Alpha inelastic scattering and cluster structures in ^{24}Mg

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- Future Perspectives
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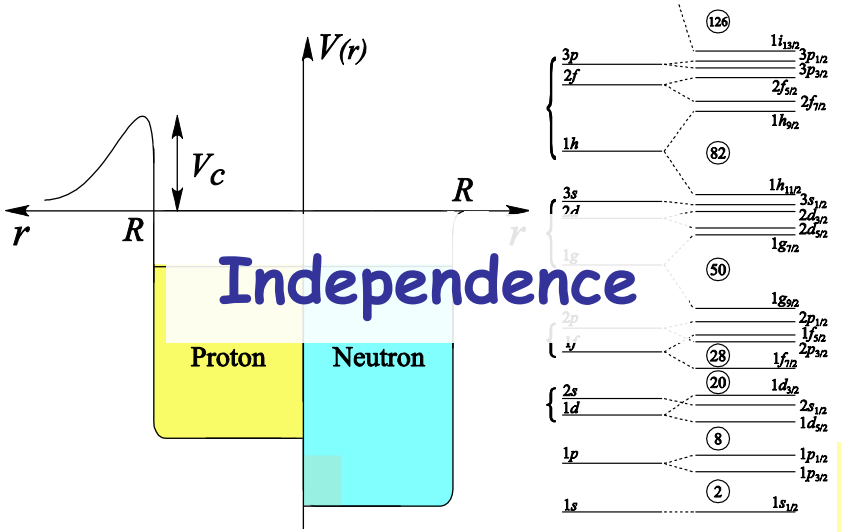
Introduction

Two different pictures of Nuclear Structure

Shell Model

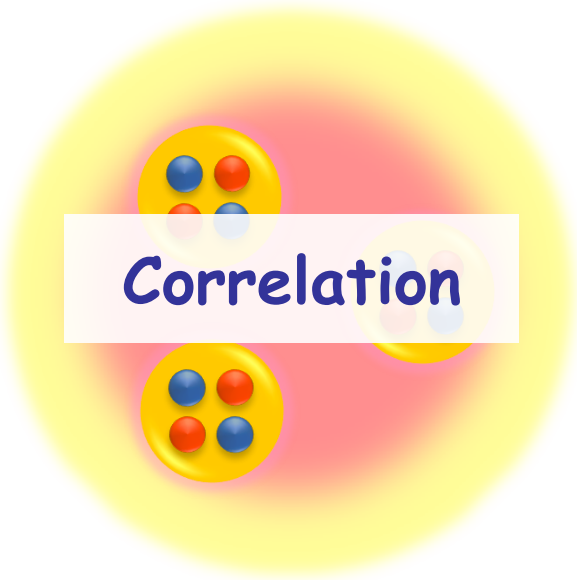


Independence

SU(3) Limit

Multi-hω Configuration

Cluster Model



Correlation

S. P. orbit in the mean-field potential.

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

Describes well S. P. excited states.

Strong correlation between nucleons.

Cluster consists of several nucleons.

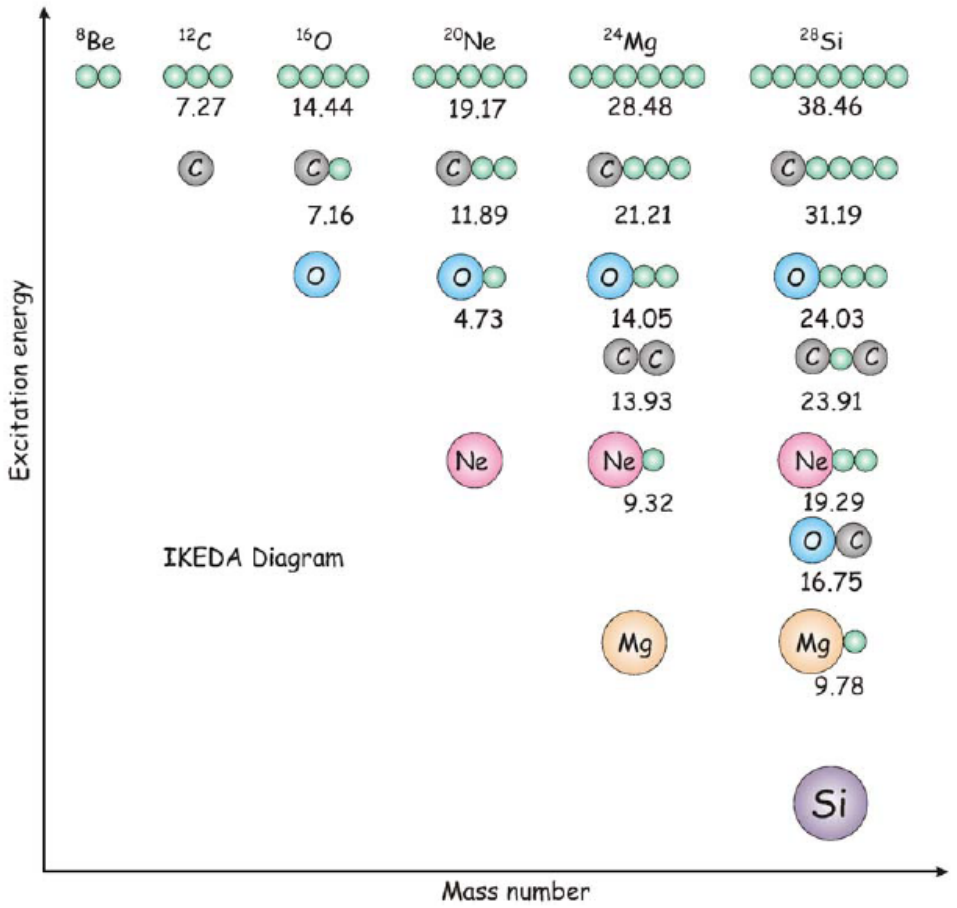
Clusters are weakly bound.

It is important to study appearance and disappearance of the cluster correlation for better understanding of "Atomic Nucleus".

Cluster States in N = 4n Nuclei

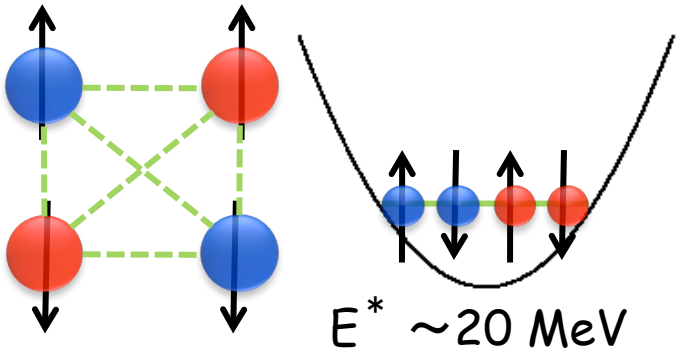
a clustering is an important concept in nuclear physics for light nuclei.

a cluster structure is expected to emerge near the α-decay thresholds in N = 4n nuclei.



The most tightly bound light cluster

α particle (quartet)

