多重崩壊α粒子測定による αクラスターガス状態の研究

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  - α gas-like structure and α condensate
  - α cluster gas phase in ^{12}C, ^{16}O
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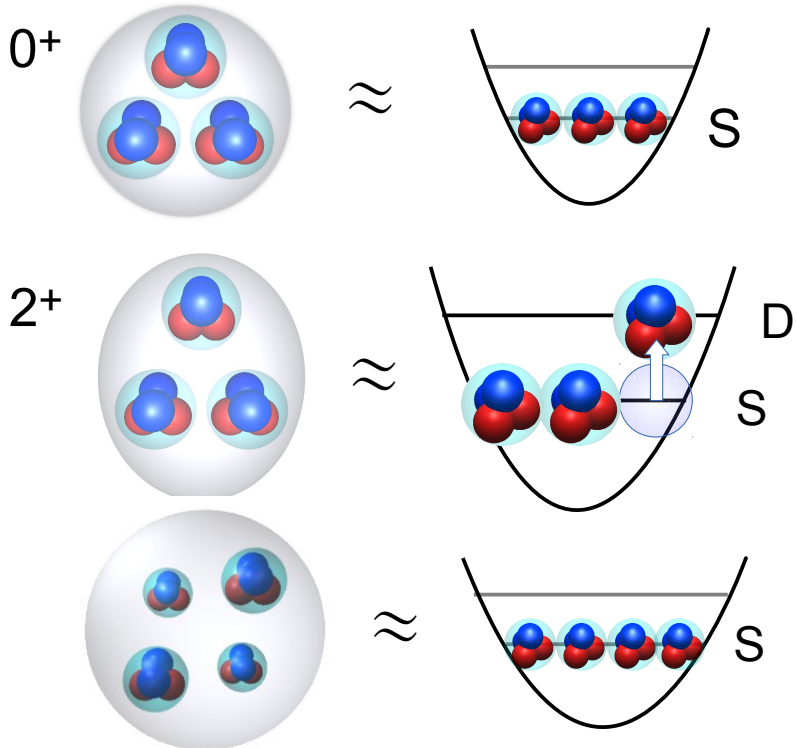
  - Experimental determination of the structure of Hoyle state in ^{12}C
- Summary

α gas-like structure and α condensate

- **Hoyle state: 0_2^+ state at 7.65 MeV in ^{12}C**
  - **Linear chain** (Morinaga, Phys.Rev.101(1956)254)
  - **Loosely coupled gas-like 3α structure**
    Horiuchi, PTP51(1975)1266,E.Uegaki *et al*, PTP57(1977)1266,M.Kamimura, NPA351(1981)456
- **Possibility of the α-particle condensate in ^{12}C and ^{16}O**
  A. Tohsaki, H. Horiuchi, P. Schuck, and G. Röpke, Phys. Rev. Lett. 87 (2001) 192501
  - α gas-like structure (Large reduced radius)
    → 3α condensate into the lowest S orbit
- **The 2^+ excitation of Hoyle state**
  P.Descouvemont and D.Baye, PRC36(1987)54,
  Y.Funaki *et al*, EPJA24(2005)321,
  C.Kurokawa, Kato, NPA792(2007)87
- **0^+ state at 15.1 MeV in ^{16}O**
  - 4α condensate
    Y. Funaki et al, Phys. Rev. Lett. 101 (2008) 082502,
    Y. Funaki et al, Phys. Rev. C 82 (2010) 024312



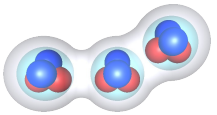
α-cluster gas-like states in ^{12}C

The α-cluster gas phase

T.Neff, H. Feldmeier, NPA738(2004)357

Y. Kanada-En'yo, PTP117(2007)655

M.Freer et al, PRC83(2011)034314

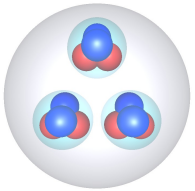


Linear-like 3α chain state (0^+)

^{8}Be(2^+) + α

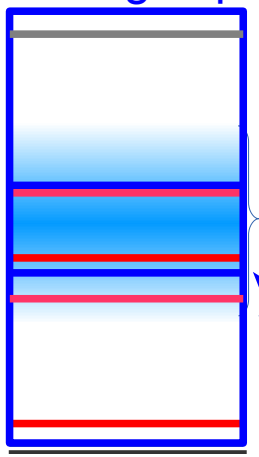
C.Kurokawa and K. Kato, NPA792(2007)87

S.Ohtsubo et al, PTEP2013,073D02

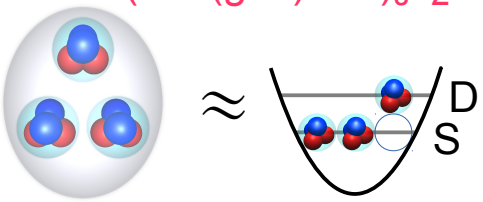


Higher nodal of Hoyle state (0^+)

^{8}Be(g.s.) + α



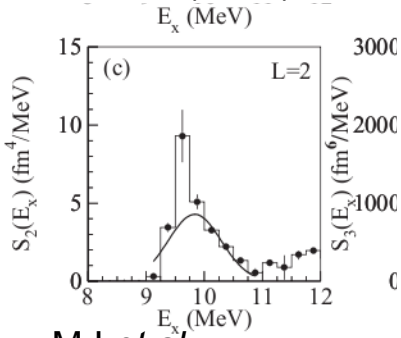
(^{8}Be(g.s.) + α)$_{J=2}$



2^+ excitation of Hoyle state

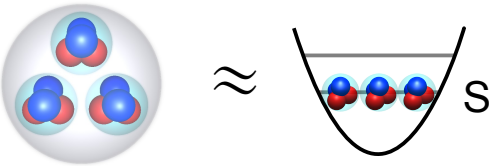
Y. Funaki et al, EPJ A24(2005)321

(α,α') in RCNP

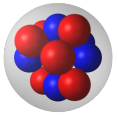


M.I *et al*, PRC84(2011)054308

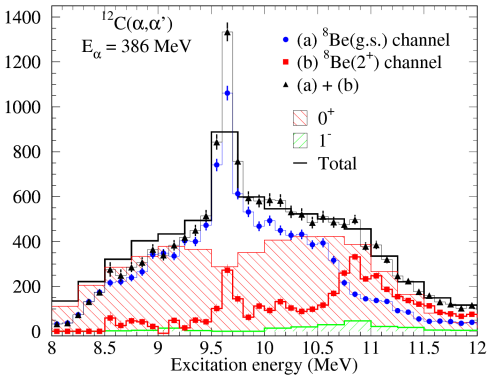
Hoyle state



Ground state of the 3α gas-like state



Ground state of ^{12}C



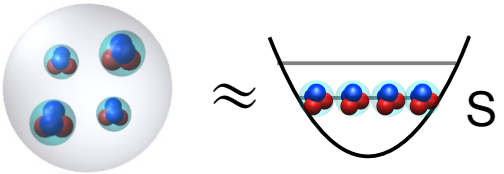
(α,α') + decay-α in RCNP

MI *et al*, J.Phys. Conf.Ser. 436, 012006 (2013)

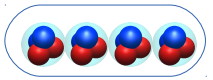
α cluster gas-like states in ^{16}O

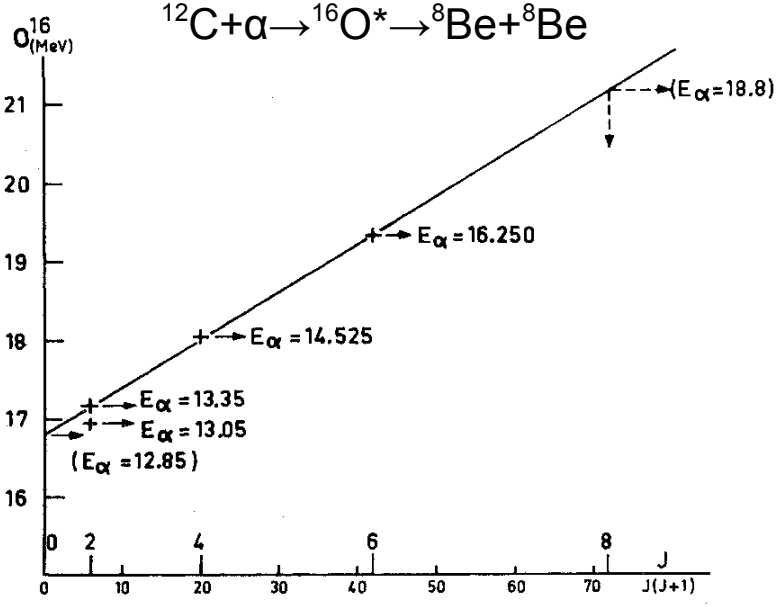
0^+ state at 15.1 MeV: α condensate state

