Cluster Structures probed by Inelastic Scattering

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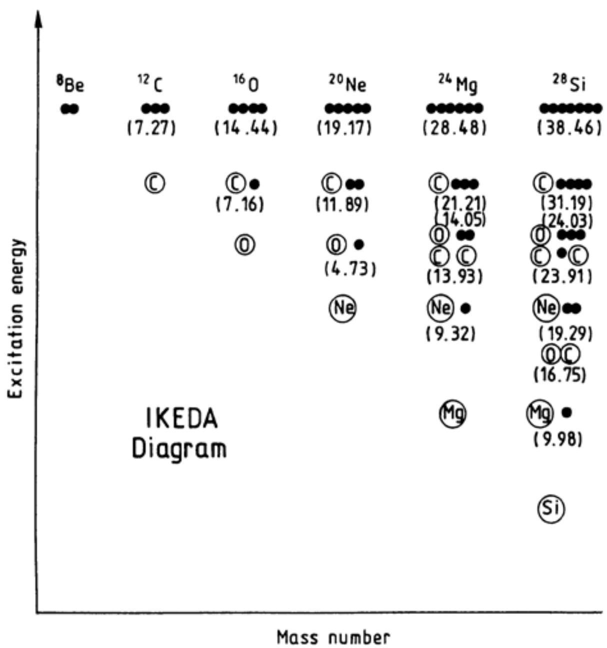
α Condensed State

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

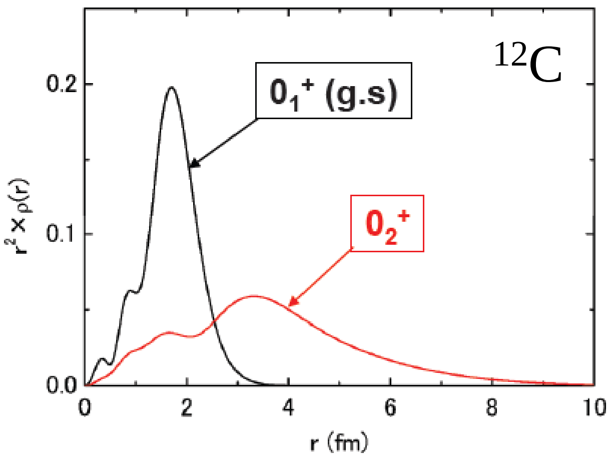
The 0^+_2 state at E_x = 7.65 MeV in ^{12}C , a famous 3α cluster state, is called “Hoyle state”.

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

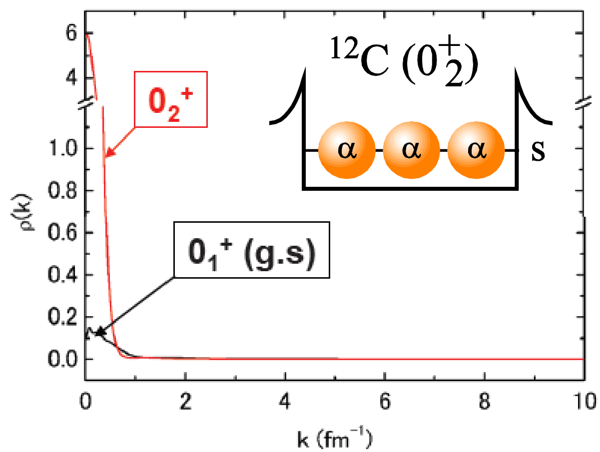


A. Tohsaki et al., Phys. Rev. Lett. **87**, 192501 (2001).

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.
Does similar α condensed state exist in heavier nuclei?

E0 Strengths and α Cluster Structure

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

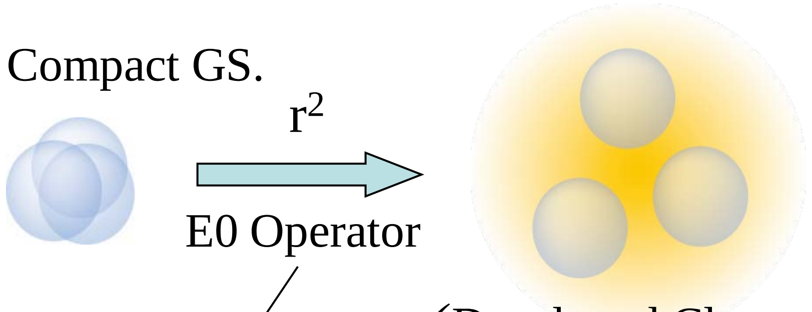
T. Kawabata *et al*., Phys. Lett. B **646**, 6 (2007).

0^+_2 state in ^{12}C: B(E0; IS) = 121 ± 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 α cluster structure.

Inelastic Alpha Scattering

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

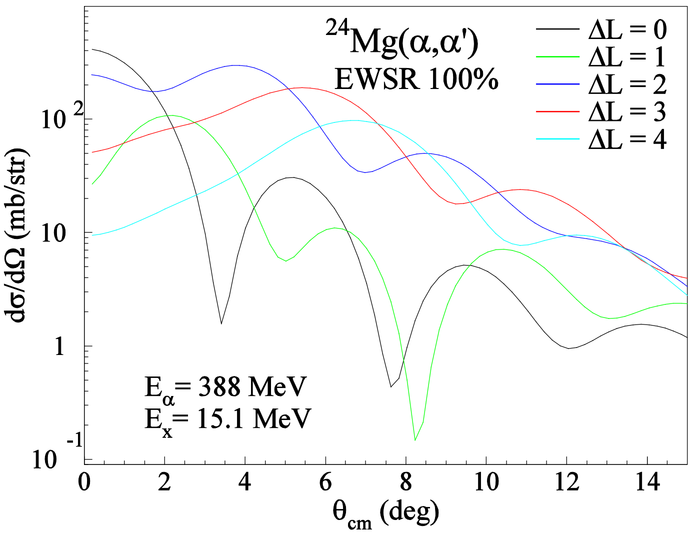
- Simple reaction mechanism
  - Good linearity between dσ/dΩ and B(ô).

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

  - 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}.

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

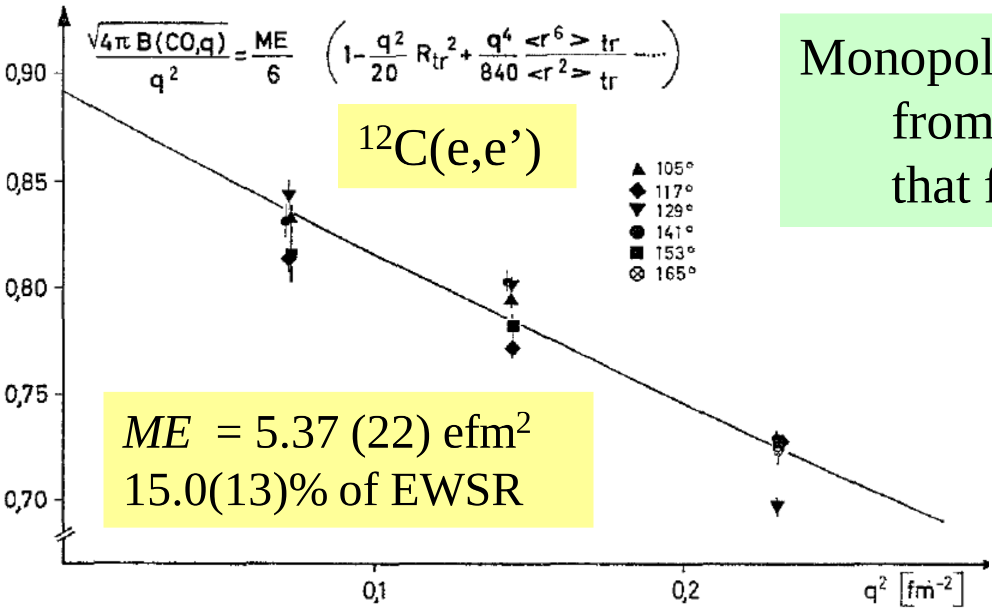


We measured inelastic α scattering to extract IS E0 strengths and to search for the α condensed states.

Missing Monopole Strength
in
Alpha Inelastic Scattering

Missing Monopole Strength

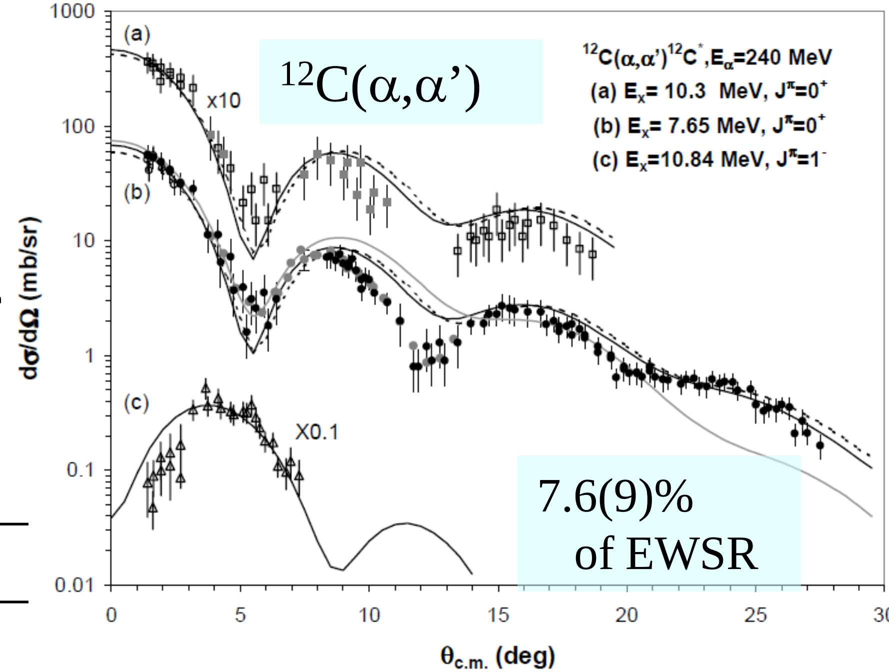
Monopole strengths for the Hoyle state from hadron scattering is 50% smaller than that from electron scattering.



^{12}C(e,e')

ME = 5.37 (22) efm^2
15.0(13)% of EWSR

E. Strehl, Z. Phys. **234**, 416—442 (1970).



^{12}C(α,α')

7.6(9)% of EWSR

B. John et all, Phys. Rev. C **68**, 014305 (1970).

Theoretical Calculation

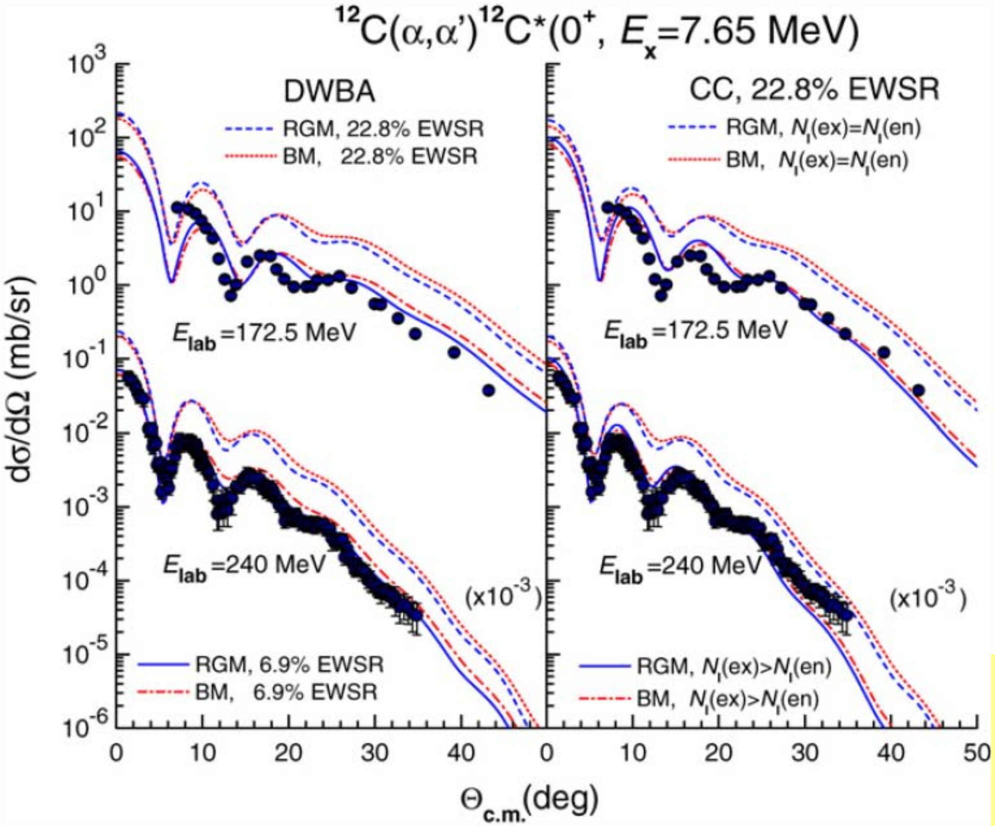
	3αRGM	FMD	BEC
ME (efm^2)	6.62	6.53	6.45
EWSR (%)	22.8	22.2	21.7

EWSR fraction extracted from (e,e') seems to be reliable.
Why is the monopole strength in (α,α') missing?

