Alpha Inelastic Scattering and Cluster Structures in Light Nuclei

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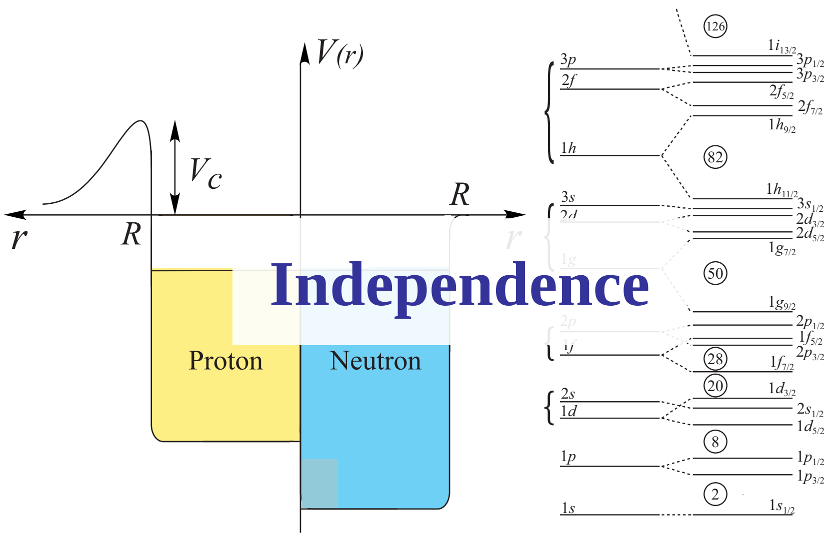
Introduction

Two different pictures of Nuclear Structure

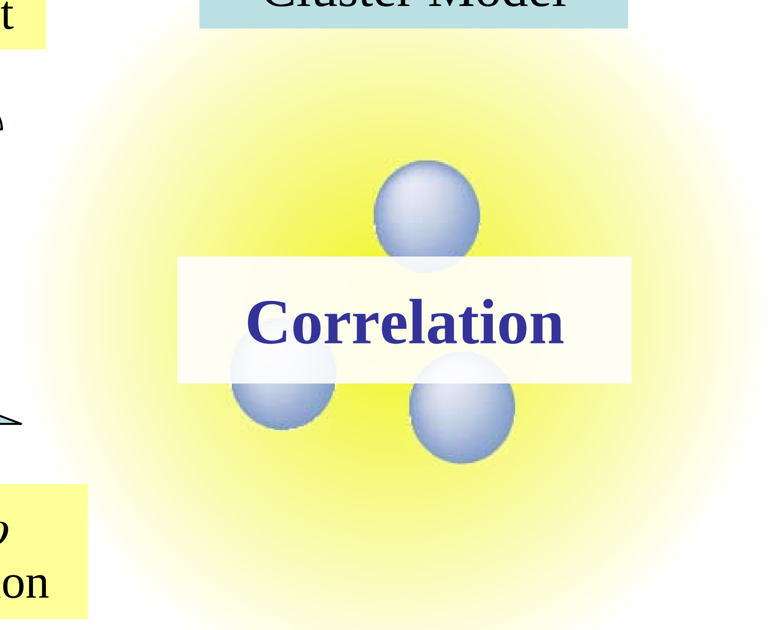
Shell Model

SU(3) Limit

Cluster Model



Independence



Correlation

Multi-$\hbar\omega$ Configuration

Single-particle orbit in the mean-field potential.

Magic numbers (2, 8, 20, ...).

Describes well single-particle excited states.

Strong correlation between nucleons.

Cluster consists of several nucleons.

Clusters are weakly bound.

It is important to study appearance and disappearance of the cluster correlation for understanding the complex quantum many-body system “Atomic Nucleus”.

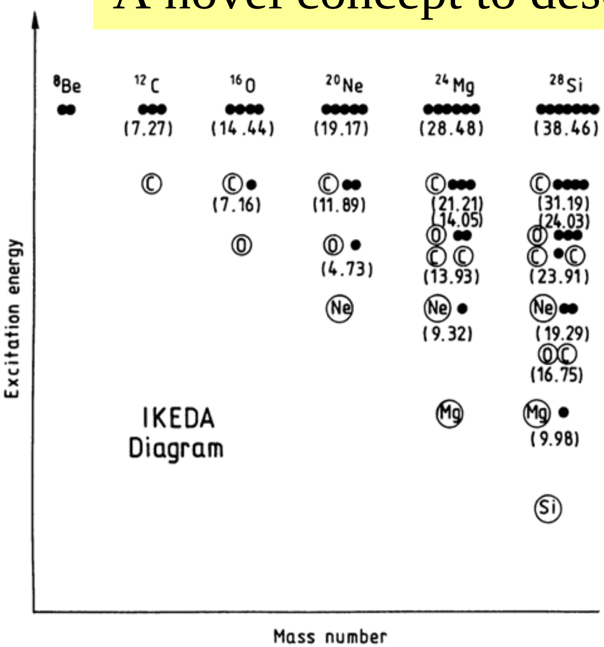
Cluster States in N = 4n Nuclei

Alpha clustering is an important concept in nuclear physics for light nuclei.

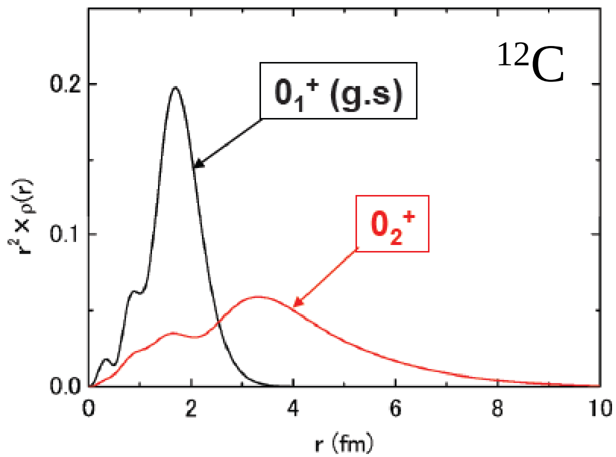
Alpha cluster structure is expected to emerge near the α-decay threshold energy in N = 4n nuclei.

The 0^+_2 state at E_x = 7.65 MeV in ^{12}C is a famous 3α cluster state.

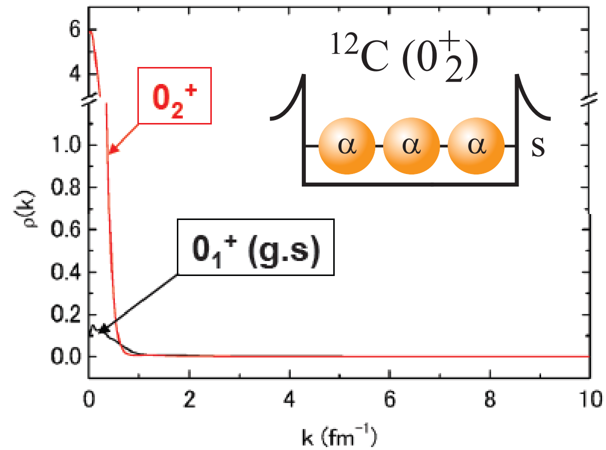
A novel concept to describe the 0^+_2 state is proposed: **α Condensation**.



