelerator (LNL)



Radiative decay of the Hoyle state

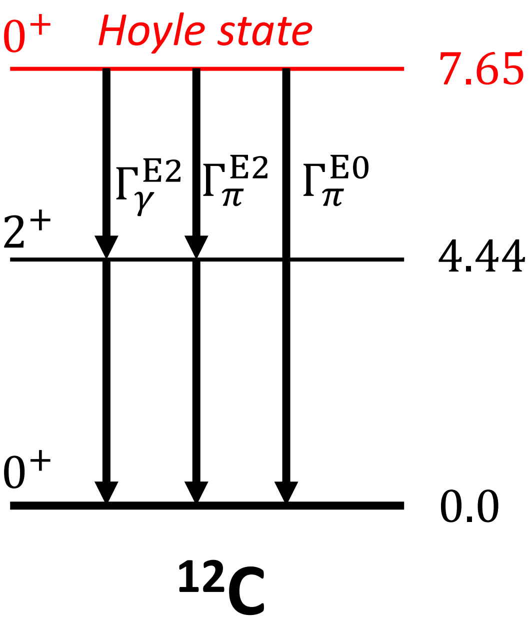


Use the $^{14}N(d,\alpha)^{12}C$ reaction to produce ^{12}C in its Hoyle state and then measure the fraction of its radiative decays by deducing the ^{12}C-α coincidence rate.

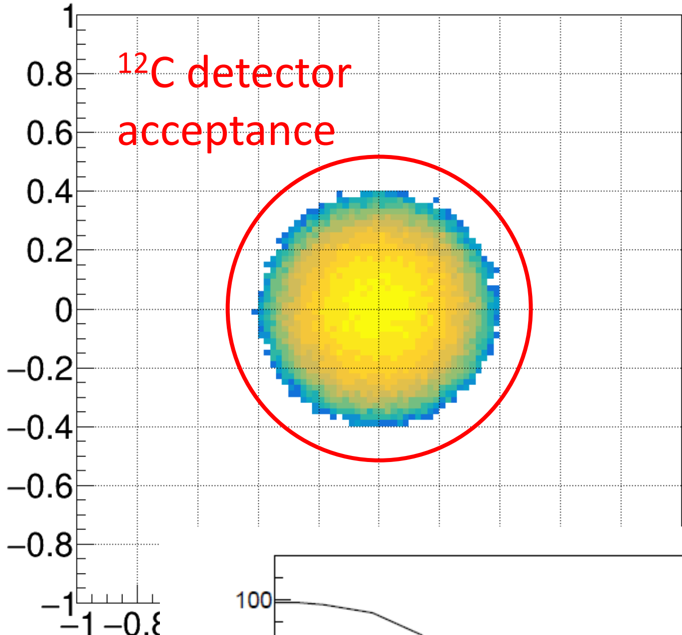
Beam: d @ 2.7 MeV (CN accelerator)

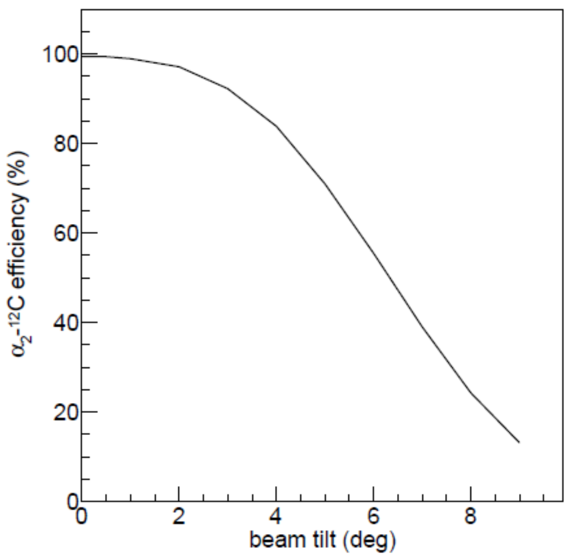
Target: $C_3H_6N_6$ + C backing

Detectors: Anti-coincidence telescope (90°) + Anti-coincidence telescope (64.8°).

