Alpha inelastic scattering
and
cluster structures in light nuclei

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Contents

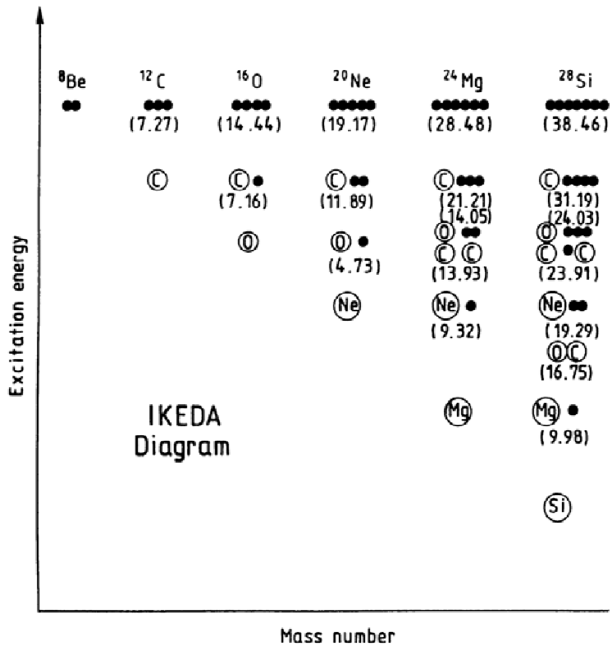
α Condensed State

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

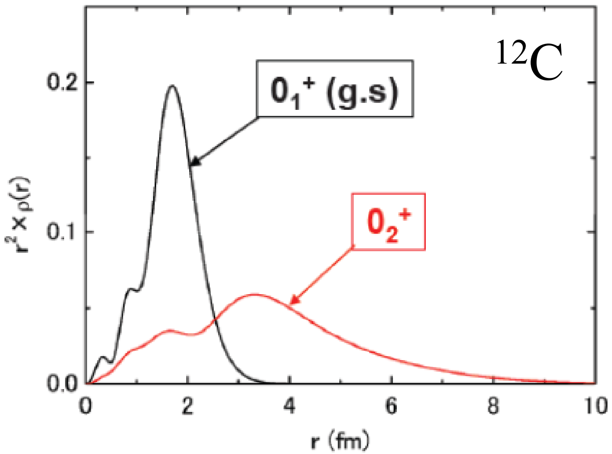
The 0^+_2 state at $E_x = 7.65$ MeV in ^{12}C , a famous 3α cluster state, is called “Hoyle state”.

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

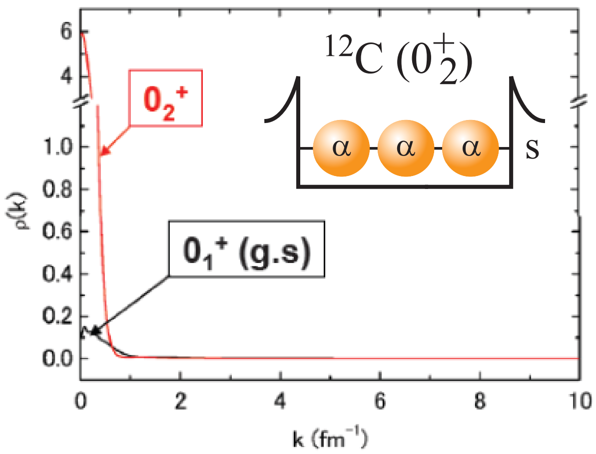
A. Tohsaki et al., Phys. Rev. Lett. **87**, 192501 (2001).



Density × r^2



Momentum Distribution

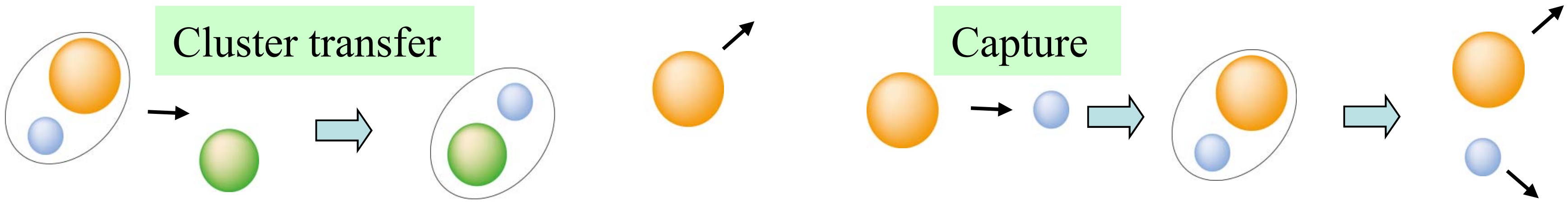


T.Yamada and P. Schuck, Euro. Phys. J. A **26**, 185 (2005).

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?

How should we excite Cluster States?

Various reactions were devoted to excite cluster states.



- ✓ Cluster-transfer reaction
  - ☹ Complex reaction mechanism due to the low incident energy.
  - ☹ Small reaction cross section.
  - ☹ Limited energy resolution.
- ✓ Low-energy resonant capture reaction
  - ☹ Sensitive above the cluster-emission threshold only.
  - ☹ Coulomb barrier disturbs the reaction near the threshold.

Inelastic scattering can be a complementary probe.

- ☺ Simple reaction mechanism at intermediate energies.
- ☺ High resolution measurement is possible.
- ☺ Sensitive to the entire E_x region.
- ☺ Selectivity for the isoscalar natural-parity excitation..

E0 Strengths and α Cluster Structure

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

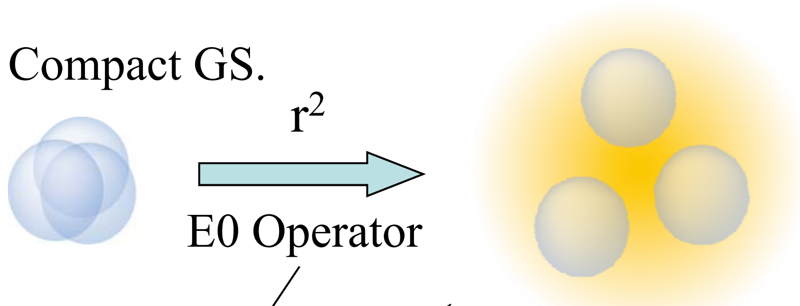
T. Kawabata *et al.*, Phys. Lett. B **646**, 6 (2007).

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.

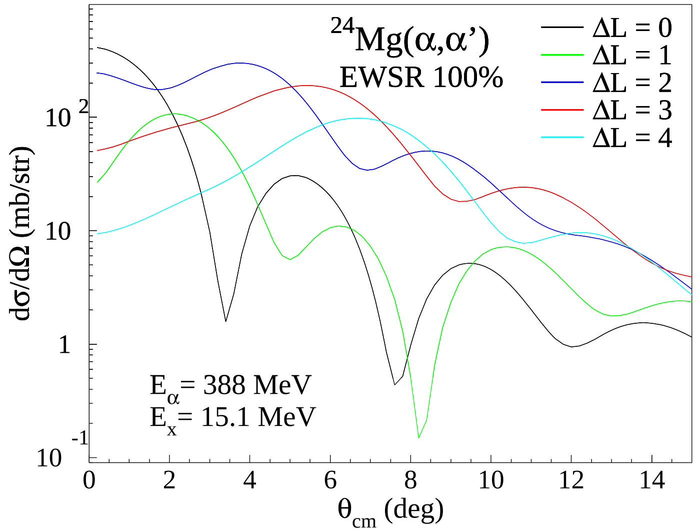
- Simple reaction mechanism
  - Good linearity between dσ/dΩ and B(ô).