Y.Funaki et al, Phys.Rev.Lett. 101(2008)082502



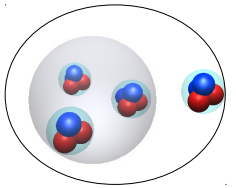
Linear chain structure

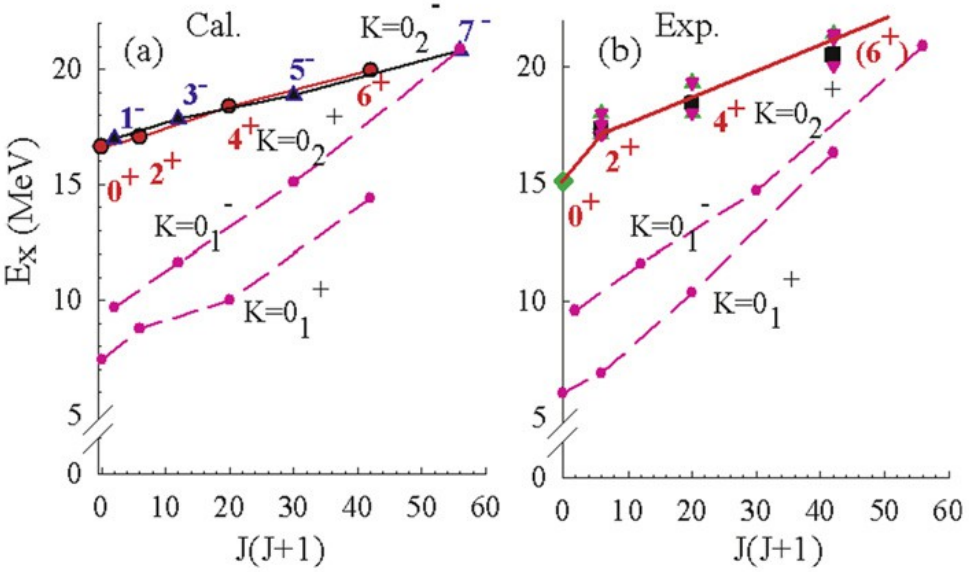




P.Chevallier and M.W. Sachs.
Phys.Rev.160(1967)827

Hoyle + α cluster





S. Ohkubo and Y. Hirabayashi,
Phys.Lett. B684(2010)127

The bandhead 0^+ state : 16 ~ 17 MeV

Next challenge

- Search for the 4α condensate state in ^{16}O

- Experimental determination of the structure of Hoyle state in ^{12}C

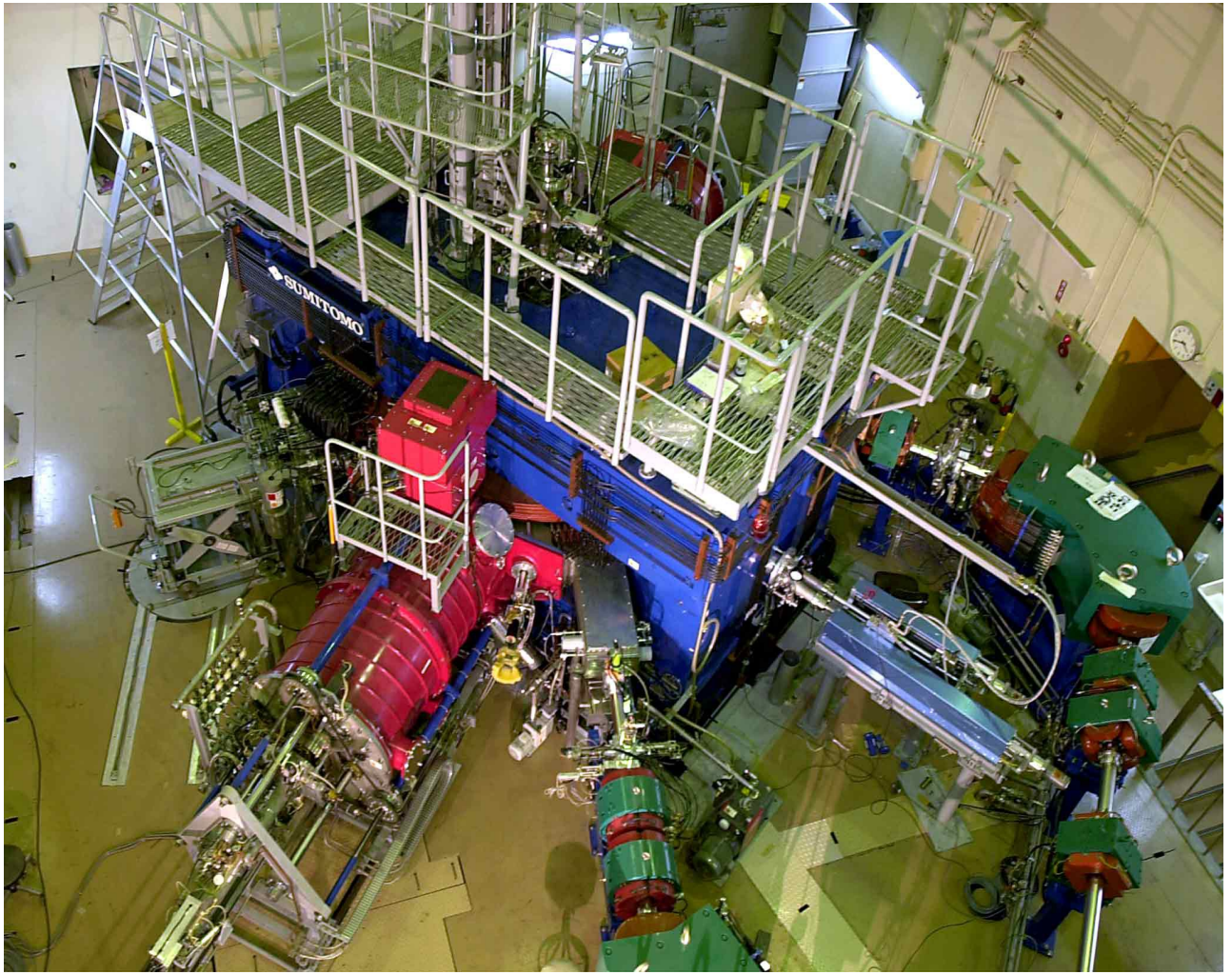
➔ Experiments in Cyclotron and Radioisotope Center, Tohoku University

Measurement of the multiple decay-α particles from α gas-like states

- **The Nα condensed state will mainly decay to (N-1)α condensed state.**
  T. Yamada and P. Schuck, PRC69 (2004) 024309
  - In the case of ^{16}O,
    1. $^{16}O^* \rightarrow \alpha + {}^{12}C(g.s.)$
    2. $^{16}O^* \rightarrow \alpha + {}^{12}C(2^+)$
    3. $^{16}O^* \rightarrow \alpha + {}^{12}C(0_2^+) \rightarrow 4\alpha$
    4. $^{16}O^* \rightarrow {}^{8}Be + {}^{8}Be \rightarrow 4\alpha$
- The Nα gas-like states decay to Nα particles.
- Decay channel reflects the structure of the excited state in the case of light nuclei, to some extent.
  - $^{12}C^* \rightarrow {}^{8}Be + \alpha \rightarrow 3\alpha$ ... ×
  - $^{12}C^* \rightarrow 3\alpha$ ... ○

Experiments in CYRIC

Facility: Cyclotoron and Radioisotope Center, Tohoku University
K=110MeV AVF Cyclotron