Density × r^2



Momentum Distribution



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

α-condensed state where three alpha particles occupy the lowest s-orbit.
Dilute-gas state of alpha particles. Large RMS.

Similar states are predicted in other self-conjugate N = 4n nuclei.

Cluster Structure in N ≠ 4n nuclei

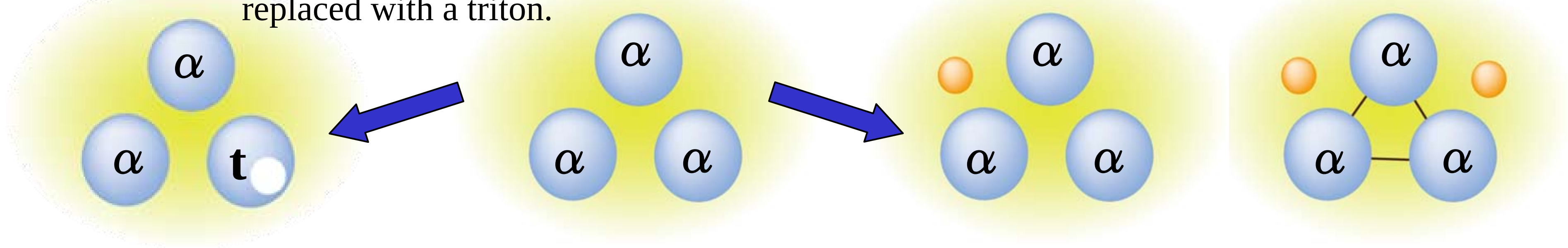
Excess particles might change cluster structure in N ≠ 4n nuclei.

- Excitation energy, width, decay scheme ....
- Cluster molecule with excess neutrons.
- Appearance and disappearance of α correlation.
- Cluster condensation in a boson-fermion mixture.

One α particle is replaced with a triton.

Excess neutron occupies the molecular orbit between the α clusters ??

Cluster structure disappears in nuclei far from stability line ??



^{11}B ^{12}C ^{13}C ^{14}C

Systematic study on the alpha cluster structure in N ≠ 4n nuclei is important.

E0 Strengths and α Cluster Structure

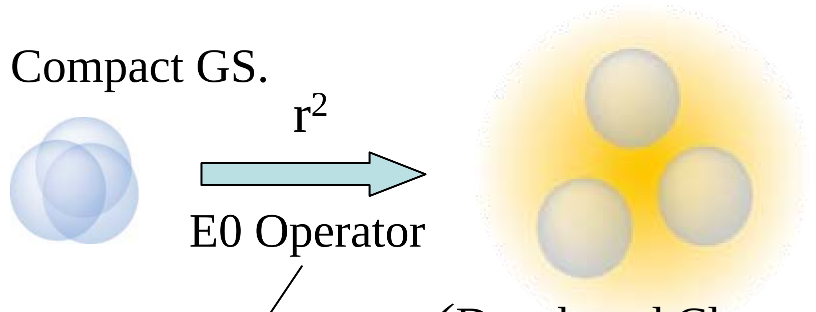
Large E0 strength could be a signature of spatially developed α cluster states.

T. Kawabata *et al.*, Phys. Lett. B **646**, 6 (2007).

0^+_2 state in ^{12}C: $B(E0; IS) = 121 \pm 9$ fm^4

Single Particle Unit: $B(E0; IS)_{s.\,p.} \sim 40$ fm^4

- ✓ SM-like compact GS w.f. is equivalent to the CM w.f. at SU(3) limit.
- ✓ GS contains CM-like component due to possible alpha correlation.



Monopole operators excite
inter-cluster relative motion.

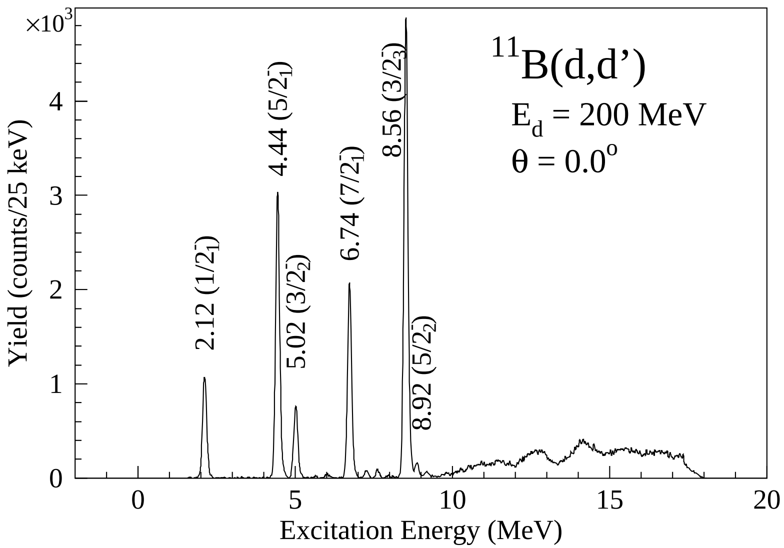
T. Yamada *et al.*,
Prog. Theor. Phys. 120, 1139 (2008).

E0 strength is a key observable to examine α cluster structure.

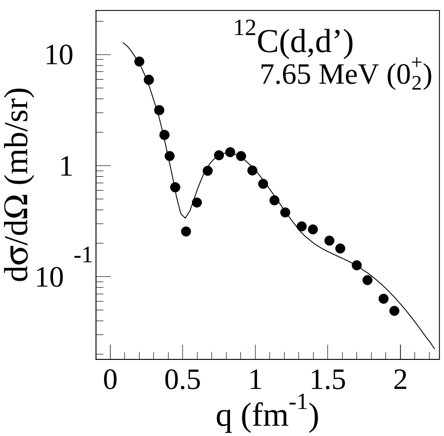
Cluster State in ^{11}B

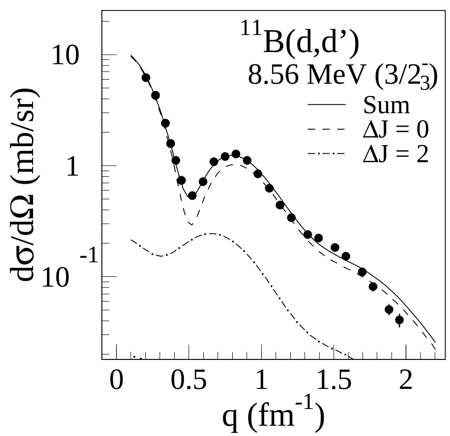
A dilute $2\alpha + t$ cluster state is excited by E0 transition with B(E0;IS) = 96±16 fm^4.

