HIGH PRECISION MEASUREMNT OF THE 3-ALPHA DECAY FROM THE HOYLE STATE IN THE $^{12}C(^{12}C,3\alpha)^{12}C$ REACTION

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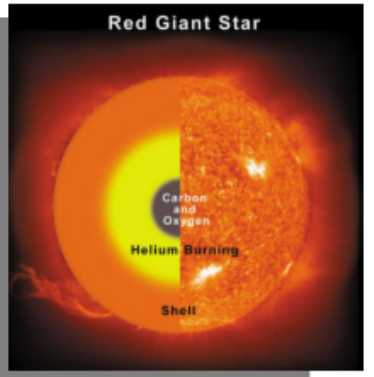
Outline

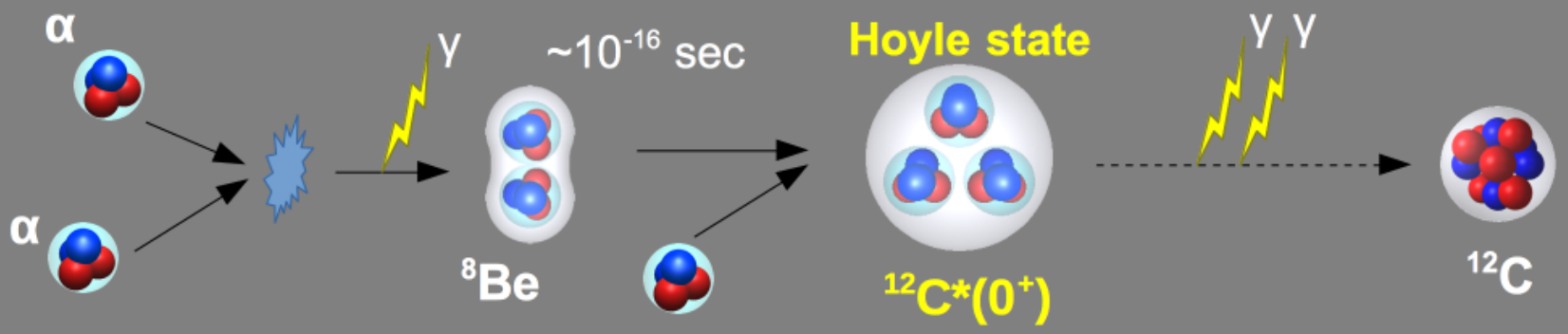
- Introduction to the Hoyle state
- Motivation of this study
- Measurement of the 3α decay of the Hoyle state
- Summary

Introduction to the Hoyle state



- **The Hoyle state is the second 0^+ state at 7.65 MeV in ^{12}C and a key state to create the carbon nucleus in the star.**

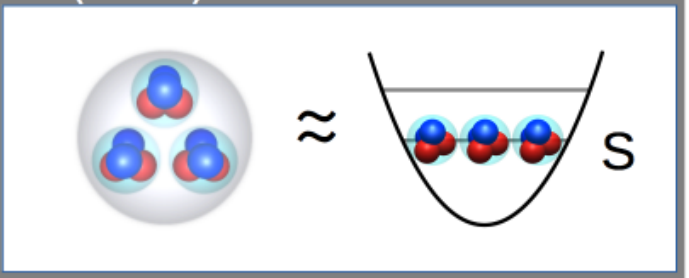
- No stable nuclei of A=5 and 8 → **Triple-alpha reaction**



- Structure of the Hoyle state strongly affect the formation of the carbon nucleus.

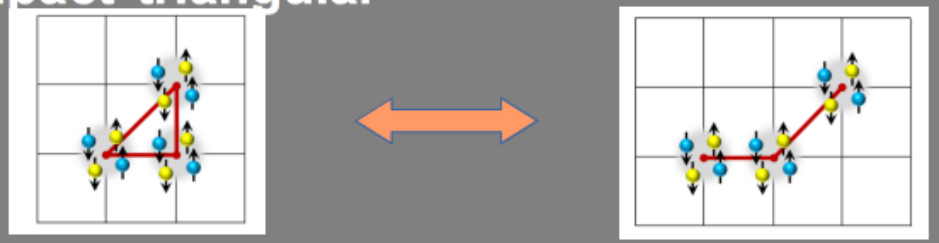
Structure of the Hoyle state

- **Possibility of the α particle condensate in ^{12}C and ^{16}O**
  A. Tohsaki, H. Horiuchi, P. Schuck, and G. Röpke, PRL 87 (2001) 192501
  - Gas-like 3α structure = 3α condensate



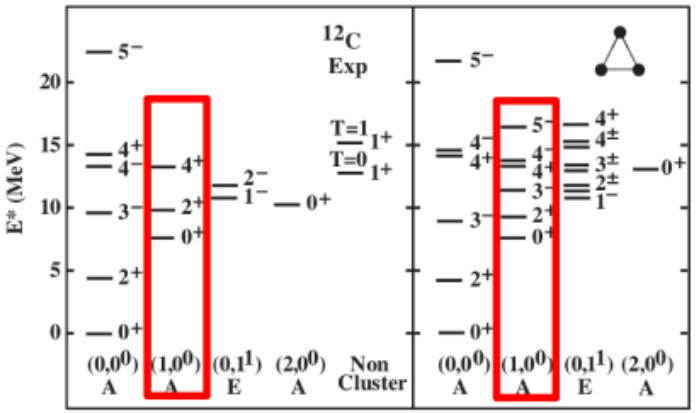
- **Ab initio lattice calculation**
  E.Epelbaum, Ulf-G.Meissner et al, PRL109(2012)252501

Compact triangular ⟷ **Bent-arm**



Ground state — **Hoyle state**

A symmetric vibration mode of the triangular configuration



Motivation

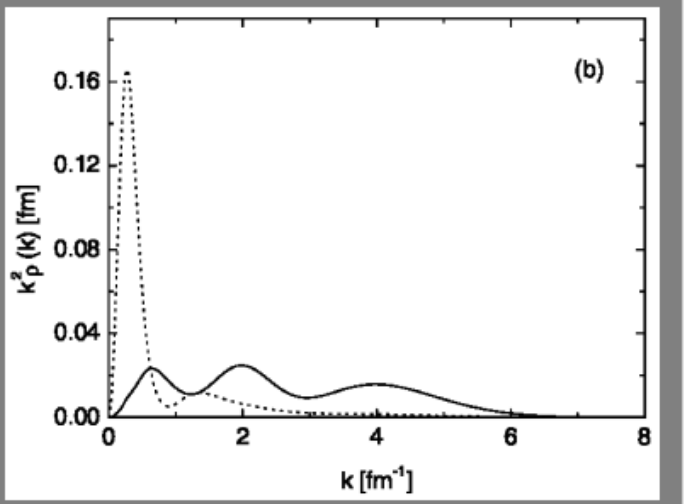
- To determine the structure of the Hoyle state experimentally
  - When the Hoyle state decay to three α particles directly, they are supposed to keep the information on the Hoyle state, although it may be very small.

$^{12}C^* \rightarrow {}^{8}Be + \alpha \rightarrow 3\alpha$ … x

$^{12}C^* \rightarrow 3\alpha$ … o

  - Momentum distribution of α clusters

Small dispersion = Spatially spreading



T. Yamada and P. Schuck, Eur. Phys. J. A 26 (2005) 185.

Outline

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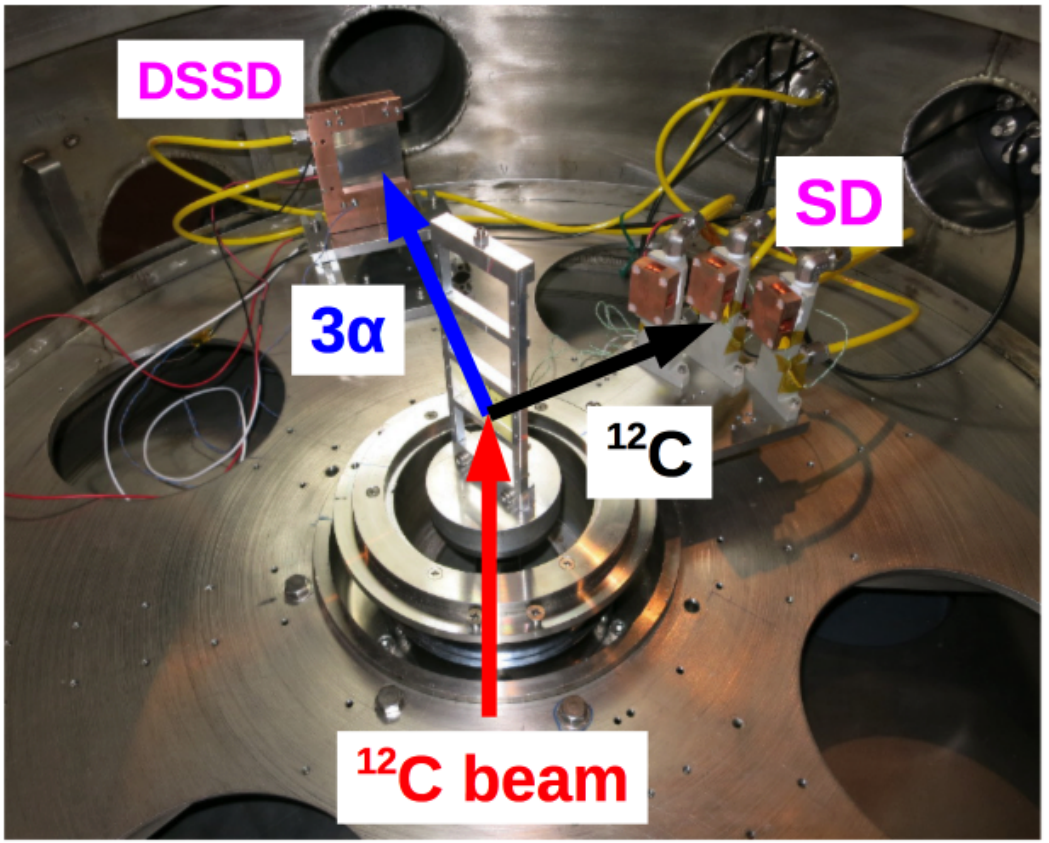
Experimental situation on the direct 3α decay