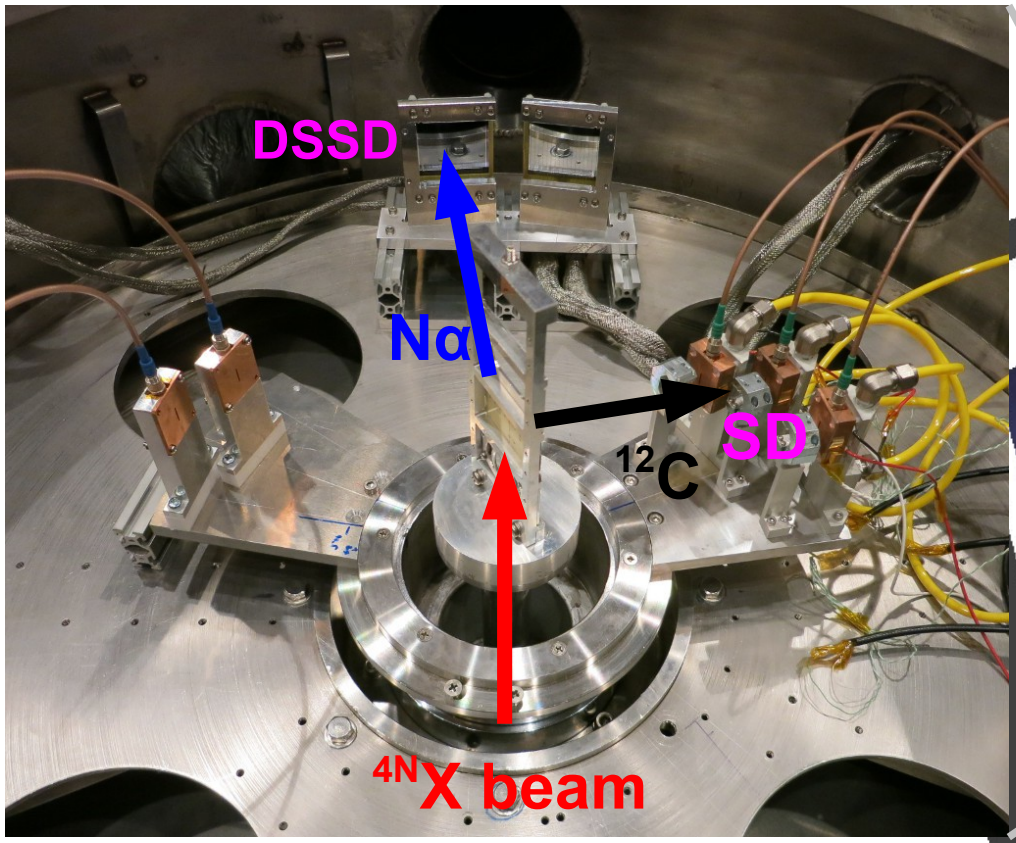


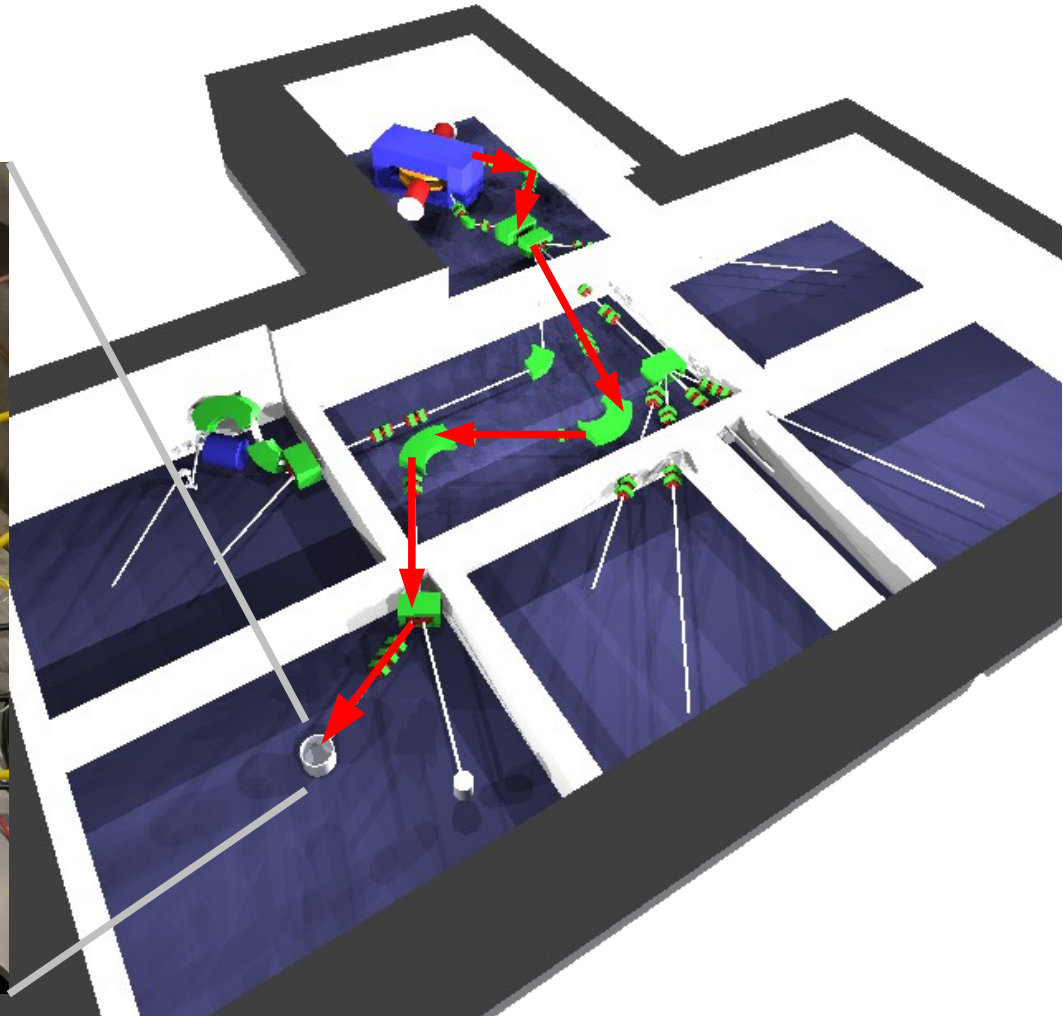
Experiments in CYRIC

Course: 41 course

$^{12}C(^{4N}X,^{4N}X^*[N\alpha])^{12}C$ reaction

Inelastic scattering by
the inverse kinematics method!

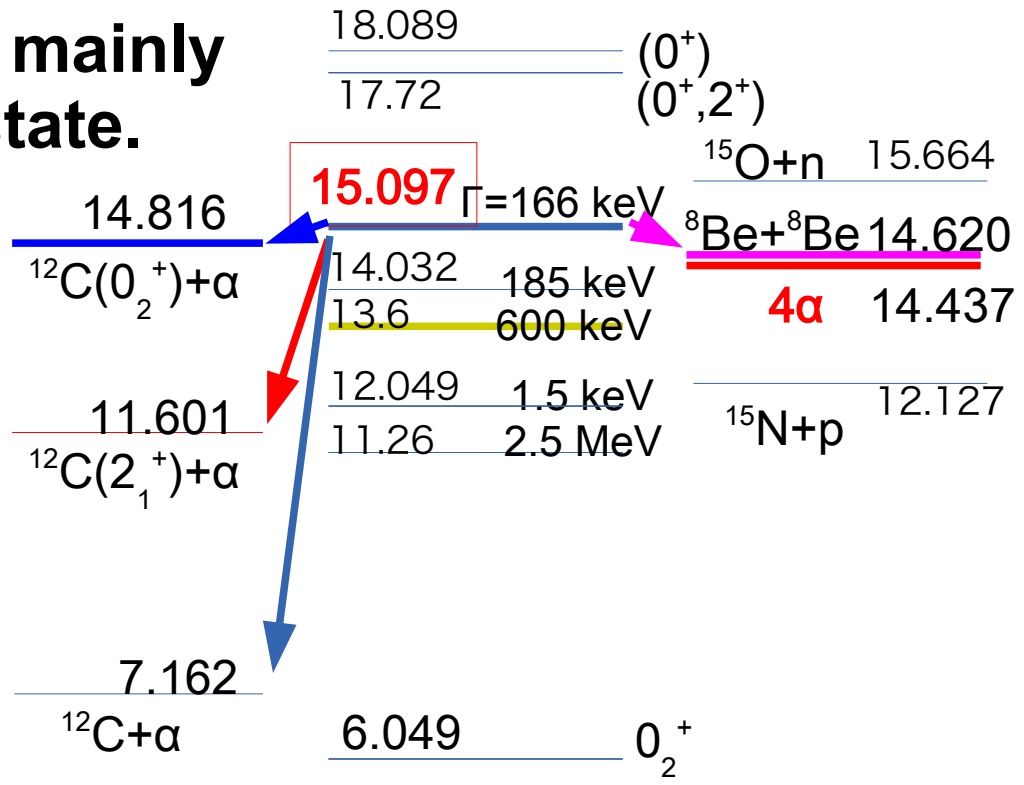




Search for the α condensed state in ^{16}O

- **The Nα condensed state will mainly decay to (N-1)α condensed state.**
  T. Yamada and P. Schuck,
  PRC69 (2004) 024309

