Search for alpha condensed states by measuring alpha inelastic scattering

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Cluster Structures

Cluster structures can be seen on all physical scale.

A galaxy contains $10^7 - 10^{12}$ stars. 50—100 galaxies constitute a cluster of galaxies.

Quarks are confined in hadron at normal T. Quarks are deconfined and form QGP at high T.

Cluster correlation is very important to study the dynamics on each physical scale.
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 $\alpha$-decay thresholds in $N = 4n$ nuclei.

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

The most tightly bound light cluster $\alpha$ particle (quartet)

The most elemental subunit in nuclear cluster structures.
Alpha Condensed States in $^{12}\text{C}$

Energy

$\sim 100$ MeV

$E/A \sim 8$ MeV

Cluster gas

$^{12}\text{C}$

$3 \alpha$-breakup threshold

$\sim 10$ MeV

$E/A \sim 1$ MeV

$\alpha$-cluster

Condensed into the lowest $s$ orbit.

$\rho_0/3 \sim \rho_0/5$

Excitation

dissolution

SM-like

Quantum liquid

Dilute matter distribution

Sharp momentum distribution


$0^+_1$ (g.s)

$0^+_2$

$0^+_2$ (g.s)

Maybe, a new conformation of dilute nuclear matter.
ACS and Symmetry Energy

If $\alpha$ condensed states universally exist in various nuclei ....

→ Establish $\alpha$ condensed phase as a conformation of the dilute nuclear matter
→ Might appear on the surface of neutron stars
→ Energy and width of ACS give an insight to the dilute nuclear matter.

ACS affects macroscopic natures of nuclear matter.

Condensed States in Heavier $N = 4n$ Nuclei

A condensed states in $^8\text{Be}$ and $^{12}\text{C}$ seem to be established.

A 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 increase 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.

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

Decay of Alpha Condensed state in $^{20}\text{Ne}$

ACS decays via ACM in lighter nuclei by emitting low-energy $\alpha$ particles

$5\alpha$ condensed state $J^{\pi} = 0^+$

several MeV

19.17 MeV

$5\alpha$

16.86 MeV $^{19}\text{Ne} + n$

11.98 MeV $^{12}\text{C} + ^{8}\text{Be}$

11.89 MeV $^{12}\text{C} + \alpha + \alpha$

alpha inelastic scattering at $0^\circ$

is useful to excite $0^+$ states.

$4\alpha$ condensed state $(0^+_6)$ in $^{16}\text{O}$

Candidate at $E_x \sim 15.1$ MeV

a few MeV

15.1 MeV ?


$4\alpha + \alpha$

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$15.1$ MeV?

$4\alpha + \alpha$
Experiment

Experiment was performed at RCNP, Osaka

Background-free measurement at extremely forward angles

RCNP-E402
S. Adachi, Y. Fujikawa, TK et al
(a, a'+a) @ 400 MeV $\theta_{\text{lab}} = 0^\circ$ with $^{20}\text{Ne}$ gas target
Ultra Thin $^{20}\text{Ne}$ Gas Target

Isotopically enriched $^{20}\text{Ne}$ gas target
→ Gas searing film causes problems to detect low-energy particles
→ Commonly used Alamid film (a few um) is too thick.

SiNx film (0.1 um) was used to make $^{20}\text{Ne}$ gas target at 14 kPa (89.6 ug/cm²).

<table>
<thead>
<tr>
<th></th>
<th>SiNx</th>
<th>Aramid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>100 nm</td>
<td>1.5 μm</td>
</tr>
<tr>
<td>Threshold energy for $\alpha$</td>
<td>0.09 MeV</td>
<td>0.51 MeV</td>
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</tbody>
</table>
Decay Particle Detectors

Si detector array
→ 3 layers × 6 segments
  1st layer (thin): 65 um 8 strip
  2nd & 3rd layers (thick):
    500 um or 600 um
→ PID by TOF
  Limitation in distance from target
  Solid Angle 4%
### Decay Particle Measurement

#### Region of Interest: 1—5 MeV above 5α threshold

<table>
<thead>
<tr>
<th>Cross Section (mb/sr/MeV)</th>
<th>Yield (counts)</th>
</tr>
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<tbody>
<tr>
<td>12C+α+α ×0.5</td>
<td>20Ne → α + X</td>
</tr>
<tr>
<td>19F+p</td>
<td>20Ne → p + X</td>
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</tbody>
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#### Particle Identification

- **α beam**
- **TOF**
- **E vs ΔE**
  - 1st
  - 2nd
  - 3rd

#### Several Structures in ROI

- **p decay event**
- **α decay event**
- **p decay event**

#### Graphs

- **Excitation Energy (MeV)**
- **Energy (MeV)**
- **E-ΔE (MeV)**
Decay to the 4\(\alpha\) condensed state

- 3.3 MeV above the 5\(\alpha\) threshold
- Strong coupling to the 4\(\alpha\) candidate in \(^{16}\text{O}\)
- Strong candidate of the 5\(\alpha\) state

23.5-MeV state enhances in the decay spectrum to the 4\(\alpha\) candidate (0\(_+\)\(_6\) in \(^{16}\text{O}\)).

Final state in \(^{16}\text{O}\)

Next step: 6\(\alpha\) in \(^{24}\text{Mg}\)
Previous Measurement in $^{24}$Mg

Decay particles from excited states in $^{24}$Mg were measured.

- 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.

- 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.
\( ^{8}\text{Be} \) Emission Events

\( ^{8}\text{Be}(O_{1}^{+}) \) emission events were identified from 2 android emission events by \( E_{x} \) in \( ^{8}\text{Be} \).

- Several states at 20.5, 22.0, and 24.3 MeV were observed near the \( ^{12}\text{C}+3\) \( \alpha \) threshold.
- Possible structures were seen above the 6\( \alpha \) threshold although statistically poor.
  \( \rightarrow \) Need more statistics. Larger solid angle.
How to Increase Detector Solid Angle

PID by TOF limits distance from target.
Long distance → Small solid angle
Need a new PID method

PSA solves the limitation from the flight distance.
→ Drastically increase detector solid angle.

PSA was successfully done for Heavy ion at $E > 100$ MeV,
but no result for low-energy $\alpha$ particle at $E < 3$ MeV.
PSA for low-energy light particles is not easy. We tried PSA using the neural network.

Pulse shape was acquired by 500 MHz Sampling FADC.

Decay particle detector with large angular coverage will be developed to search for alpha condensed states.
Summary

Alpha condensed state is a new conformation of dilute nuclear matter.

Inelastic α scattering and decay particle measurements are useful probes to examine α cluster structure in nuclei.

- Low-energy α particle detection over large solid angle is important.

A new particle detector will be developed.

- PSA using a neural network technique