Exp.	Reaction	Events	Direct Decay branch	comment
M.Freer *et al*, PRC49,R1751(1994)	$^{12}C(^{12}C,3\alpha)$	~2000	< 4%	E_{12C} = 58 MeV
Ad.R.Raduta *et al*, PLB705, 65(2011)	$^{40}Ca+^{12}C$	~1000	17(5)%	25 MeV/u
J.Manfredi *et al*, PRC85,037603(2012)	^{10}C+Be, C	~4000	<3.9%	10.7 MeV/u
O.S.Kirsebom et al, PRL108,202501(2012)	$^{11}B(^{3}He,d3\alpha)$	~5000	<0.5%	E_{3He} = 8.5 MeV
T.K.Rana et al, PRC88,021601(R) (2013)	$^{12}C(\alpha,\alpha' 3\alpha)$	~20000	0.91(14)%	E_{α} = 60 MeV

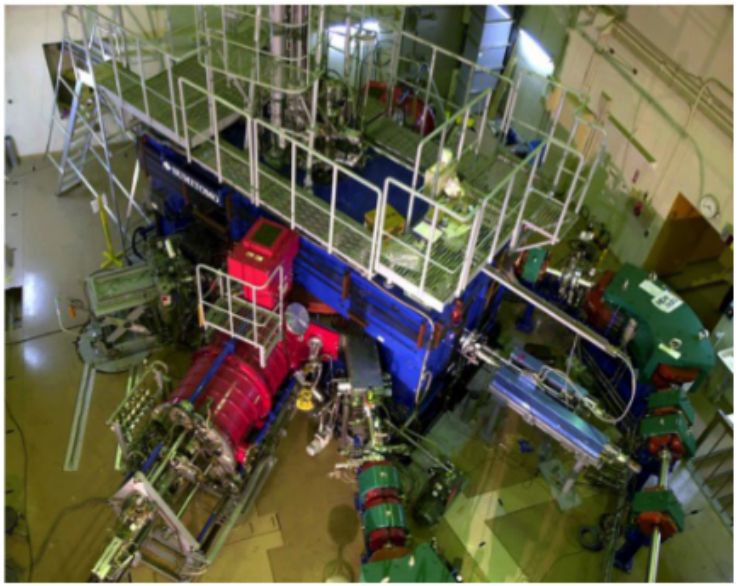
Experiment at CYRIC

$^{12}C(^{12}C, ^{12}C^*[3\alpha])^{12}C$ reaction at E_{12C} = 110 MeV

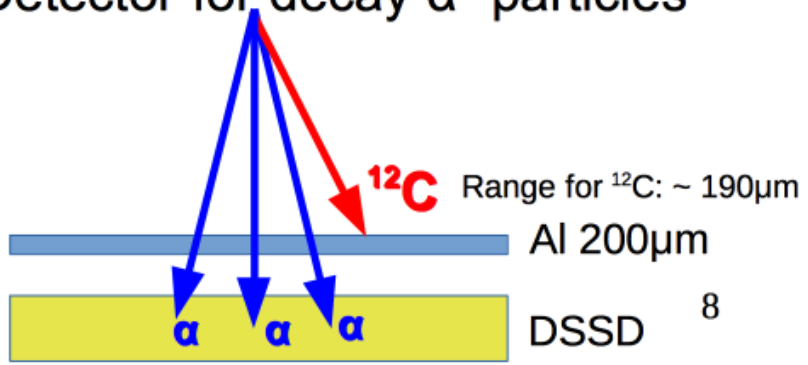
Experimental Set-up



AVF cyclotron in CYRIC



Detector for decay α particles



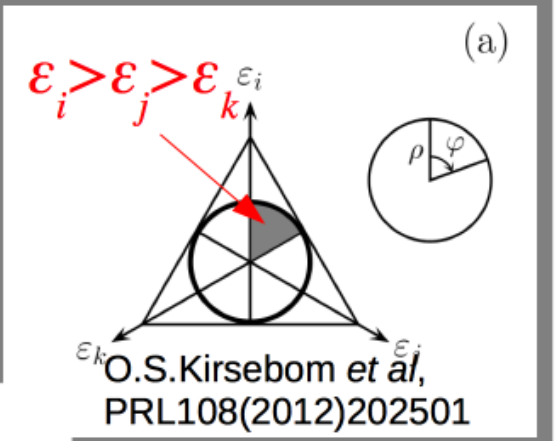
Symmetric Dalitz plot for the 3α-decay

- To visualize the energy correlation, the **symmetric Dalitz plot** for three equal masses is adopted.

$$(3\rho)^2 = 3(\varepsilon_i - \varepsilon_k)^2 + (2\varepsilon_i - \varepsilon_j - \varepsilon_k)^2$$

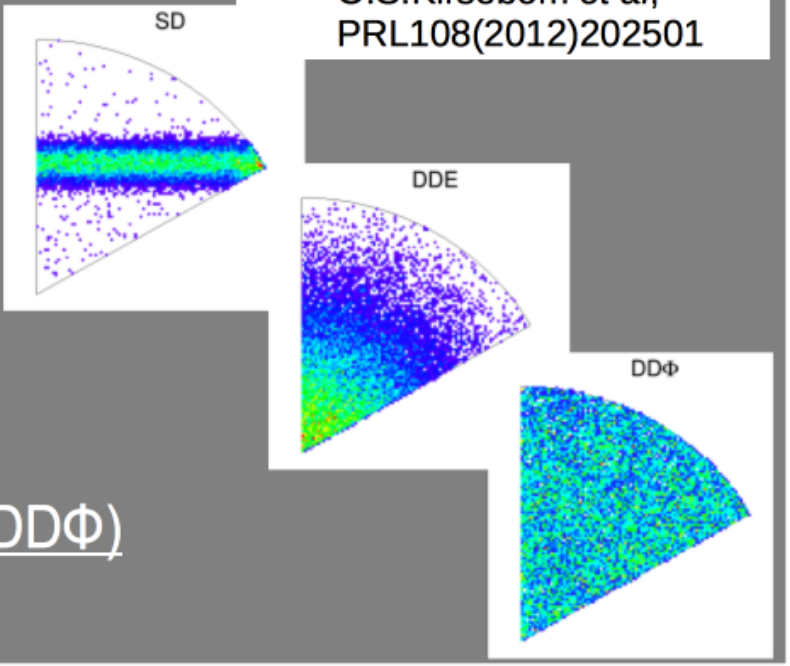
$$\varepsilon_{i,j,k} = E_{i,j,k}/(E_i + E_j + E_k)$$

$E_{i,j,k}$: Kinetic energy of α particles



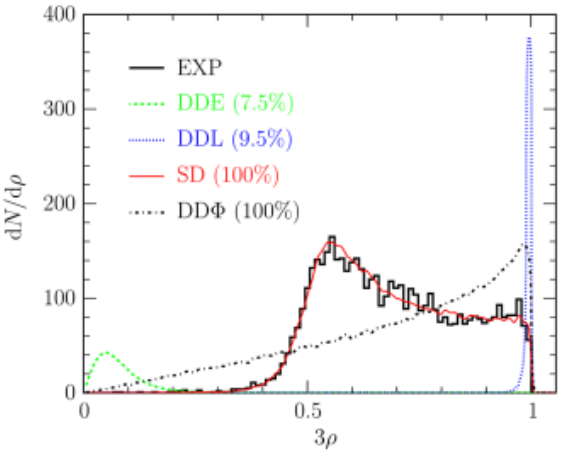
O.S.Kirsebom *et al*, PRL108(2012)202501

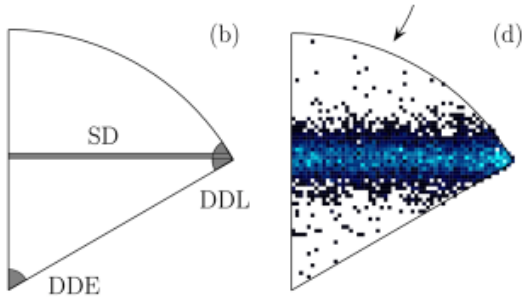
- **Three decay mechanisms**
  - Sequential decay (SD)
    $^{12}C^* \rightarrow {}^{8}Be + \alpha \rightarrow 3\alpha$
  - Direct decay with equal energies(DDE)
    $^{12}C^* \rightarrow 3\alpha$, $E(\alpha_1)=E(\alpha_2)=E(\alpha_3)$
  - Direct decay to phase space uniformly(DDΦ)
    $^{12}C^* \rightarrow 3\alpha$



Comparison with recent experiments

O.S.Kirsebom et al,
PRL108,202501(2012)



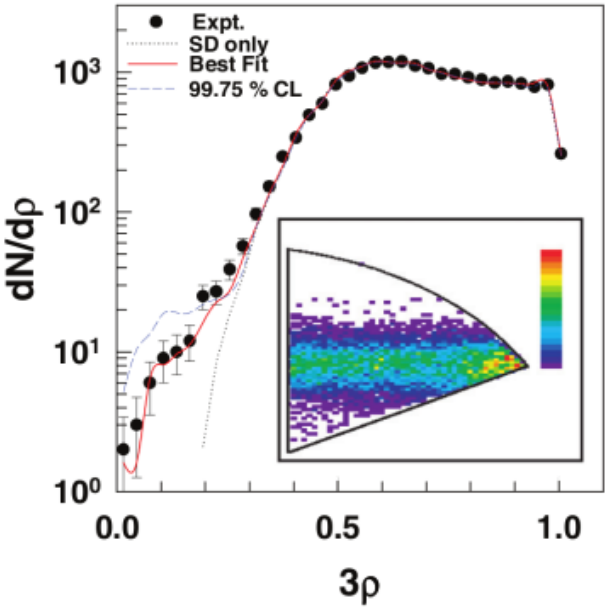


$^{11}B(^{3}He,d3\alpha)$

~ 5000 events

Direct decay < 0.5%

T.K.Rana et al,
PRC88, 021601(R)(2013)