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

  - 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}.

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



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

α Condensed States in Heavier N = 4n Nuclei

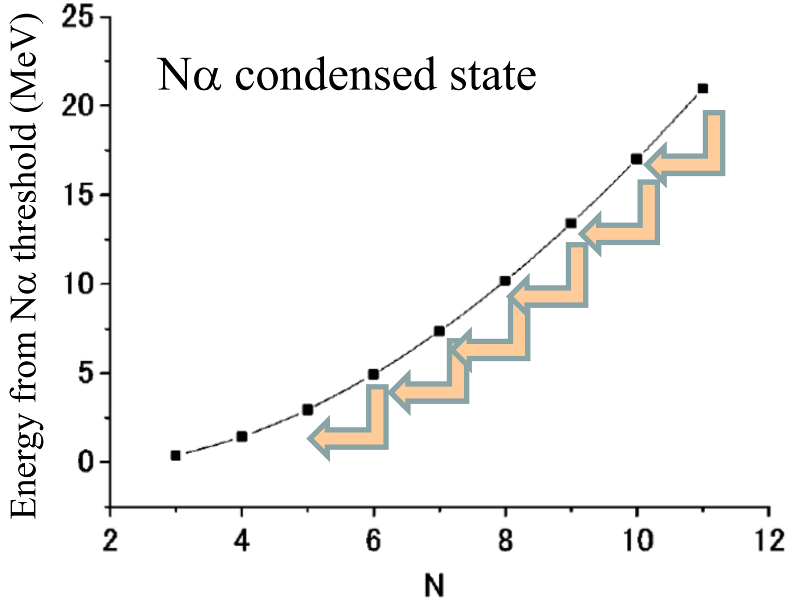
α condensed states in ^{8}Be and ^{12}C seem to be established.

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.

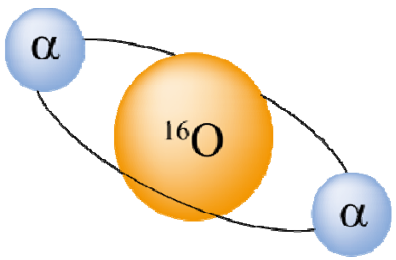
Attractive potential for α clusters provided by the core nucleus might stabilize the α condensed state in heavy nuclei.

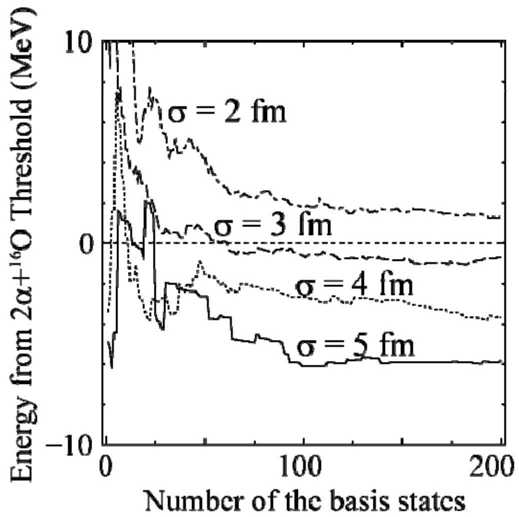
N. Itagaki *et al.*, Phys. Rev. C **75**, 037303 (2007).

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





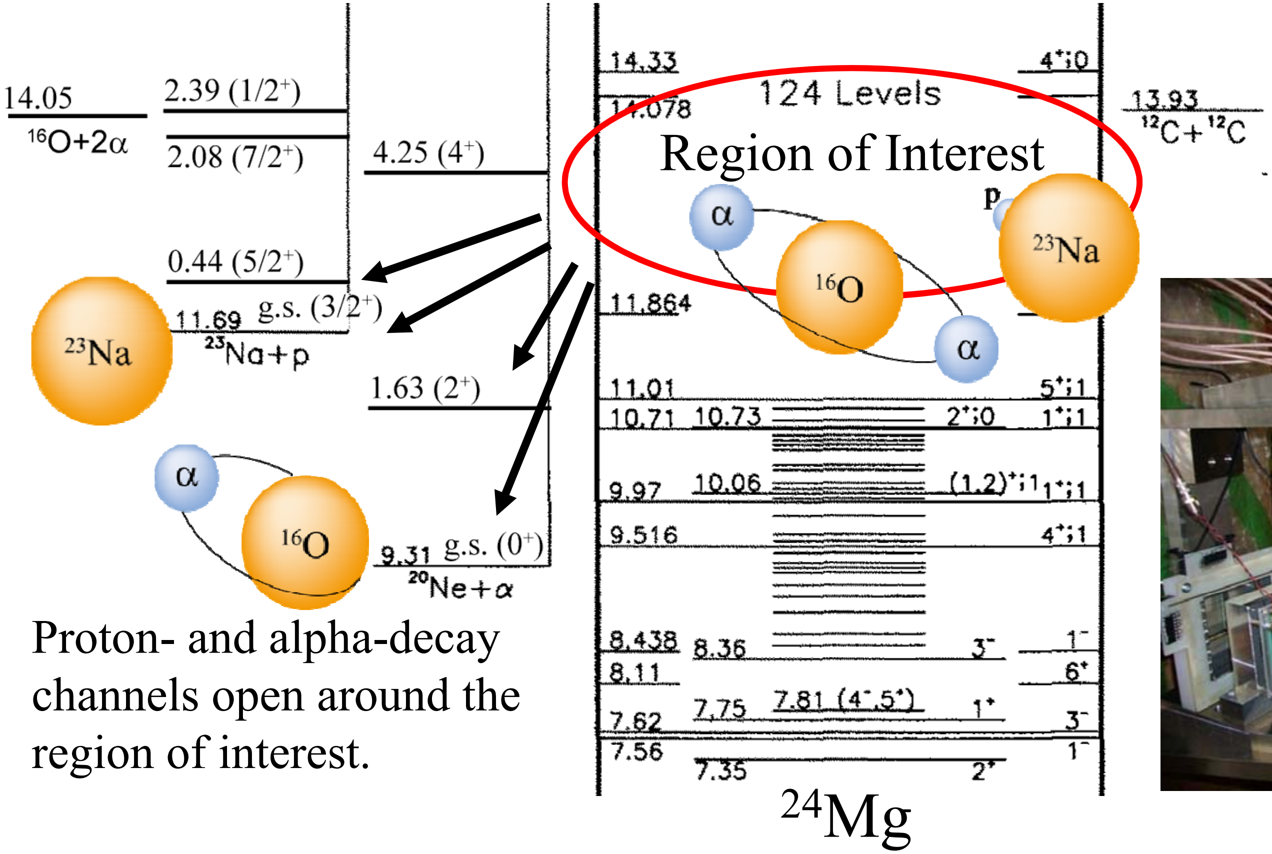
The ^{16}O core is expressed by the tetrahedron configuration of 4α with the relative distance of 1 fm.

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.