Double Folding Model Analysis

Microscopic analysis was done by D. T. Khoa and D. C. Cuong.

D. T. Khoa and D. C. Cuong, Phys. Lett. B **660**, 331—338 (2008).



- ✓ CDJLM (modified version of CDM3Y)
- ✓ 3αRGM or Breathing Mode (BM) transition density.
- ✓ DWBA or CC (0^+_1—2^+_1—0^+_2—0^+_1)

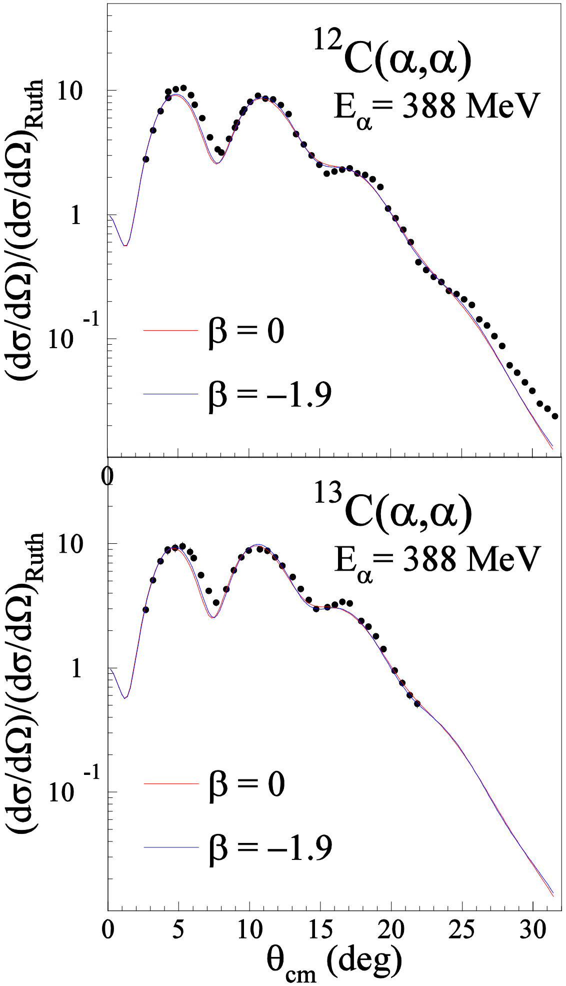
- ✓ Both DWBA and CC systematically overestimate at all energies.
- ✓ 3αRGM and BM give similar results.
- ✓ Consistent to the previous results.

N_I for the α + $^{12}C(0^+_2)$ channel was adjusted to obtain a reasonable CC result (NI ~ 2.5—3.4).

Strong absorption due to the dilute and weakly bound natures of the Hoyle state ???

Single Folding Model Analysis

Experimental data at RCNP is analyzed by single folding model.



Single folding by phenomenological αN interaction.

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

- GS densities are taken from
  - ^{12}C: ρ_{0p}: Electron Scattering
    - Assumption: $\rho_{0p} = \rho_{0n}$
  - ^{13}C: ρ_{0p}: Electron Scattering
    - $\rho_{0n}(r) = \rho_{0p}(r')$, $r' = (6/7)^{1/3} r$
- Two choices of αN interaction to fit dσ/dΩ

$$V\left(\left|\vec{r}-\vec{r}'\right|, \rho_0(r')\right) = -V\left(1+\beta_V \rho_0(r')^{2/3}\right)\exp\left(-\left|\vec{r}-\vec{r}'\right|^2/\alpha_V\right)$$
$$-iW\left(1+\beta_W \rho_0(r')^{2/3}\right)\exp\left(-\left|\vec{r}-\vec{r}'\right|^2/\alpha_W\right)$$

Density-independent (DI)

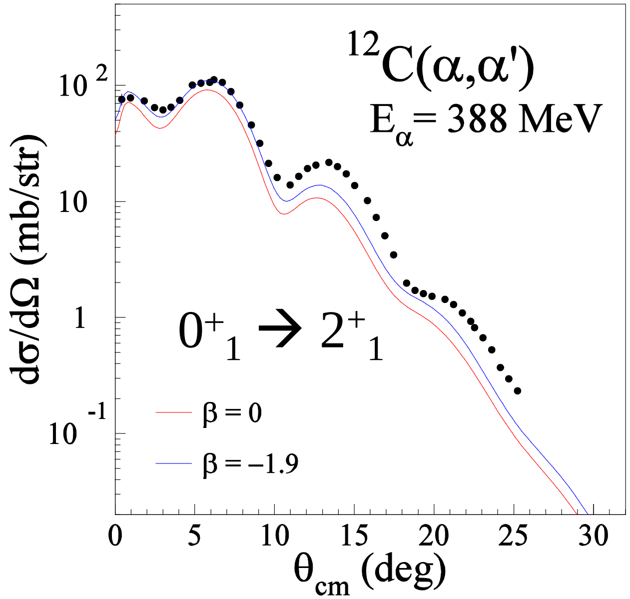
$$V = 16.9 \text{ MeV}, W = 11.7 \text{ MeV},$$
$$\alpha_V = \alpha_W = 4.38 \text{ fm}^2, \beta_V = \beta_W = 0$$

Density-dependent (DD)

$$V = 36.6 \text{ MeV}, W = 24.7 \text{ MeV},$$
$$\alpha_V = \alpha_W = 3.60 \text{ fm}^2, \beta_V = \beta_W = -1.9$$

Both DI and DD interaction give reasonable results.

Inelastic Scattering from ^{12}C

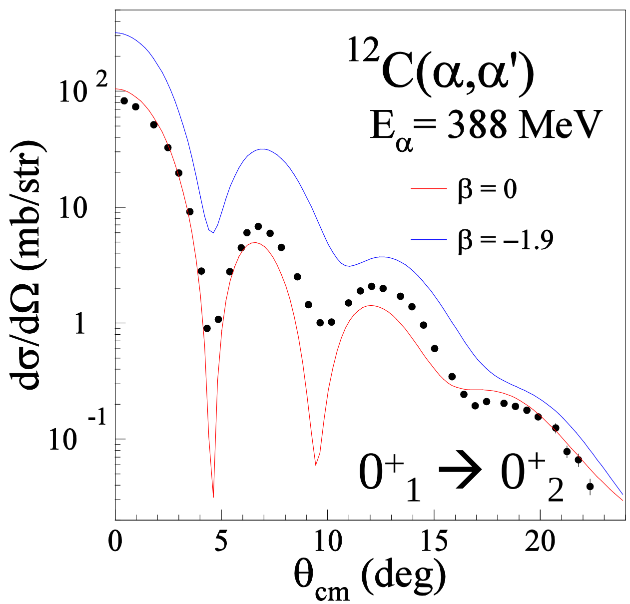


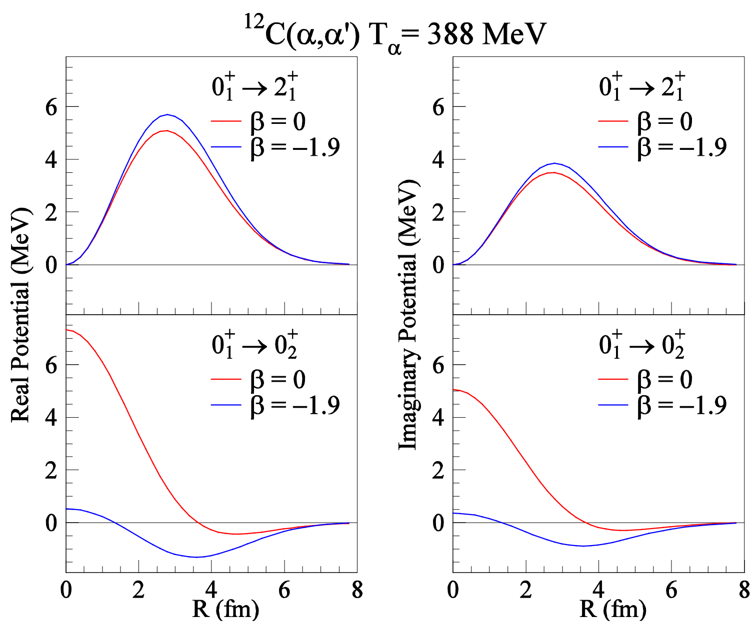
- Transition potential is obtained by a single folding model.

$$\delta U_L(r) = \int d\vec{r}'\,\delta\rho_L(r)\left(V\left(\left|\vec{r}-\vec{r}'\right|, \rho_0(r')\right) + \rho_0(r')\frac{\partial V\left(\left|\vec{r}-\vec{r}'\right|, \rho_0(r')\right)}{\partial \rho_0(r')} \right)$$

- Transition densities
  - $0^+_1 \rightarrow 2^+_1$: From macroscopic model and known B(E2) value.
  - $0^+_1 \rightarrow 0^+_2$: From electron scattering.

DD int. significantly overestimates E0 cross section.