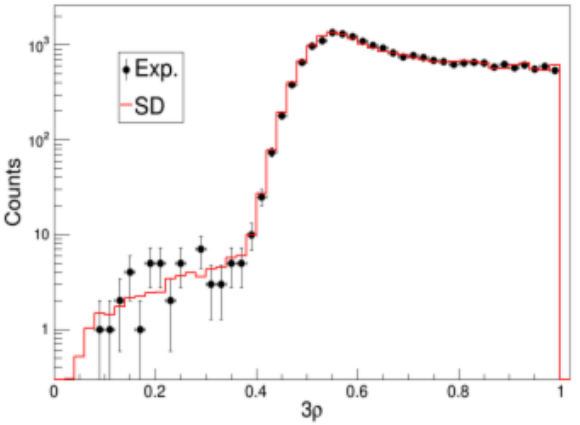


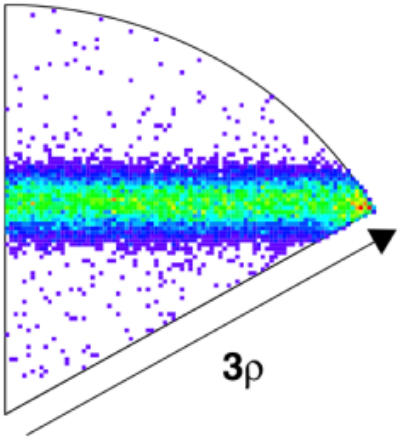
$^{12}C(\alpha,\alpha'3\alpha)$

~ 20000 events

Direct decay : 0.9%
(DDΦ:0.6%, DDE:0.3%)

CYRIC



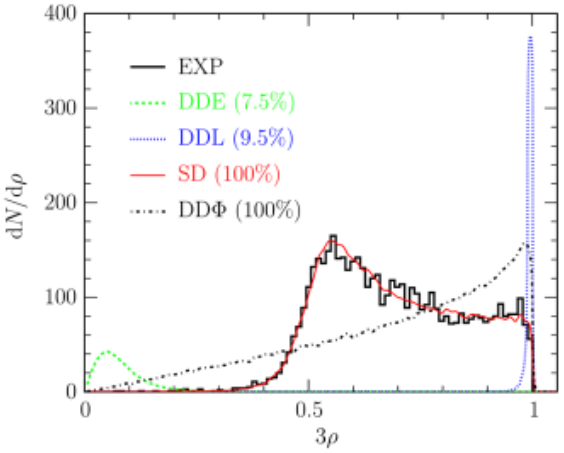


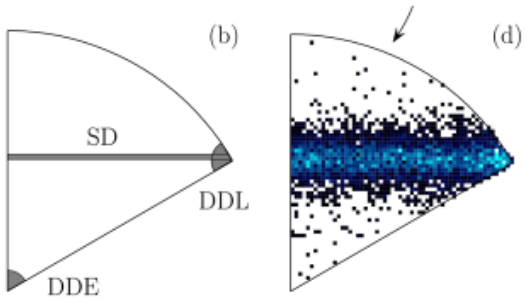
$^{12}C(^{12}C,3\alpha)^{12}C$

~ 21000 events

Comparison with recent experiments

O.S.Kirsebom et al,
PRL108,202501(2012)



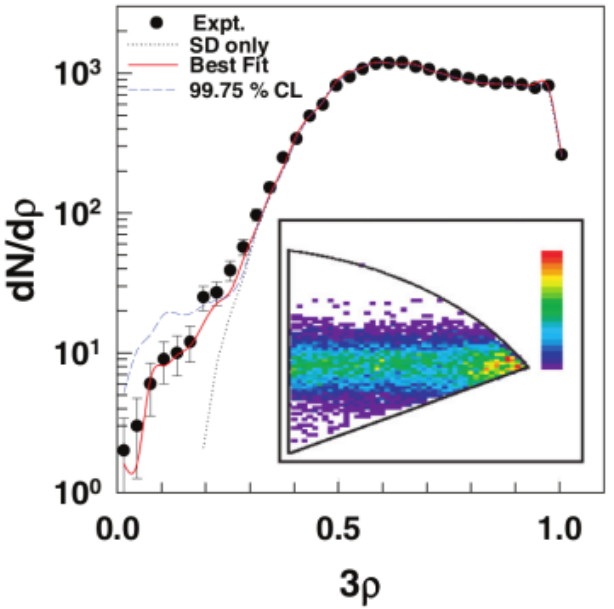


$^{11}B(^{3}He,d3\alpha)$

~ 5000 events

Direct decay < 0.5%

T.K.Rana et al,
PRC88, 021601(R)(2013)

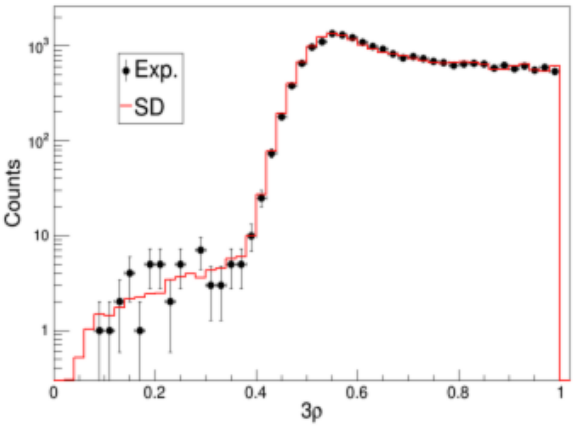


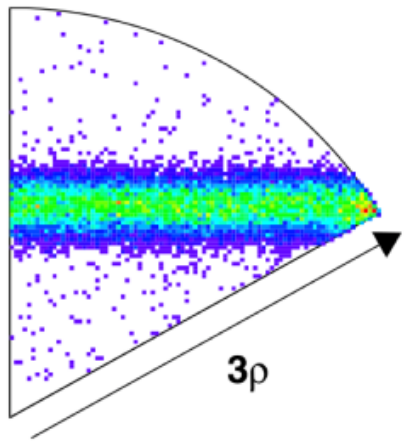
$^{12}C(\alpha,\alpha'3\alpha)$

~ 20000 events

Direct decay : 0.9%
(DDΦ:0.6%, DDE:0.3%)

CYRIC





Direct decay < 0.2 %
MI et al, PRL113,102501(2014)

~ 21000 events

Decay mode of the Hoyle state in the 3α particle model

- $E_2 < \delta E_{DDL}$ (~ 30 keV)
- $E_{rms} < \delta E_{DDE}$(~ 30 keV)

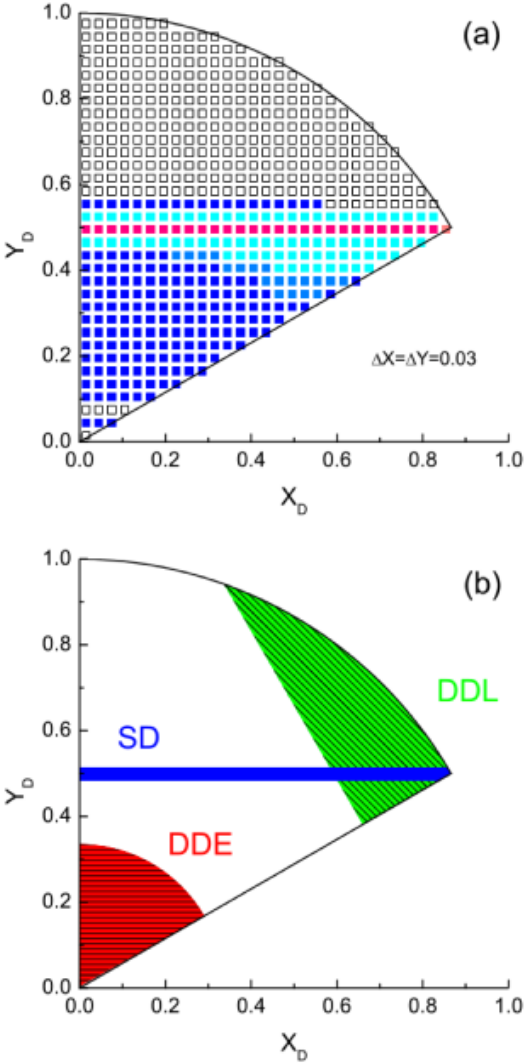
SD: 99.9%

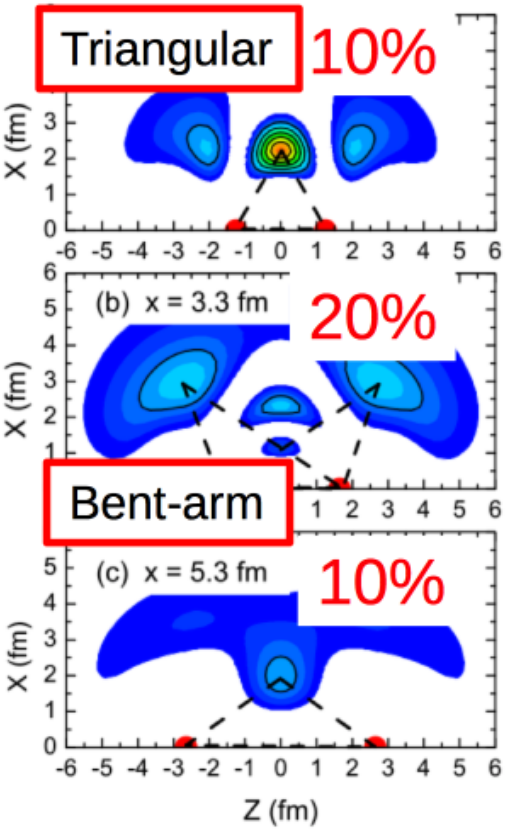
DDE: 0.005%

DDL: 0.03%

Upper limit on Direct Decay
DDΦ < 0.2%

M.I *et al*, Phys.Rev.Lett.113, 102501(2014)





S.Ishikawa, Phys.Rev.C90,061604(R)(2014)

Summary

- We performed the precise measurement of decay 3-α particles from the Hoyle state using $^{12}C(^{12}C,3\alpha)^{12}C$ reaction at 110 MeV.
- **Direct decay of the Hoyle state**
  - **Further improvement of the upper limit on the direct 3-α decay : 0.5% → 0.2%**
  - In order to observe the direct 3-α decay, the sensitivity need to be improved.