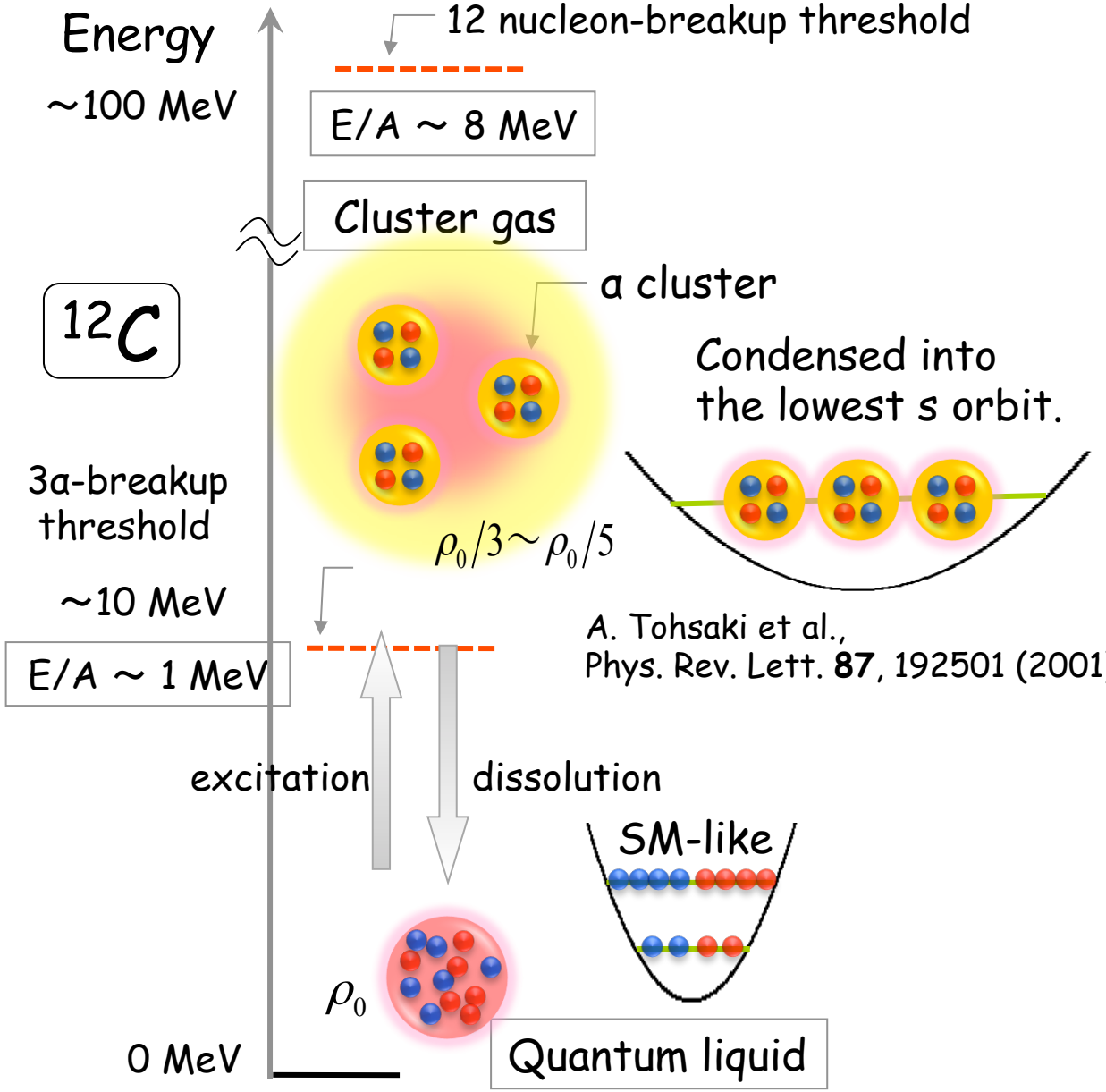


E^* ~20 MeV stiff

The most elemental subunit in nuclear cluster structures.

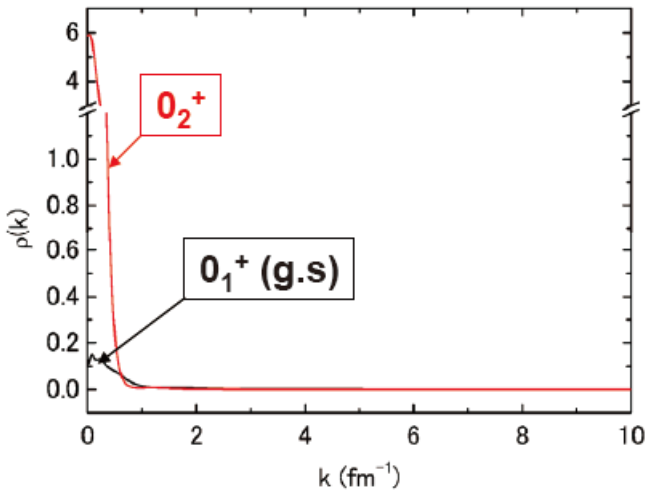
The 0^+_2 state at E_x = 7.65 MeV in ^{12}C is a famous 3α cluster state.

Cluster Gas-like States in ^{12}C

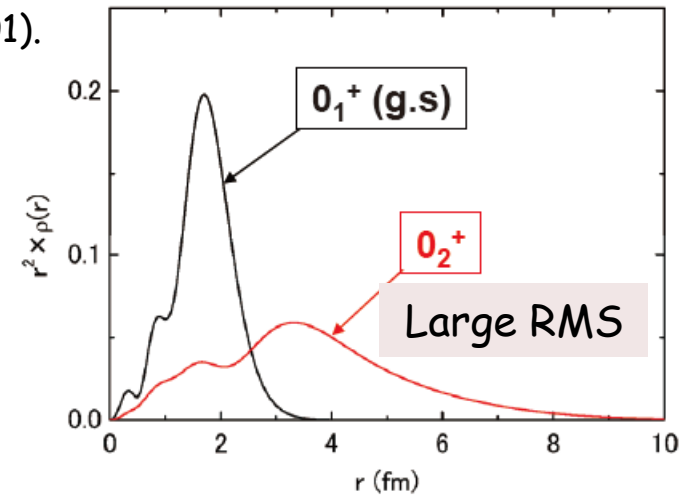


A. Tohsaki et al.,
Phys. Rev. Lett. **87**, 192501 (2001).

Sharp momentum distribution



Dilute matter distribution

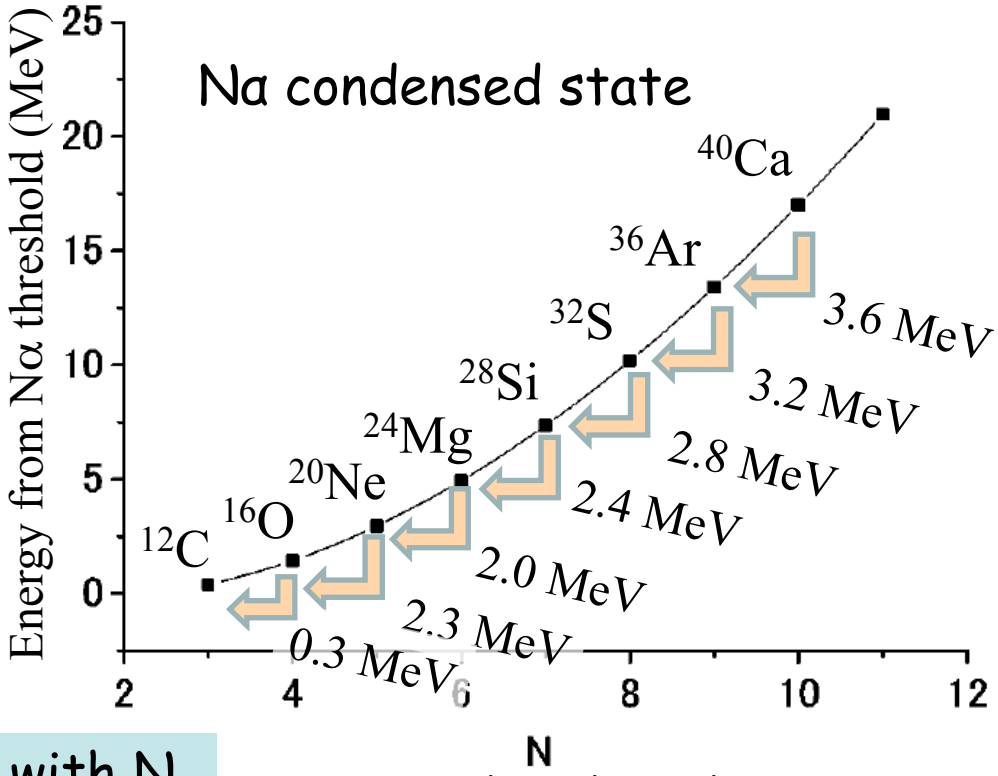


α Condensed States in Heavier N = 4n Nuclei

α condensed states in ^{8}Be and ^{12}C seem to be established.

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

Short range α-α attraction
Long range Coulomb repulsion



Energy of dilute Nα state increase with N.
Nα are confined in Coulomb barrier.

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

If such nα condensed states are formed, they should sequentially decay into lighter α condensed states by emitting α particles.

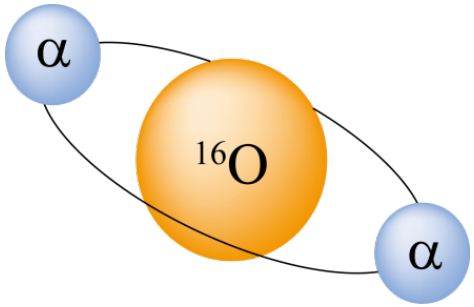
α decay measurement could be a probe to search for the α condensed state.

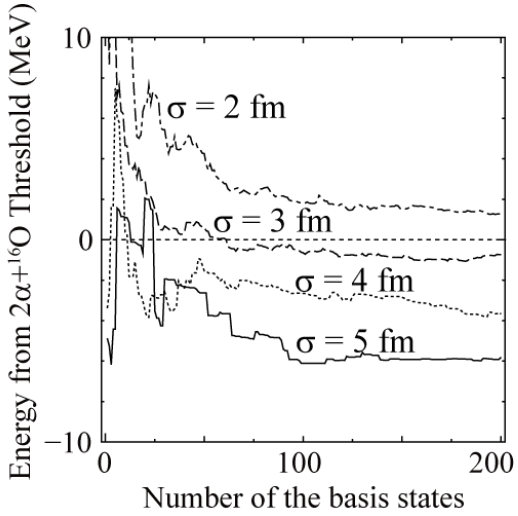
a Condensed State with Core Nucleus

Possibility of a condensed states with core nuclei is proposed.