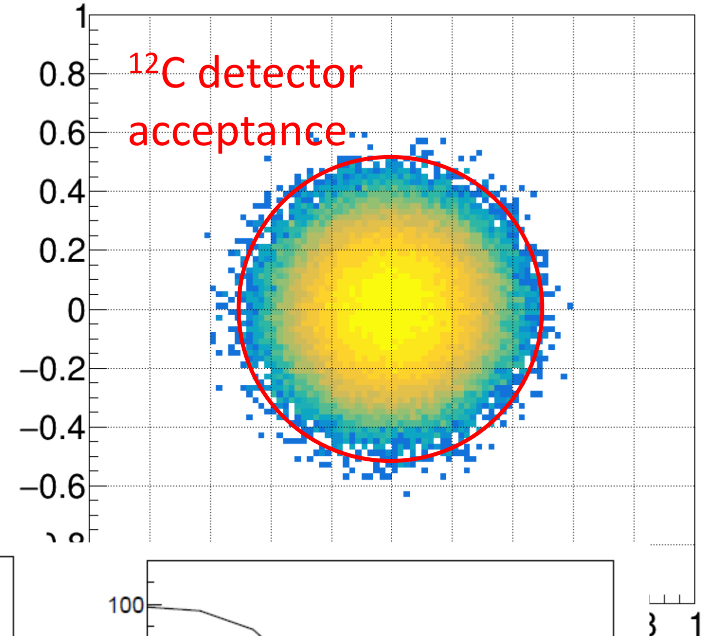


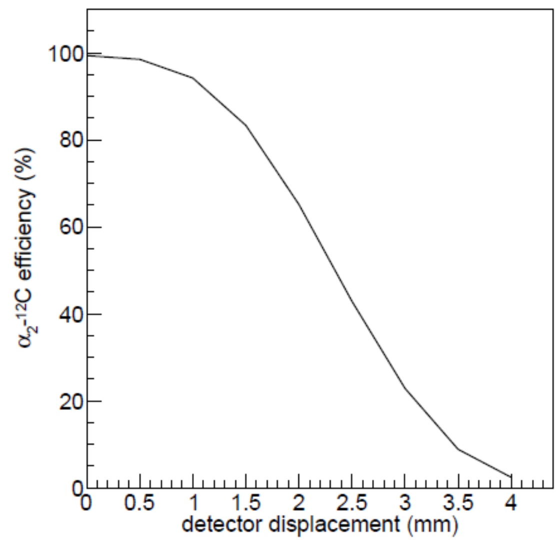
- *Without straggling effects in the target*



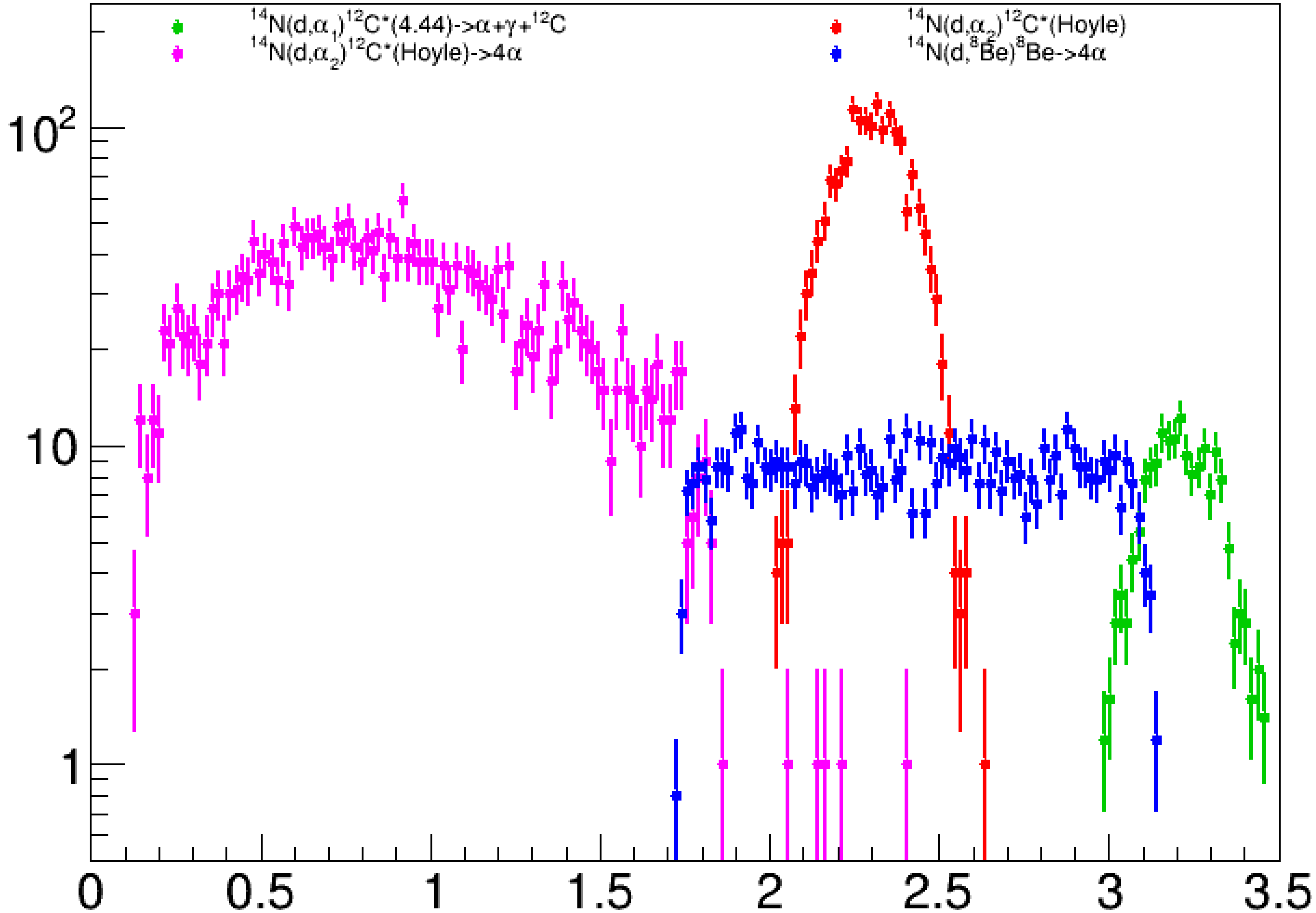


- *With straggling effects in the target*





^{12}C spectrum seen at the forward detector (full simulation with energy loss and energy and angular straggling + beam energy and angular straggling)



Conclusions

- Carbon isotopes are key nuclei to investigate clustering aspects as they are the simplest systems candidate to form linear chain structures;

- The Hoyle state in ^{12}C has a pronounced cluster nature that has a deep impact in nuclear astrophysics and nuclear structure;

- The alpha-decay of the Hoyle state in ^{12}C has been for a long time an open question in nuclear physics due to the numerous contrasting experiments reported in the literature;

- Modern high-precision experiments allowed to explore with enhanced sensitivity the direct decay of the Hoyle state, which seem to agree with theoretical investigations;

- Another open issue relates to the radiative decay width of the Hoyle state, which directly impacts the rate of the three-alpha process in stars → new experiment at INFN-LNL in the near future.

Thank you for your attention!