Collaborators

Cyclotron and Radioisotope Center (CYRIC)

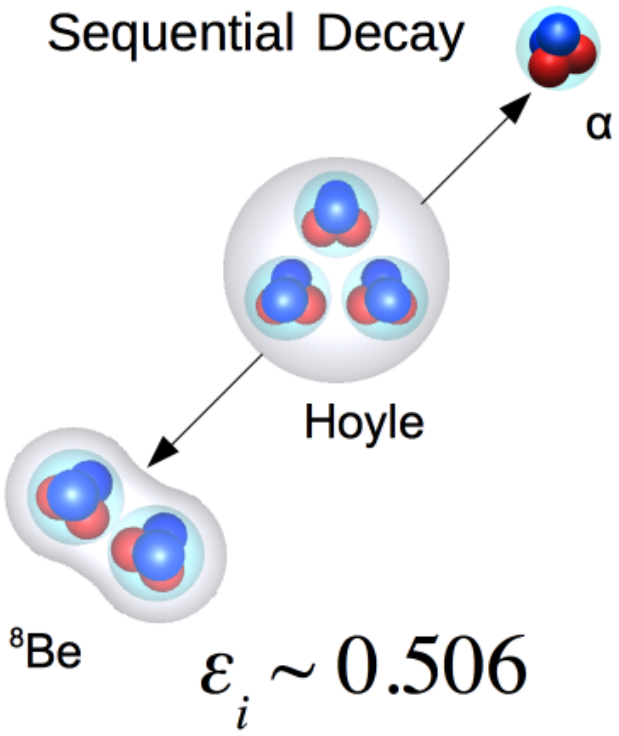
Tohoku University

S. Ando, T. Aoki, H. Arikawa, S. Ezure, K. Harada, T. Hayamizu, T. Inoue, T. Ishikawa, K. Kato, H. Kawamura, A. Uchiyama, Y. Sakemi

Thank you for your attention!

Energy distribution of decay alpha particles

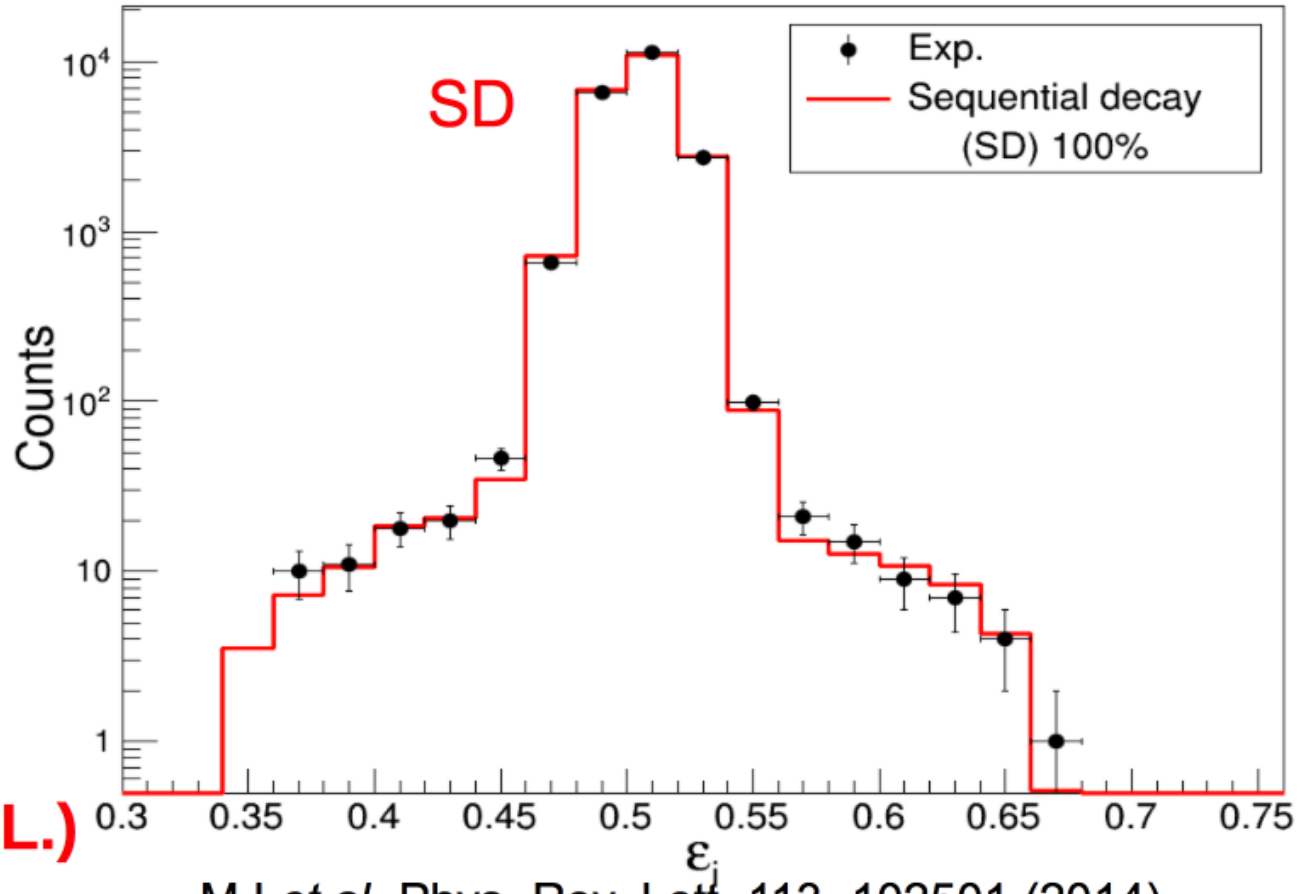
- "ε_i" : Highest normalized energy among three decay-α particles



$$\varepsilon_i \sim 0.506$$

Direct decay < 0.2%
(95%C.L.)

Normalized energy distribution
for the highest energy α particles

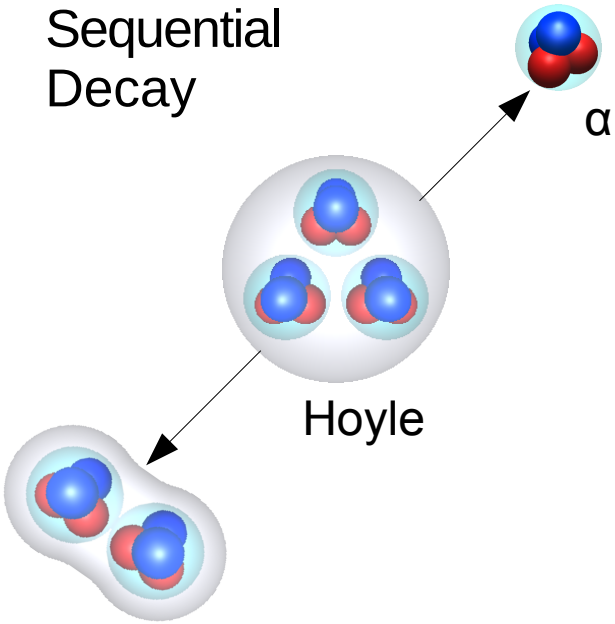


M.I *et al*, Phys. Rev. Lett. 113, 102501 (2014)

Energy distribution of decay alpha particles

- "ε_i" : Highest normalized energy among three decay-α particle

Sequential Decay



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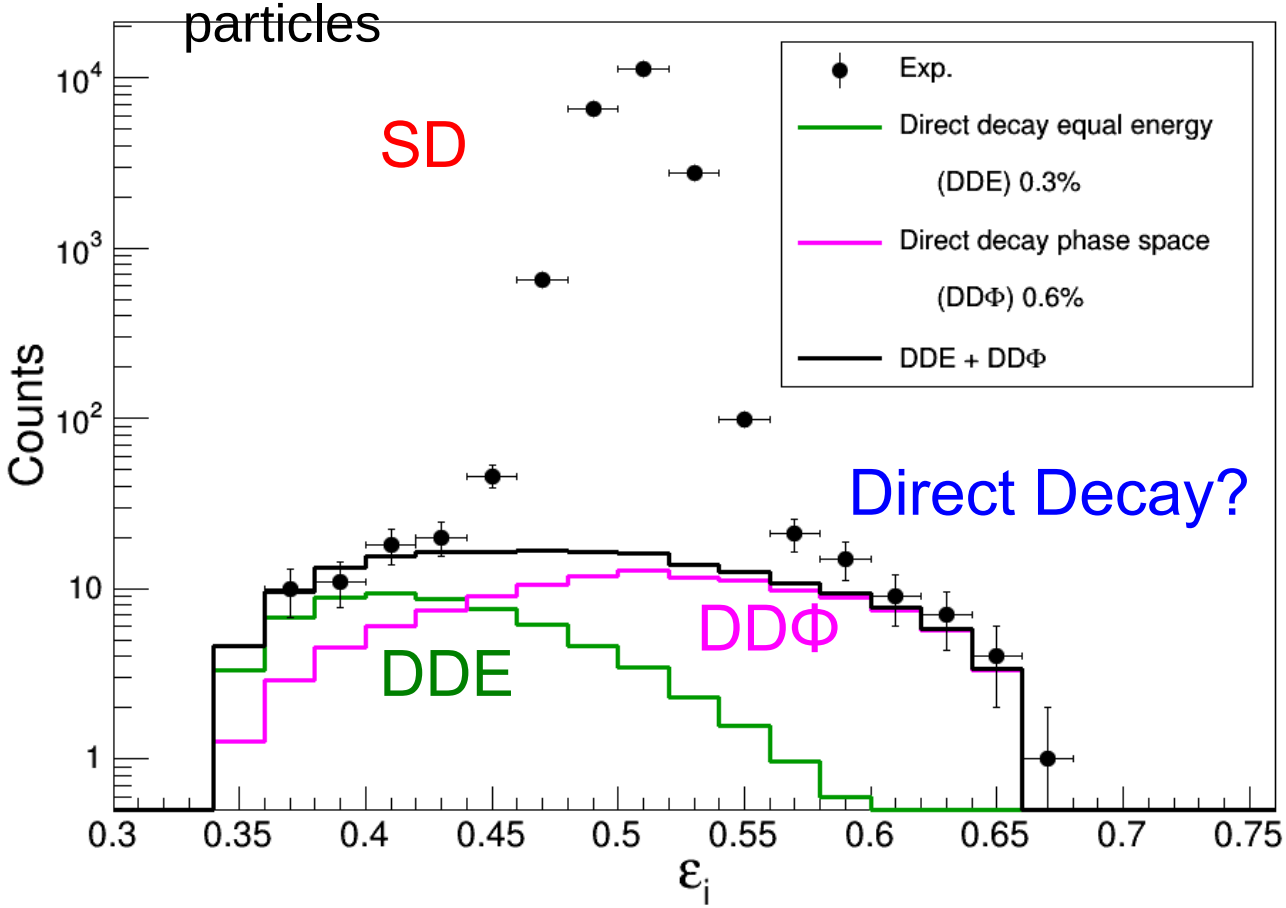
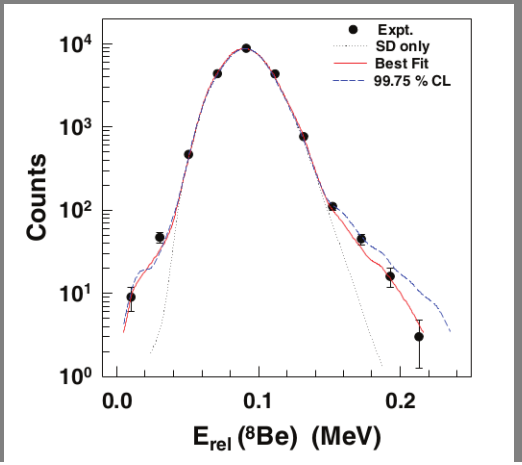
Normalized energy distribution for the highest energy α particles