- **Measure decay α particles**
  to obtain the branching ratio for
  1. $^{16}O^* \rightarrow \alpha + {}^{12}C(g.s.)$
  2. $^{16}O^* \rightarrow \alpha + {}^{12}C(2^+)$
  3. $^{16}O^* \rightarrow \alpha + {}^{12}C(0_2^+) \rightarrow 4\alpha$
  4. $^{16}O^* \rightarrow {}^{8}Be + {}^{8}Be \rightarrow 4\alpha$



- To detect α patricles decayed from states near 4α threshold energy, we adopted the inverse kinematics technique as the $^{12}C(^{16}O, {}^{16}O^*[\alpha+X])^{12}C$ reaction at E_{16O} = 160 MeV.

Theoretical calculation

- Calculation of partial α widths corresponding to the 15.1 MeV 0^+ state
  Y. Funaki *et al*,
  PRC80 (2009)064326

TABLE I. Partial α widths in the 0_6^+ state of ^{16}O decaying into possible channels and the total width. The reduced widths defined in Eq. (28) are also shown. Variable a is the channel radius.

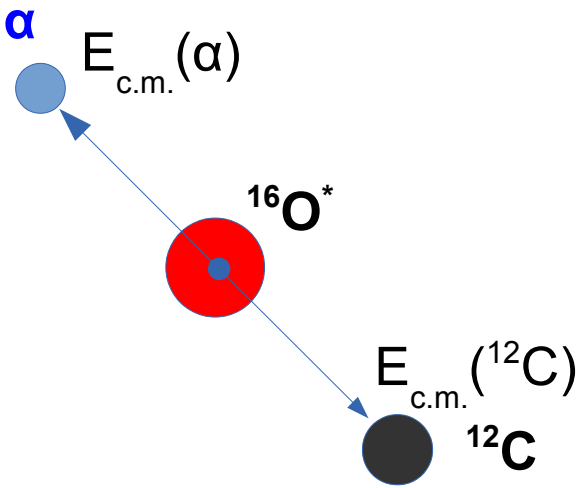
	$^{12}\mathrm{C}(0_1^+)+\alpha$ ($a=8.0$ fm)	$^{12}\mathrm{C}(2_1^+)+\alpha$ ($a=7.4$ fm)	$^{12}\mathrm{C}(0_2^+)+\alpha$ ($a=8.0$ fm)	Total
Γ_L (keV)	26	8	2×10^{-7}	34
$\theta_L^2(a)$	0.006	0.004	0.15	

- Reduced width (θ_L) of $^{12}\mathrm{C}(0_2^+)$ + α channel is larger than those of ^{12}C(g.s.) + α and $^{12}\mathrm{C}(2^+)$ + α channels.
- However, decay width of $^{12}\mathrm{C}(0_2^+)$ + α channel is very small (2×10^{-7} keV) due to the Coulomb barrier.

Missing mass spectra

- Missing mass

$$M_x = M(^{16}O) + E_x(^{16}O) - E_{c.m.}(\alpha) - E_{c.m.}(^{12}C)$$



- $E_{not\ detect}$: calculated from E_{detect}
- Decay channels

  D1. $^{16}O^* \rightarrow \alpha + {}^{12}C(g.s.)$

  D2. $^{16}O^* \rightarrow \alpha + {}^{12}C(2^+)$

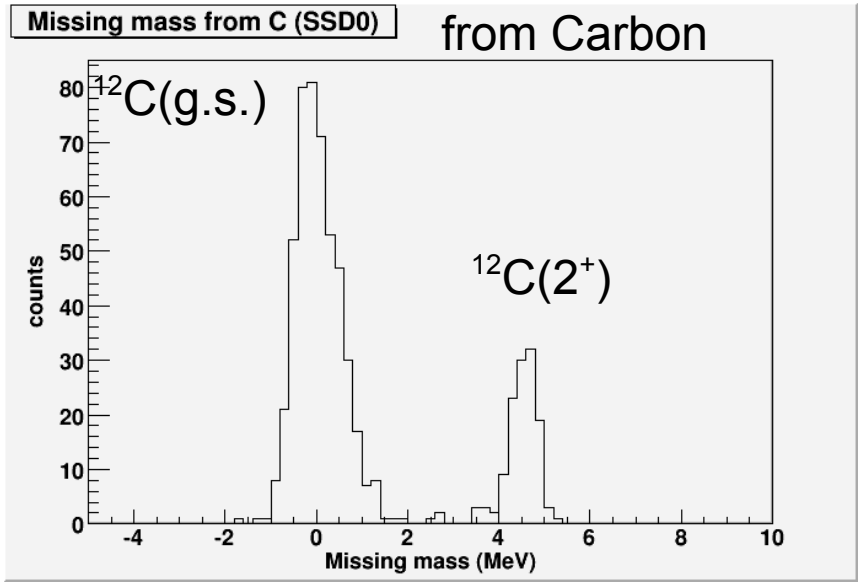
  D3. $^{16}O^* \rightarrow \alpha + {}^{12}C(0_2^+) \rightarrow 4\alpha$

  D4. $^{16}O^* \rightarrow {}^{8}Be + {}^{8}Be \rightarrow 4\alpha$

- Branching ratio between D1 and D2

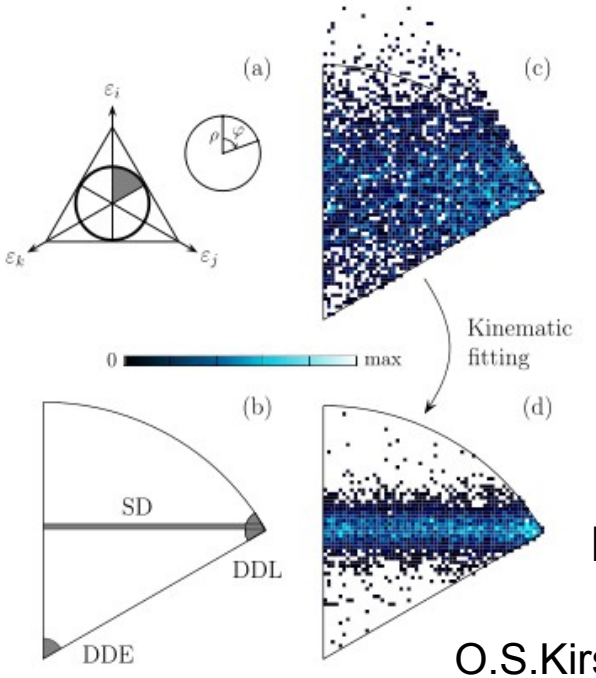
  D1 : D2 ~ 7 : 3

- D3 and D4 channels could not be observed



Measurement of decay-α particles from Hoyle state in ^{12}C

- Experimental study for the structure of Hoyle state:
  - α-cluster gas state ~ α condensate state
    Momentum distribution of α-clusters
  - Linear 3α chain state
    Decay property



$^{11}B + {}^{3}He \rightarrow d + {}^{12}C^{*}$
$\rightarrow d + 3\alpha$

SD: Sequential decay
DDL: Linear chain
(α←α→α)
DDE: α condensate

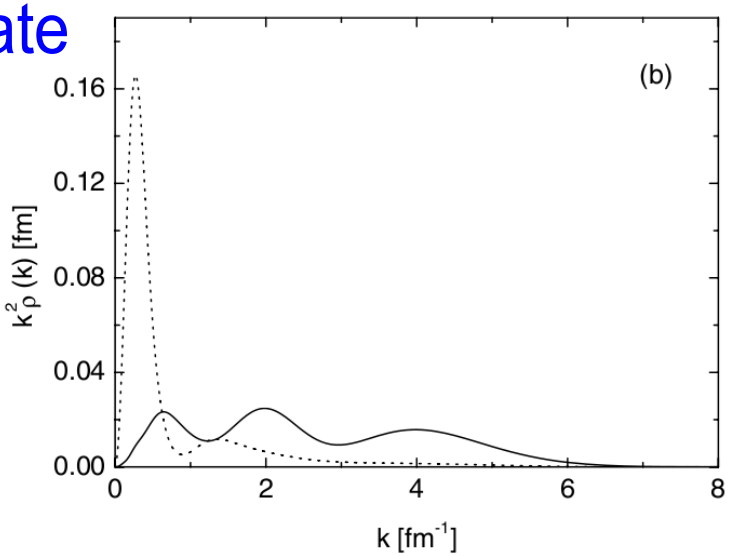


Fig. 7. Momentum distribution of the α particle, (a) $\rho(k)$ and (b) $k^2 \times \rho(k)$, for the 0_1^+ (solid line) and 0_2^+ (dotted line) states.