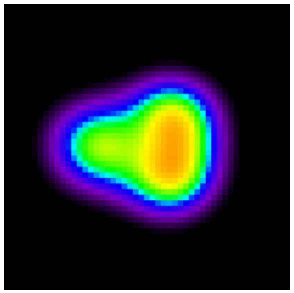
T. Kawabata *et al.*, Phys. Lett. B **646**, 6 (2007).



- $3/2^-_3$ state in ^{11}B is strongly excited by the E0 transition in the (d,d') reaction.
- Analogies between the $3/2^-_3$ state and the 0^+_2 state in ^{12}C (dilute-gas-like 3α cluster state) have been observed.
  - ➢ Similar excitation energies and E0 strengths.
  - ➢ Locates near the α decay thresholds.
  - ➢ Not predicted in SM calculations.
- AMD (VAP) successfully describes the $3/2^-_3$ state with a dilute $2\alpha + t$ cluster wave function.

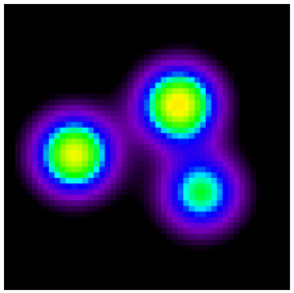






$3/2_1^-$ (g.s.)

$\langle r^2\rangle^{1/2}$ = 2.5 fm



$3/2_3^-$

$\langle r^2\rangle^{1/2}$ = 3.0 fm

Y. Kanada-En'yo, Phys. Rev. C **75**, 024302 (2007).

E0 measurement is a new useful spectroscopic tool to search for α cluster states.

Inelastic Alpha Scattering

Inelastic α scattering is a good probe for nuclear excitation strengths.

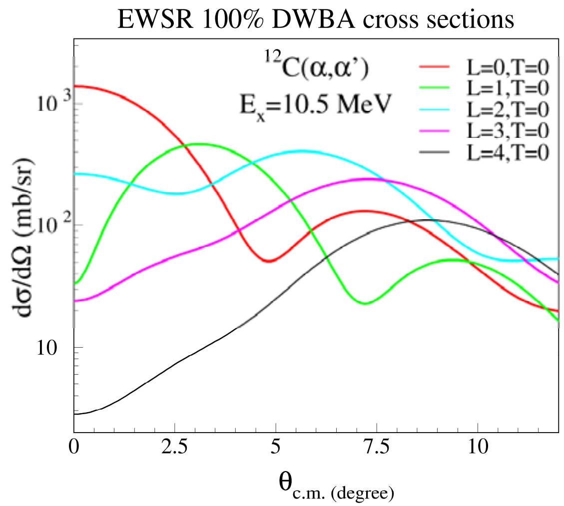
- Simple reaction mechanism
  - Good linearity between dσ/dΩ and B(ô).

$$\frac{d\sigma}{d\Omega}(\Delta J^{\pi}) \approx KN\left|J(q)\right|^{2} B(\hat{O})$$

  - Folding model gives a reasonable description of dσ/dΩ.

- Selectivity for the ΔT = 0 and natural-parity transitions.
- Multiple decomposition analysis is useful to separate ΔJ^{π}.

$$\frac{d\sigma}{d\Omega}^{\mathrm{exp}} = \sum_{\Delta J^{\pi}} A(\Delta J^{\pi}) \frac{d\sigma}{d\Omega}(\Delta J^{\pi})^{\mathrm{calc}}$$



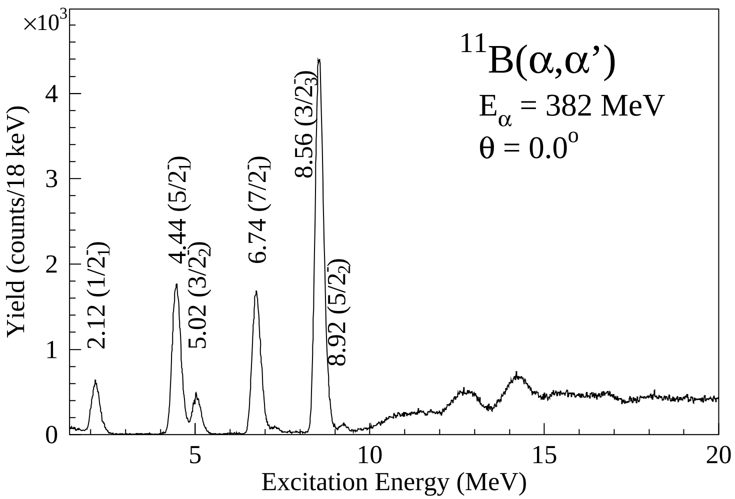
We measured inelastic α scattering to extract IS E0 strengths and to examine cluster structures in light nuclei.

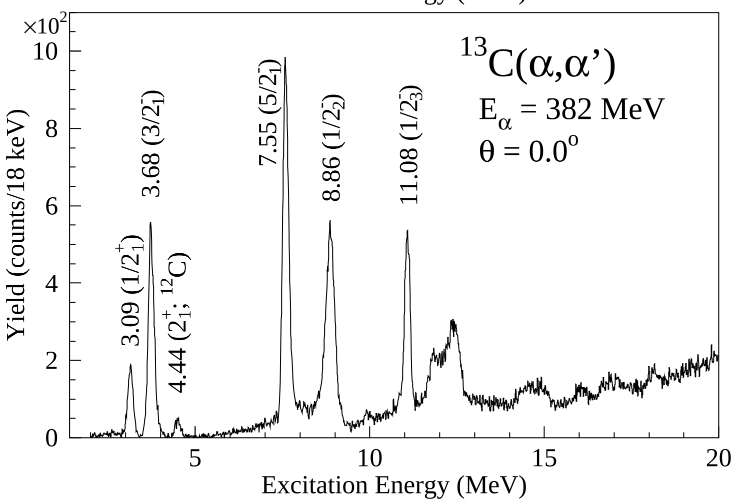
Inelastic α Scattering
and
Cluster Structure in ^{13}C