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

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





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

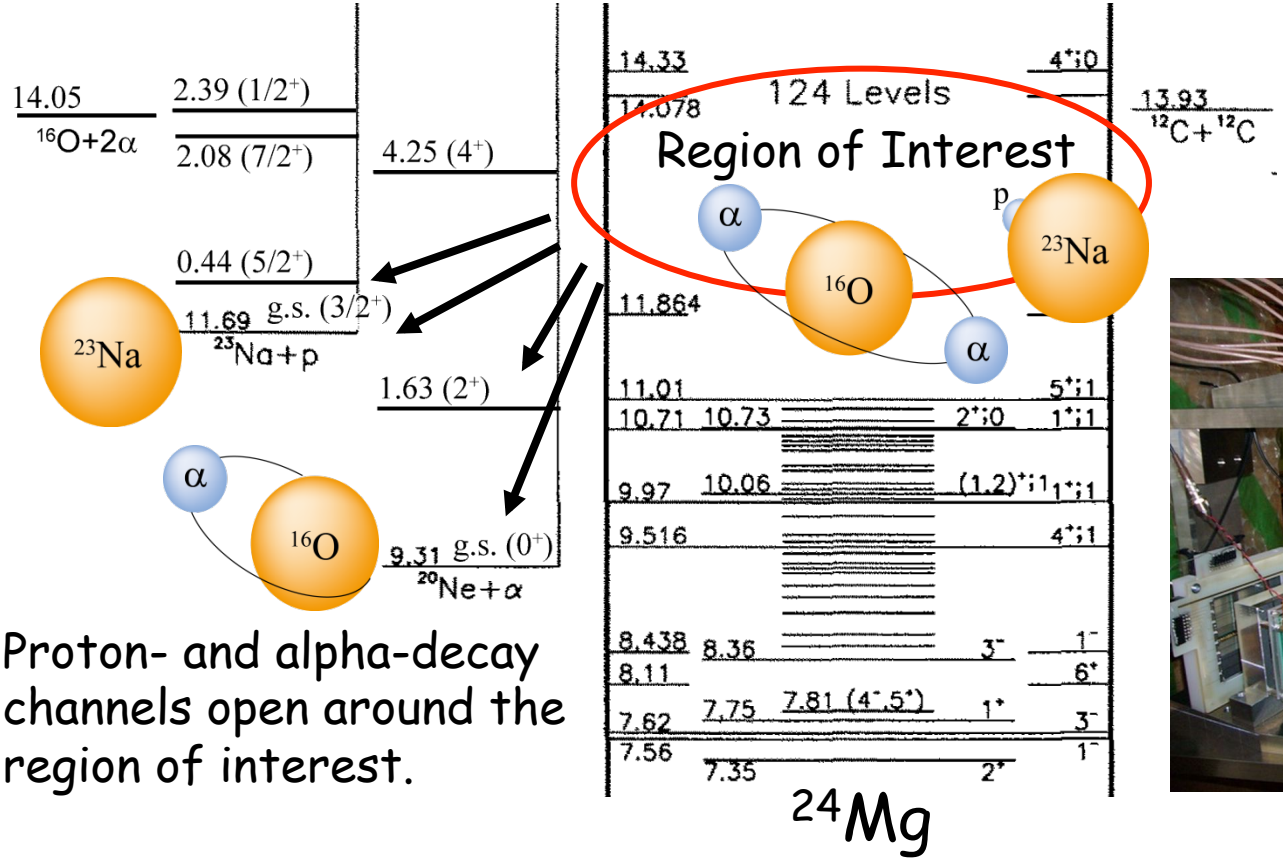
$\vec{R}_i$: i-th α-cluster center (Randamly generated)

σ: Oscillator parameter for the α condensation

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

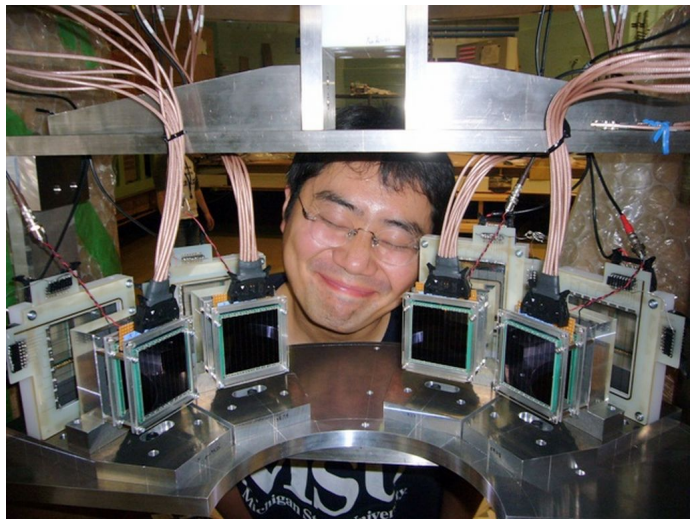
Decay Particles from a Condensed States

Decay-particle measurement provides structural information.



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

4 Si counter telescopes (5 layers) are installed in the SC, and cover 2.5% of 4π (309 mSr).



- Complementary information for the E0 strength is expected.
  - a cluster state should prefer to decay into the alpha-decay channel.
  - GS in ^{20}Ne is a well-known a + ^{16}O cluster state.

E0 Strengths and a 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).

Isoscalar E0 transition:
ΔL=0, ΔS=0, ΔT=0

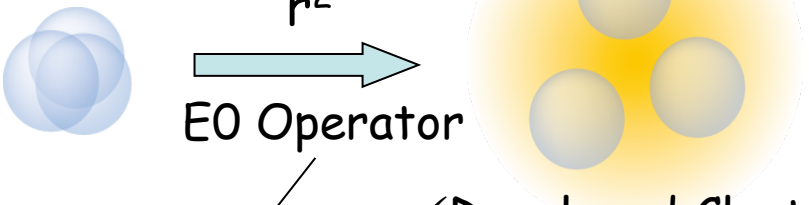
$$B(E0;IS) = \left|ME\left(E0;IS\right)\right|^2$$

$$ME\left(E0;IS\right) = \left\langle J_f \left\| \sum_{i=1}^{A} r_i^2 \right\| J_i \right\rangle = \int_0^{\infty} \left(\rho_t^p + \rho_t^n\right) r^4 dr$$

0^+_2 state in ^{12}C: B(E0; IS) = 121±9 fm^4
Single Particle Unit: B(E0; IS)$_{s.p.}$ ~ 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.

✓SM-like Compact GS.



✓Developed Cluster State

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 a cluster structure.

Inelastic Alpha Scattering

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

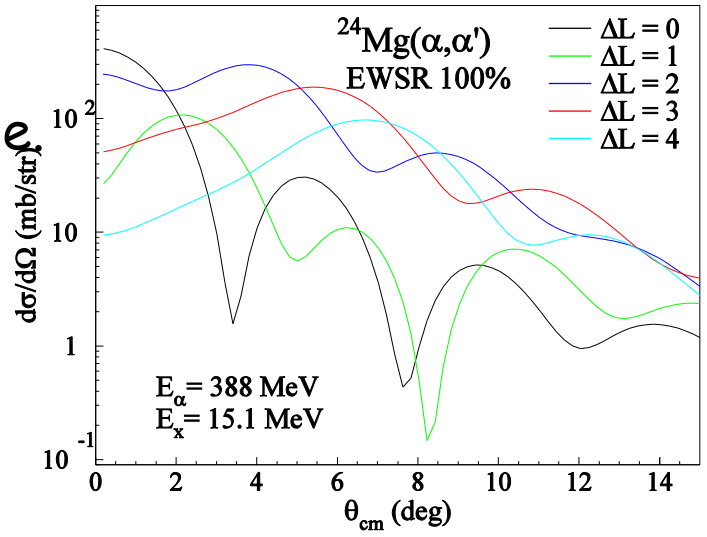
- Simple reaction mechanism
  - Good linearity between dσ/dΩ and B(Ô).

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

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

- Relatively large cross section.
- High resolution measurement is possible.
- Selectivity for the ΔT = 0 and natural-parity transitions.
- Multiple decomposition analysis is useful to separate ΔJ^{π}.