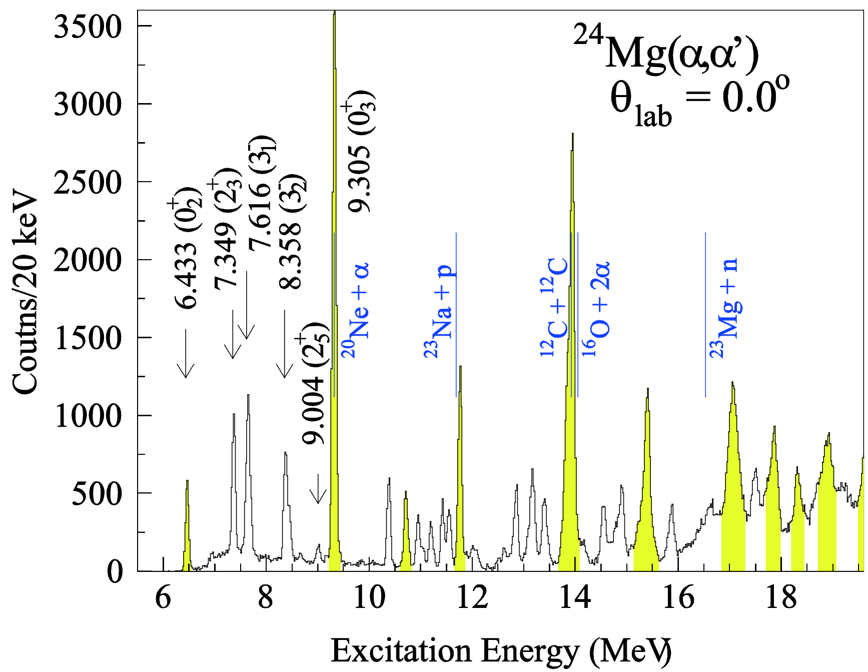


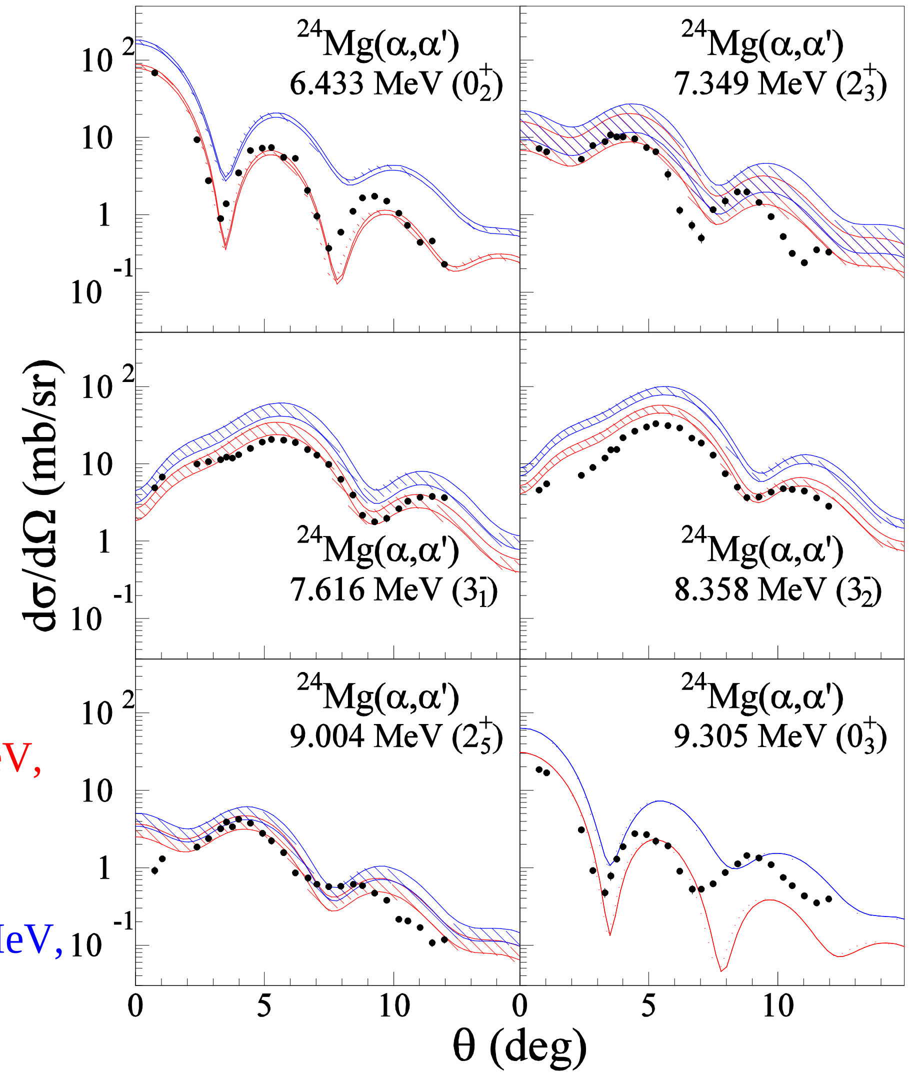


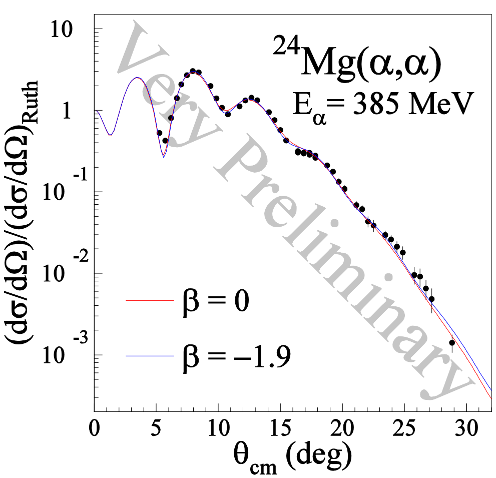
Too strong density dependence in the inner region of the Hoyle state.
Is the strong absorption really needed?

Discrete States in ^{24}Mg

Discrete states in ^{24}Mg are also analyzed by the single folding model.







$V = 13.1$ MeV, $W = 8.8$ MeV,
$\alpha_V = \alpha_W = 5.03$ fm,
$\beta_V = \beta_W = 0$

$V = 28.8$ MeV, $W = 19.6$ MeV,
$\alpha_V = \alpha_W = 4.05$ fm,
$\beta_V = \beta_W = -1.9$

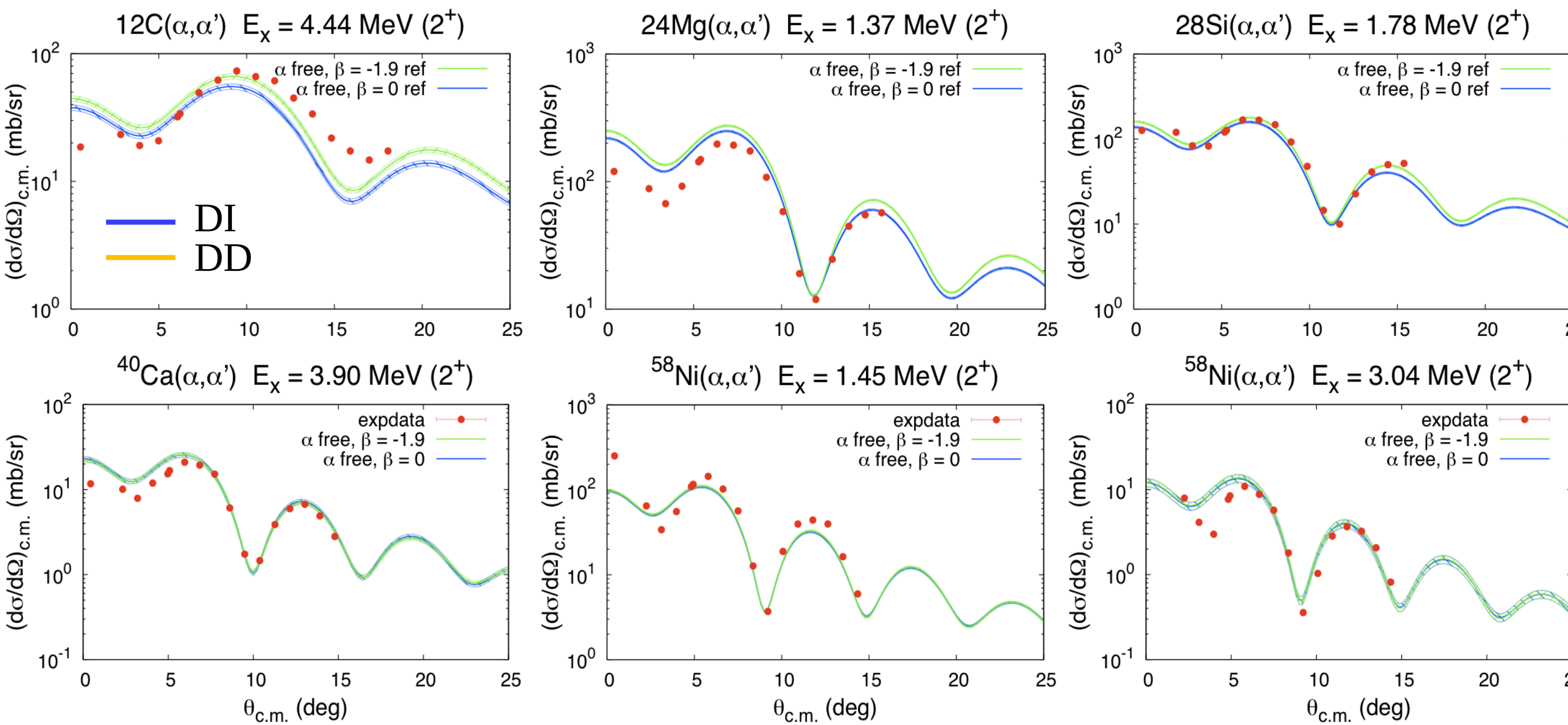
DD overestimates cross section for the 0^+ and 3^- states.

Inelastic α Scattering at 130 MeV

Both DD and DI calculation agree with the experiment for the 2^+ transitions.

Nuclide	E_x (MeV)	J_n^{π}	$B(\mathrm{E2})_{\mathrm{exp}}$ ($e^2\mathrm{fm}^4$)
^{12}C	4.44	2_1^+	39.0 ± 1.9
^{24}Mg	1.37	2_1^+	437 ± 9.0
^{28}Si	1.78	2_1^+	328 ± 9.4

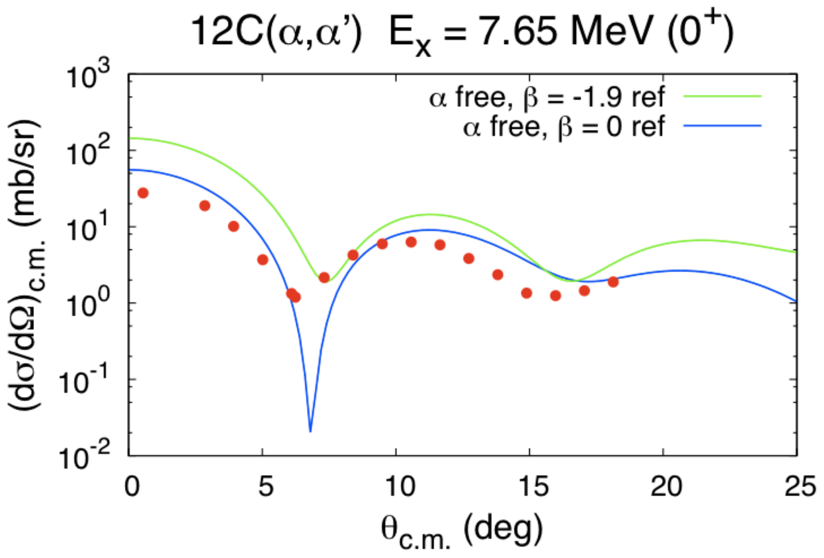
Nuclide	E_x (MeV)	J_n^{π}	$B(\mathrm{E2})_{\mathrm{exp}}$ ($e^2\mathrm{fm}^4$)
^{40}Ca	3.90	2_1^+	92.5 ± 5.7
^{58}Ni	1.45	2_1^+	665 ± 18
^{58}Ni	3.04	2_2^+	85 ± 9.2

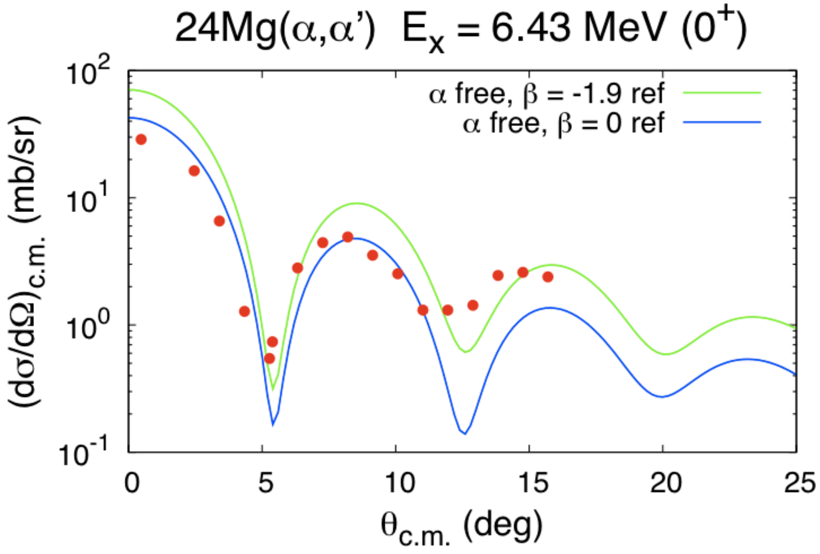


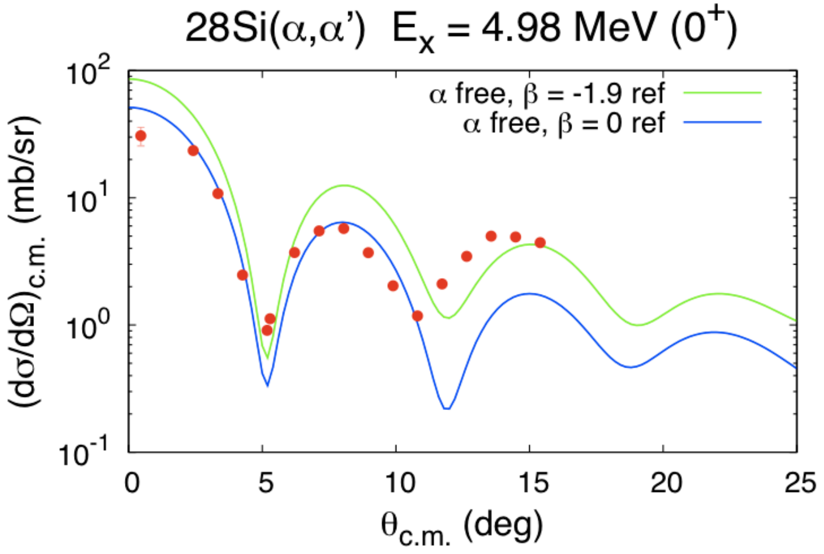
Monopole transitions at 130 MeV

DI calculation agrees with the experiment, but DD calculation overestimates.

Nuclide	E_x (MeV)	J_n^π	$B(E0)_{exp}$ (e^2)
^{12}C	7.65	0_2^+	30.3 ± 0.04
^{24}Mg	6.43	0_2^+	44.9 ± 0.16
^{28}Si	4.98	0_2^+	46.2 ± 0.16







Summary of the first part

- Missing monopole strength is not special for the Hoyle state.
- Missing monopole strength is observed in the other nuclei.
- Density independent calculation does not draw the missing monopole strength.
- Need for help from reaction theorists.

