Search for $\alpha$ condensed states by measuring $\alpha$ inelastic scattering under normal kinematic conditions.

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$\alpha$ Condensed State

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

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

A novel concept to describe the $0^+_2$ state is proposed: $\alpha$ Condensation.


$\alpha$-condensed state where three alpha particles occupy the lowest s-orbit.
Dilute-gas state of alpha particles. Large RMS.
Does similar $\alpha$ 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 $\alpha$ Cluster Structure

Large E0 strength could be a signature of spatially developed $\alpha$ cluster states.

$0^+_2$ state in $^{12}$C: $B(E0; IS) = 121 \pm 9 \text{ fm}^4$
Single Particle Unit: $B(E0; IS)_{s.p.} \sim 40 \text{ fm}^4$

- 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.

E0 strength is a key observable to examine $\alpha$ cluster structure.

Inelastic Alpha Scattering

Inelastic $\alpha$ scattering is a good probe for nuclear excitation strengths.

- Simple reaction mechanism
  - Good linearity between $d\sigma/d\Omega$ and $B(\hat{o})$.
    \[ \frac{d\sigma}{d\Omega}(\Delta J^\pi) \approx KN|J(q)|^2 B(\hat{O}) \]
  - Folding model gives a reasonable description of $d\sigma/d\Omega$.

- Selectivity for the $\Delta T = 0$ and natural-parity transitions.

- Multiple decomposition analysis is useful to separate $\Delta J^\pi$.
  \[ \frac{d\sigma_{\text{exp}}}{d\Omega} = \sum_{\Delta J^\pi} A(\Delta J^\pi) \frac{d\sigma}{d\Omega}(\Delta J^\pi)_{\text{calc}} \]

We measured inelastic $\alpha$ scattering to extract IS E0 strengths and to search for the $\alpha$ condensed states.
Condensed States in Heavier $N = 4n$ Nuclei

- $\alpha$ condensed states in $^8$Be and $^{12}$C seem to be established.
- $\alpha$ condensed states in heavier nuclei ($A < 40$) are theoretically predicted.

Short range $\alpha$-$\alpha$ attraction
Long range Coulomb repulsion

Energy of dilute $N\alpha$ state increases with $N$. $N\alpha$ are confined in Coulomb barrier.

If such $n\alpha$ condensed states are formed, they should sequentially decay into lighter $\alpha$ condensed states by emitting $\alpha$ particles.

$N\alpha$ decay measurement could be a probe to search for the $\alpha$ condensed state.

α Condensed State in $^{16}\text{O}$

Energy levels, rms radii, monopole matrix elements and density distribution.

Low lying $0^+$ levels of $^{16}\text{O}$

- $0^+_0$: 15.2 MeV
- $0^+_1$: 14.0 MeV
- $0^+_2$: 13.6 MeV
- $0^+_3$: 12.1 MeV
- $0^+_4$: 12.1 MeV
- $0^+_5$: 12.1 MeV
- $0^+_6$: 12.1 MeV

4α cond. state

- $\Gamma (0^+_4)_{\text{OCM}} \sim 0.2$ MeV
- $\Gamma (0^+_5)_{\text{OCM}} < 0.05$ MeV
- $\Gamma (0^+_6)_{\text{OCM}} \approx 0.05$ MeV

<table>
<thead>
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<th>$R_{\text{rms}}$ (fm)</th>
<th>M(E0)(fm²)</th>
<th>M(E0)(fm²) Exp.</th>
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<td>$(0^+<em>1)</em>{\text{OCM}}$</td>
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<td>$(0^+<em>5)</em>{\text{OCM}}$</td>
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<td>$(0^+<em>6)</em>{\text{OCM}}$</td>
<td>5.6</td>
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</table>

Large monopole matrix element can be the evidence of cluster states.

T. Yamada, Y. F. et al., PTP120, 1139 (2008).

Previous Measurement of $^{16}\text{O}$

$^{12}\text{C}(^{16}\text{O},4\alpha+^{12}\text{C})$ reaction was measured under the inverse kinematics.

- $\Delta E_x (^{12}\text{C}) = 350$ keV
- Not direct reaction.
- Angular distribution of $(^{12}\text{C},^{12}\text{C}')$ was not discussed.
- $\theta_{\text{CM}} = 0^\circ$ was not covered.

Kinematics: Normal or Inverse?

Is the inverse kinematics measurement useful to search for the $\alpha$ condensed state?

High resolution measurement at $0^\circ$ is difficult under the inverse kinematics …

- Energy of recoil $\alpha$ is less than 200 keV.
  \[ \Delta E_{\text{recoil}} = 10 \text{ keV for 200-keV } \alpha \text{ to obtain } \Delta E_x(^{16}\text{O}) = 300 \text{ keV.} \]
- Decay $\alpha$ particles are emitted at very forward angles.
  Same emission angle with elastically scattered $^{16}\text{O}$ at $\theta_{\text{CM}} < 8^\circ$.

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**Graphical Data**

- **Graph 1:**
  - Reaction: $^{16}\text{O}(\alpha,\alpha')$
  - Energy: 100 MeV/u
  - Data for $E = 0 \text{ MeV}$, $E = 5 \text{ MeV}$, $E = 10 \text{ MeV}$, $E = 15 \text{ MeV}$, $E = 20 \text{ MeV}$
  - $E_{\text{recoil}}$ vs $\theta_{\text{lab}} (\text{deg})$

- **Graph 2:**
  - Reaction: $^{16}\text{O}(\alpha,\alpha')$
  - Energy: 100 MeV/u
  - Inverse Kinematics
  - Elastic Scattering
  - Decay $\alpha$ Particles
  - $\theta_{\text{CM}} < 5 \text{ deg.}$
  - $2\pi \sin \theta \sigma d\Omega (\text{mb/deg})$ vs $\theta_{\text{lab}} (\text{deg})$
Normal Kinematics

High resolution measurement is possible under the normal kinematics.

Decay $\alpha$ measurement under the normal kinematics is still difficult, because the energy of $\alpha$ from $^{16}\text{O}(0^+_6) \rightarrow ^{12}\text{C}(0^+_2) + \alpha$ is 210 keV.

- Range of 210-keV $\alpha$ particles in O$_2$ gas is 5.4 mm·atm.
  → Very thin Oxygen target is needed.

Heavier nuclei might be easier once the a condensed state is established in $^{16}\text{O}$. 
Thin Oxygen Target

Possible thin targets are …

✓ Gas jet target (typical thickness is: $10^{12} - 10^{14}$ cm$^{-2}$)

✓ Window-less gas target with the differential pumping technique. Si detectors should be installed in the gas volume. Thickness should be less than 1 Torr ($\sim 10^{16}$ cm$^{-2}$ ($\sim 1 \mu$g/cm$^2$) for 1-cm target).

$\rightarrow \Delta E = 17$ keV along a 15-cm flight path for 210-keV $\alpha$.

✓ High intensity beam ($\sim 1 \mu$A) is required to compensate the target thickness.

✓ Beam quality is important for the 0-degree measurement as well as the intensity.
Summary

α Condensed states in heavier nuclei should be searched.

– Alpha inelastic scattering and decay-particle measurement are useful tools.
– Isoscalar E0 strength
– Sequential decay of the α condensed states.

Experimental framework was discussed.

– Inverse kinematic experiment is not suitable to measure the E0 strength and sequential decay.

Possible experimental setup was presented.

– Thin O2 gas target should be introduced.
– Intense and high quality beam should be developed.