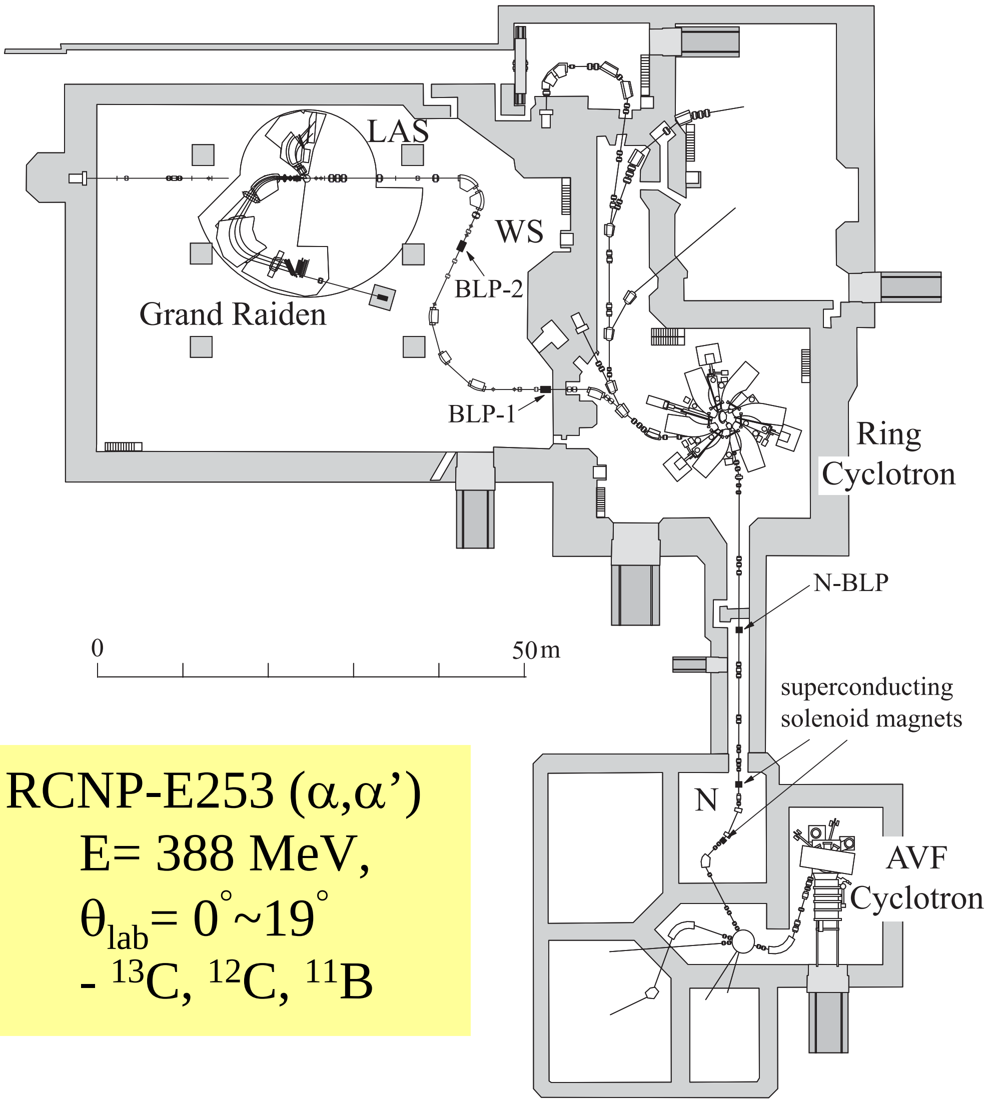
Experiment

Experiment was performed at RCNP, Osaka University.