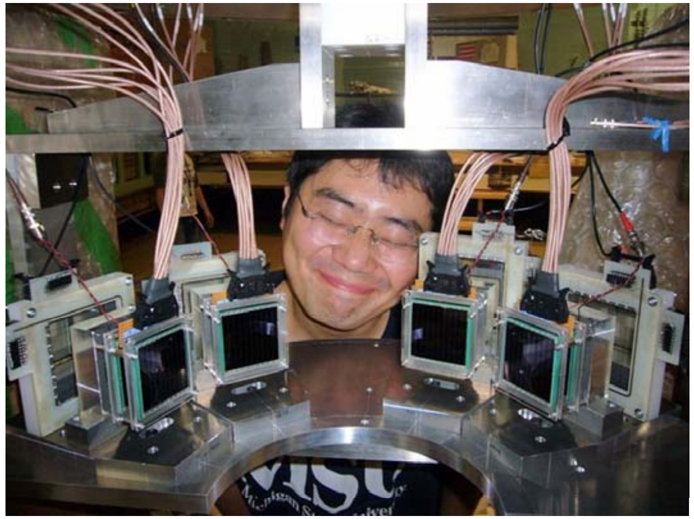
Decay Particles from α Condensed States

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).

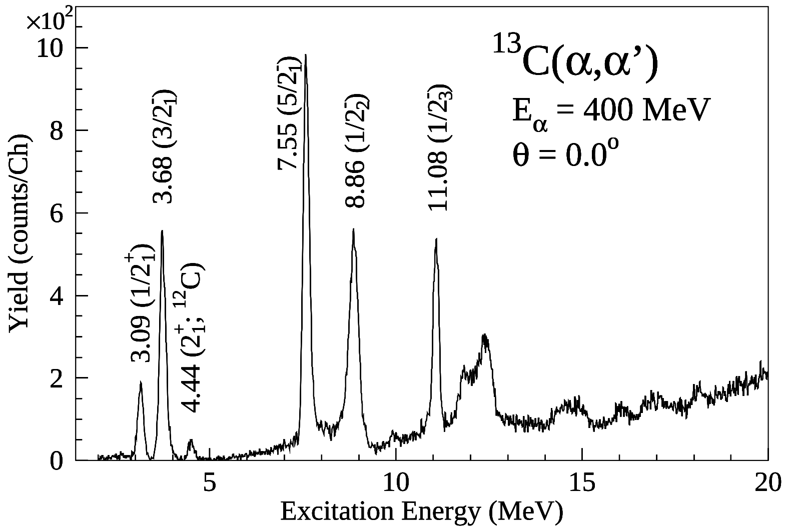


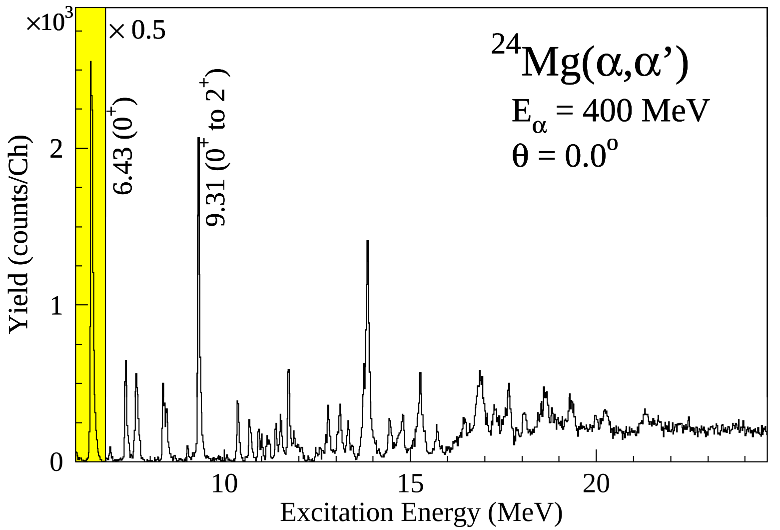
- Complementary information for the E0 strength is expected.
  - α cluster state should prefer to decay into the alpha-decay channel.
  - GS in ^{20}Ne is a well-known α + ^{16}O cluster state.

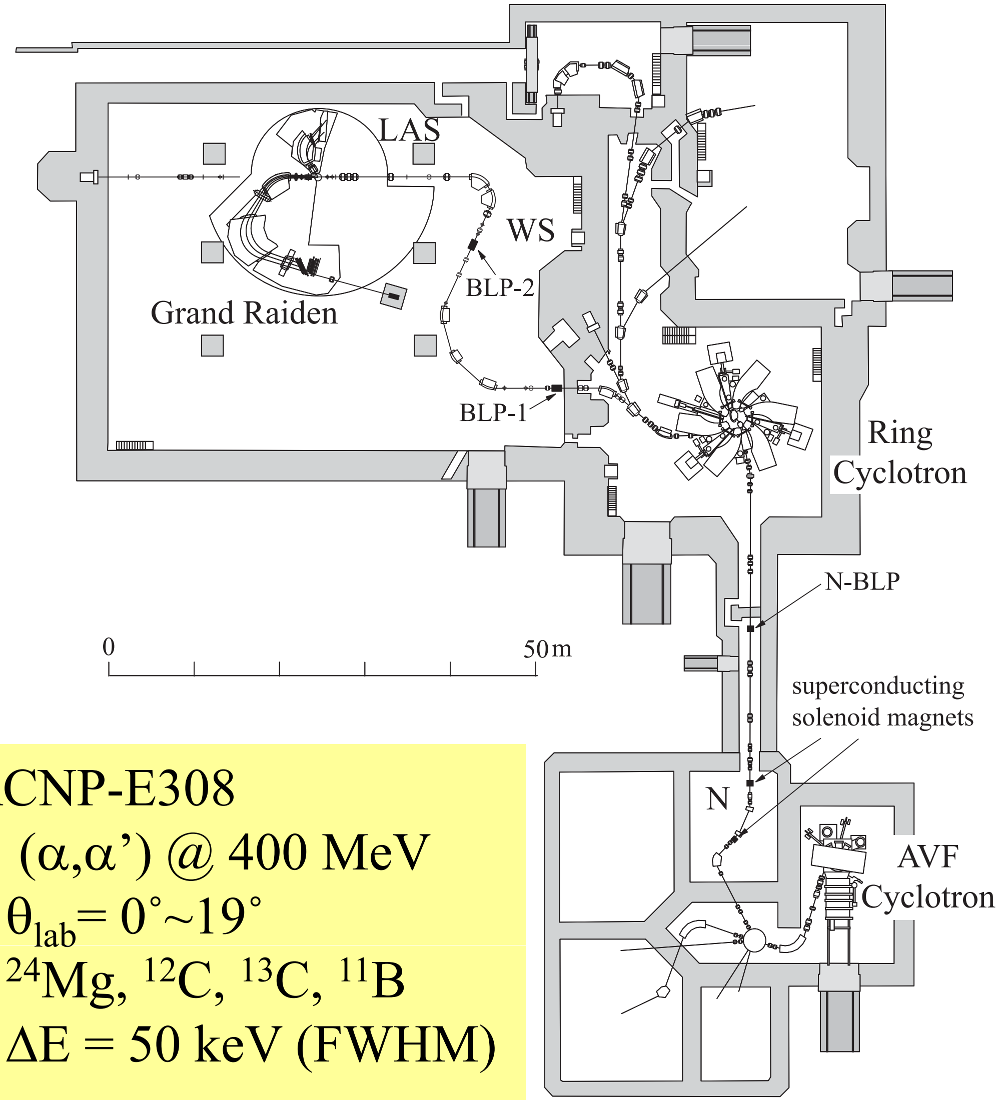
Experiment

Experiment was performed at RCNP, Osaka University.