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

Direct α decay of the Hoyle state < 5×10^{-3}

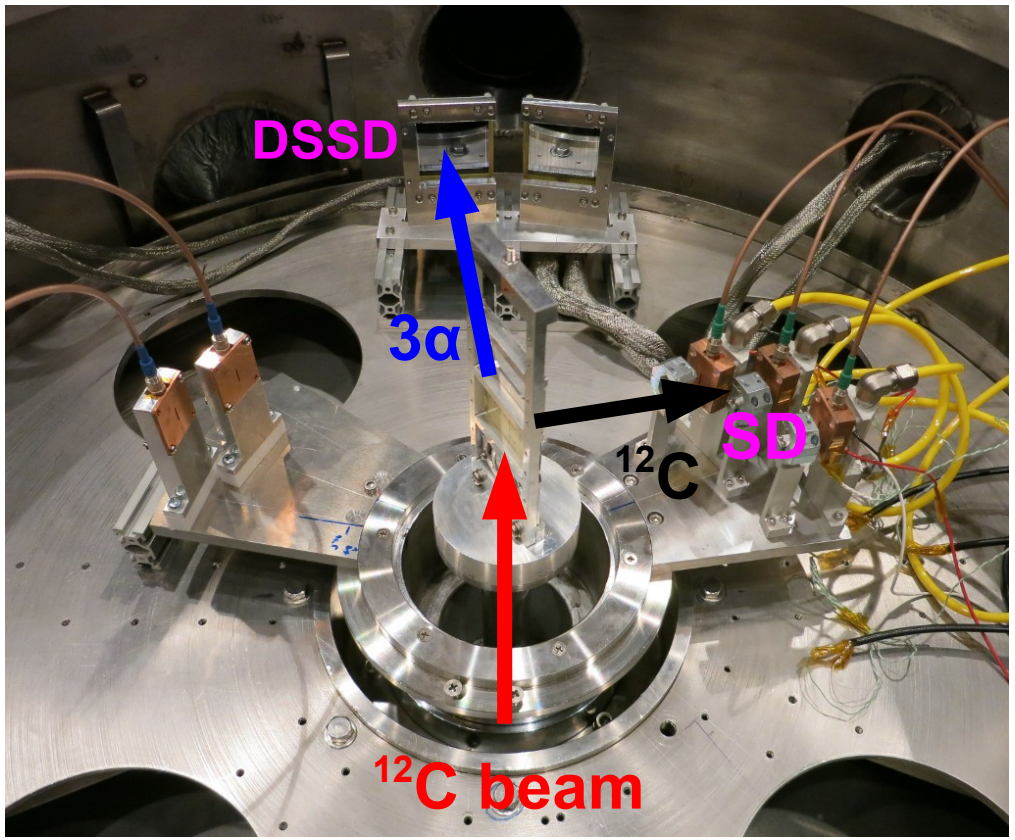
O.S.Kirsebom *et al*, PRL108(2012)202501

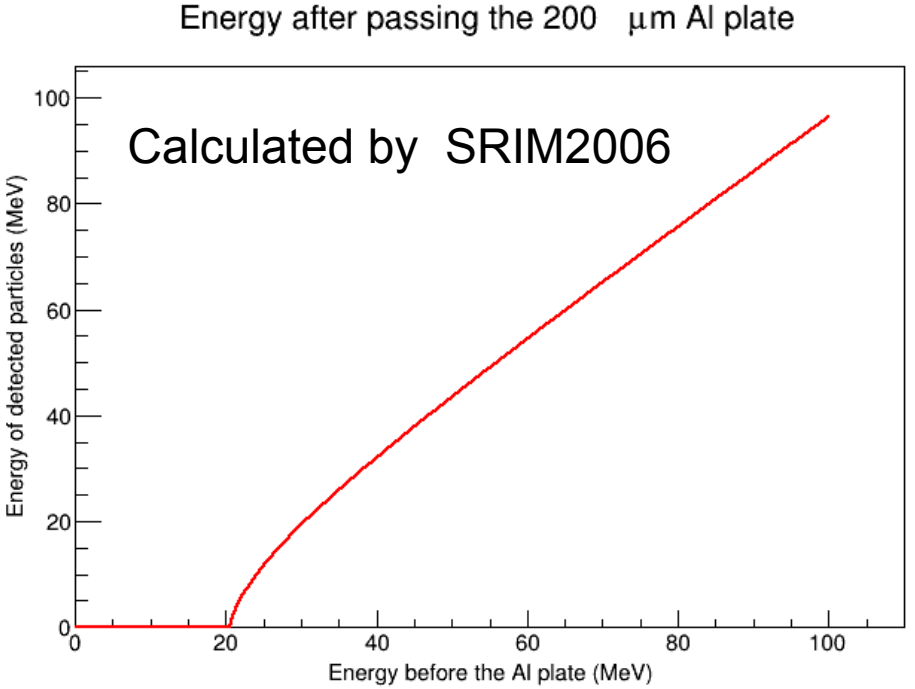
Experimental set-up

$^{12}C(^{12}C, ^{12}C^*[3\alpha])^{12}C$ reaction

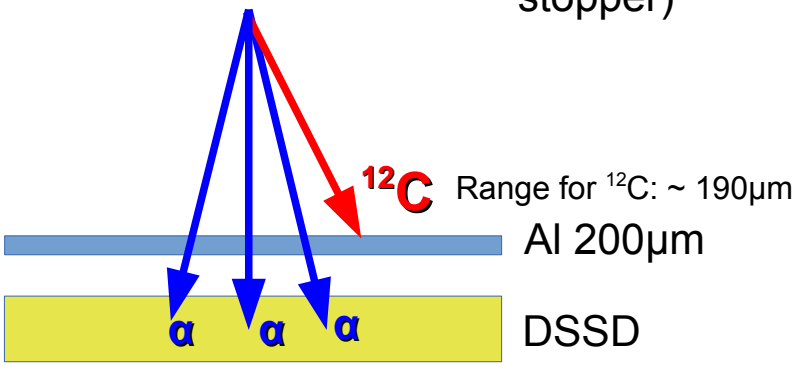
Recoil ^{12}C: Silicon Detector (SD) cooled at 0 °C
at 59°, 67°

Decay α-particles:
Double-sided Silicon Strip Detector (DSSD) at 7.6°
50 mm [16 ch(X)] × 50 mm [16 ch(Y)]