Background-free measurement at extremely forward angles

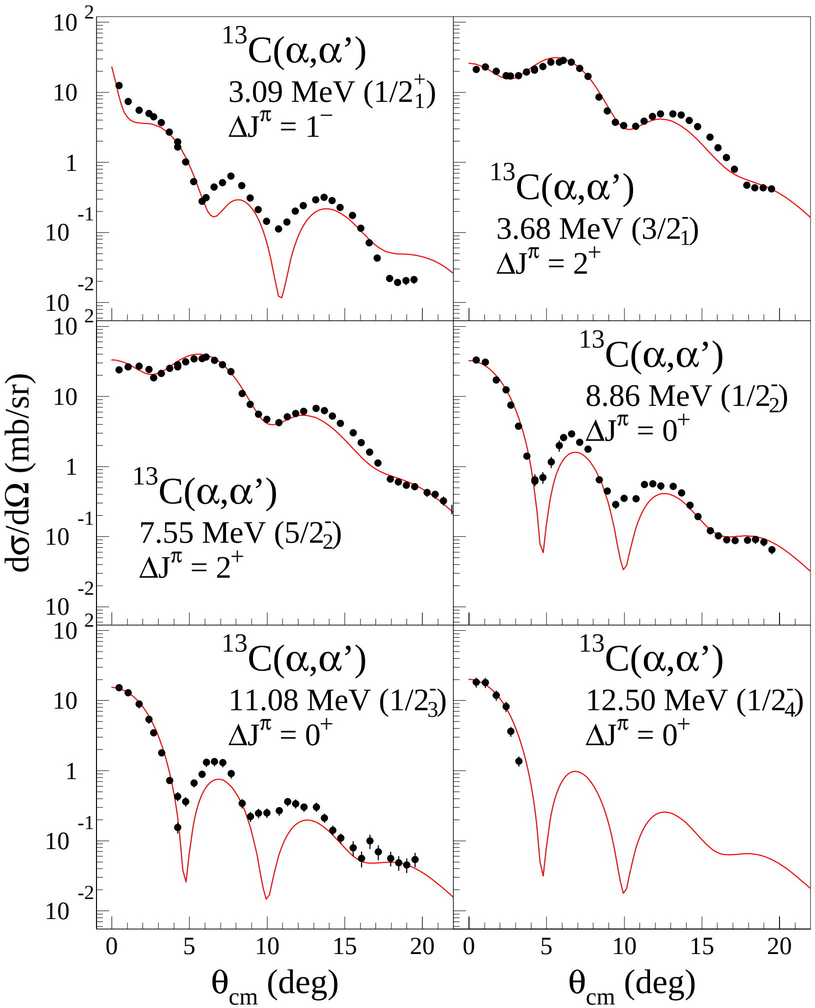


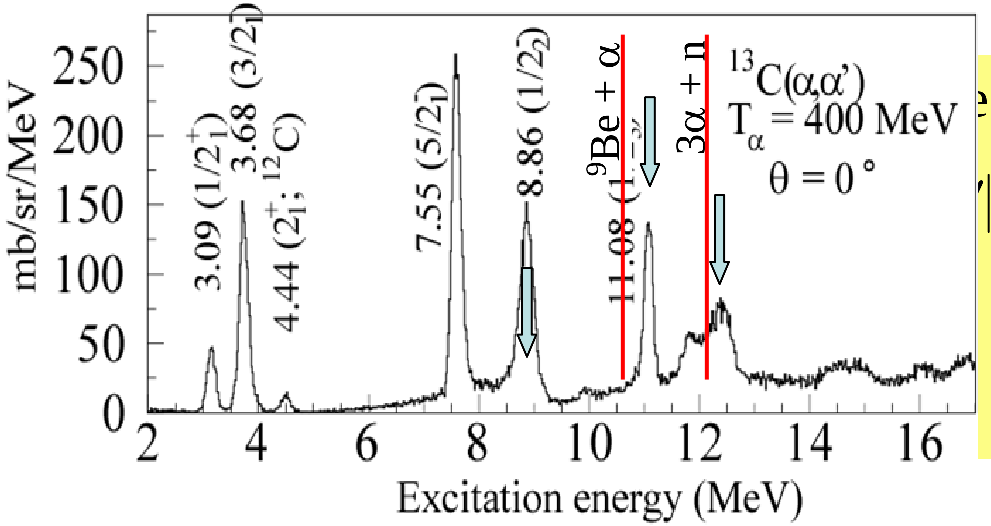




RCNP-E253 (α,α')
E= 388 MeV,
θ_{lab}= 0°~19°
- ^{13}C, ^{12}C, ^{11}B

Inelastic Scattering from ^{13}C





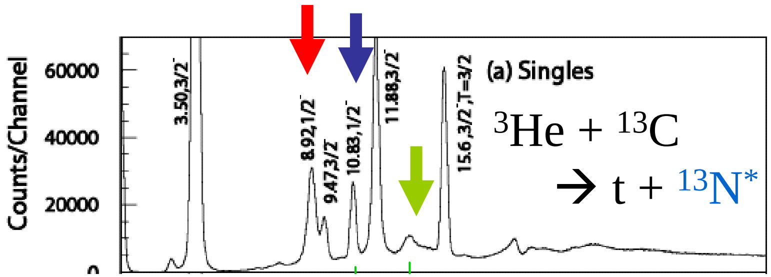
		Present	
E_x (MeV)	J^π	B(E0;IS) (fm^4)	B(E2;IS) (fm^4)
3.68	$3/2^-_1$		47±5
7.55	$5/2^-_1$		61±6
8.86	$1/2^-_2$	37±6	
11.08	$1/2^-_3$	18±3	
12.5	$1/2^-_4$	24±4	

The three $1/2^-$ states at 8.86, 11.08, and 12.5 MeV are strongly excited by the E0 transitions.

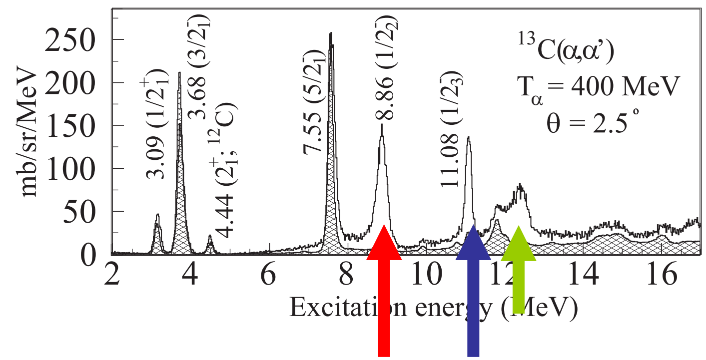
→ Possible candidates for spatially developed α cluster states.

Comparison with Charge Exchange Reaction

$^{13}C(^3He,tp)$ reaction at 150 MeV/u was measured by H. Fujimura *et al.*



Good mirror symmetric relation.



J^π	E_x (^{13}C) (MeV)	E_x (^{13}N) (MeV)	B(GT)
$1/2^-_2$	8.86	8.92	0.16±0.02
$1/2^-_3$	11.08	10.83	0.12±0.01
$1/2^-_4$	12.5	13.5	0.12±0.1

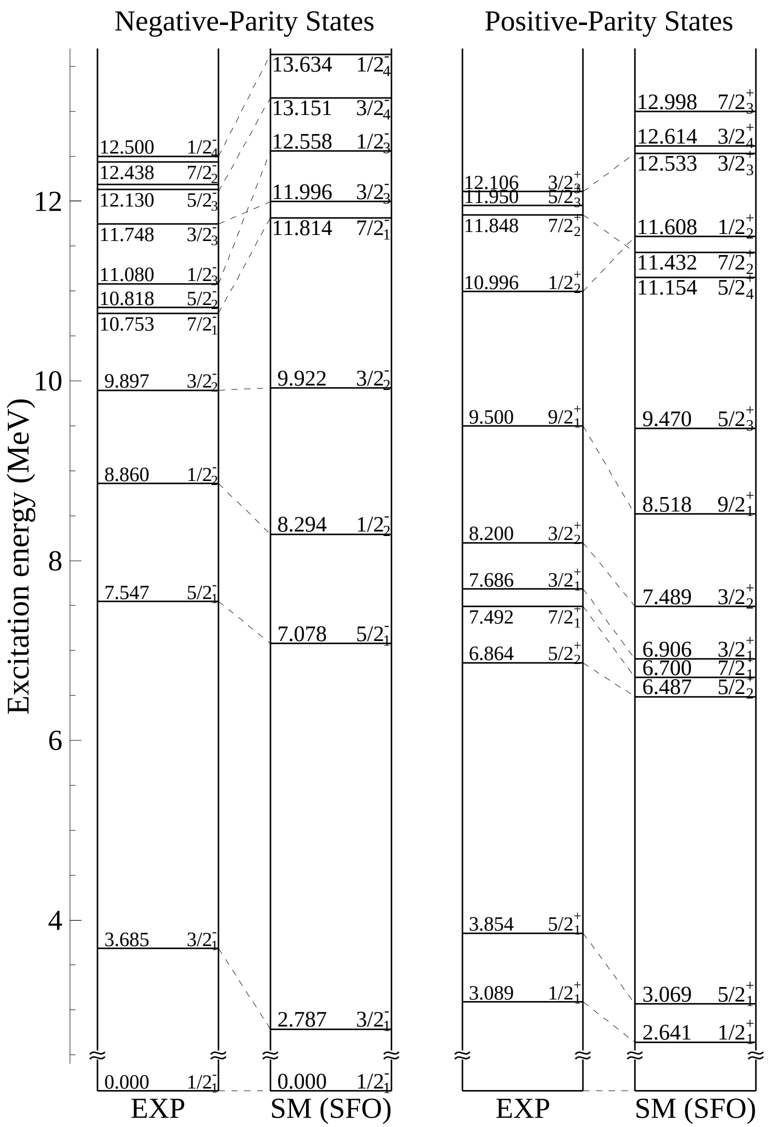
J^π	0.00 (0^+)	4.44 (2^+)	7.65 (0^+)
$1/2^-_2$	0.60±0.09	0.30±0.05	
$1/2^-_3$	0.05±0.01	0.54±0.09	0.43±0.16

Small decay branch of $1/2^-_3$ to the ground state in ^{12}C.

Large decay branch of $1/2^-_4$ to the Hoyle state.

Comparison with Shell Model

Experimental results were compared with SM using SFO interaction.



SM Calculation:

Interaction: SFO (T. Suzuki et al., PRC 67 (2003) 044302.)