Background-free measurement at extremely forward angles





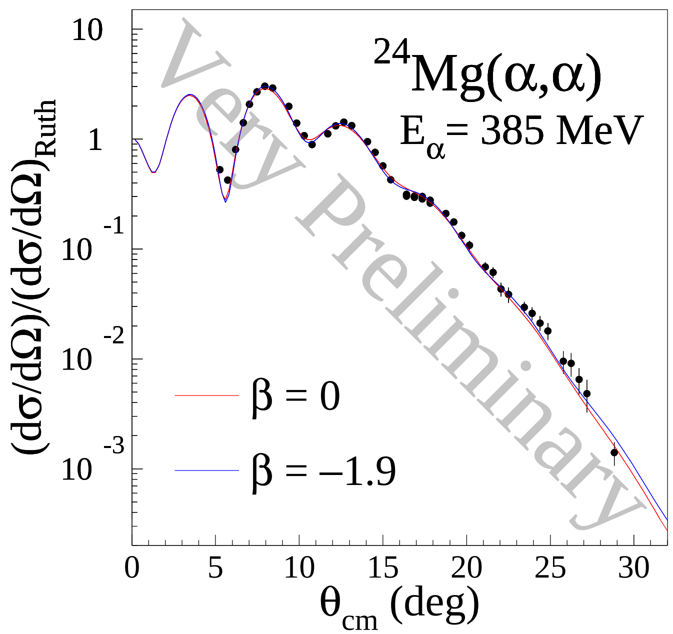


RCNP-E308
(α,α') @ 400 MeV
θ_{lab}= 0°~19°
^{24}Mg, ^{12}C, ^{13}C, ^{11}B
ΔE = 50 keV (FWHM)

Single Folding Model Analysis

Experimental data at RCNP is analyzed by single folding model.

Elastic scattering on ^{24}Mg



Single folding by phenomenological αN interaction.

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

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

- GS densities are taken from electron scattering assuming $\rho_{0p} = \rho_{0n}$.
- Two choices of αN interaction to fit dσ/dΩ .

Density Independent (DI)

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

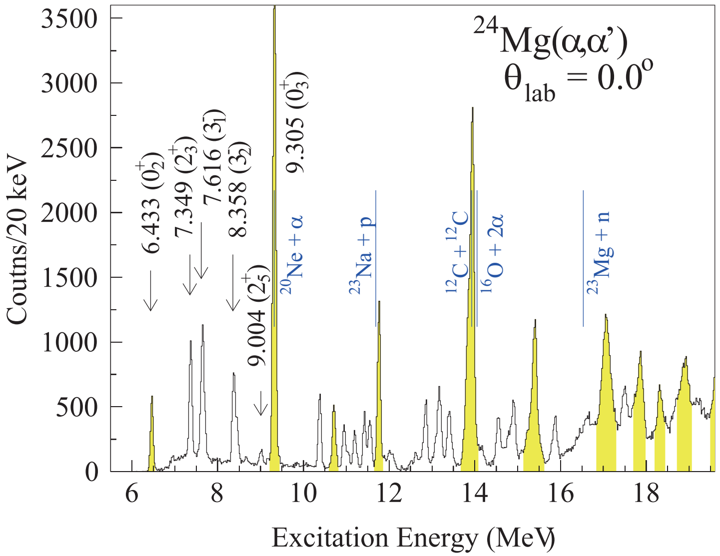
Density Dependent (DD)

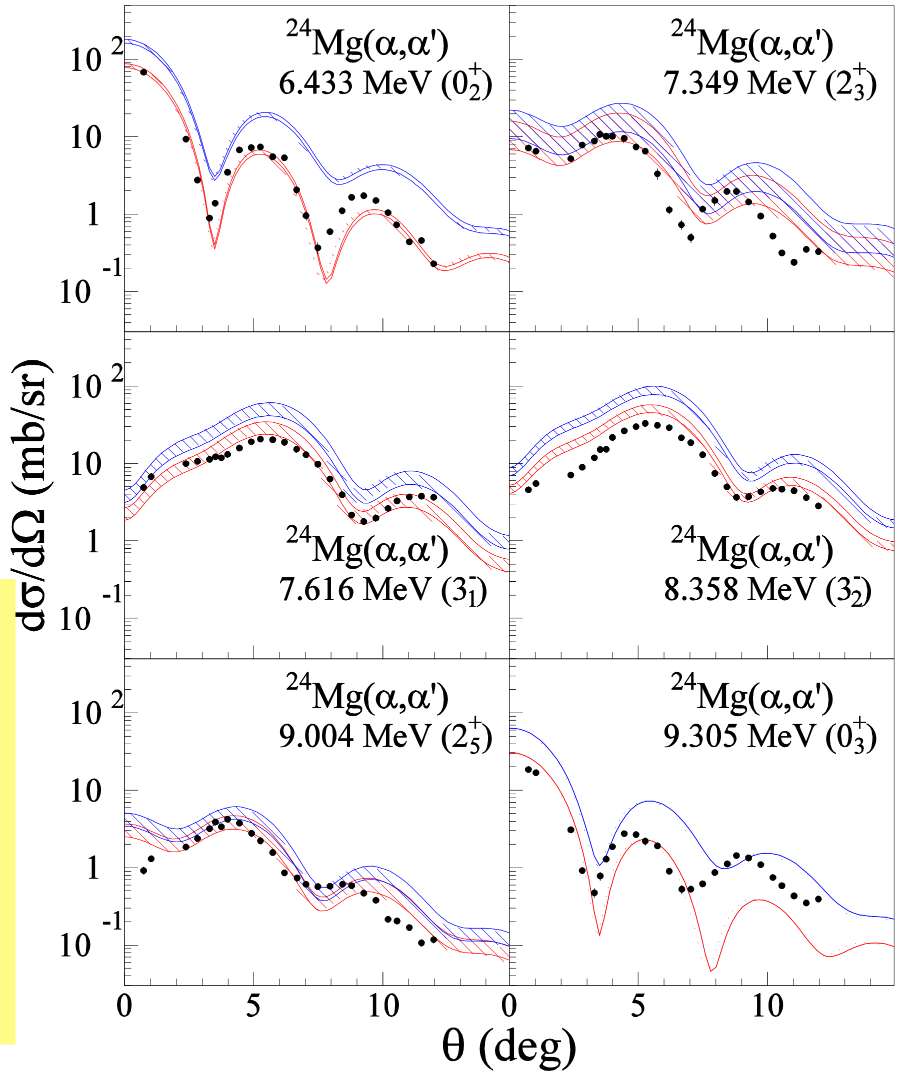
$$V = 28.8\text{ MeV},\ W = 19.6\text{ MeV},$$
$$\alpha_V = \alpha_W = 4.05\text{ fm},\ \beta_V = \beta_W = -1.9$$

Both DI and DD interactions give reasonable descriptions on the elastic scattering.

Discrete States in ^{24}Mg

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





- Transition potential is obtained by a single folding model.