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

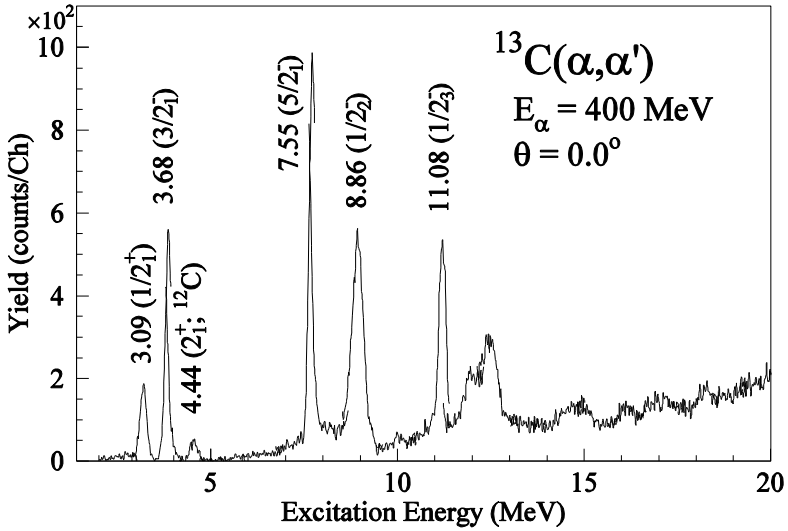


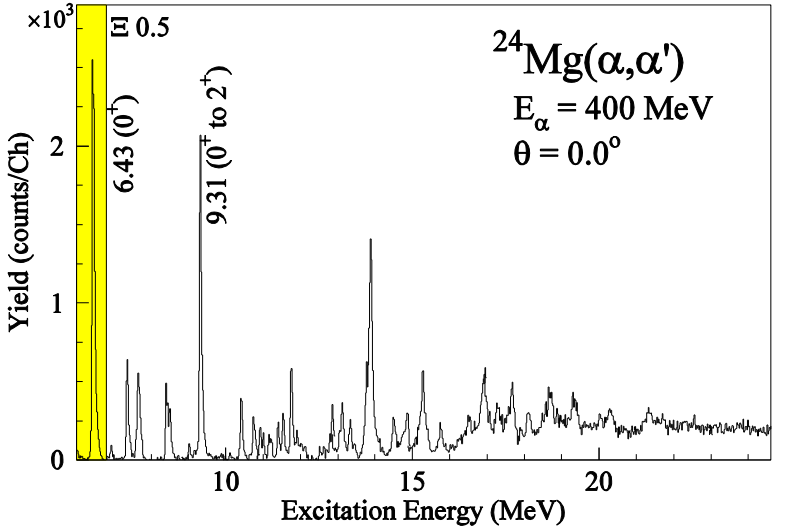
We measured inelastic α scattering to extract IS E0 strengths and to examine cluster structures in light nuclei.

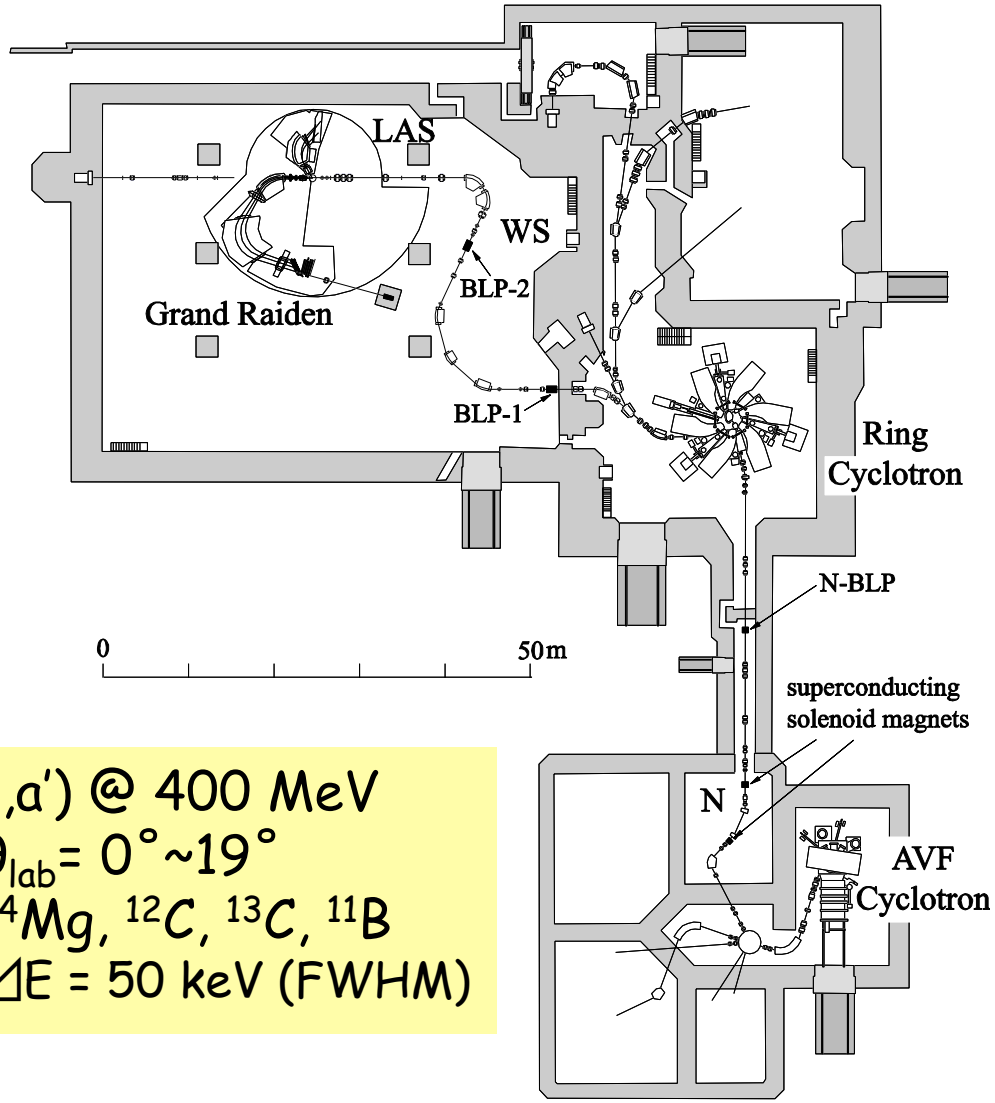
Experiment

Experiment was performed at RCNP, Osaka

Background-free measurement at extremely forward angles



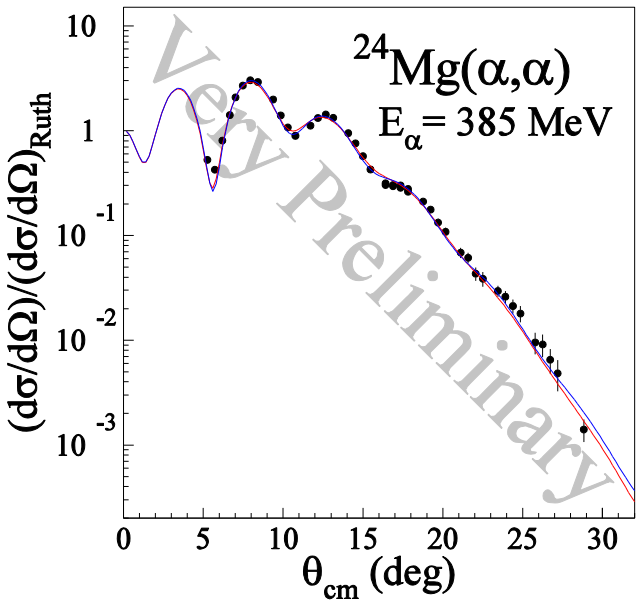




(a,a') @ 400 MeV
$θ_{lab}$= 0°~19°
^{24}Mg, ^{12}C, ^{13}C, ^{11}B
⊿E = 50 keV (FWHM)

Single Folding Model Analysis

Experimental data at RCNP is analyzed by single folding model.



Single folding by phenomenological aN interaction.

$$U_0(r) = \int d\vec{r}' \rho_0(r') V\left(\left|\vec{r} - \vec{r}'\right|\right)$$

$$V\left(\left|\vec{r} - \vec{r}'\right|\right) = -V \exp\left(-\left|\vec{r} - \vec{r}'\right|^2 / \alpha_V\right) - iW \exp\left(-\left|\vec{r} - \vec{r}'\right|^2 / \alpha_W\right)$$

- GS densities are taken from electron scattering assuming $\rho_{0p} = \rho_{0n}$.
- aN interaction is determined to reproduce the elastic scattering data.

$V = 13.1$ MeV, $W = 8.8$ MeV, $\alpha_V = \alpha_W = 5.03$ fm^2

Single folding model gives reasonable description on the elastic scattering.

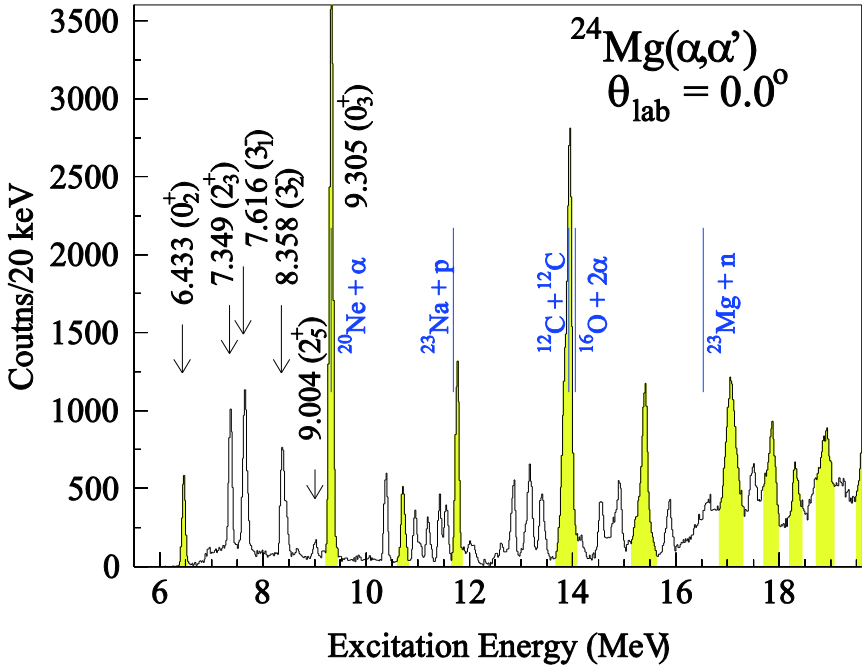
- Transition potential is obtained by a single folding model.