Search for α Cluster States in ^{24}Mg

α Condensed States in Heavier N = 4n Nuclei

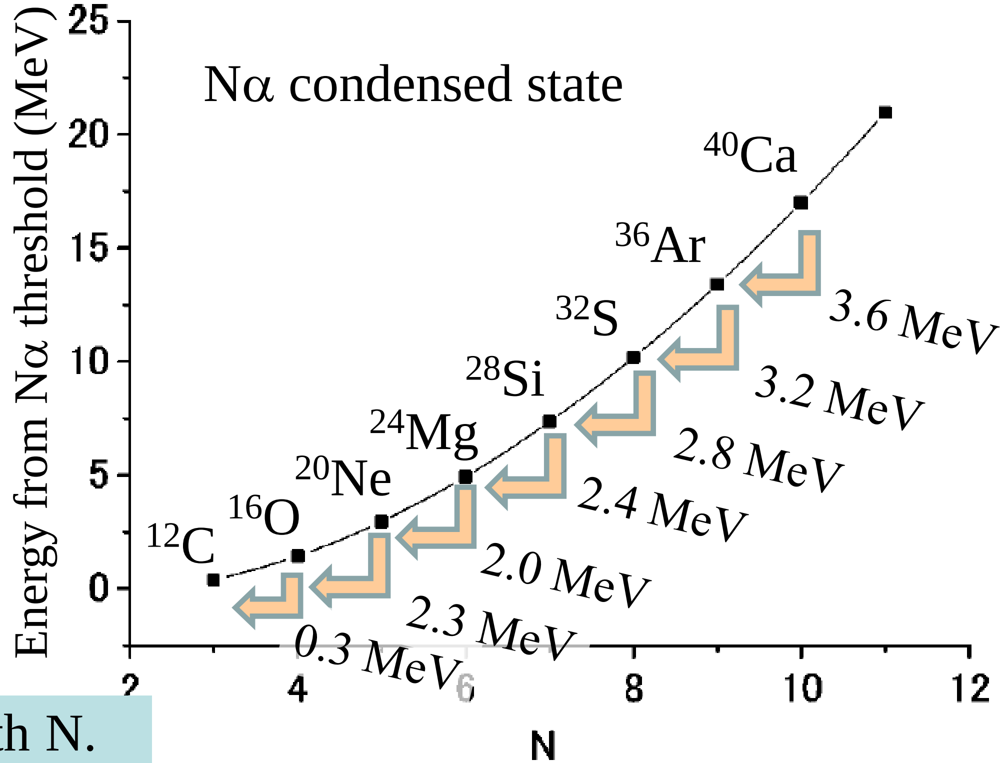
α condensed states in ^{8}Be and ^{12}C seem to be established.

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.

α Condensed State with Core Nucleus

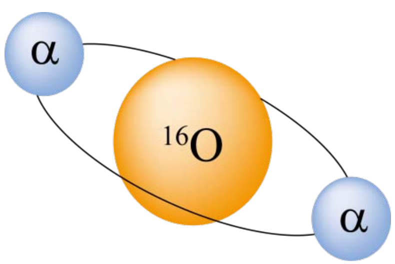
Possibility of α condensed states with core nuclei is proposed.

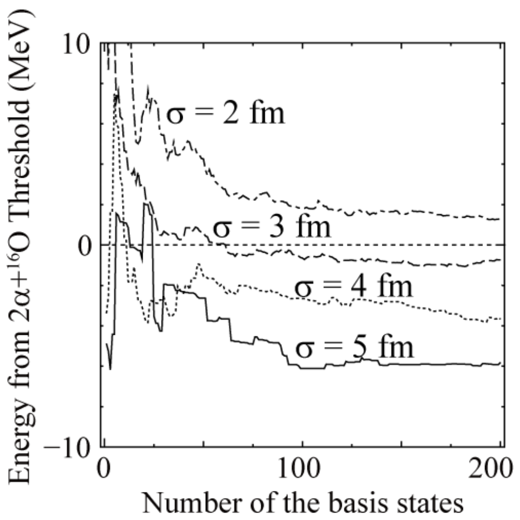
Attractive potential for α clusters provided by the core nucleus might stabilize the α condensed state in heavy nuclei.

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

Schuck-type wave function for ^{24}Mg

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





$\mathcal{A}$: 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

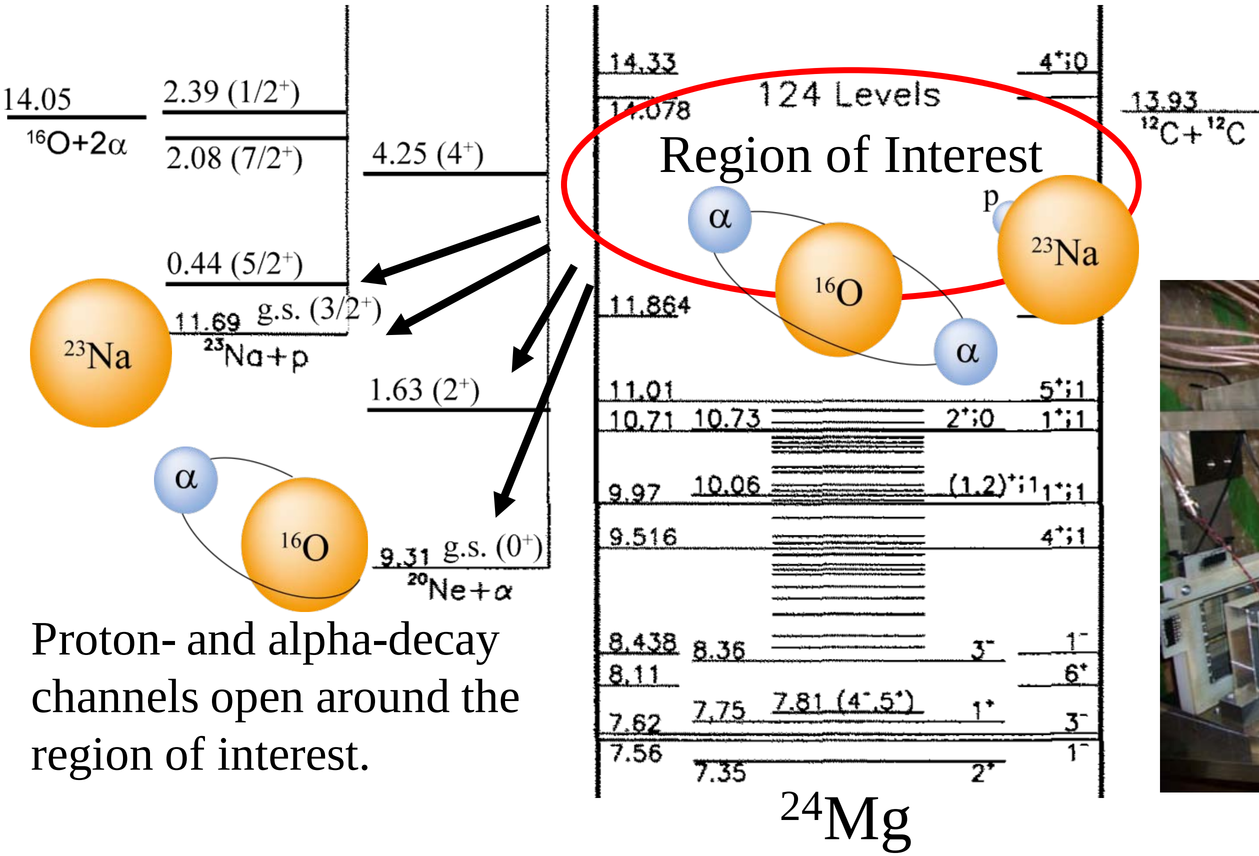
The ^{16}O core is expressed by the tetrahedron configuration of 4α with the relative distance of 1 fm.

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 in ^{24}Mg was proposed.

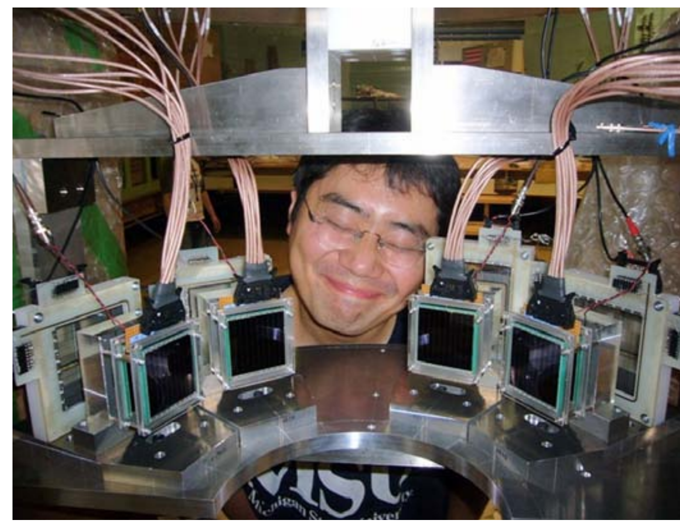
Decay Particles from α Condensed States

Decay-particle measurement provides structural information.



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

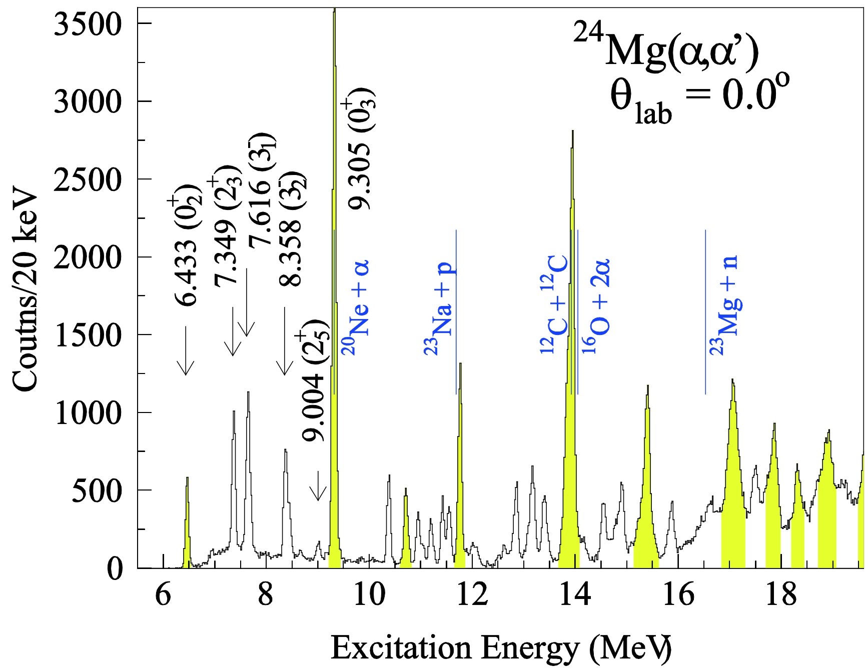
4 Silicon counter telescopes (5 layers) are installed in the scattering chamber, and cover 2.5% of 4π (309 mSr).

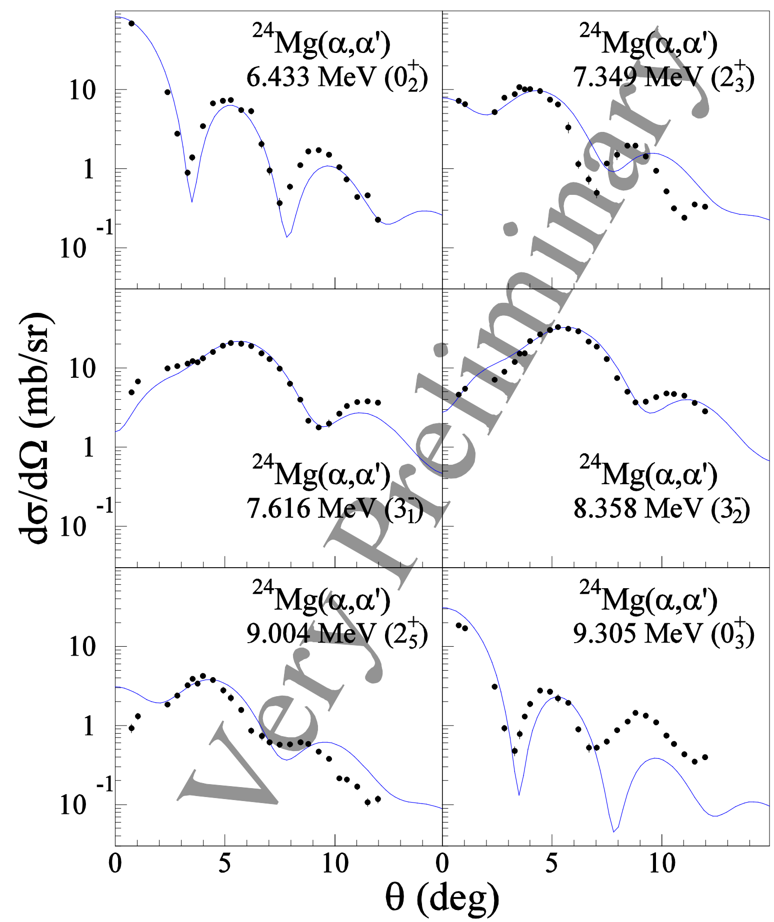


- Complementary information for the E0 strength is expected.
  - – α cluster state should prefer to decay into the alpha-decay channel.
  - – GS in ^{20}Ne is a well-known α + ^{16}O cluster state.