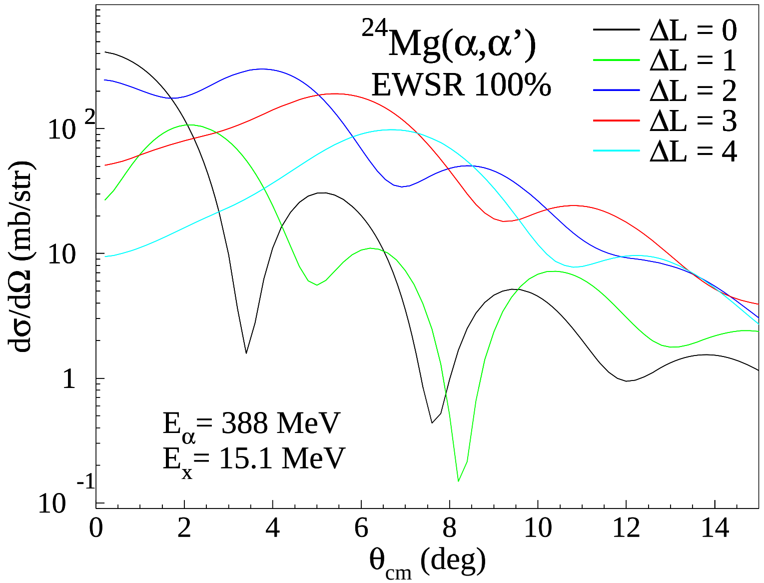
$$\delta U_L(r) = \int d\vec{r}'\,\delta\rho_L(r)\left(V\left(\left|\vec{r}-\vec{r}'\right|, \rho_0(r')\right) + \rho_0(r')\frac{\partial V\left(\left|\vec{r}-\vec{r}'\right|, \rho_0(r')\right)}{\partial \rho_0(r')}\right)$$

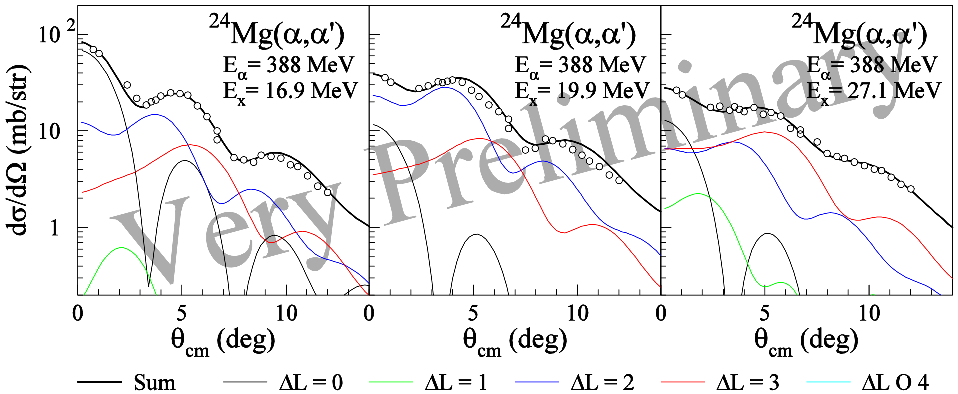
- Transition densities:
  Taken from macroscopic model and known B(EL) values.

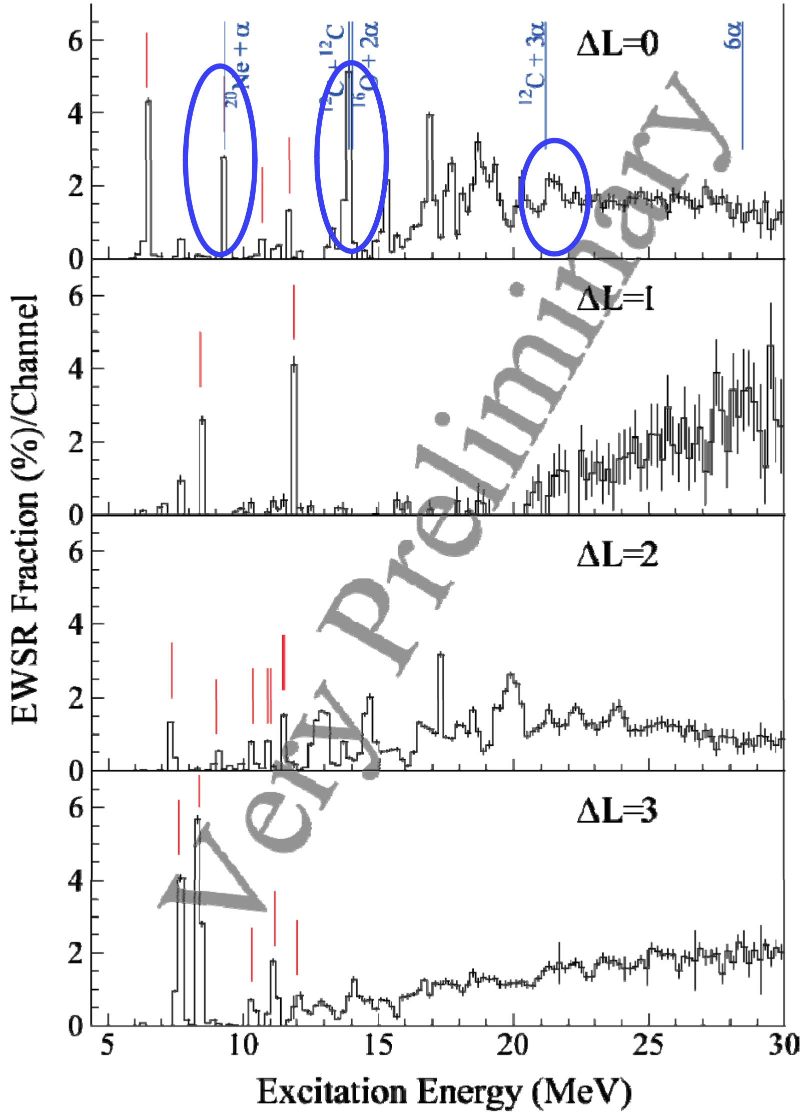
DI gives reasonable results better then DD, especially for the 0^+ and 3^- states.

Multipole Decomposition Analysis

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







Fine structure in ΔL=0 strengths was observed.

Comparison with ACM

Measured E0 strengths near the $^{16}O+2\alpha$ threshold were compared with the ACM prediction.

Recent calculation by T. Ichikawa, N. Itagaki et al.

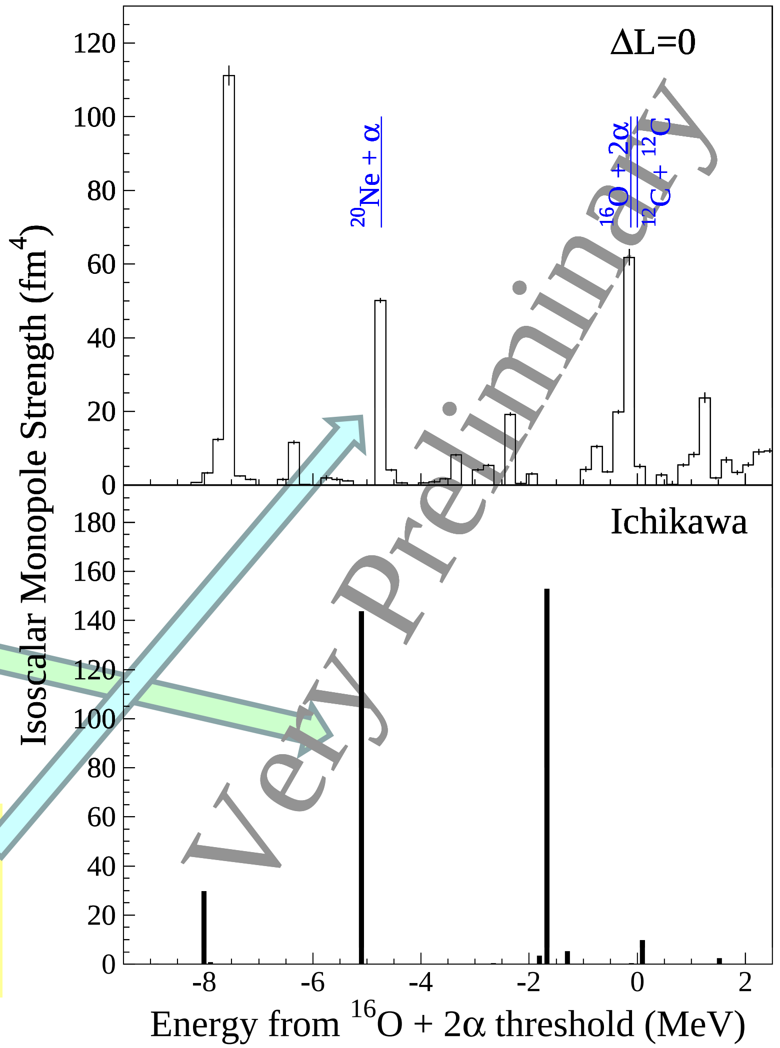
Coupling between the gas-like α condensed w.f. and the normal cluster w.f. are considered.