Configuration Space: psd ($2\hbar\omega$)

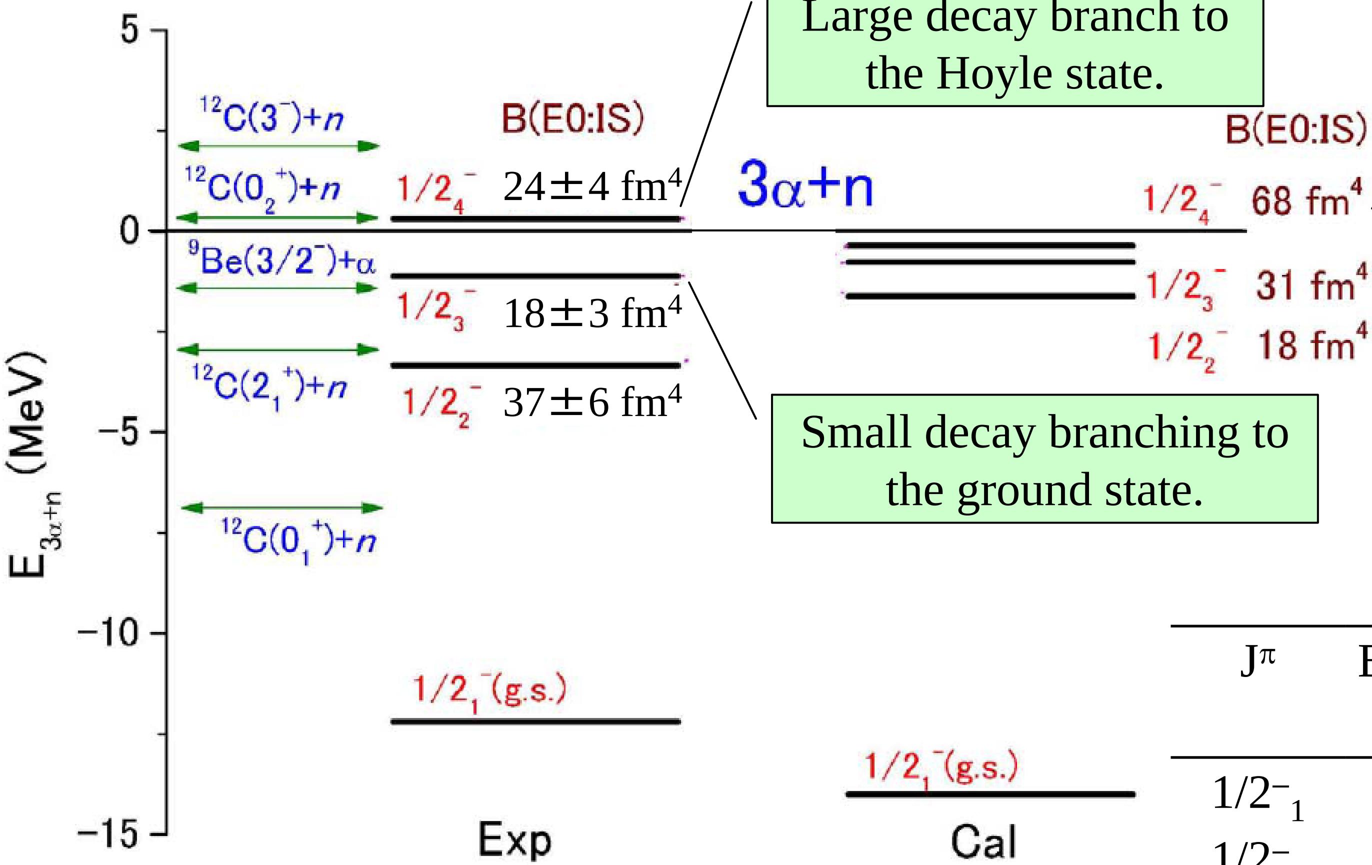
		Experiment		SM (SFO)	
J^π	Eλ	B(Eλ;IS) (fm⁴)	B(GT)	B(Eλ;IS) (fm⁴)	B(GT)
$3/2^-_1$	E2	47±5	1.06±0.02	46	2.11
$5/2^-_1$	E2	61±6		44	
$1/2^-_2$	E0	37±6	0.16±0.02	0.01	0.57
$1/2^-_3$	E0	18±3	0.12±0.01	0.08	0.10
$1/2^-_4$	E0	24±4	0.12±0.1	0.18	0.01

Predicted level structure is reasonable.
GT and E2 strengths are also reasonable.
→ Coexistence of CM and SM components?

Comparison with 3α+n OCM Calculation

3α + n OCM calculation was performed by T. Yamada *et al.*

Four 1/2⁻ states are successfully predicted by OCM.



Large decay branch to the Hoyle state.

Small decay branching to the ground state.

^{12}C (Hoyle) + n
^{9}Be + α
^{12}C (2⁺) + n

^{9}Be + α
^{12}C (3⁻) + n

^{12}C (gs, 2⁺) + n

J^π	B(E0;IS) (fm^4)	R_{rms} (fm)	$R_{3\alpha\text{-}n}$ (fm)
$1/2^-_1$		2.39	2.82
$1/2^-_2$	18	3.36	8.79
$1/2^-_3$	31	2.97	4.33
$1/2^-_4$	68	3.19	6.37

Correspondence between Exp. and OCM is still unclear.
S. P. excitation (SM-like component) might be needed.

Search for α Cluster States in ^{24}Mg

α Condensed States in Heavier N = 4n Nuclei

α condensed states in ^{8}Be, ^{12}C, and ^{16}O (?) seem to be established.

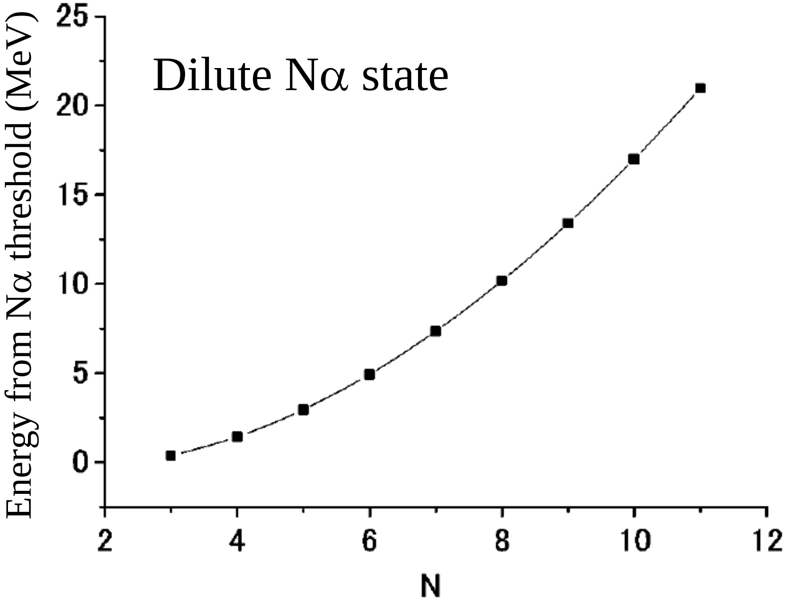
α condensed states in heavier nuclei (A<40) are theoretically predicted.