M.I *et al*, Phys. Rev. Lett. 113, 102501 (2014)

^{12}C(α,α'3α) experiment in India

- The non-zero direct components of the decay from the Hoyle state have been reported using the ^{12}C(α,α'3α) reaction.
  T.K.Rana *et al*, PRC88,021601(R)(2013)



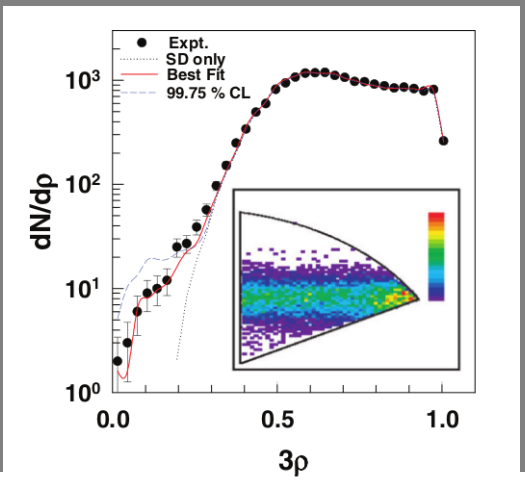


TABLE I. Comparison of different experimental estimates of direct decay modes of the Hoyle state.

Expt.	Total events	DDE (%)	DDL (%)	DDΦ (%)	Total (%)	CL
Ref. [22]	~2000[a]	–	–	–	<4	99.5
Ref. [23]	~1000[b]	7.5(4)[c]	9.5(4)[c]	–	17(5)[c]	
Ref. [24]	~4000[b]	<0.45	–	<3.9	<4.35	99.75
Ref. [25]	~5000[a]	<0.09	<0.09	<0.5	<0.68	95
Present	~20000[a]	0.3(1)[c]	0.01(3)[c]	0.60(9)[c]	0.91(14)[c]	

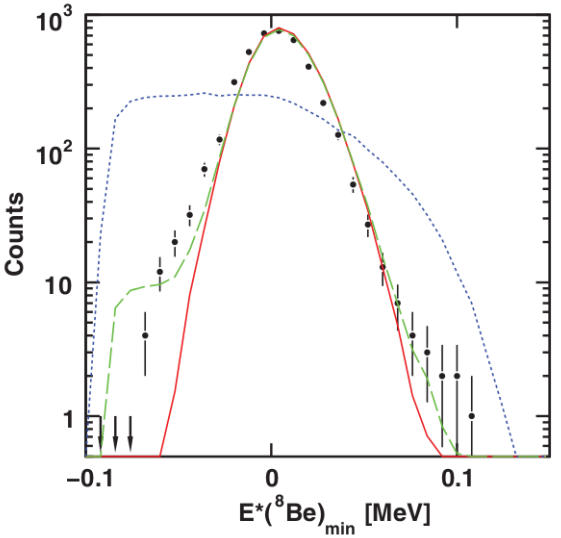
[a]Fully detected events only.
[b]3α reconstructed events.
[c]Total error from statistical, χ^2, and background.

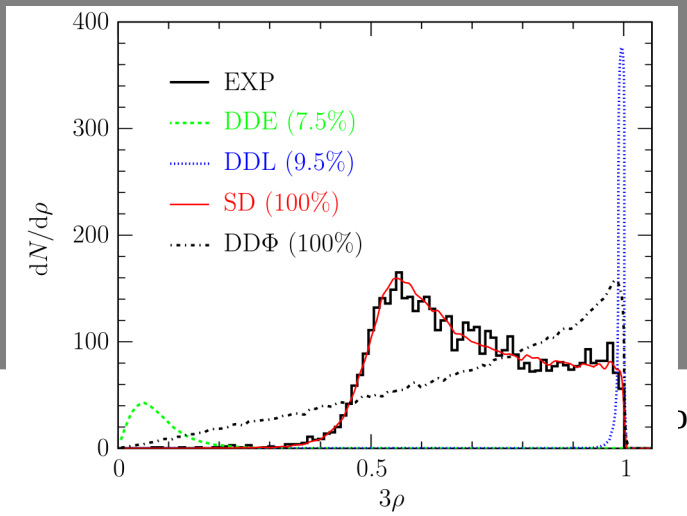
0.91(14) %

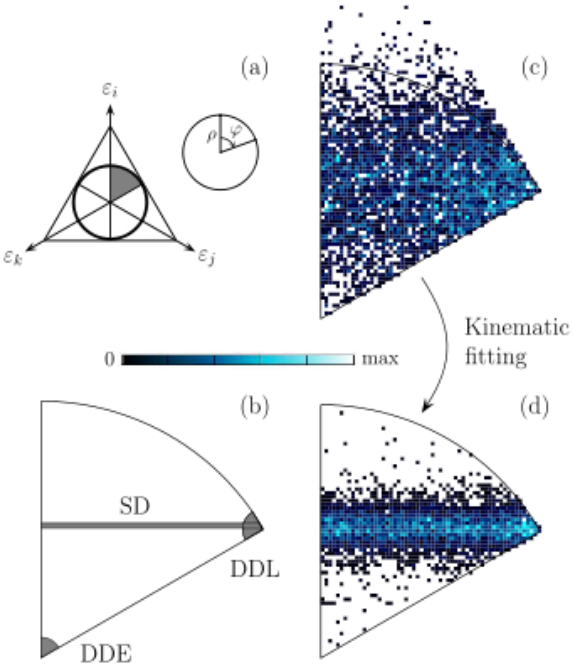
Recent experiments

- The ^{10}C+ C(Be) experiment
  They obtained the upper limit of 3.9% for the direct 3α decay from the Hoyle state
  J.Manfredi et al,PRC85,037603(2012).

- The ^{11}B(^{3}He,d3α) experiment
  They improved the upper limit of the direct 3α decay to be 5×10^{-3}.
  O.S.Kirsebom et al,PRL108,202501(2012).

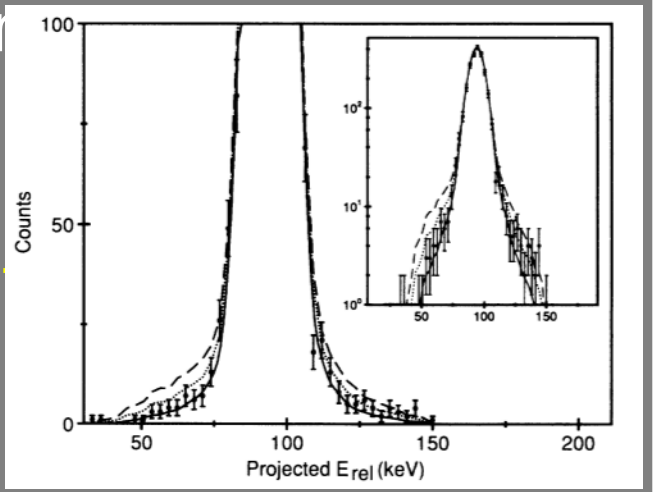




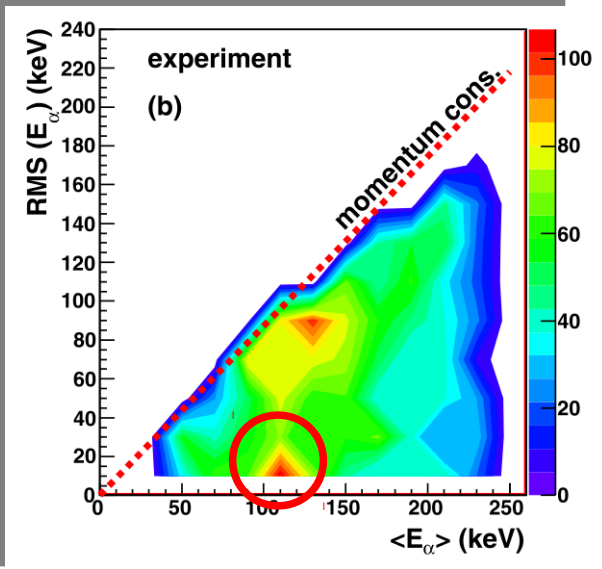


Experimental situation on the direct 3α decay

- Experiment of the $^{12}C(^{12}C,3\alpha)^{12}C$ reaction
  M.Freer *et al*, PRC49(1994)R1751
  - Upper limits of 4% for the contribution of the direct decay process to Γ_α



- In 2011, the direct decay branch of ±15% had been reported by Catania group. Among them, the direct decay with three α particles of equal energies was ±7.4±0.5%.
  Ad.R.Raduta *et al*, PLB705(2011)65.