$$\Psi = \sum_j c_{nc}^j \Psi_{nc}^j + \sum_\sigma c^\sigma \Psi^\sigma$$

Normal Cluster α Condensate

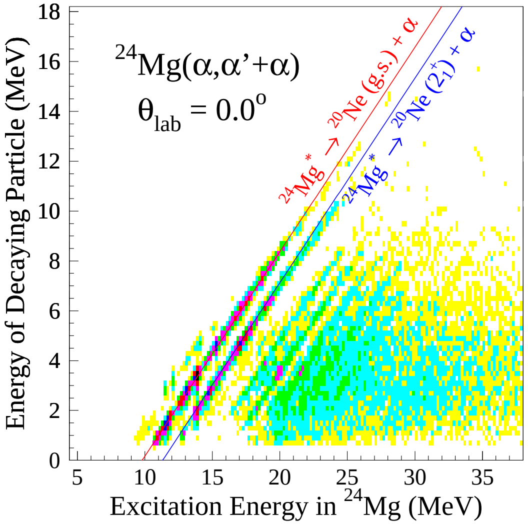
The 7th 0^+ state at –4.267 MeV
- Strong E0 excitation with 187.5 fm^4.
- Large overlap with the 2α condensed state around ^{16}O core.

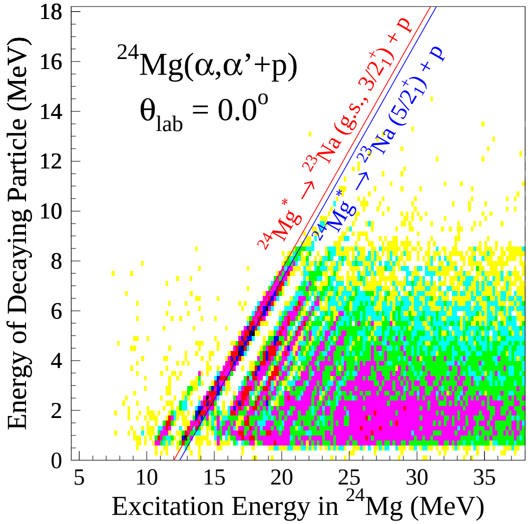
The 9.31-MeV state near $^{20}Ne + \alpha$ threshold is the most probable candidate for the $2\alpha + {}^{16}O$ state.
- Cross section suggests the enhanced radius.

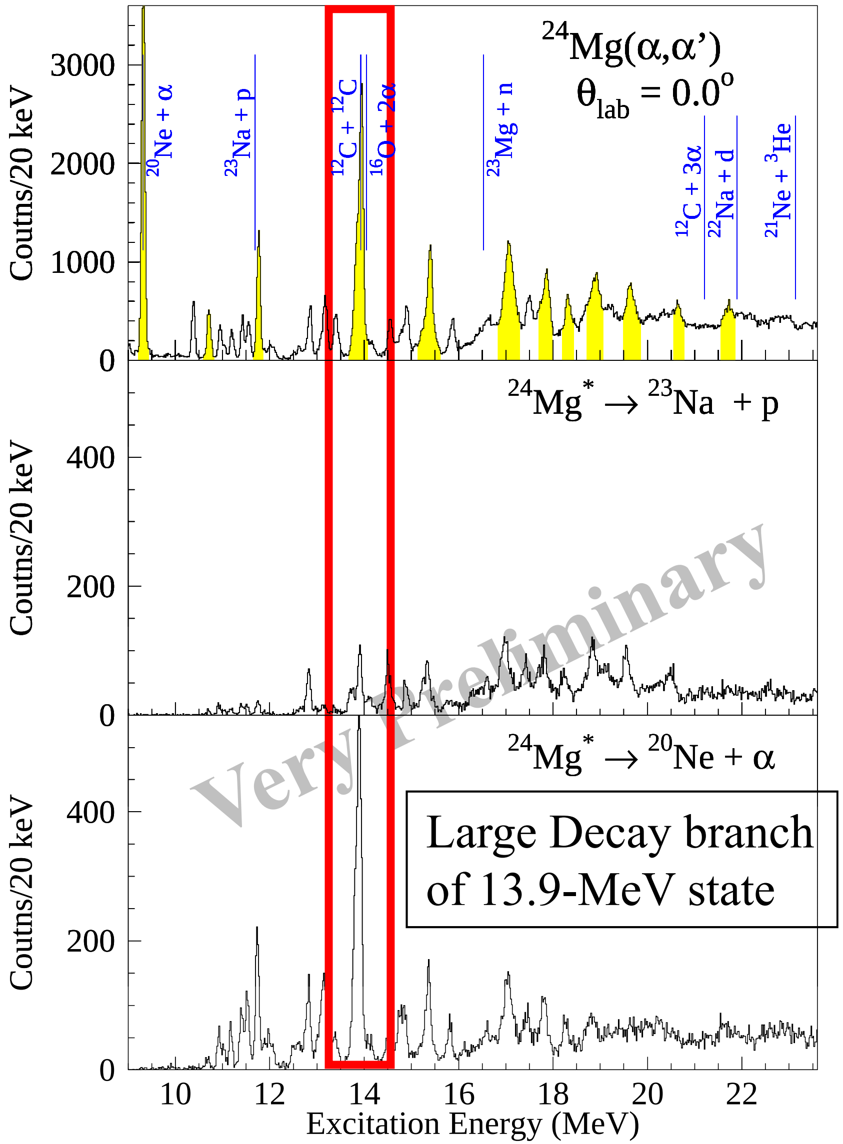


Decay Particle Measurement

Decay channels to the ground and first excited states in ^{20}Ne were identified.



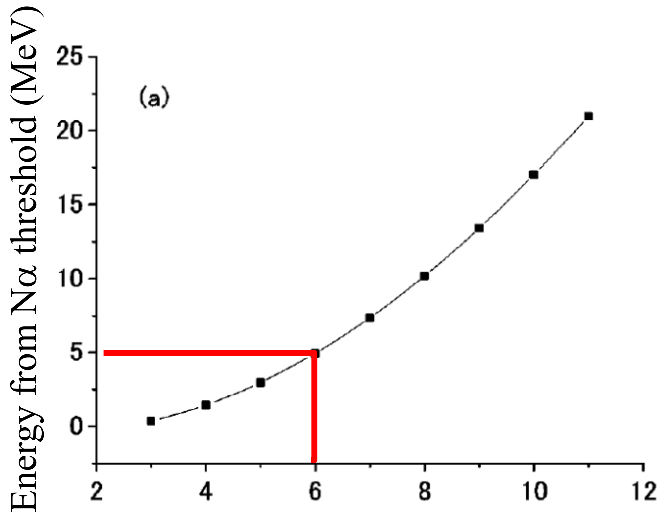




- Proton and alpha decay channels are separated.
- 0^+ state at 13.9 MeV near the ^{12}C + ^{12}C and ^{16}O + 2α thresholds has a large decay branch to ^{20}Ne.
- Further analysis is needed to clarify the cluster structures in ^{24}Mg.