However....

Short range α-α attraction
Long range Coulomb repulsion

⇩

Energy and width of dilute Nα state increase with N.



T. Yamada and P. Schuck, Phys. Rev. C **69**, 024309 (2004).

Experimental identification of Nα condensed state in heavier nuclei might be difficult at the moment.

α Condensed State with Core Nucleus

Possibility of α condensed states with core nuclei is proposed.

Attractive potential for α clusters provided by the core nucleus might stabilize the α condensed state in heavy nuclei.

N. Itagaki *et al.*, Phys. Rev. C **75**, 037303 (2007).

Schuck-type wave function for ^{24}Mg

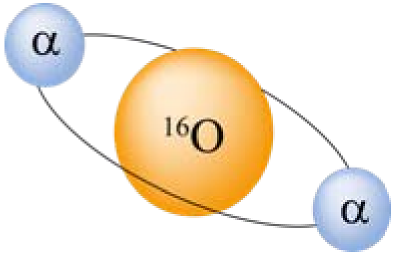
$$\Phi = \mathrm{A} \prod_{i=1}^{6} d\vec{R}_i \, G_i(\vec{R}_i) \exp\left[-\vec{R}_i^{\,2} / \sigma^2 \right]$$

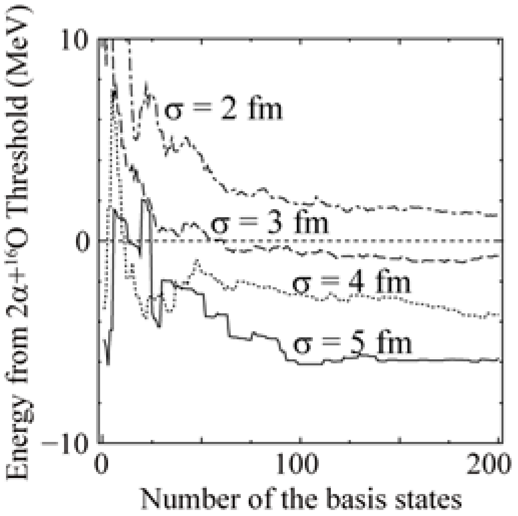
A : Antisymmetrizer

$G_i(\vec{R}_i)$: Wave function for the i-th α cluster

$\vec{R}_i$: i-th α-cluster center (Randamly generated)

σ: Oscillator parameter for the α condensation





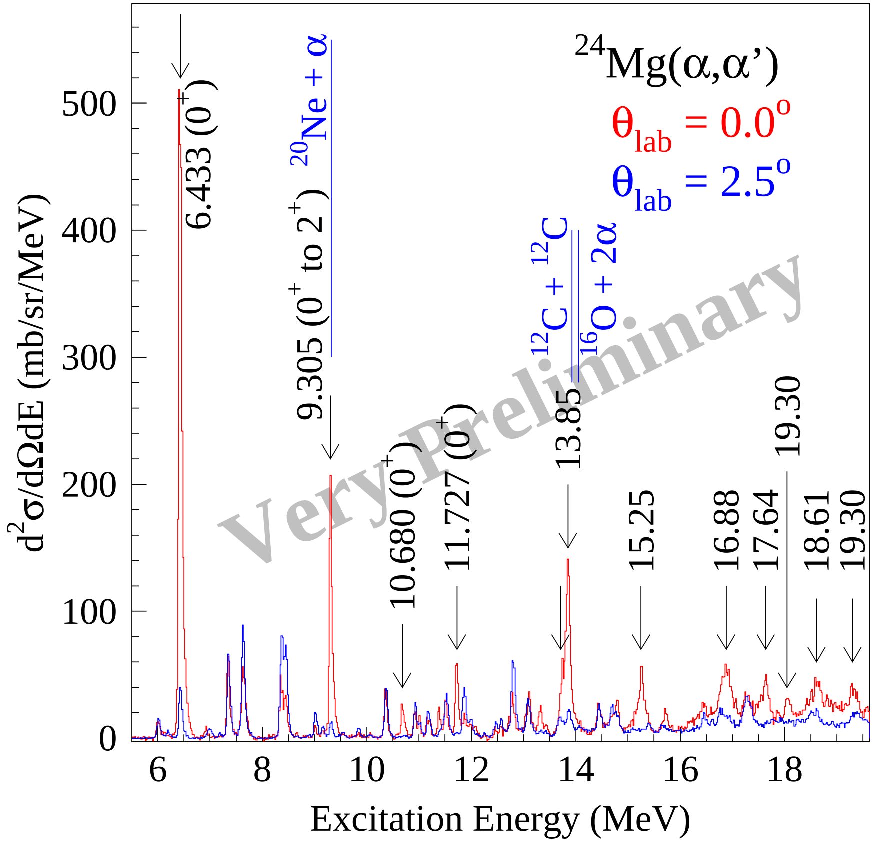
The ^{16}O core is expressed by the tetrahedron configuration of 4α with the relative distance of 1 fm.

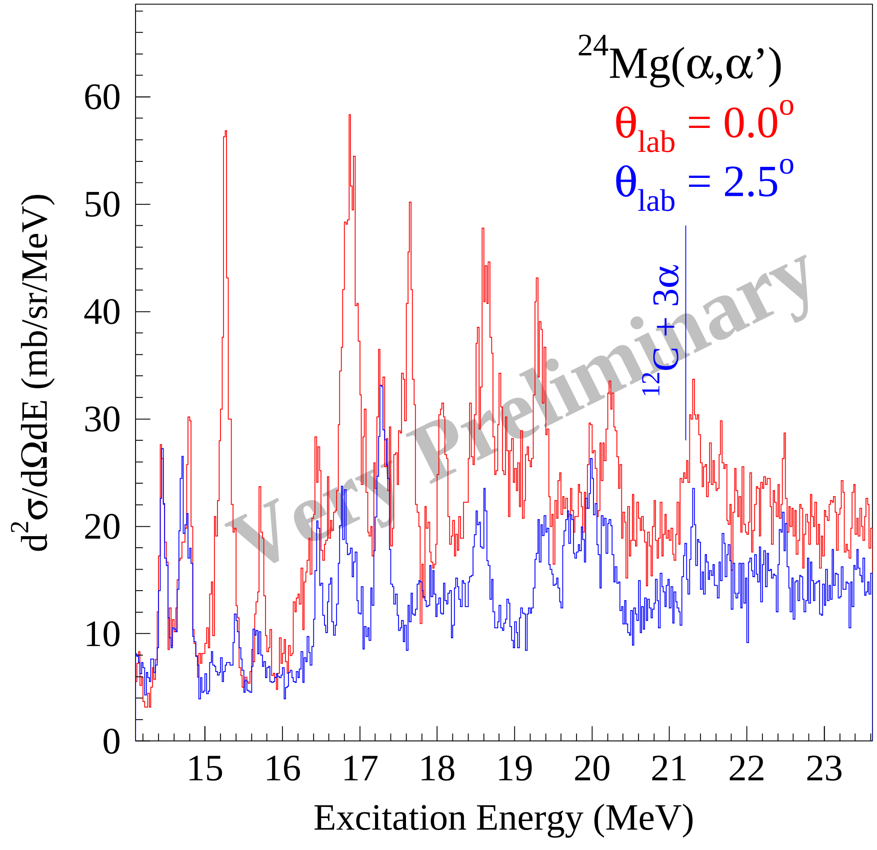
The α condensed state is predicted at E_x=12.2 MeV with B(E0; IS) = 168.4 fm^4.