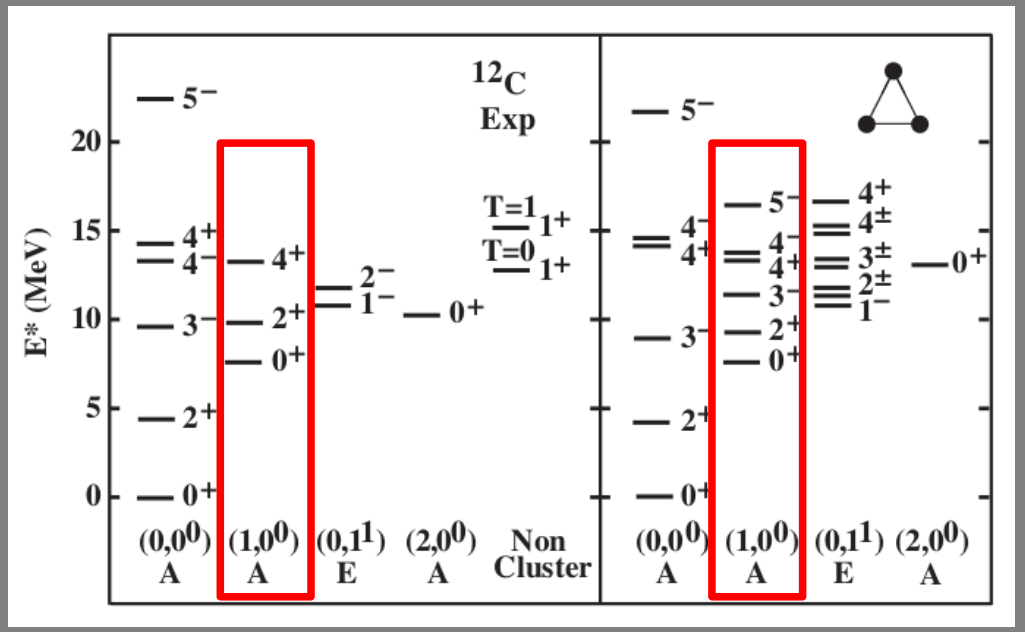


Evidence for α condensation of the Hoyle state??

Algebraic Cluster Model in ^{12}C

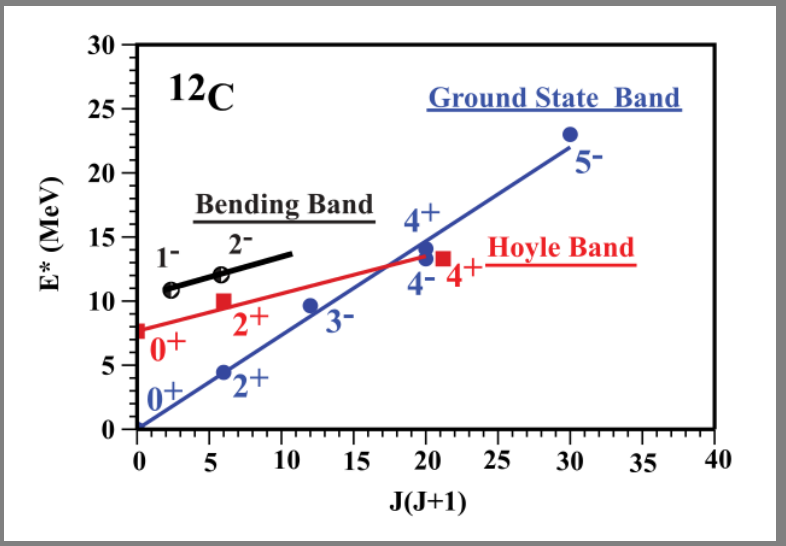
- Hoyle state:the *A* symmetric stretching vibration (breathing mode) of the triangular configuration

  R.Bijker and F.Iachello, PRC61(2000)067305



$^{12}C(^{4}He,\alpha)^{4}He$ experiment at Birmingham

they found 5^- state at 22.4 MeV



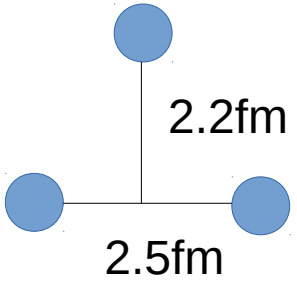
D.J.Marín-Lámbarri *et al*, Phys.Rev.Lett.113, 012502 (2014)

Structure of the Hoyle state

- Root mean square radius

S.Ishikawa,
Phys.Rev.C90, 061604(R)(2014)

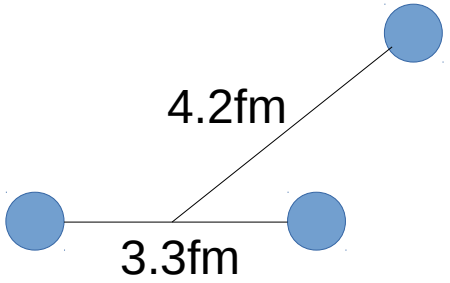
A



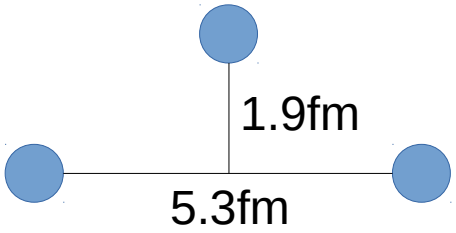
$$R_{rms} = \sqrt{R_\alpha^2 + \frac{1}{6}\langle x^2\rangle + \frac{2}{9}\langle y^2\rangle}$$

R_{rms} ~ 3.43 fm

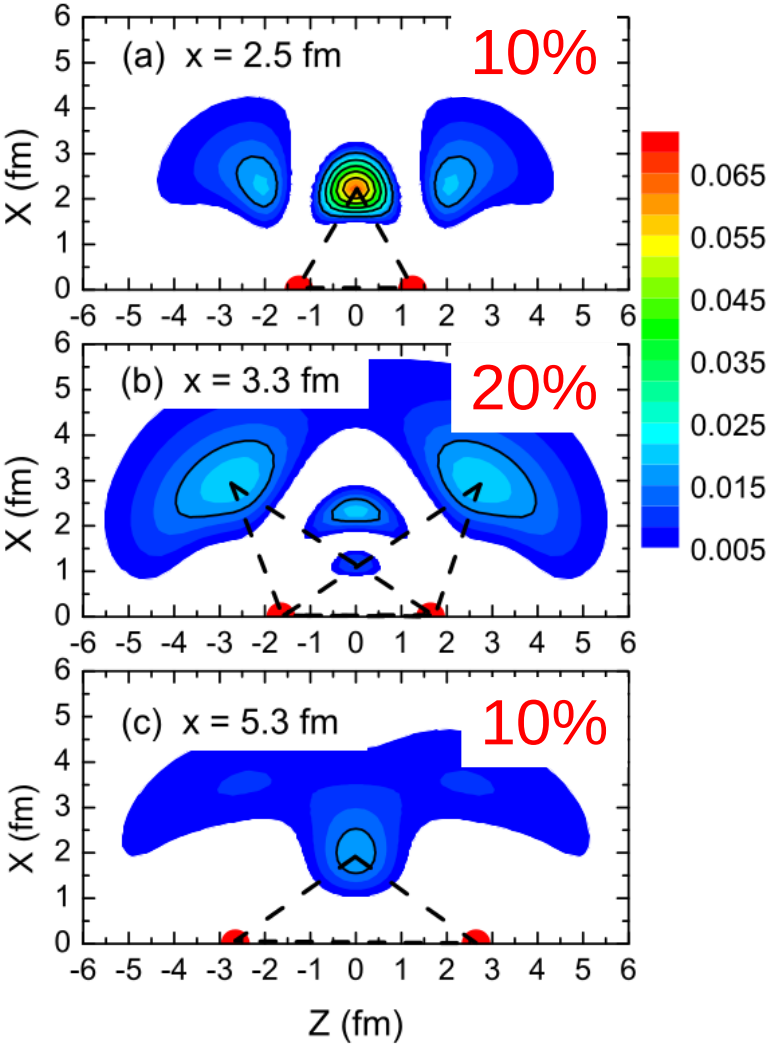
B



C

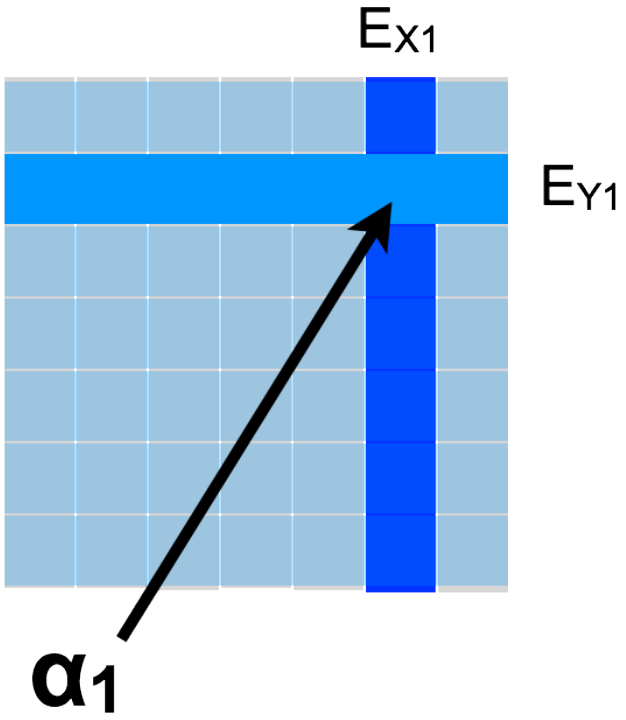


B=
C



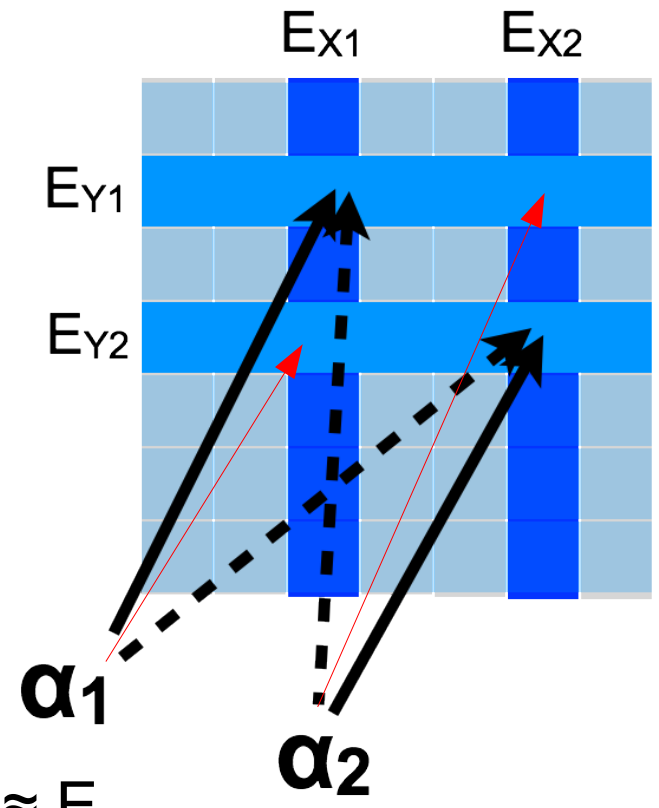
Misassignment of decay alpha particles

Why do the shoulders appear? … Misassignment of decay alpha particles



$E_{X1} \approx E_{Y1}$

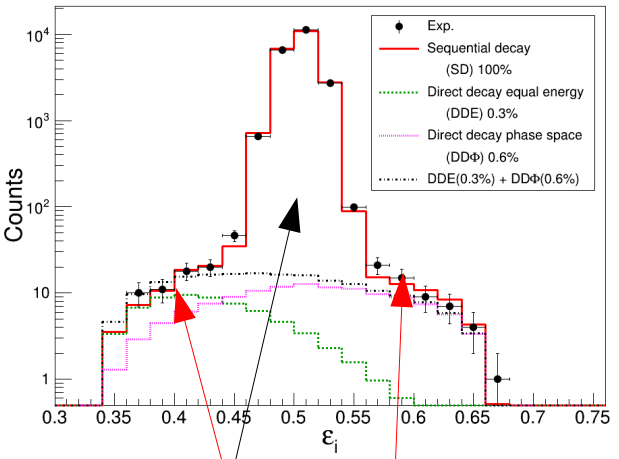
→ α1 (X1,Y1)