Discrete States in ^{24}Mg

Several discrete states were analyzed by the single folding model.

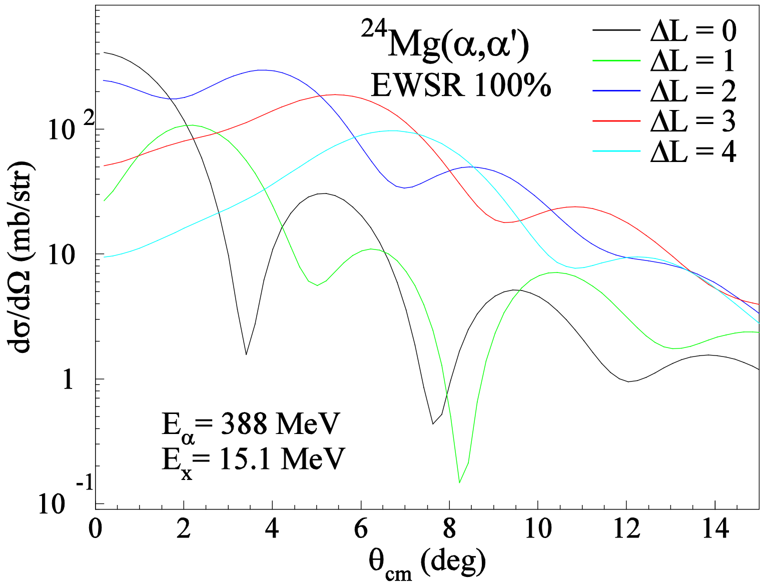


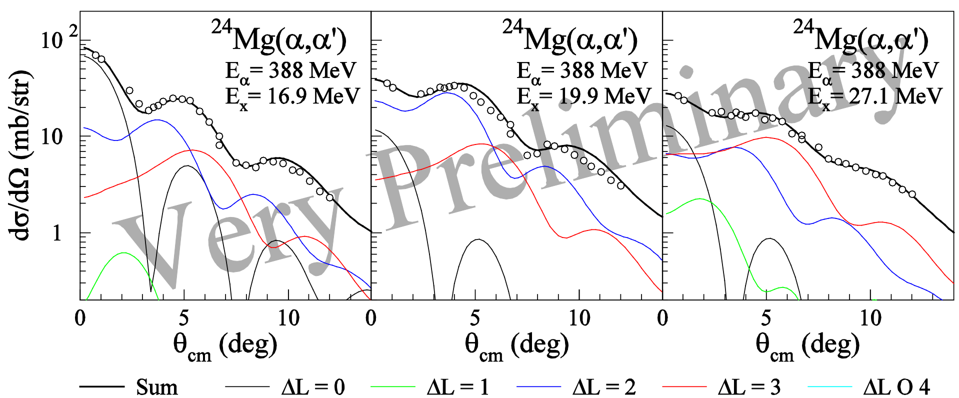


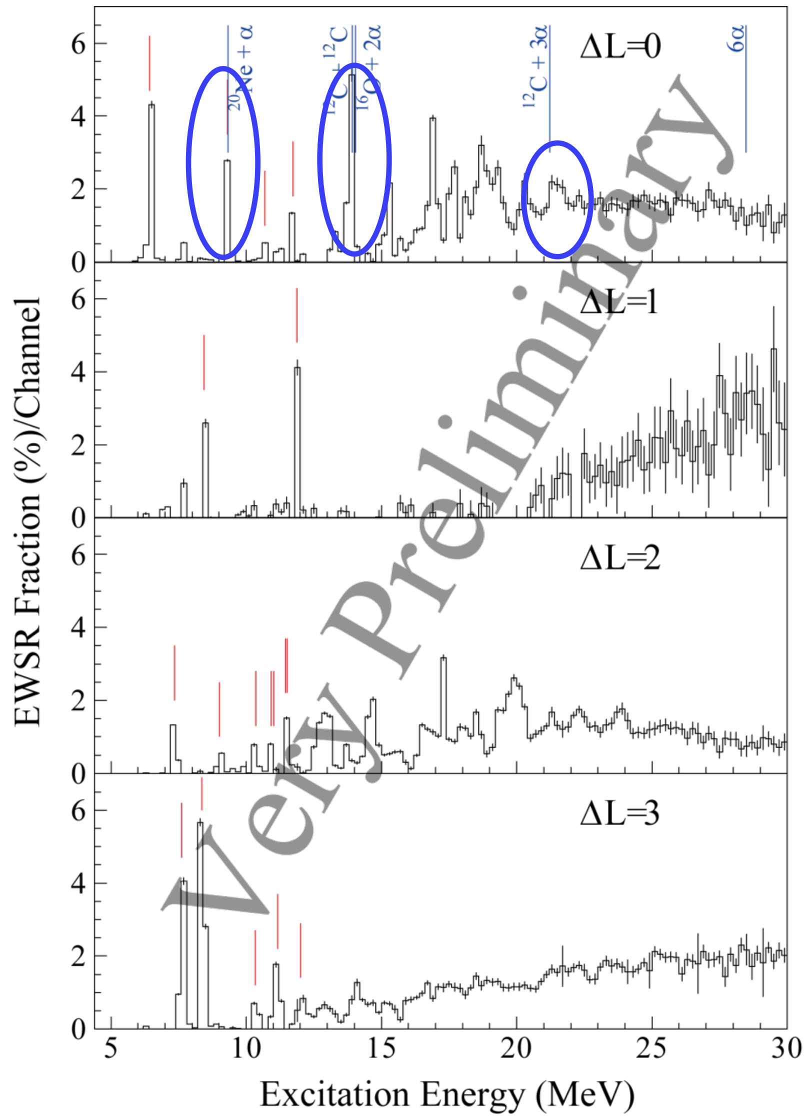
Reasonable results were obtained
for the discrete states.

Multipole Decomposition Analysis

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



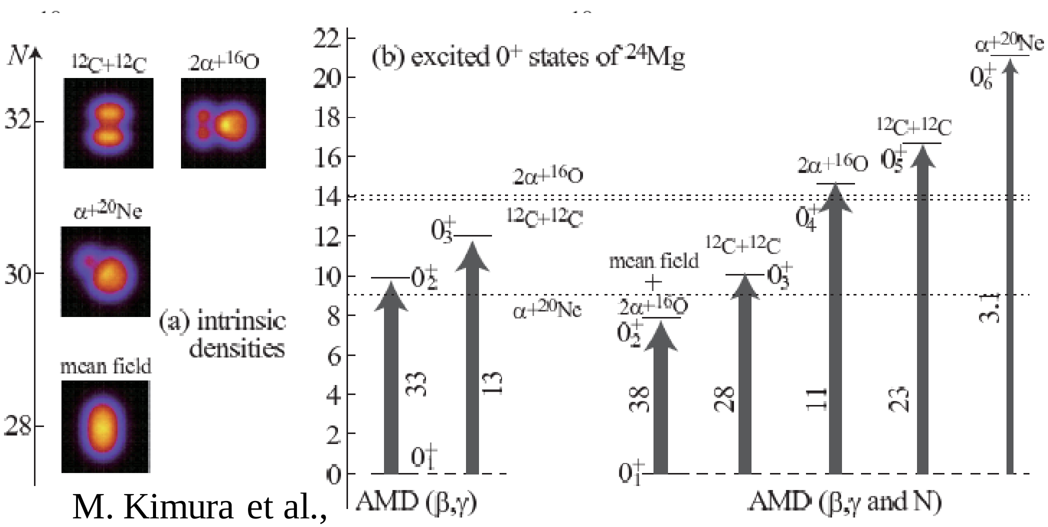




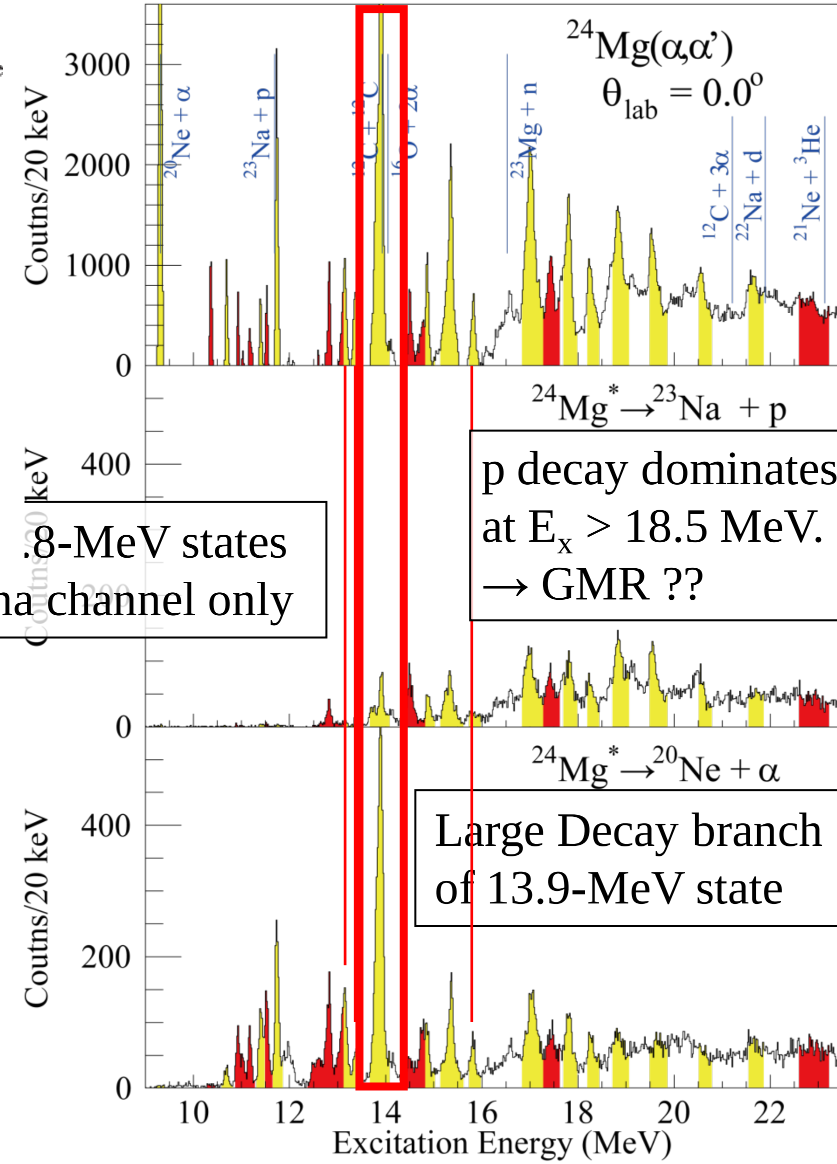
Fine structure in ΔL=0 strengths was observed.

Decay Particle Measurement

Decay to the proton and alpha emission channels were identified.



M. Kimura et al.,



...8-MeV states decay to the alpha channel only

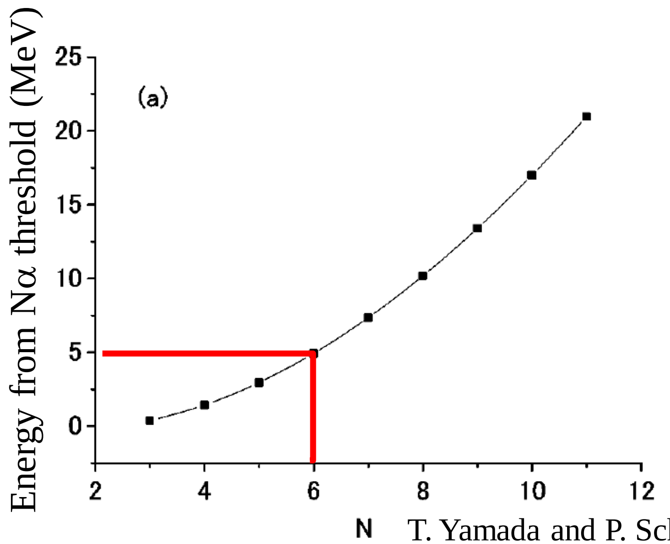
p decay dominates at E_x > 18.5 MeV. → GMR ??