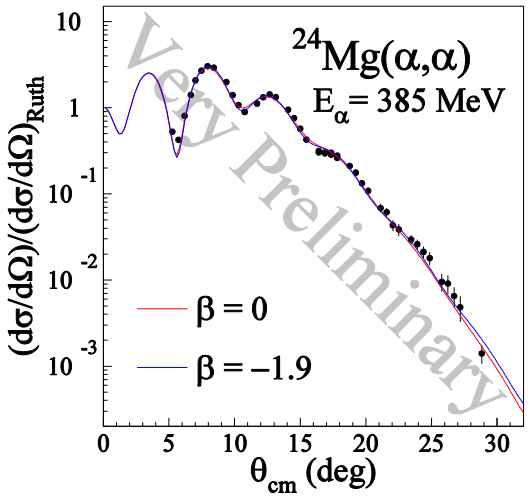
$$\delta U_L(r) = \int d\vec{r}' \, \delta\rho_L(r) V\left(\left|\vec{r} - \vec{r}'\right|\right)$$

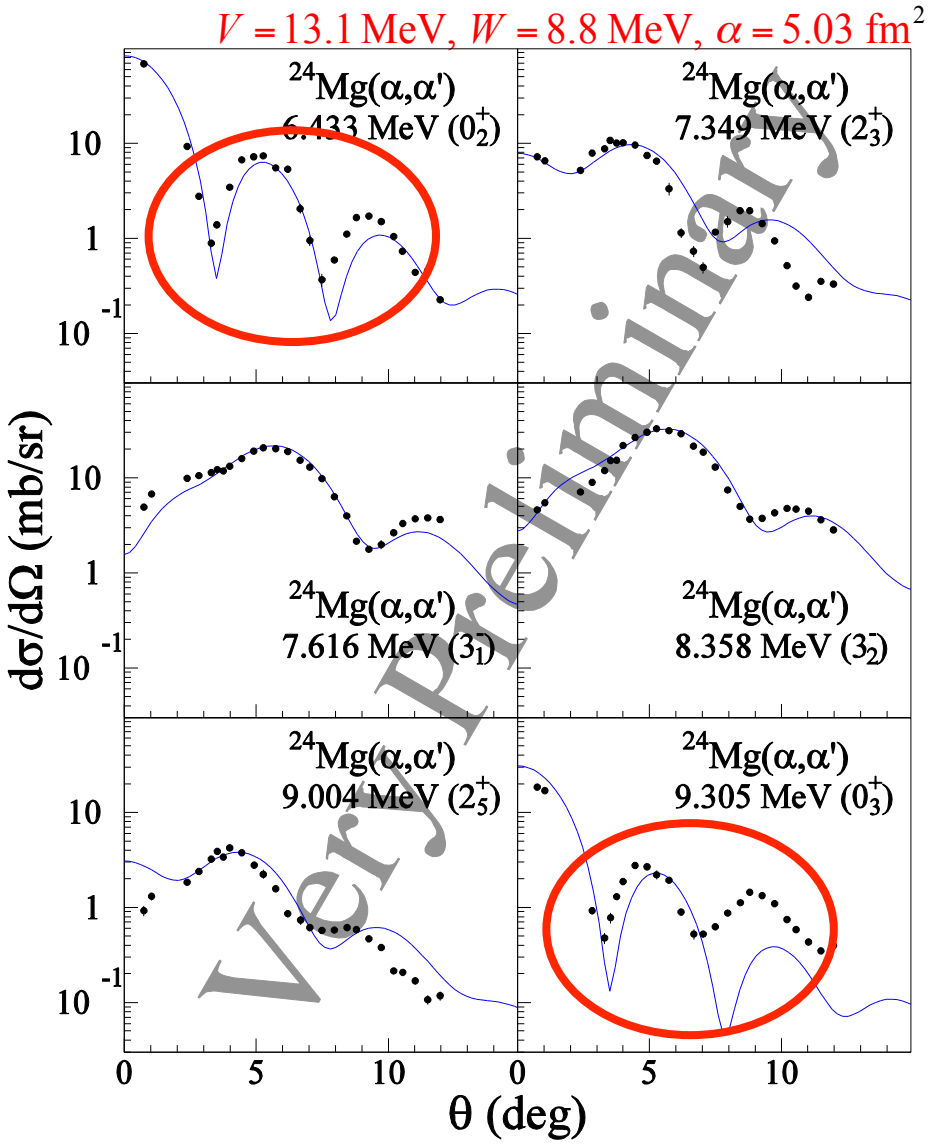
- Transition densities are taken from the macroscopic model

Discrete States in ^{24}Mg

Several discrete states were analyzed by the single folding model.