$E_{\alpha 1} \approx E_{\alpha 2}$

α1(X1,Y2), α2(X2,Y1)

α1(X2,Y1), α2(X1,Y2)

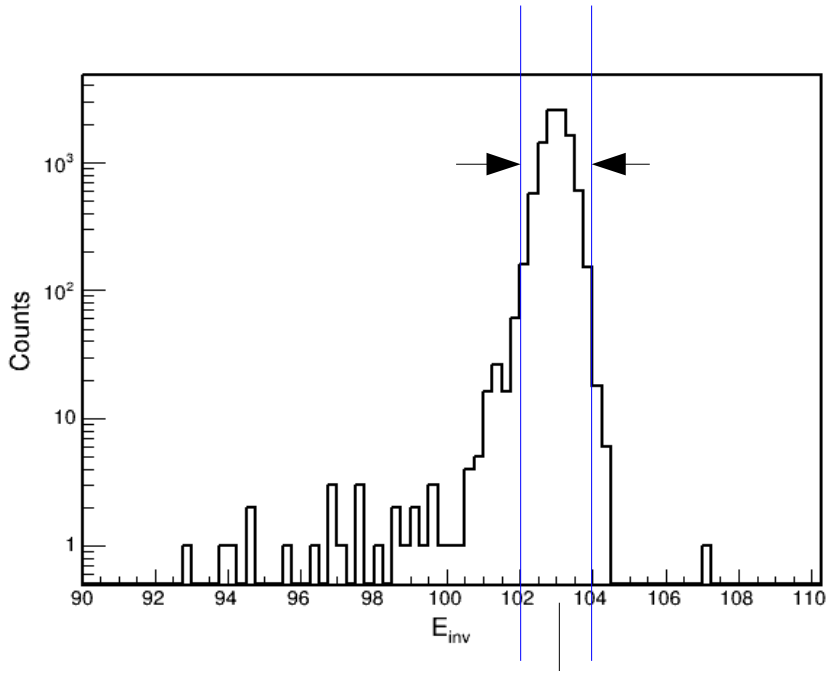


Misassignment

Energy spectrum for the decay 3α particles

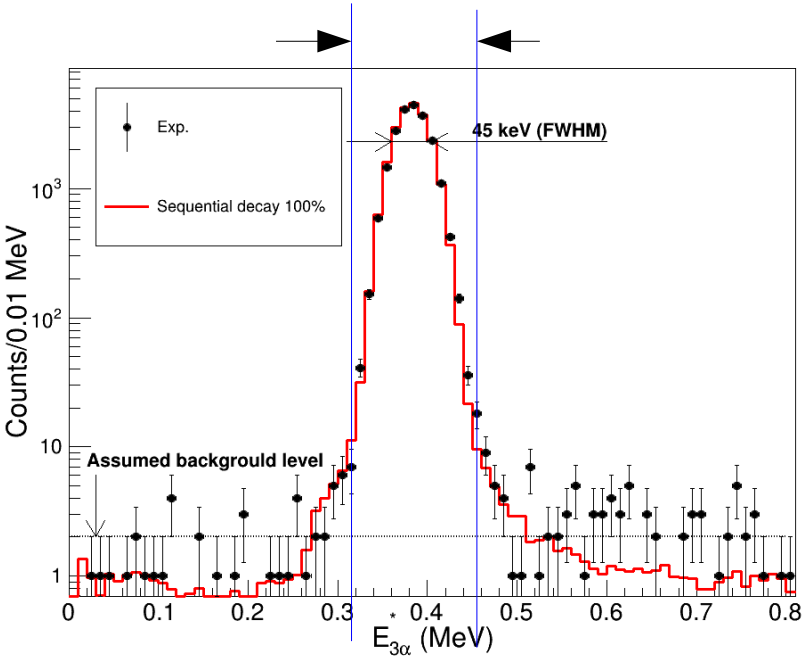
Invariant Mass spectrum

$$E_{inv} = E_{recoil12C} + E_{\alpha 1} + E_{\alpha 2} + E_{\alpha 3}$$



~103 MeV

Total 3α energy spectrum in the $^{12}C^*$ rest frame

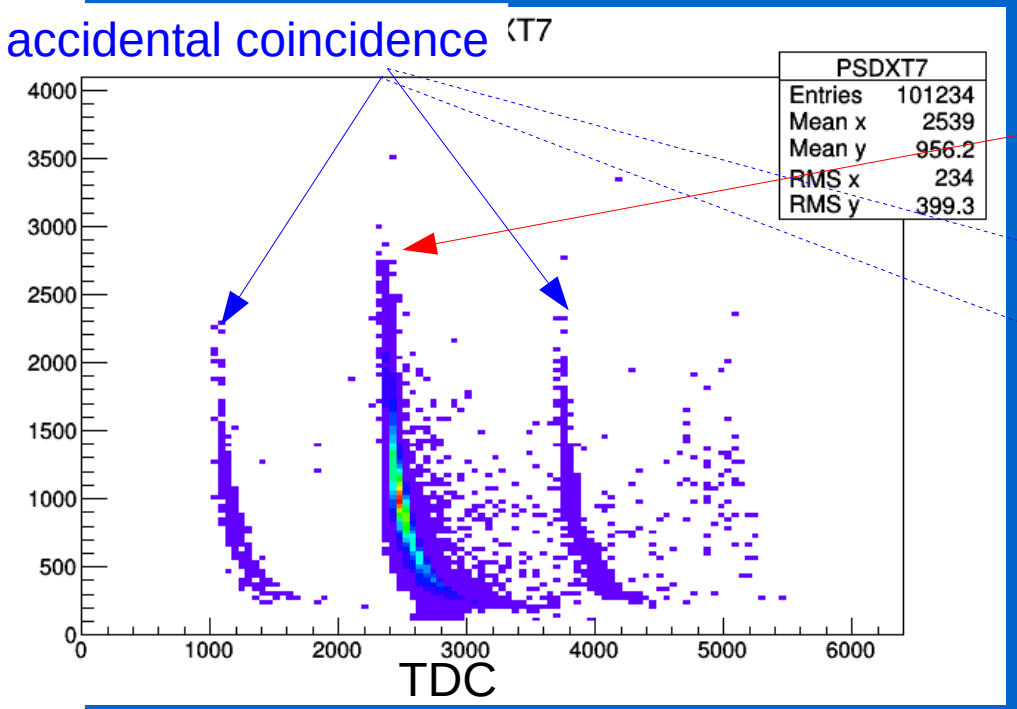


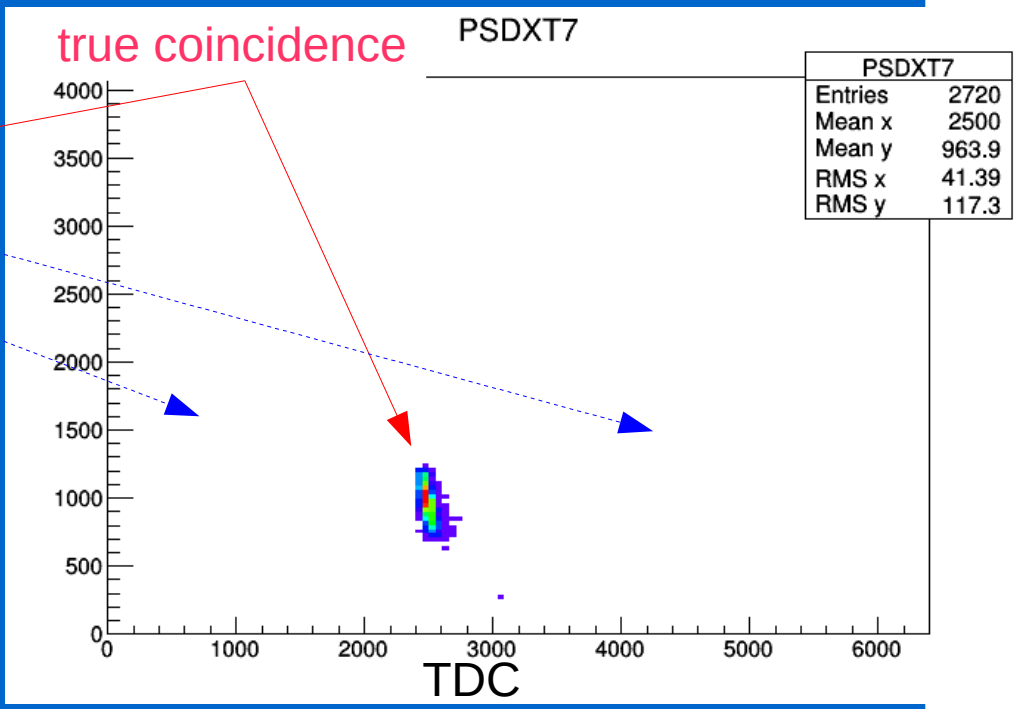
Accidental coincidence

- There was no accidental 3α coincidence.