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 + 2α thresholds has a large decay branch to ^{20}Ne.
- Further analysis is needed to clarify the cluster structures in ^{24}Mg.

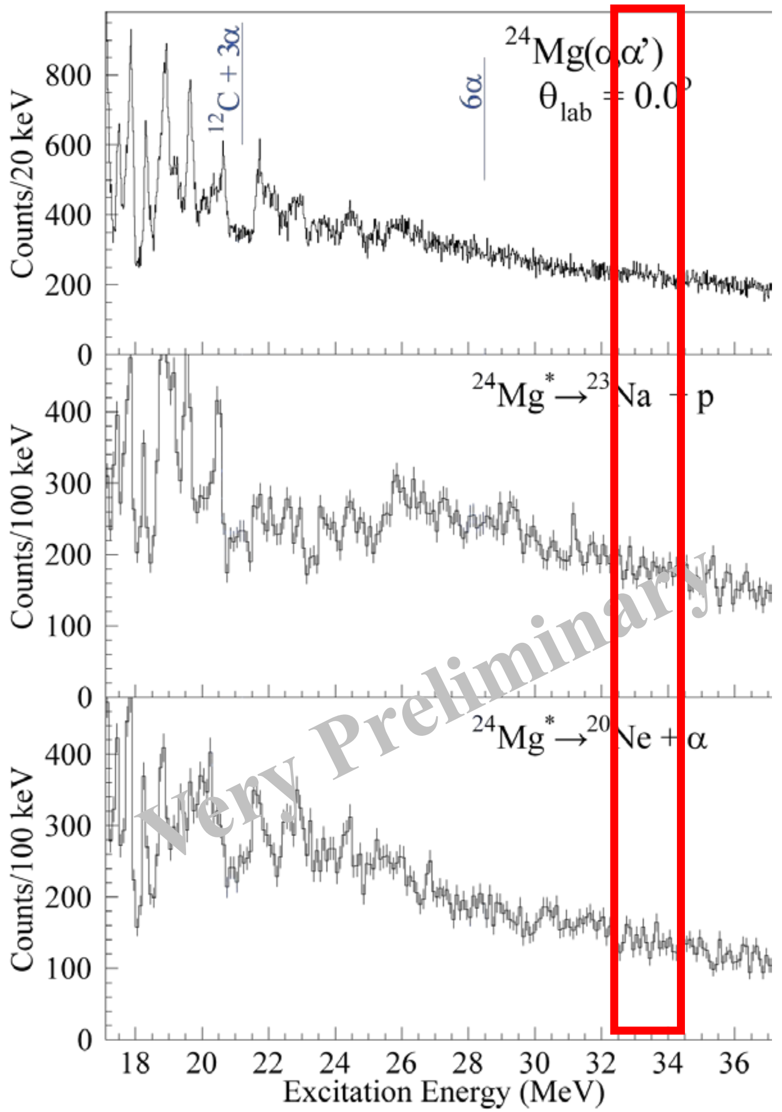
Highly Excited Region

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



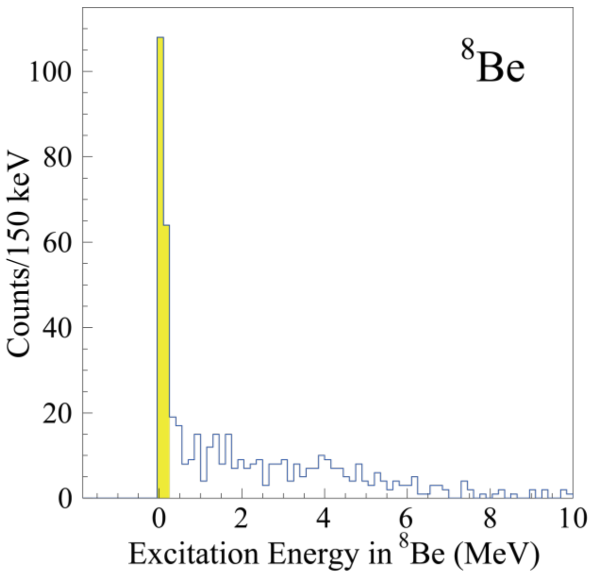
T. Yamada and P. Schuck,
Phys. Rev. C **69**, 024309 (2004).

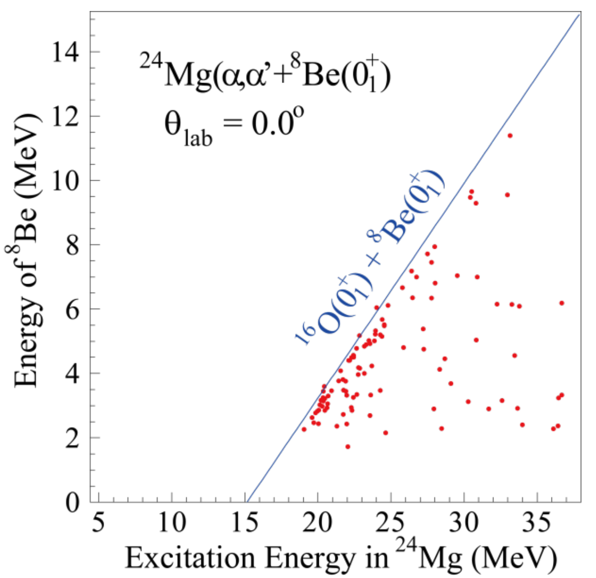
- 6α condensed state is expected at 5 MeV above the 6α threshold.
  - $E_x \sim 28.5 + 5 = 33.5$ MeV
- No significant structure suggesting the 6α condensed state.
  - Several small structures indistinguishable from the statistical fluctuation. → Need more statistics.

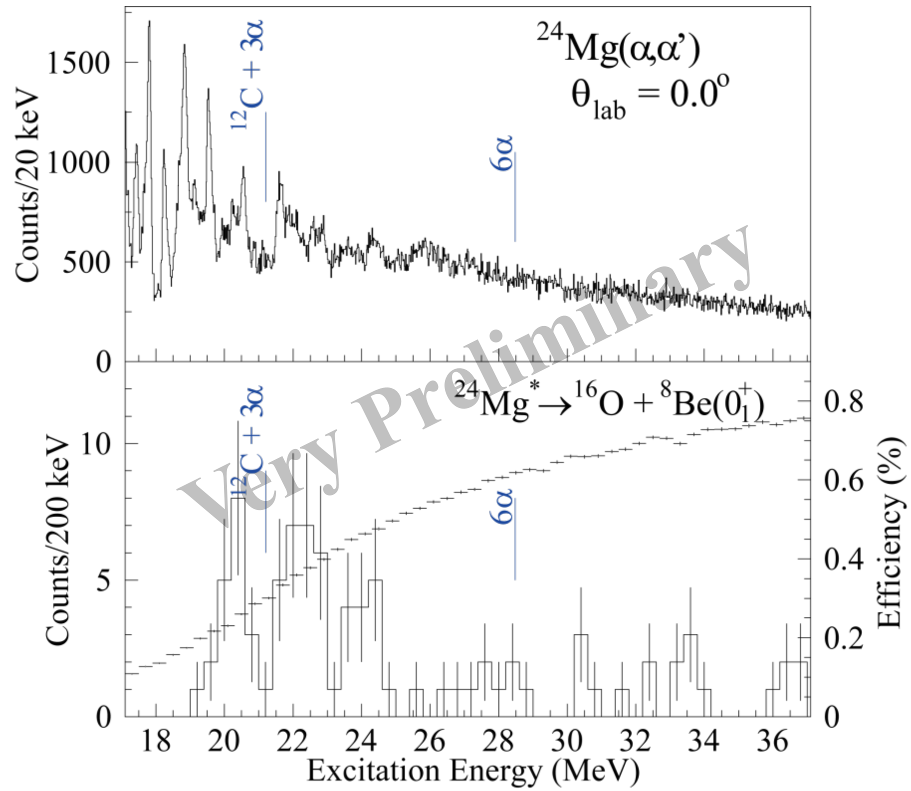


^{8}Be Emission Events

^{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.

Summary

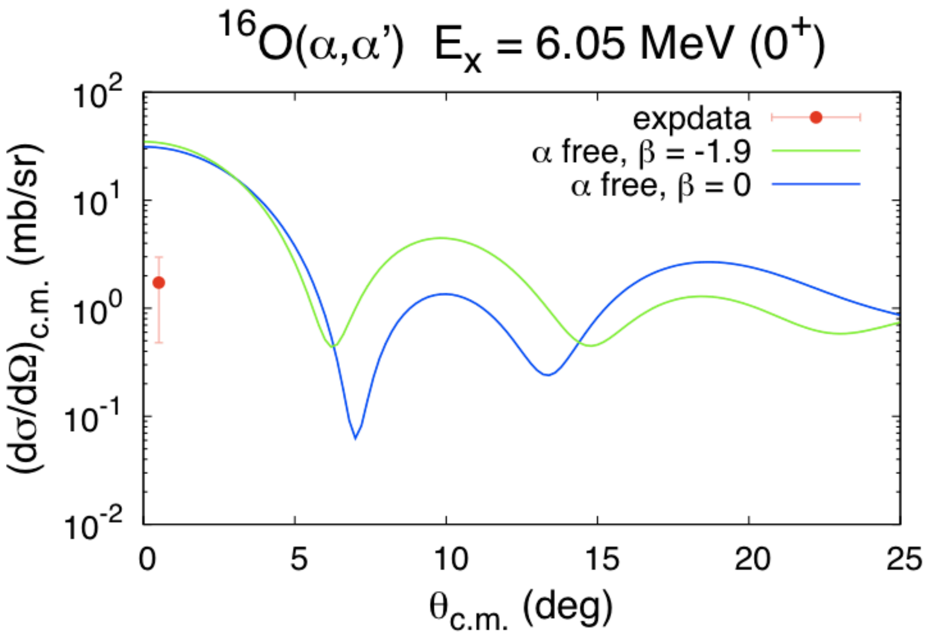
- Inelastic α scattering should be a useful tool to search for α cluster states.
  - "Missing monopole strength" problems are partially solved by using the DI interaction, but still need for help from reaction theorists.
- α Condensed states in ^{24}Mg were searched.
  - The 13.9-MeV state is the most probable candidate of the 2α condensed state around the ^{16}O core.
  - The 13.1, 13.4 and 15.8-MeV states decay to the ^{20}Ne + α channel only.
  - Several states at 20.5, 22.0, and 24.3 MeV were found to decay into the ^{16}O + ^{8}Be(0^+_1) channel.
  - Expected 6α condensed state was not identified.

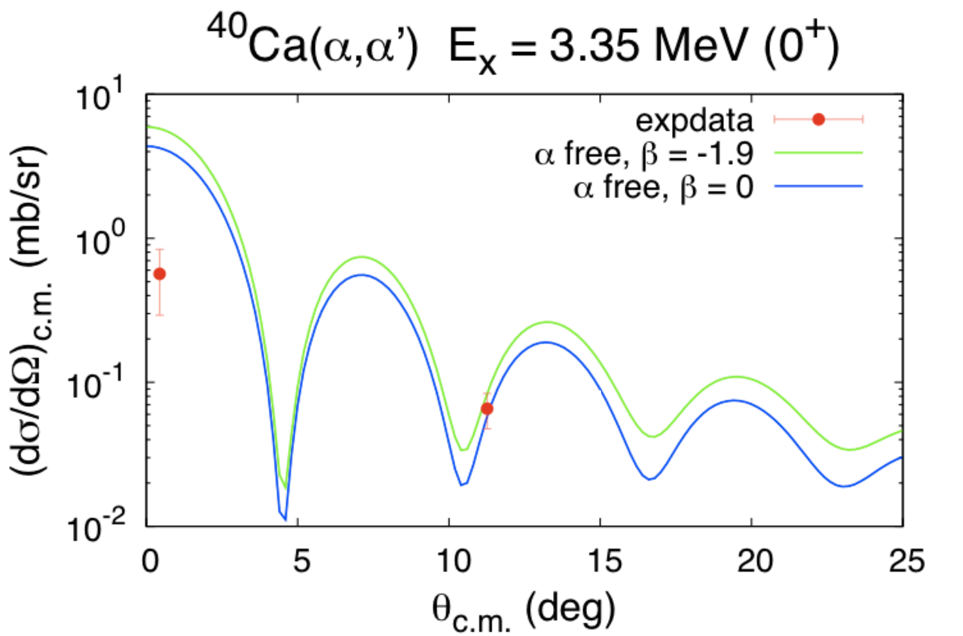
Monopole transitions in ^{16}O and ^{40}Ca

DWBA extraordinary overestimates $d\sigma/d\Omega$ for the 0^+_2 states in ^{16}O and ^{40}Ca.