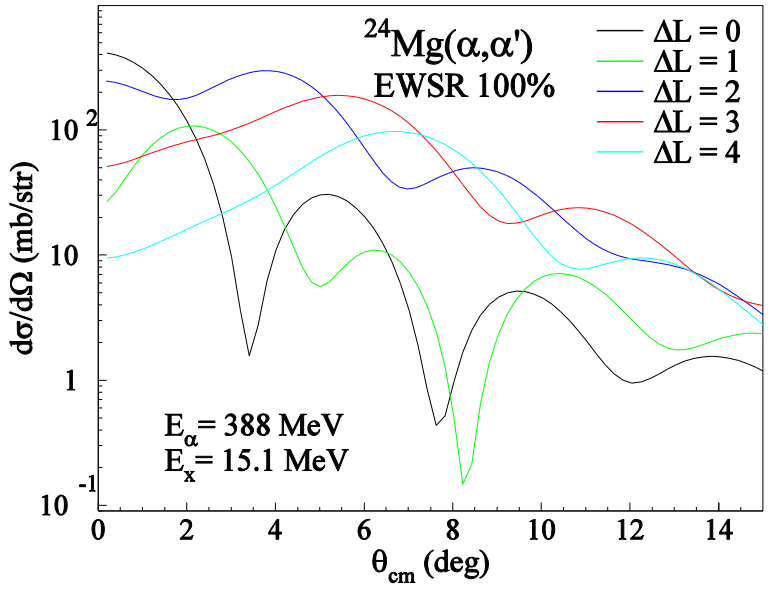


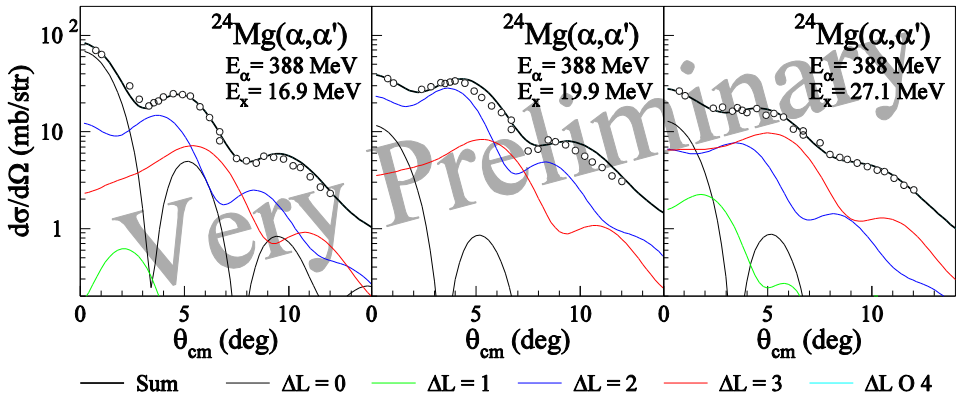


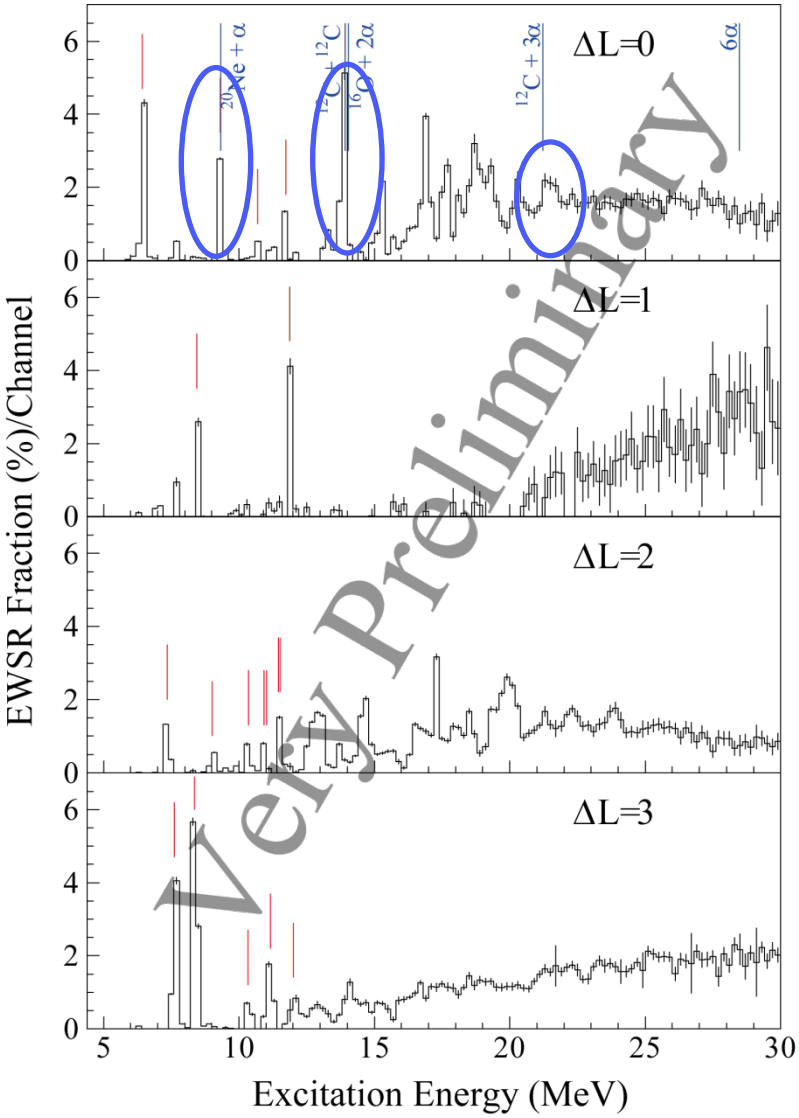


Multipole Decomposition Analysis

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



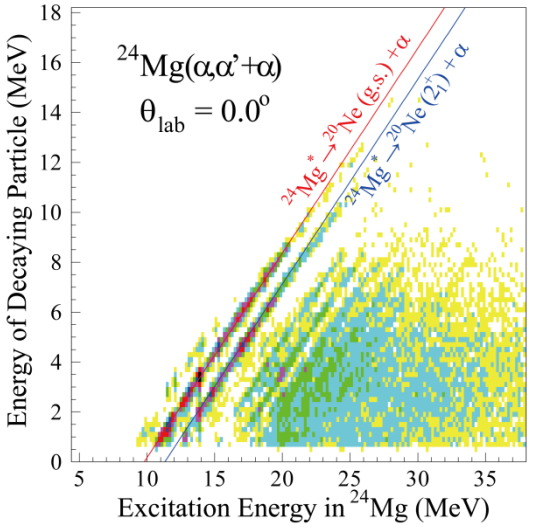


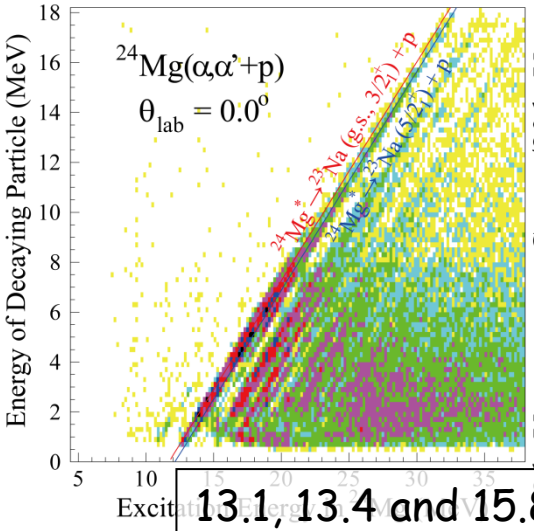


Fine structure in ΔL=0 strengths was observed.

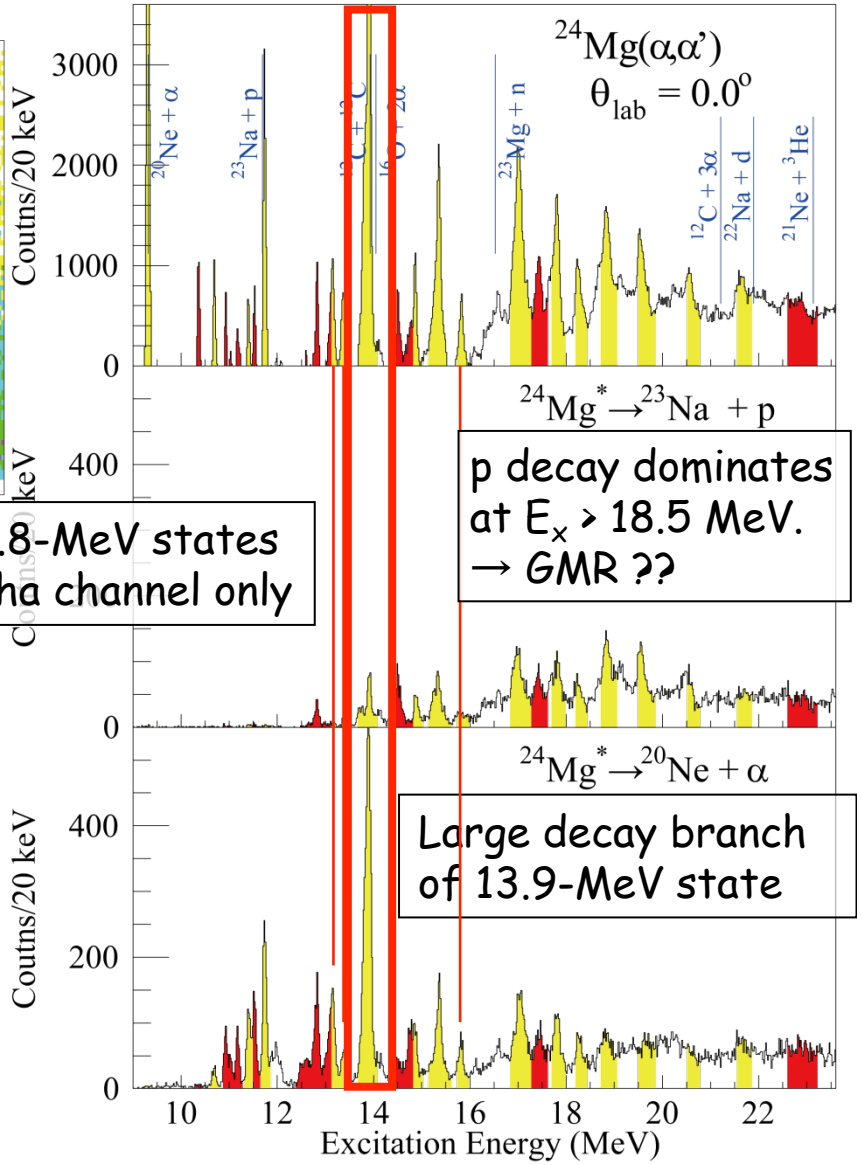
Decay Particle Measurement

Decay to the proton and alpha emission channels were identified.





13.1, 13.4 and 15.8-MeV states decay to the alpha channel only



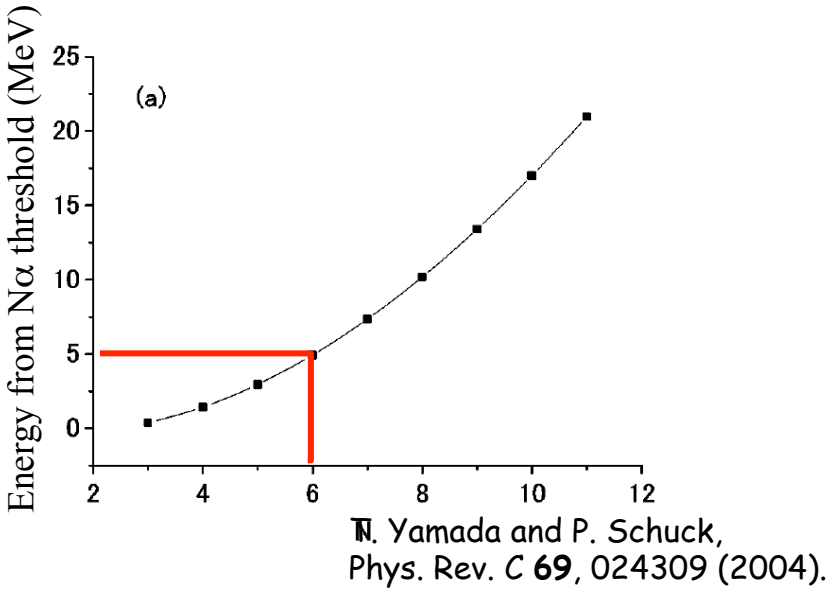
p decay dominates at E_x > 18.5 MeV. → GMR ??