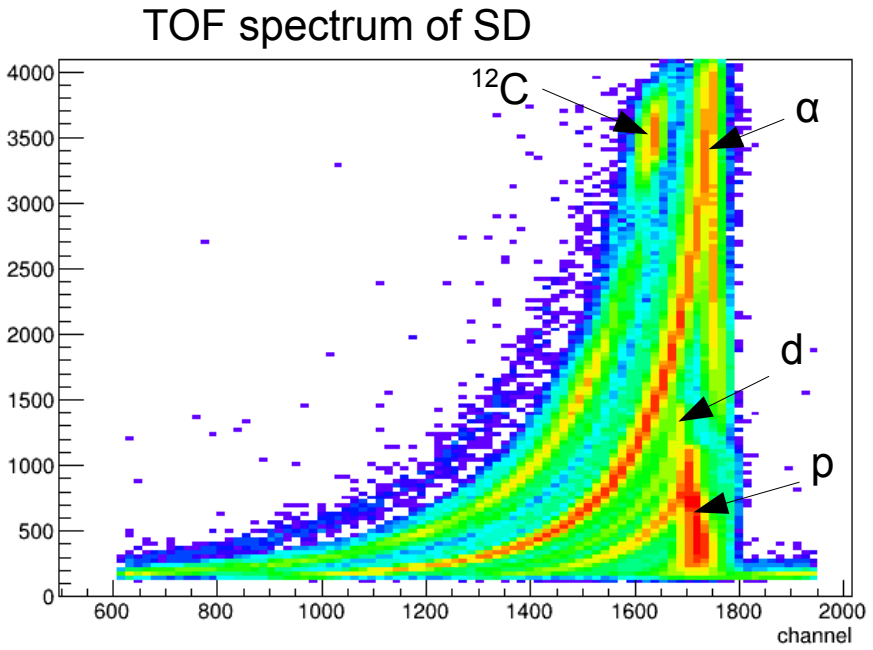


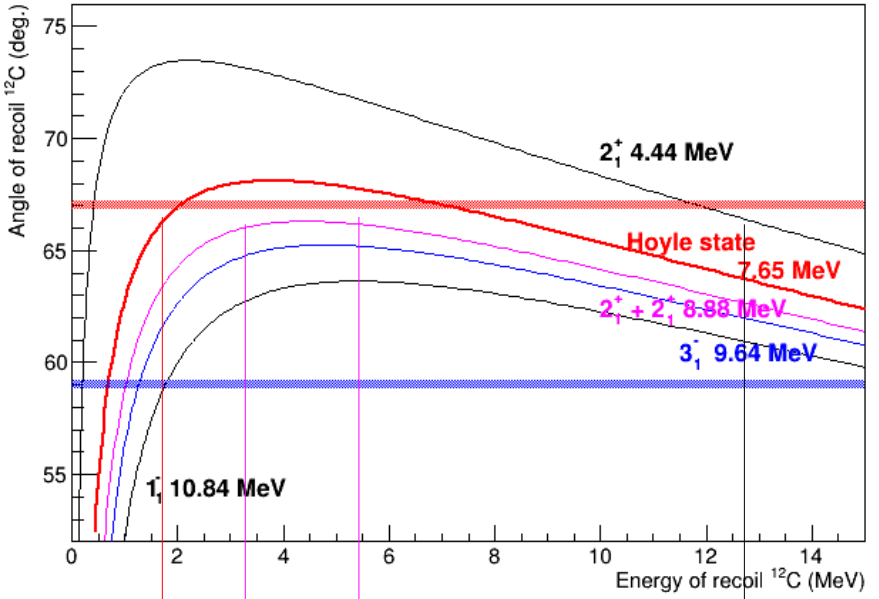


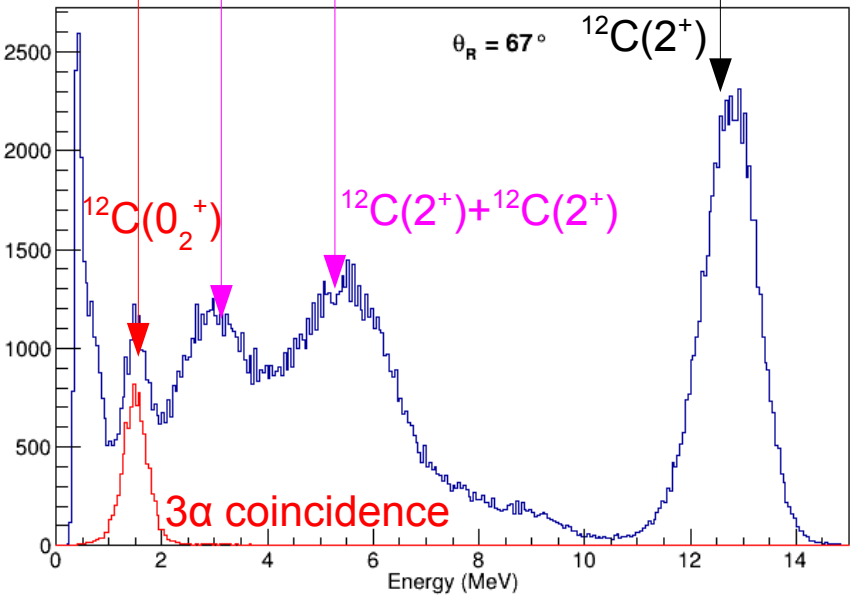
Al plate: 200μm
(Elastic/Inelastic scattering stopper)