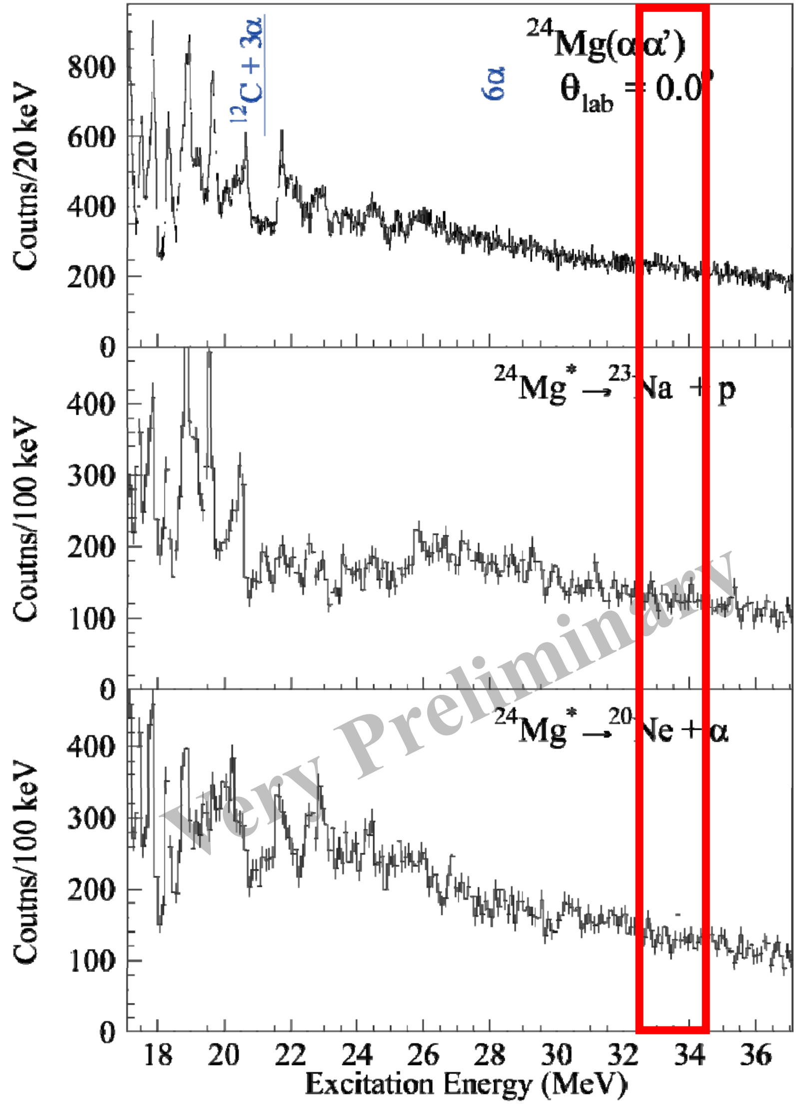
Highly Excited Region

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.



Summary of the first part

α Condensed states in ^{24}Mg were searched.

- Alpha inelastic scattering and decay-particle measurement is a useful tool.

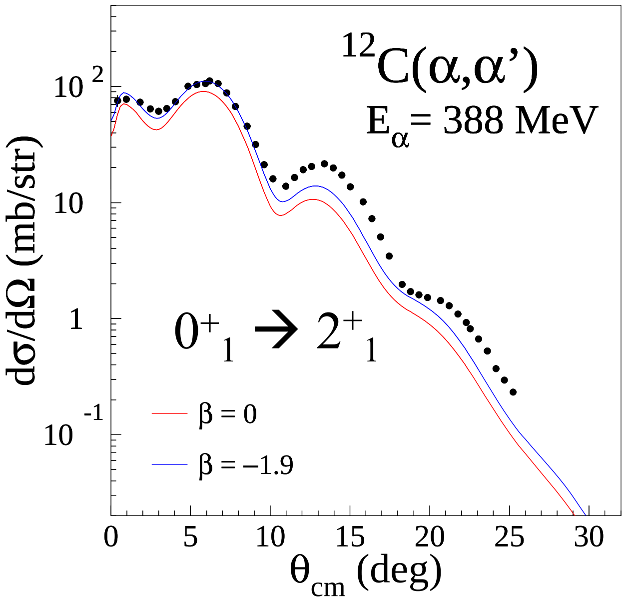
Comparison with the theoretical prediction was done.

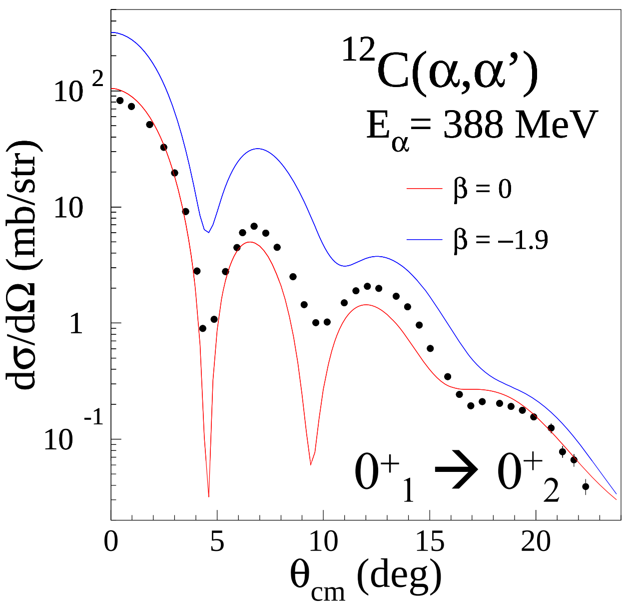
- The 9.31-MeV state is the most probable candidate of the 2α condensed state around the ^{16}O core.
- The 13.9-MeV state is also a candidate.
- Expected 6α condensed state was not observed.

Analysis is still going on.

The results will be reported elsewhere soon.

Discrepancy between DD and DI interactions

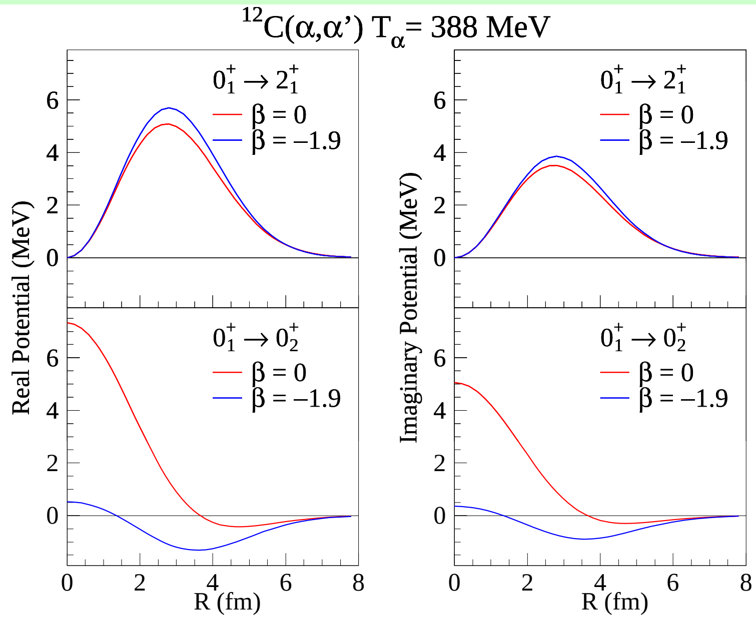




- Discrepancy between DD and DI int. studied in ^{12}C.
- Nuclear structure in ^{12}C is well examined.
  - Transition densities are taken from electron scattering.