Large decay branch of 13.9-MeV state

- Proton and alpha decay channels are separated.
- 13.1, 13.4 and 15.8-MeV states decay to ^{20}Ne only.
- 0^+ state at 13.9 MeV near the $^{12}C + ^{12}C$ and $^{16}O + 2a$ thresholds has a large decay branch to ^{20}Ne.

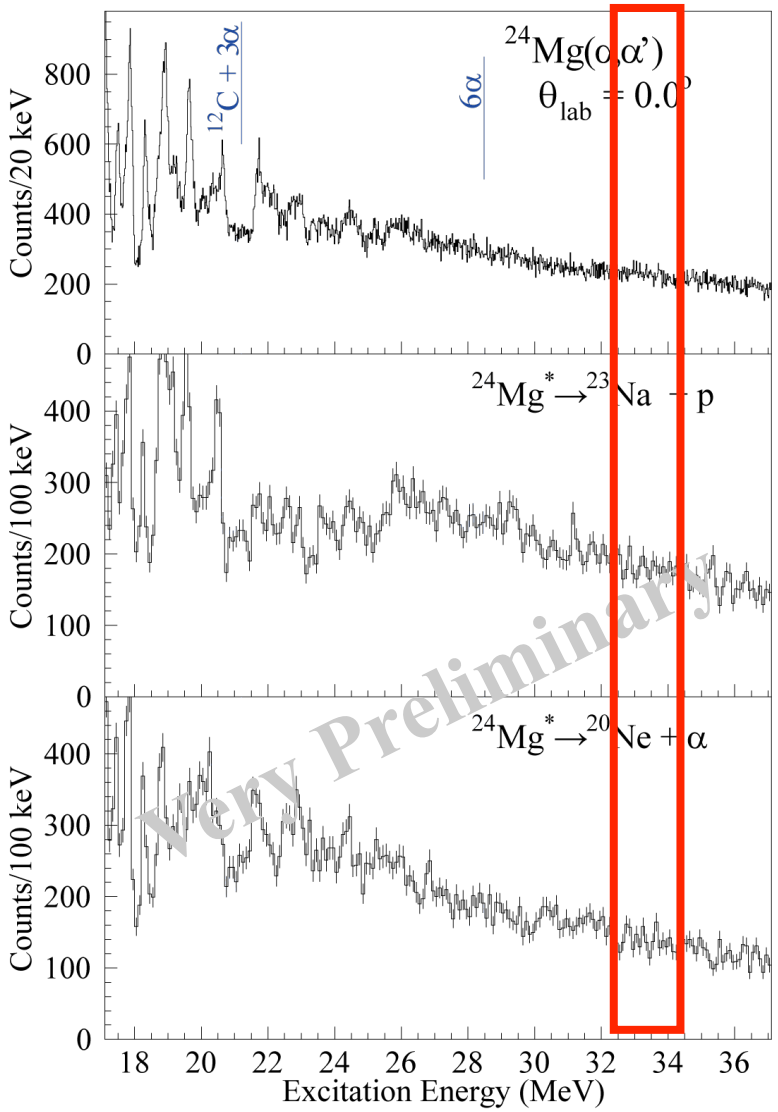
Highly Excited Region

6α condensed state was searched for in the highly excited region.



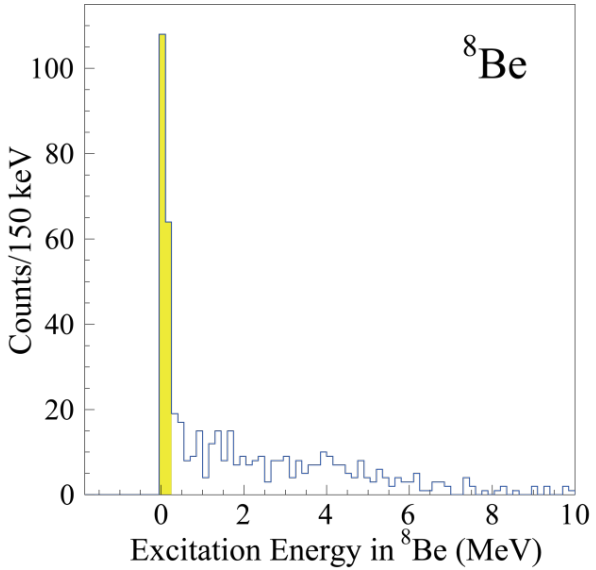
N. Yamada and P. Schuck,
Phys. Rev. C **69**, 024309 (2004).

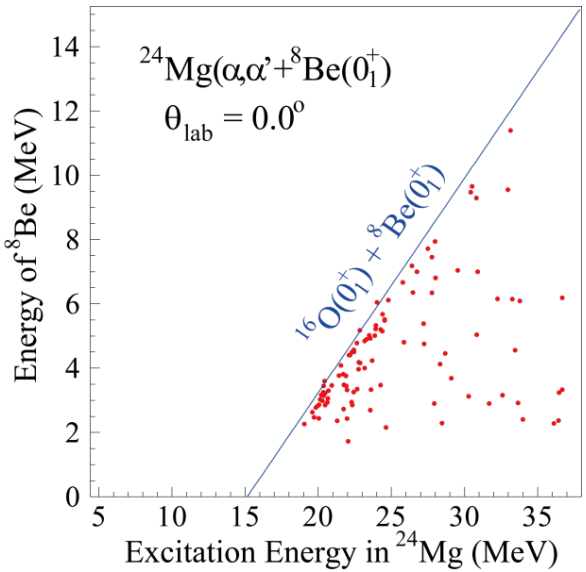
- 6α condensed state is expected at 5 MeV above the 6α threshold.
  - E_x ~ 28.5 + 5 = 33.5 MeV
- No significant structure suggesting the 6α condensed state.
  - Several small structures indistinguishable from the statistical fluctuation.
    → Need more statistics.

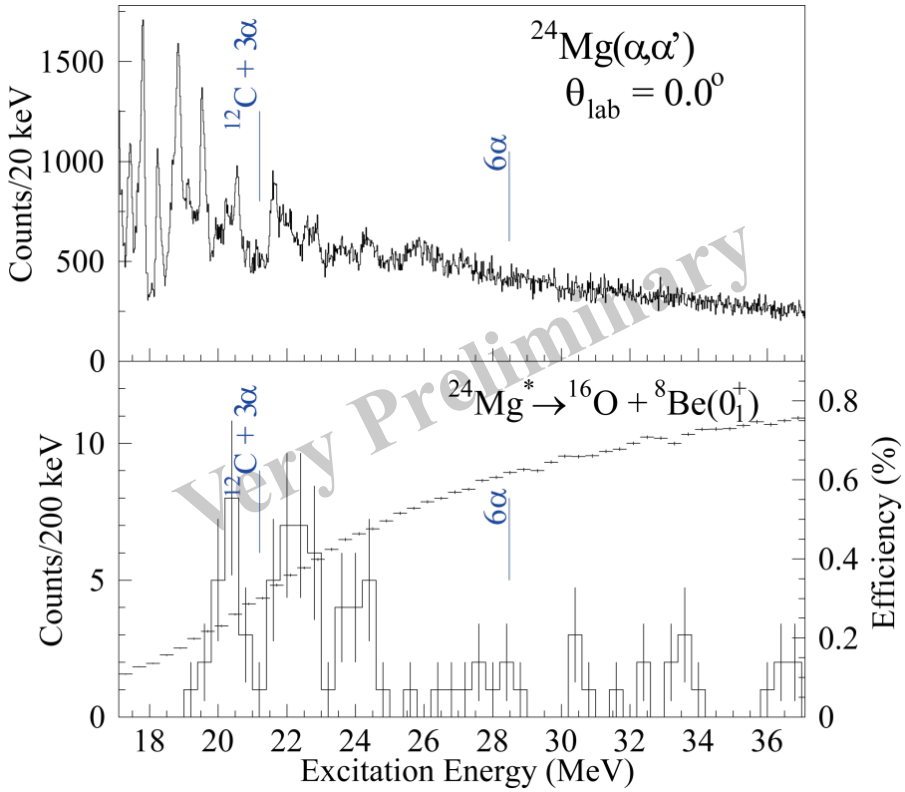


^{8}Be Emission Events

^{8}Be(0^{+}_{1}) emission events were indentified from 2α emission events by E_x in ^{8}Be.