Recoil ^{12}C + 1-α

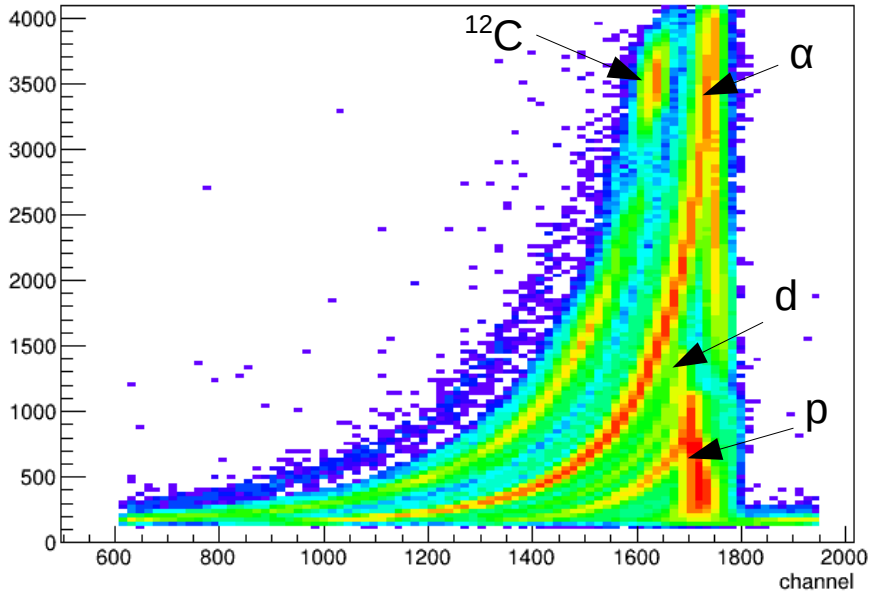
Recoil ^{12}C + 3-α

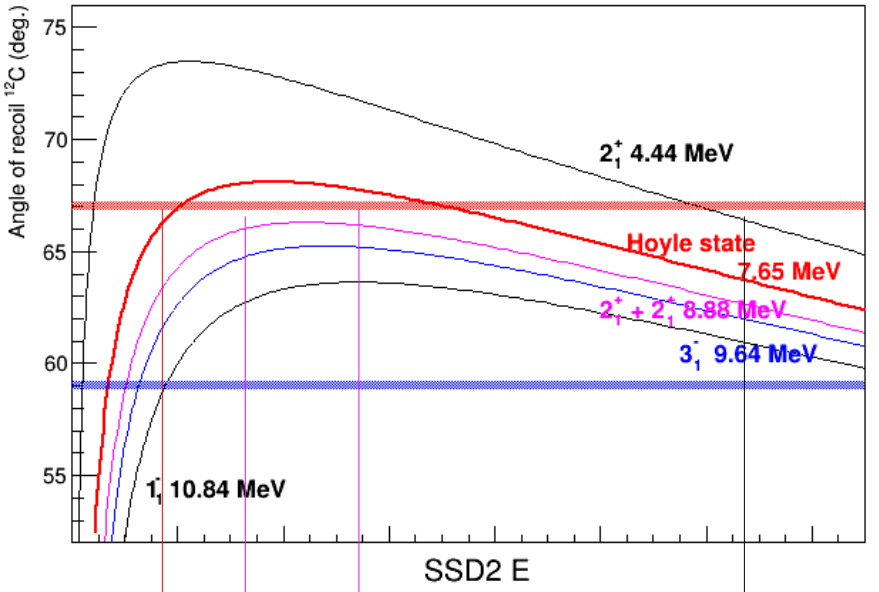




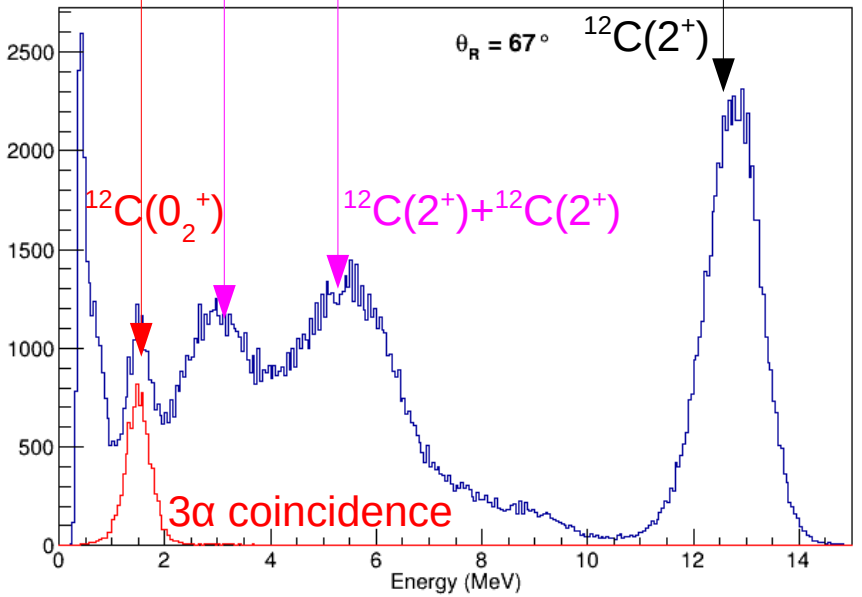
Kinematics and Recoil ^{12}C spectrum

TOF spectrum of SD





- Particle Identification: TOF method
- Excitation energy is determined from the energy of the recoil ^{12}C.



Decay and structure of Hoyle state

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Decay and structure of the Hoyle state

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The first 0^+ resonant state of the ^{12}C nucleus, $^{12}C(0_2^+)$, the so-called Hoyle state, is investigated in a three-α-particle (3-α) model. A wave function for the photodisintegration reaction of a ^{12}C bound state to 3-α final states is defined and calculated by the Faddeev three-body formalism, in which three-body bound and continuum states are treated consistently. From the wave function at the Hoyle state energy, I calculated distributions of outgoing α particles and density distributions at interior region of the Hoyle state. Results show that a process through a two-α resonant state is dominant in the decay and contributions of the rest process are very small, less than 1%. There appear to be some peaks in the interior density distribution corresponding to configurations of equilateral and isosceles triangles. It turns out that these results are obtained independently of the choice of α-particle interaction models, when they are made to reproduce the Hoyle state energy.

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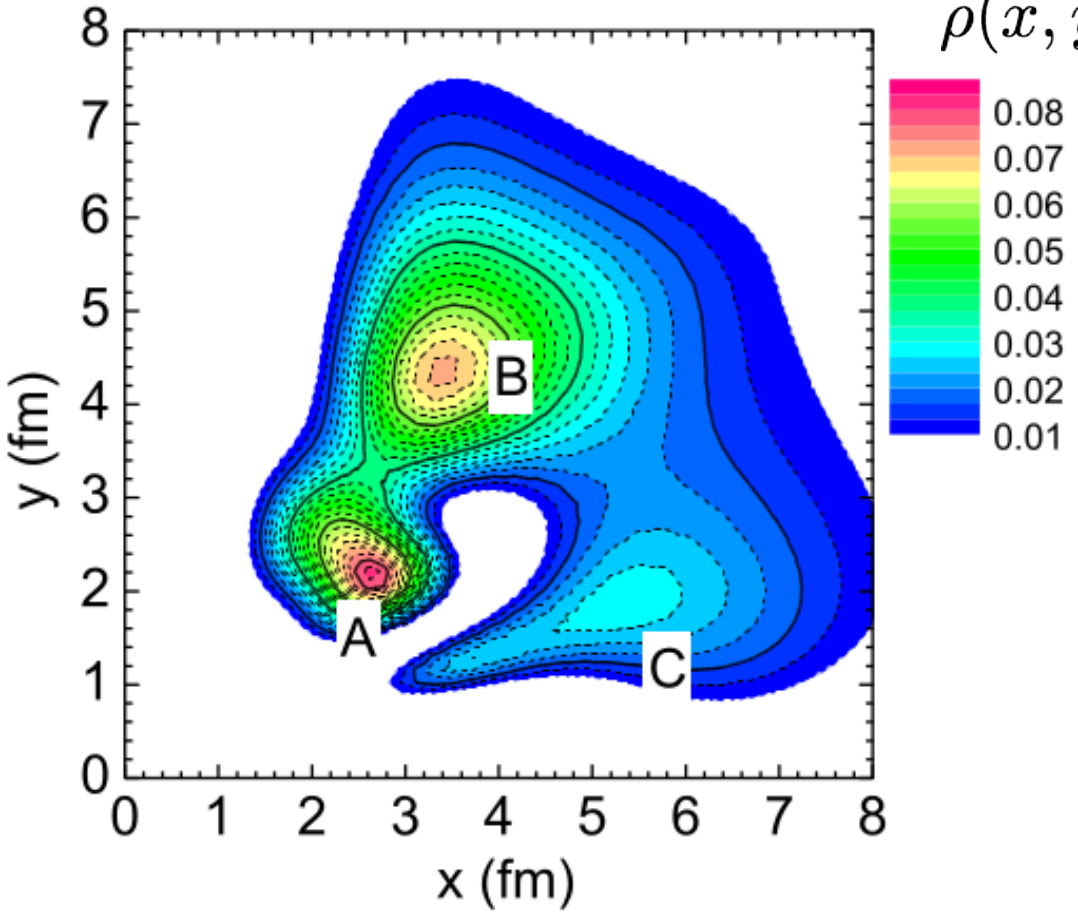
Structure of the Hoyle state 1

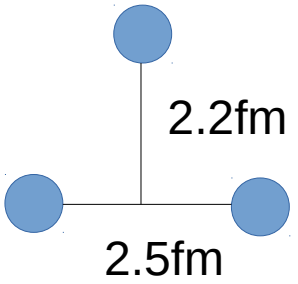
- Density distribution

$$\rho(x,y) = x^2 y^2 \int d\hat{x} d\hat{y} |\Psi(x,y)|^2$$

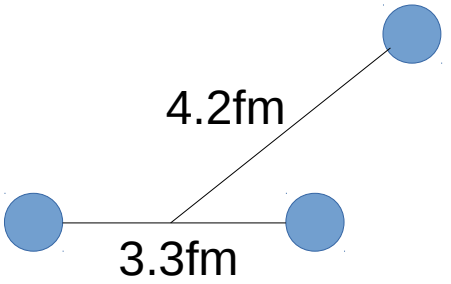


S.Ishikawa, Phys.Rev.C90, 061604(R)(2014)

A



B



C