Kinematics and Recoil ^{12}C spectrum



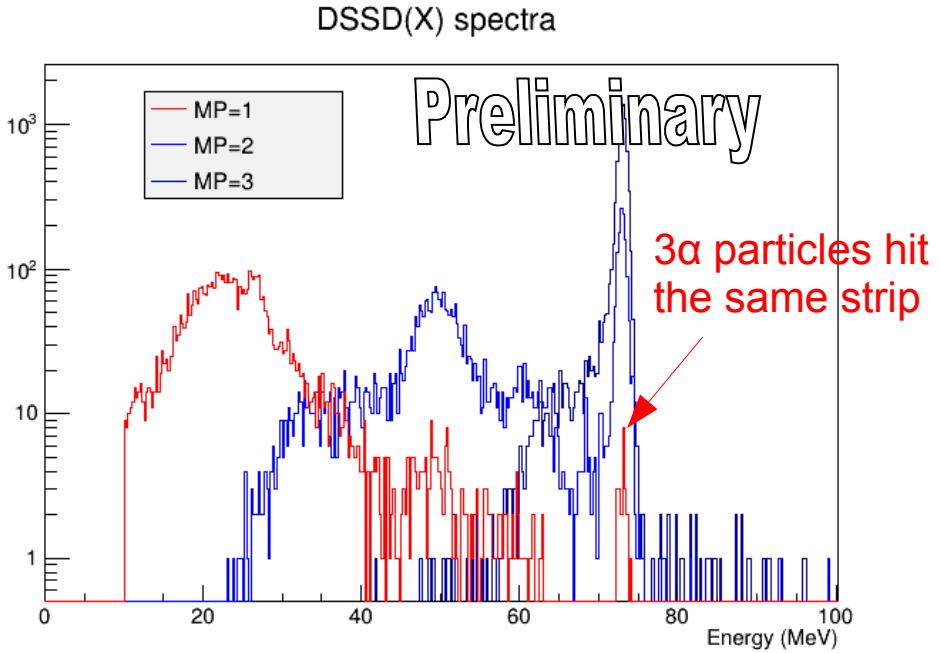


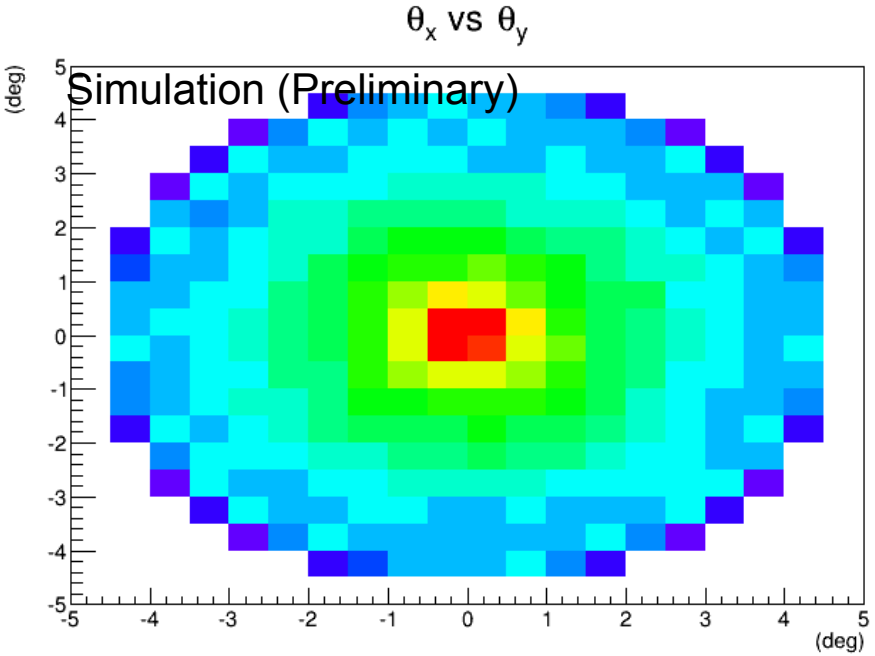


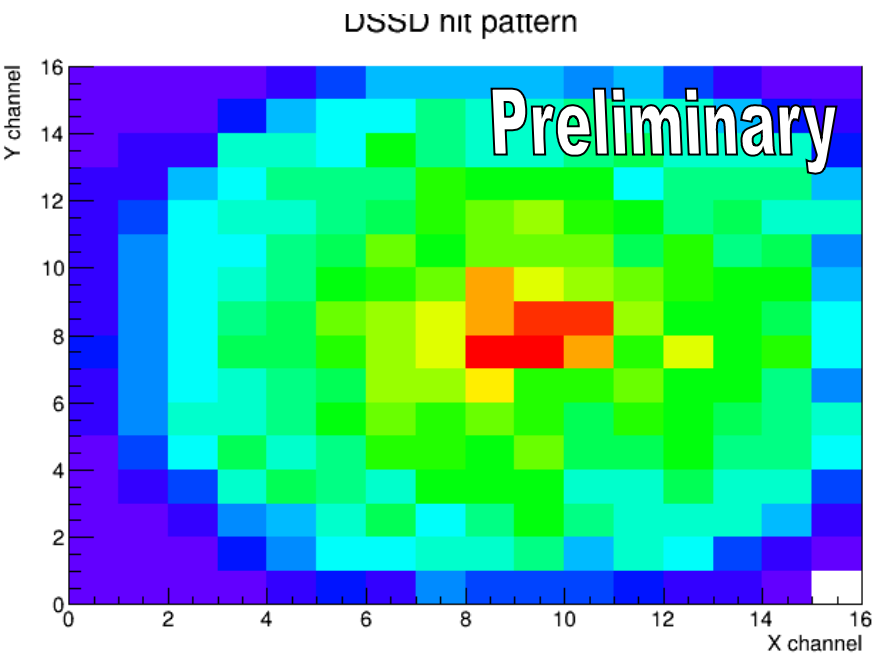
- Particle Identification: TOF method
- Excitation energy is determined from the energy of the recoil ^{12}C.

Decay α particles

- DSSD total energy spectra
- Total energies of decay-3α particles: ~ 72 MeV
- Acceptance for decay-3α particles is almost 100%.

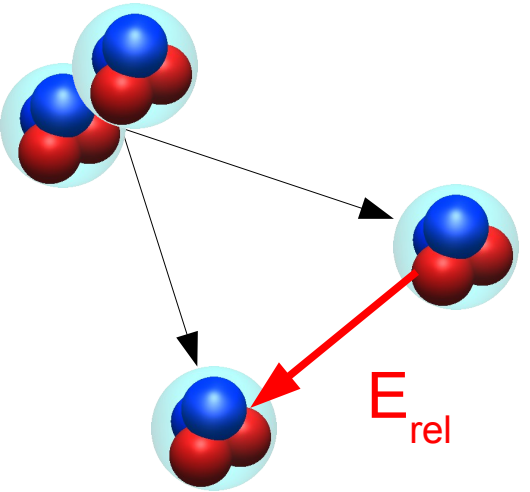


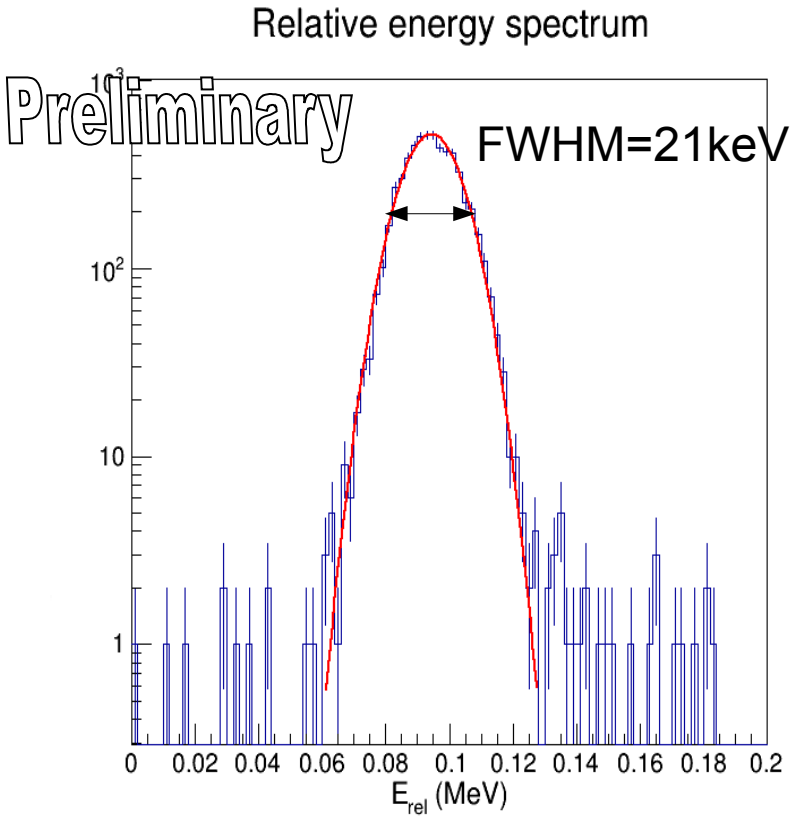


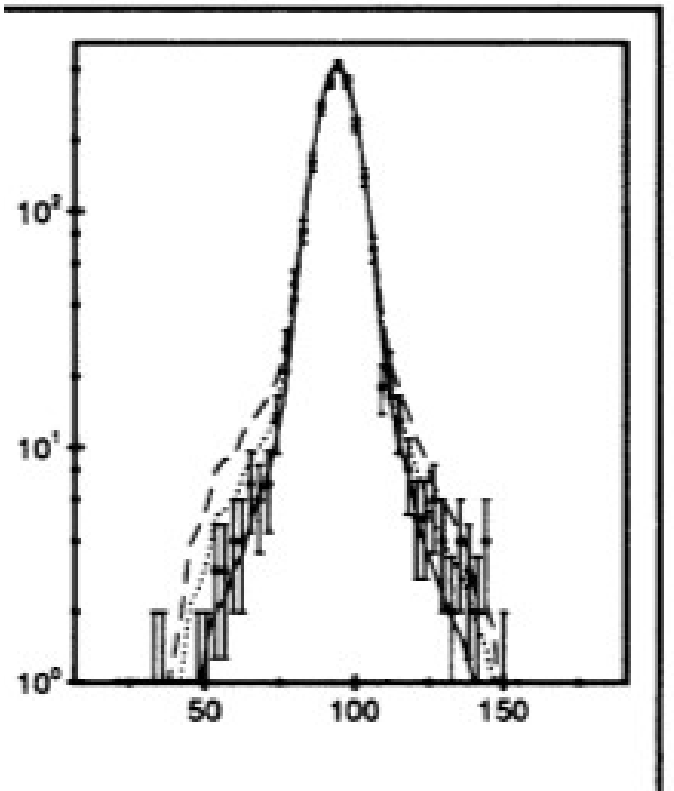


Relative energy spectra

- $E_{rel} = 1/2\mu|v_i - v_j|^2$
- If 2α came from the decay of ^{8}Be, $E_{rel} \sim 92$ keV







M.Freer *et al*, PRC49(1994) R1751

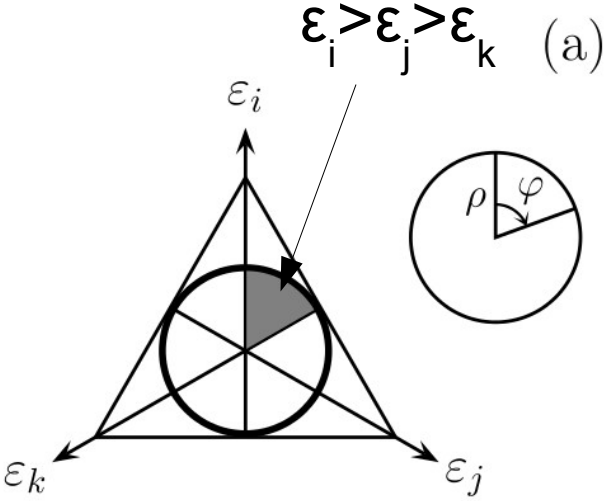
Dalitz plot for 3α decay

- To compare with ^{11}B(^{3}He,d) reaction, Dalitz plot for 3α decay is shown.