DD int. significantly overestimates E0 cross section.
Similar to the ^{24}Mg case !!

DI gives better results although DD is commonly used.

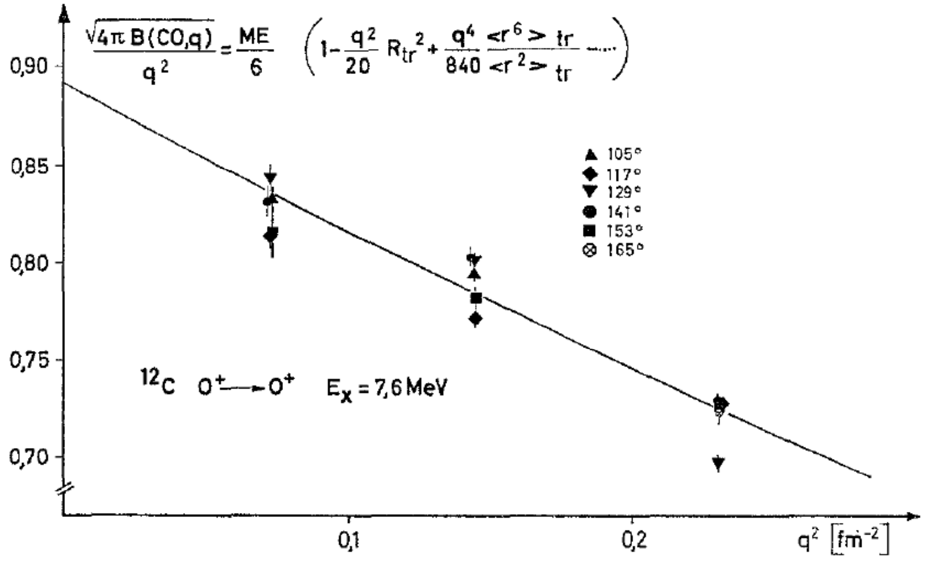


Density dependence plays a crucial role
in the inner region of the Hoyle state.

Missing Monopole Strength

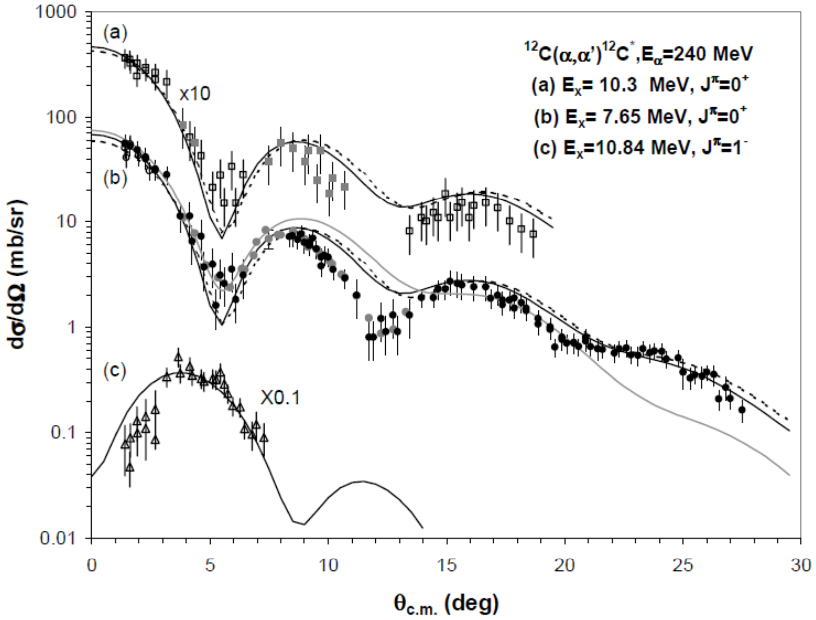
This problem was recognized as "Missing monopole strength" problem in ^{12}C.

Electron Scattering:
15.0(13)% of EWSR



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

Alpha Scattering:
7.6(9)% of EWSR

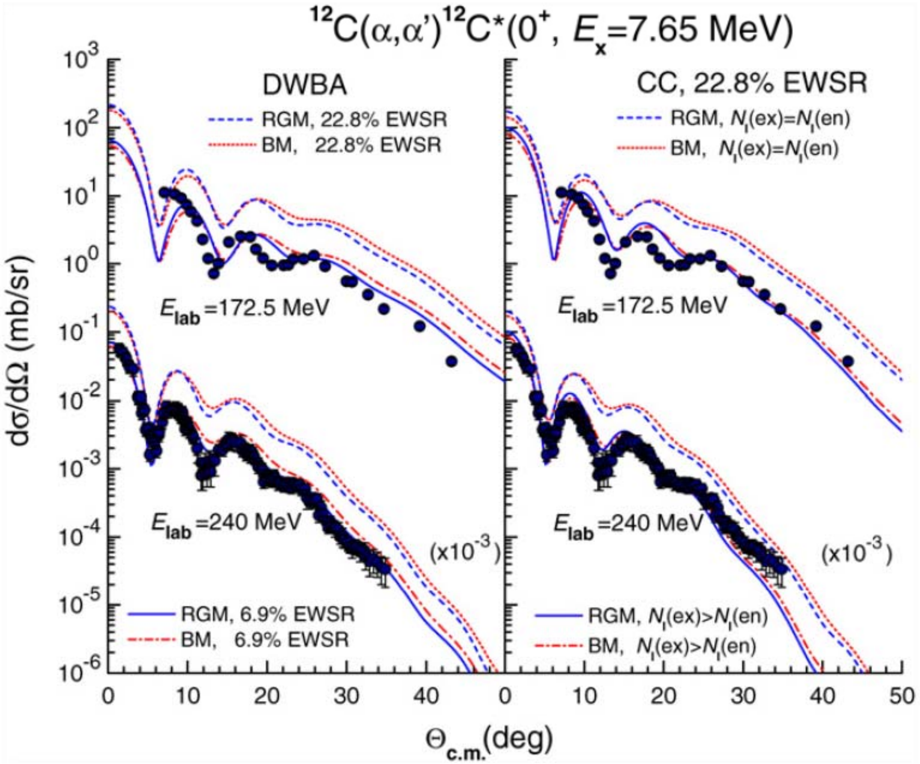


B. John et all, Phys. Rev. C **68**, 014305 (1970).

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

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 $\alpha + {}^{12}C(0^+_2)$ channel was adjusted to obtain a reasonable CC result ($N_I \sim 2.5$—3.4).
N_I enhances due to the dilute and weakly bound nature of the Hoyle state??

However…..,
Similar problem is observed in ^{24}Mg.
It is not special for the Hoyle state.

It is a universal problem. It might affect EWSR values of GMR.

Summary of the second part

Discrepancy between DD and DI int. were found.

- DI gives reasonable description, but many experiments (RCNP, TAMU) were analyzed by using DD int.

This was recognized as “Missing monopole strengths” problem in ^{12}C.

- Is it special for the Hoyle state?
- No!! It is observed in the other nuclei.
- EWSR value of GMR might be affected.

Systematic study is needed.