Uncertainties in the αN interaction still remain.
Effects of isovector component???

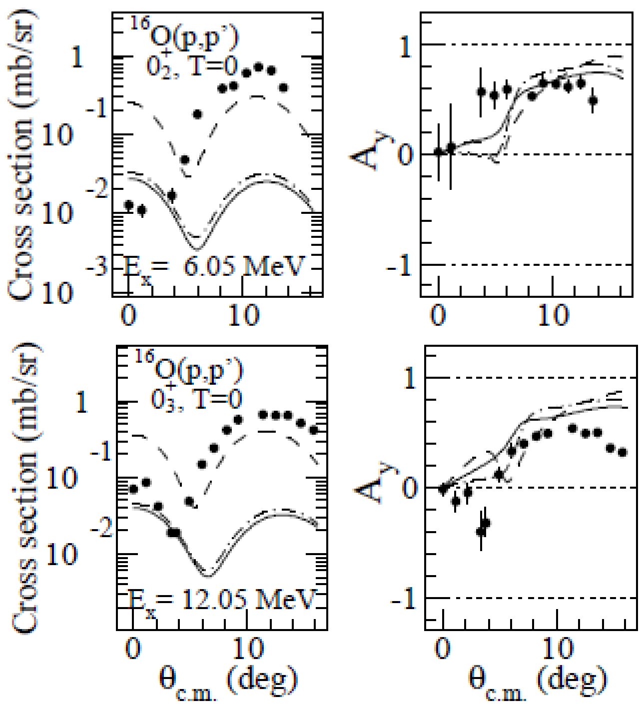
Nuclide	E_x (MeV)	J_n^π	$B(E0)_{ele}$ (e^2)
^{16}O	6.05	0_2^+	11.4 ± 0.01
^{40}Ca	3.35	0_2^+	7.34 ± 0.002

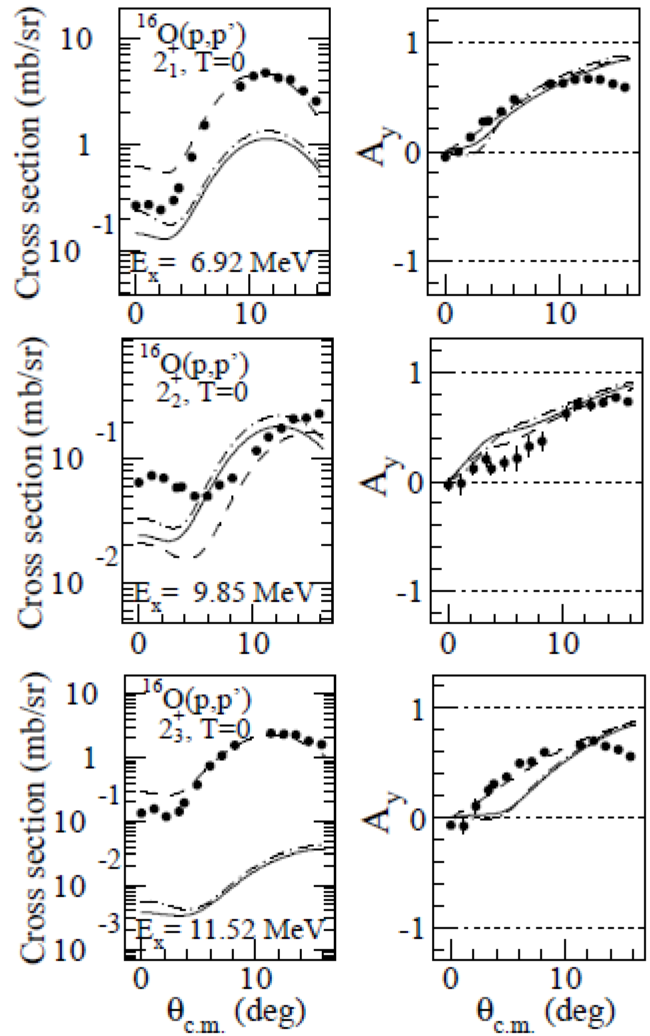




Inelastic proton scattering from ^{16}O

Inelastic proton scattering from ^{16}O was measured at 400 MeV.



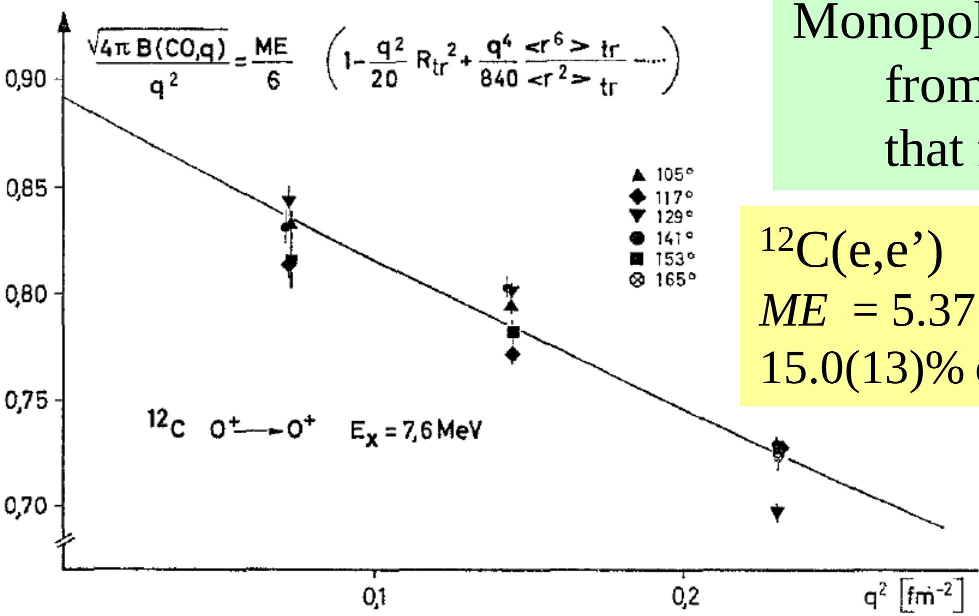


Dash-dotted lines: LDA with (e,e') form factor

0^+_1, 0^+_2 : LDA underestimates by a factor of ~2.
2^+_1, 2^+_3 : LDA agrees with the experiment.
2^+_2 : Strange behavior

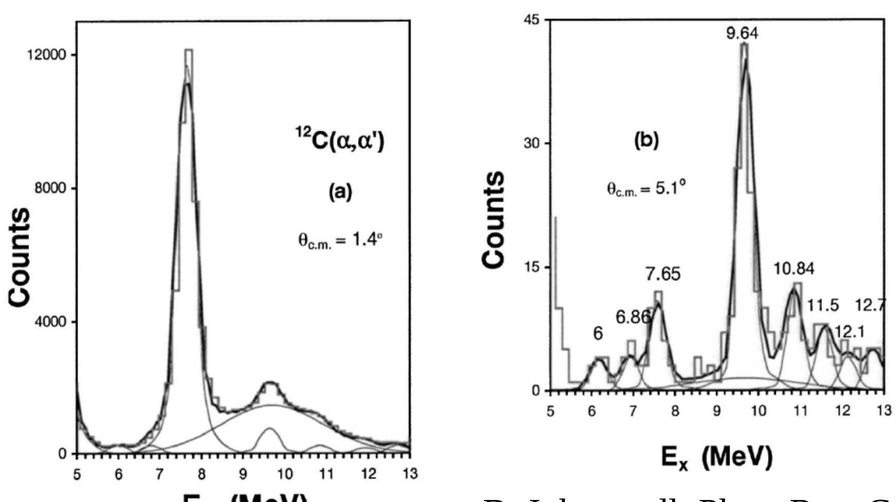
Missing Monopole Strength

Monopole strengths for the Hoyle state from hadron scattering is 50% smaller than that from electron scattering.

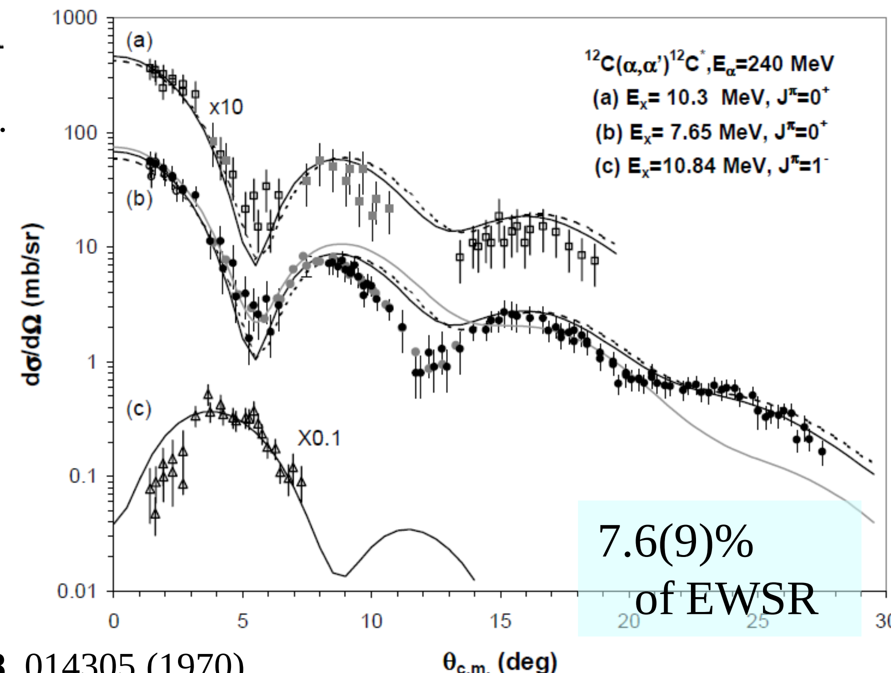


^{12}C(e,e')
ME = 5.37 (22) efm^2
15.0(13)% of EWSR

E. Strehl, Z. Phys. **234**, 416—442 (1970).



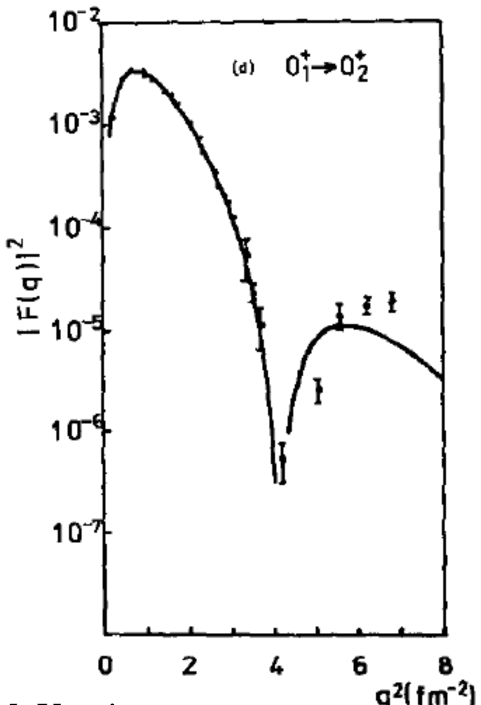
B. John et all, Phys. Rev. C **68**, 014305 (1970).



7.6(9)% of EWSR

Theoretical Models

3α RGM



M. Kamimura, Nucl. Phys. A**351**, 456—480 (1981).

Fig. 1d.