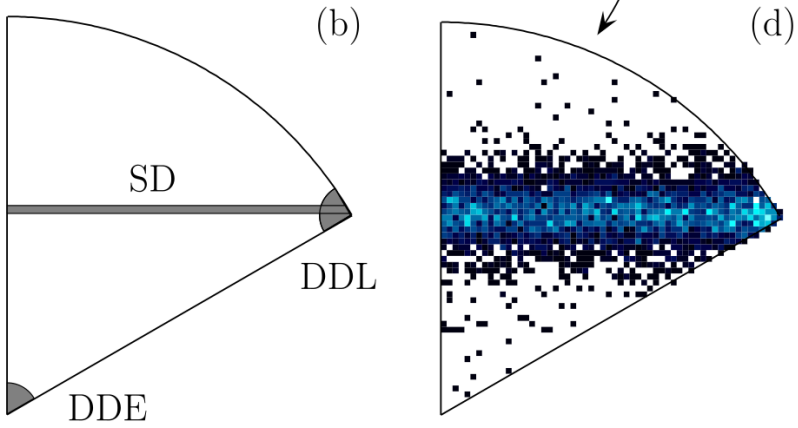
$$(2\rho)^2 = 3(\varepsilon_j - \varepsilon_k)^2 + (2\varepsilon_i - \varepsilon_j - \varepsilon_k)^2$$

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

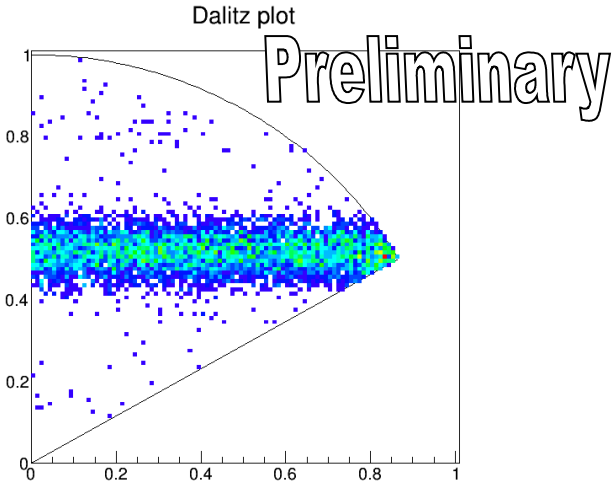
$E_{i,j,k}$: Kinetic energy of α particles in c.m. frame



^{11}B(^{3}He,d)3α



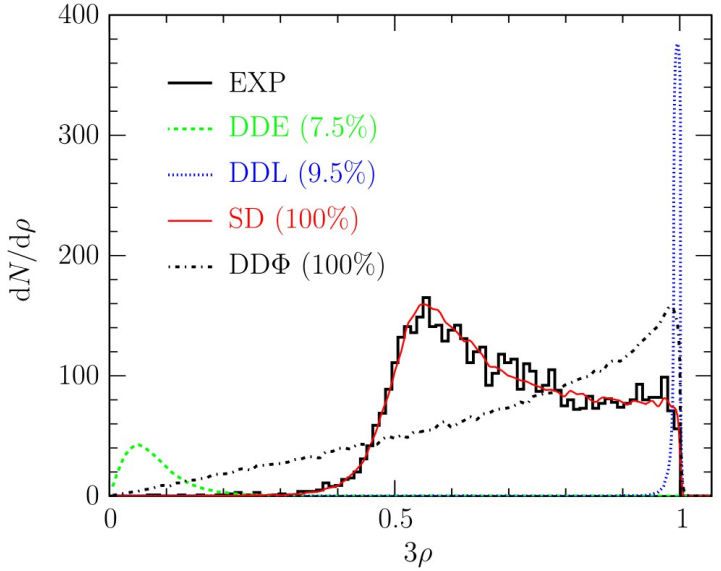
^{12}C(^{12}C,^{12}C*[3α])^{12}C



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

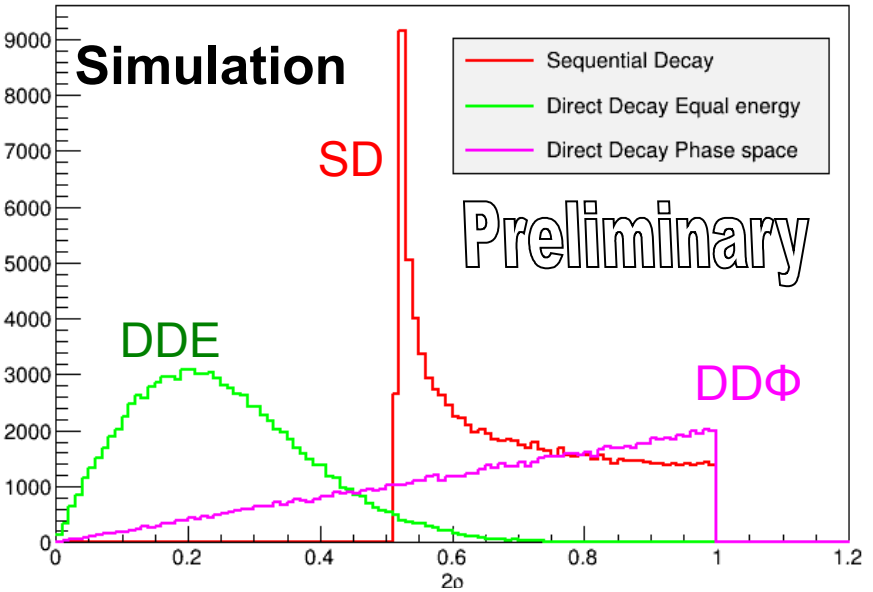
Components of the direct 3α decay

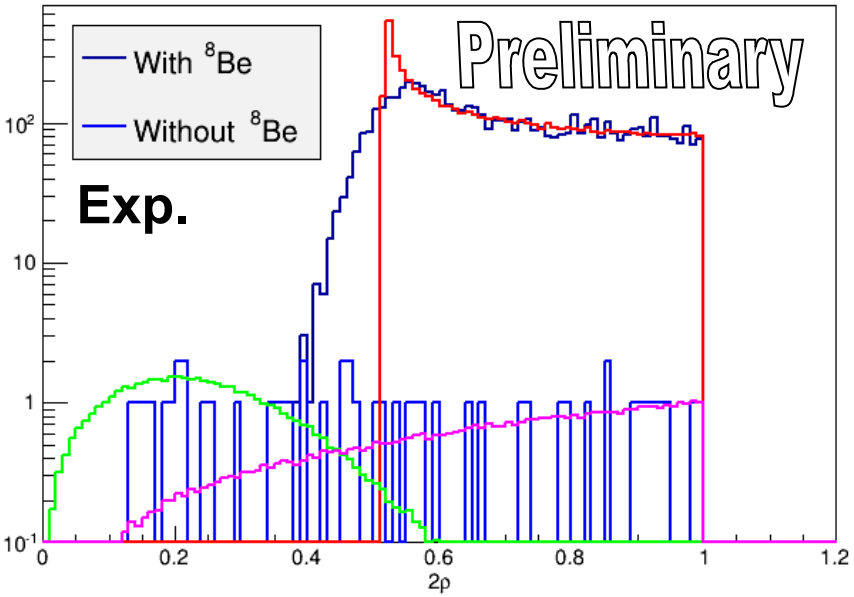
- Radial projection of Dalitz plot



Direct α decay < 5×10^{-3}

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





まとめ

- ^{12}Cおよび^{16}O原子核では、多くのαクラスターガス状態が理論的に予言されている。
- 我々は東北大CYRICにおいて、予言されている^{12}C, ^{16}Oのαクラスターガス状態から崩壊して多重に放出されるα粒子を測定することによって、その性質を調べている。
  - ^{16}Oにおける４α凝縮状態の探索
    ^{12}C(^{16}O,^{16}O*[α+X])^{12}C反応 $E_{^{16}O}$ = 160 MeV
    ^{16}O*(0^+ at 15.1MeV) → ^{12}C(g.s.) + α, ^{12}C(2^+)+αの比を得た。
    理論計算と一致していたが、4α崩壊チャンネルは測定できなかった。
  - ^{12}Cのホイル状態の構造の実験的な決定
    ^{12}C(^{12}C,^{12}C*[3α])^{12}C反応 $E_{^{12}C}$ = 110 MeV
    Direct 3α decayのイベントが観測できた！

Collaborators

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- ^{12}C
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