A new experiment to search for the α condensed state near 2α + ^{16}O threshold in ^{24}Mg was performed at RCNP.

Preliminary Results

^{24}Mg(α,α') reaction has been measured to search for the ^{16}O + 2α cluster states.

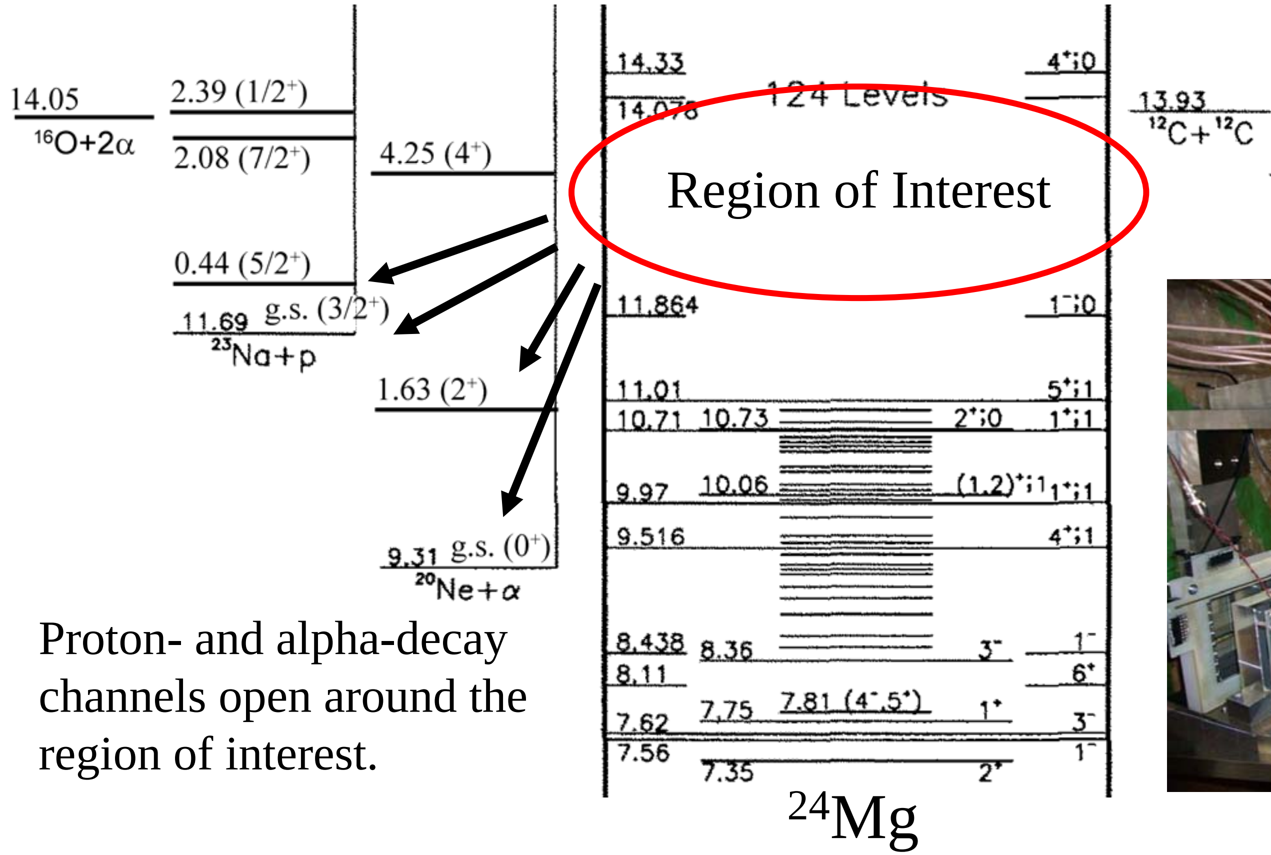




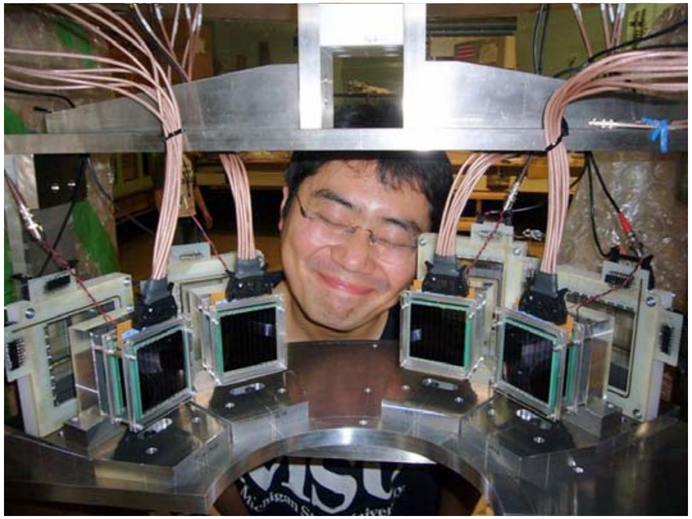
- Many known and unknown monopole states are observed.
- Detailed comparison with theoretical calculations are desired.

Decay Particles from α Condensed States

Decay-particle measurement provides structural information.



4 Silicon counter telescopes (3 layers) are installed in the scattering chamber.



Proton- and alpha-decay channels open around the region of interest.

- Complementary information for the E0 strength is expected.
  - α cluster state should prefer to decay into the alpha-decay channel.
- Data analysis is still going on. The results will be presented elsewhere!

Summary

Cluster structures in light nuclei ^{13}C and ^{24}Mg were studied by measuring inelastic α scattering.

- E0 strength is a key observable.
- Folding model calculation and MD analysis have been performed.
- Several candidates for the spatially developed cluster states were found.
- Complementary information is expected from the decaying-particle measurement.