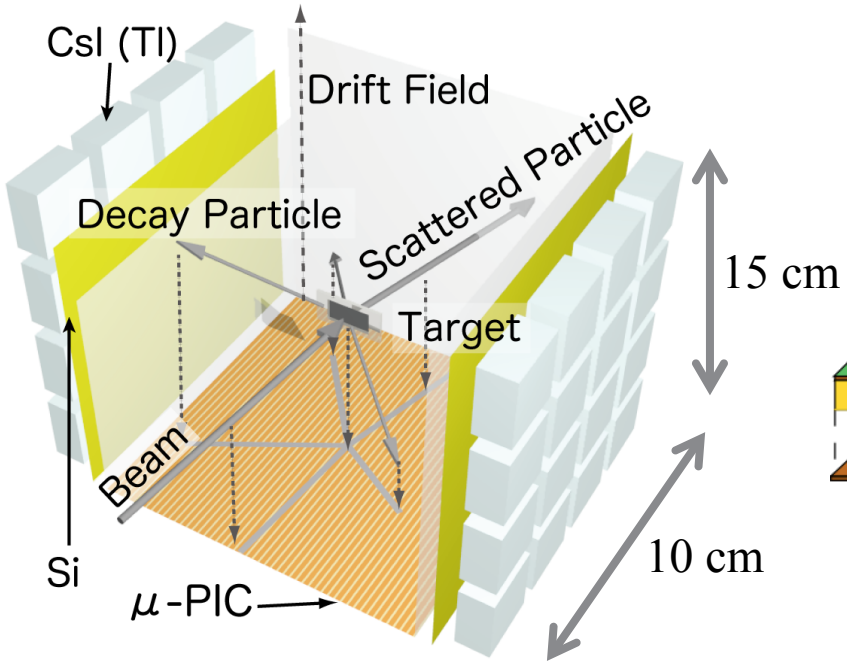
- Several states at 20.5, 22.0, and 24.3 MeV were observed near the ^{12}C+3α threshold.
- Possible structures were seen above the 6α threshold although statistically poor .
  → Need more statistics.

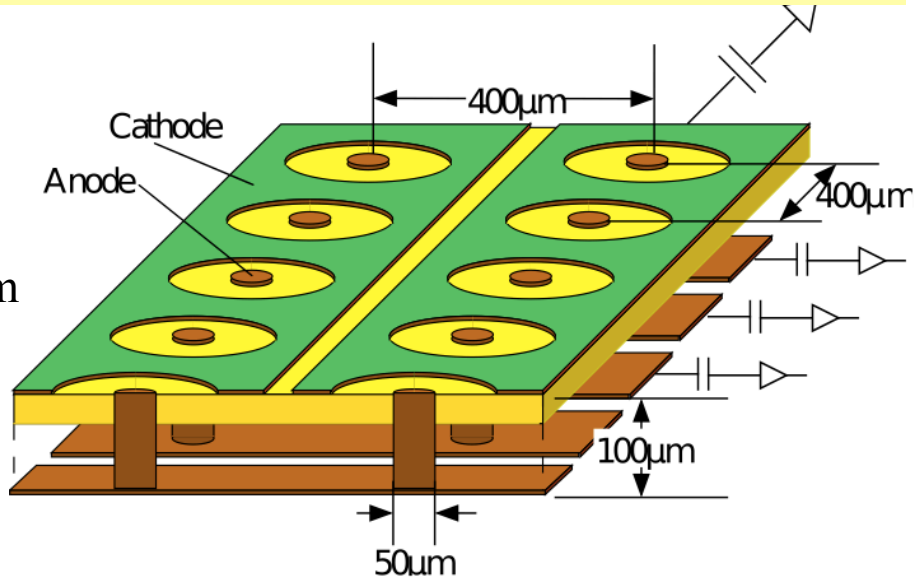
Future Prospects

New experiment using MAIKo.

MAIKo Time Projection Chamber

MAIKo TPC is developed by the Kyoto and RCNP groups.
It will be installed at the target position of Grand Raiden.

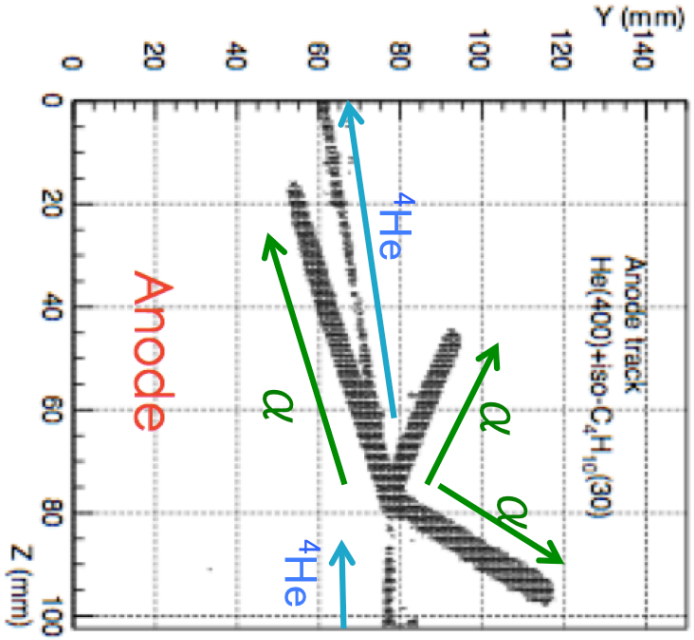


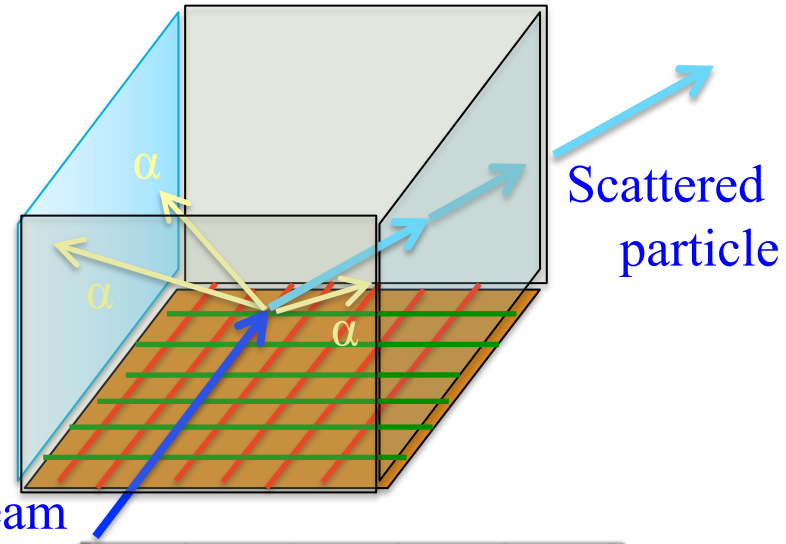


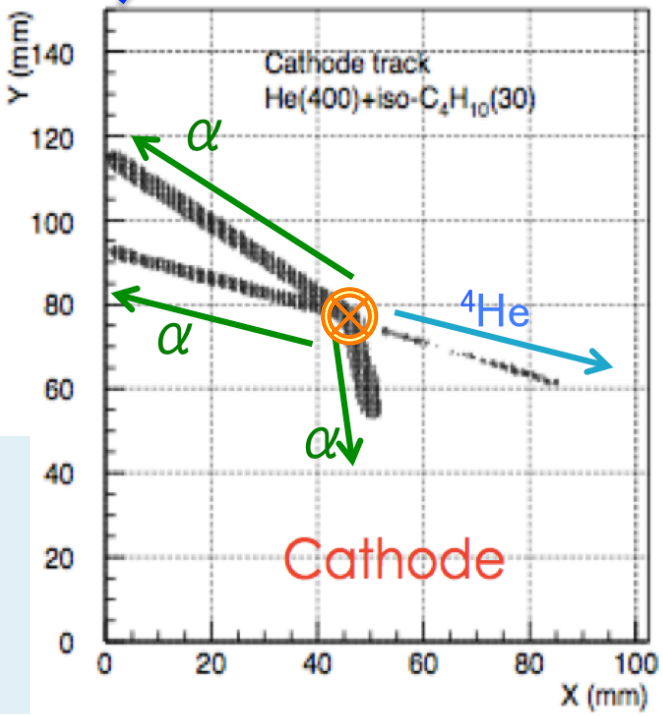
Micro-Pixel Chamber (μ-PIC)
A. Ochi, *et. al.* NIM A **478**, 196 (2002).

- Detect low-energy decay particles with large angular coverage.
- Introduce μ-PIC + GEM for multiplication and detection of electrons.
  - μ-PIC : 2-dimensional strip readout (400 μm pitch).
    256A+256C = 512 ch.
  - GEM: 140 μm pitch, d=70 μm, t=100 μm (thick GEM)

Test measurement of 3α decay







- Beam: ^{4}He @ 12.5 MeV/u
- Gas: He(93%) + iC_4H_{10}(7%) @430 hPa

Scattered α particle and
3 decay α particles are clearly observed.

dΩ for previous detector: 309 mSr
dΩ for MAIKo: ~ 4π
MAIKo will gain solid angle by a factor of
$(0.3/4\pi)^6 \sim 5 \times 10^6$ for 6α measurement.

Summary

Inelastic α scattering is an useful tool to examine α cluster structure in nuclei.

- E0 strength is a key observable.
- Complementary information is expected from the decaying-particle measurement.

α condensed states in ^{24}Mg are searched.

- Several candidates of the α condensed states emitting α or 8Be are found.

New experiments are under going.

- A new time projection chamber MAIKo is under developed.
- Multi α decay events will be measured in combination of Grand Raiden.

Collaboration

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