Solid: FMD, Dotted: BEC

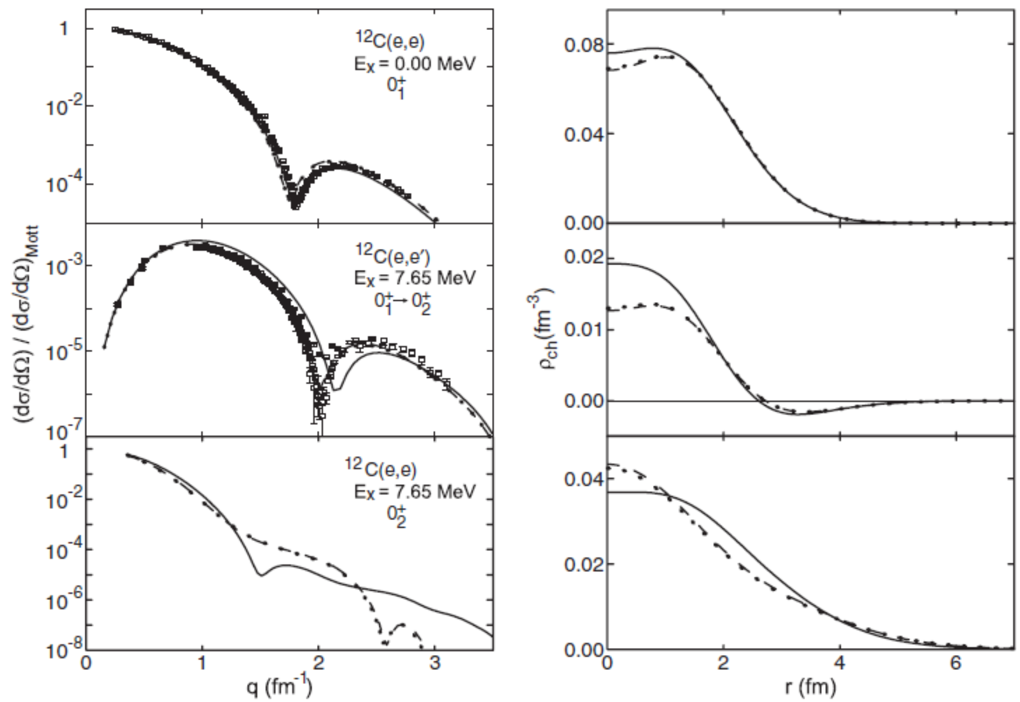


FIG. 1. Left column: FMD (solid lines), α cluster (dashed lines), and BEC (from [17], dotted lines) predictions of the charge form factors in ^{12}C in comparison to experimental data (open squares). Elastic scattering on g.s. (top panel), transition to the Hoyle state (middle panel), elastic scattering on the Hoyle state (bottom panel). Right column: Corresponding charge density distributions.

M. Chernykh et all, Phys. Rev. Lett. **98**, 032501 (2007).

	3αRGM	FMD	BEC
ME (efm^2)	6.62	6.53	6.45
EWSR Fraction (%)	22.8	22.2	21.7

EWSR fraction extracted from (e,e’) seems to be reliable.
Why is the monopole strength in (α,α’) missing?

Inelastic α Scattering to the 2^+_1 state in ^{12}C

Inelastic α scattering to the 2^+_1 state at 4.44 MeV was also examined.

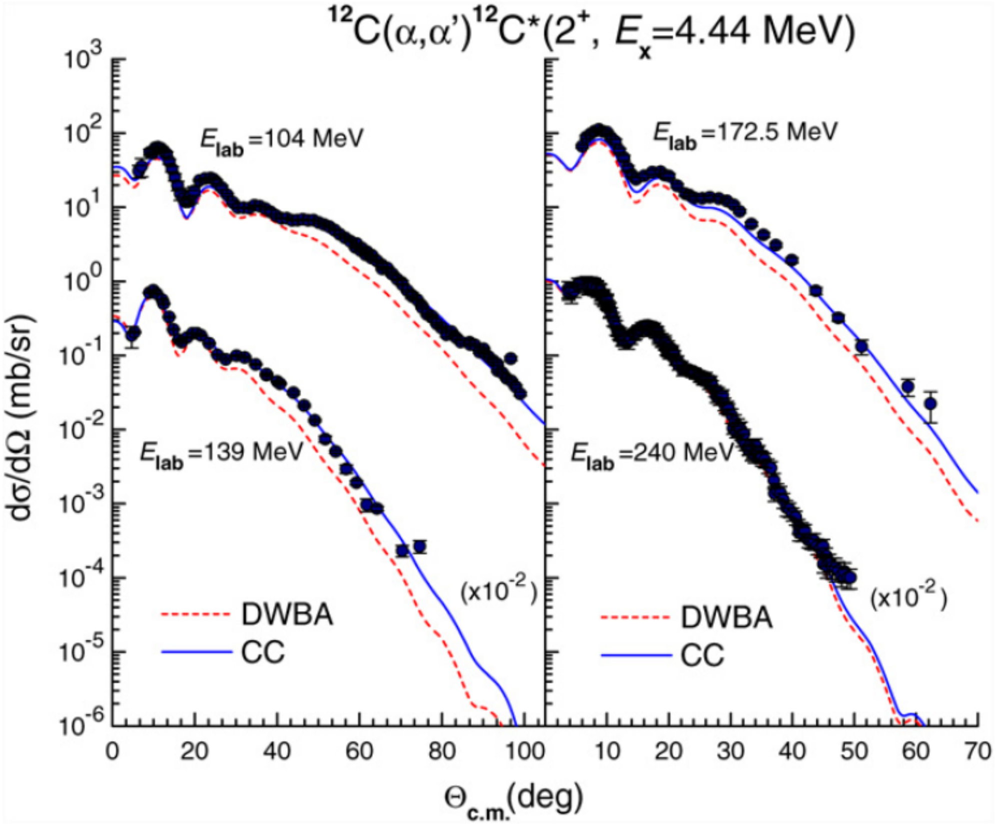


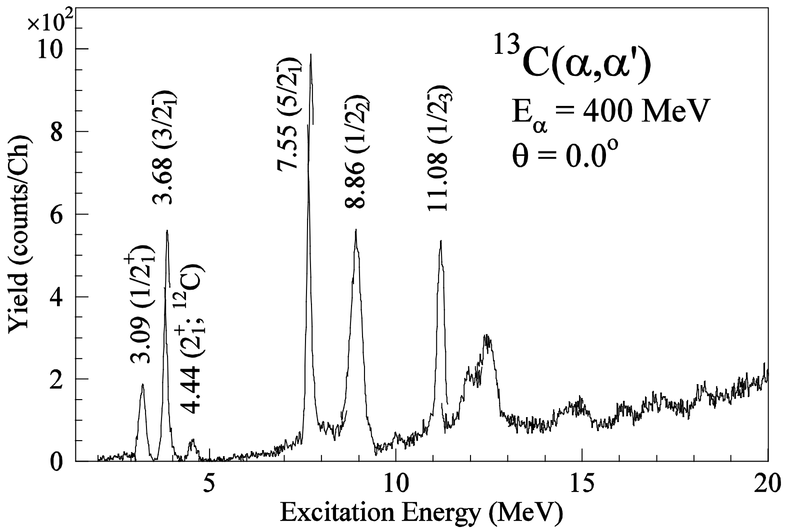
Fig. 5. Inelastic $\alpha + {}^{12}C$ scattering data measured at $E_{lab} = 104$ [1,2], 139 [3], 172.5 [4] and 240 [15] MeV for the 2_1^+ excitation at 4.44 MeV in ^{12}C in comparison with the DWBA and CC results obtained with the complex folded OP and inelastic folded FF. See more details in text.

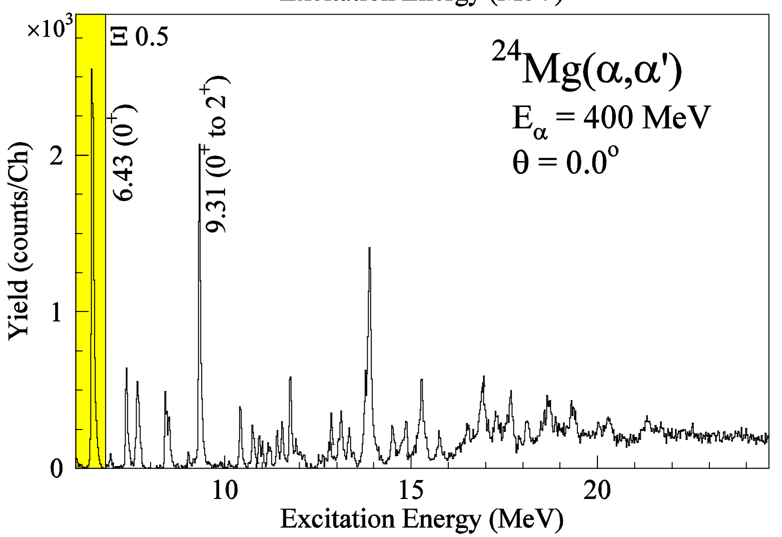
- Experimental data is nicely reproduced by the CC calculation at all energies **without the enhancement of N_I** in the $\alpha + {}^{12}C(2^+_1)$ channel.
- Enhanced absorption found for the $\alpha + {}^{12}C(0^+_2)$ channel seems to be associated with the fragile structure and short lifetime of the Hoyle state.
  - 2^+_1 lives about 600 times longer than the Hoyle state.
  - 3^-_1 also shows a sizable enhancement of absorption.

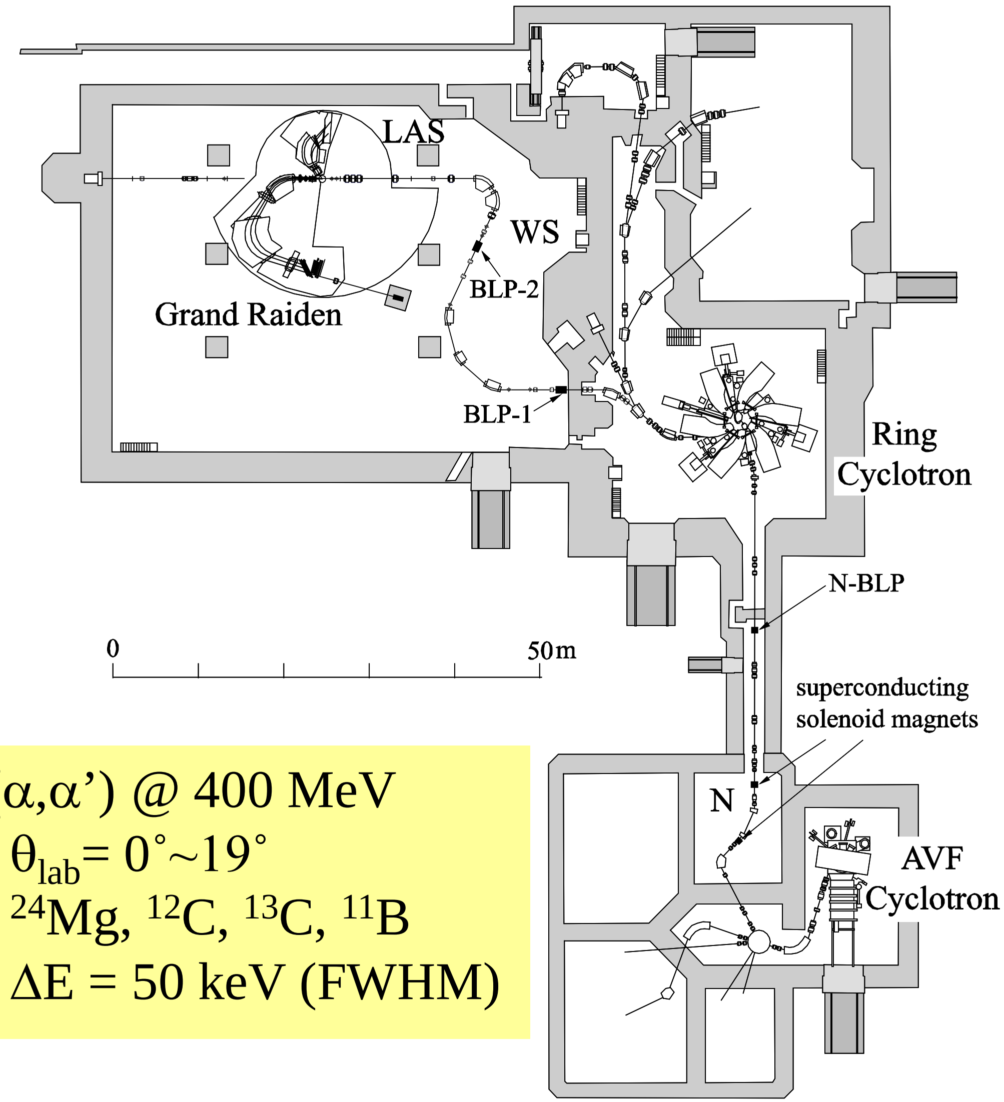
Experiment

Experiment was performed at RCNP, Osaka University.

Background-free measurement at extremely forward angles







(α,α') @ 400 MeV

$\theta_{lab} = 0^\circ \sim 19^\circ$

^{24}Mg, ^{12}C, ^{13}C, ^{11}B

ΔE = 50 keV (FWHM)