Search for alpha condensed states in ^{24}Mg

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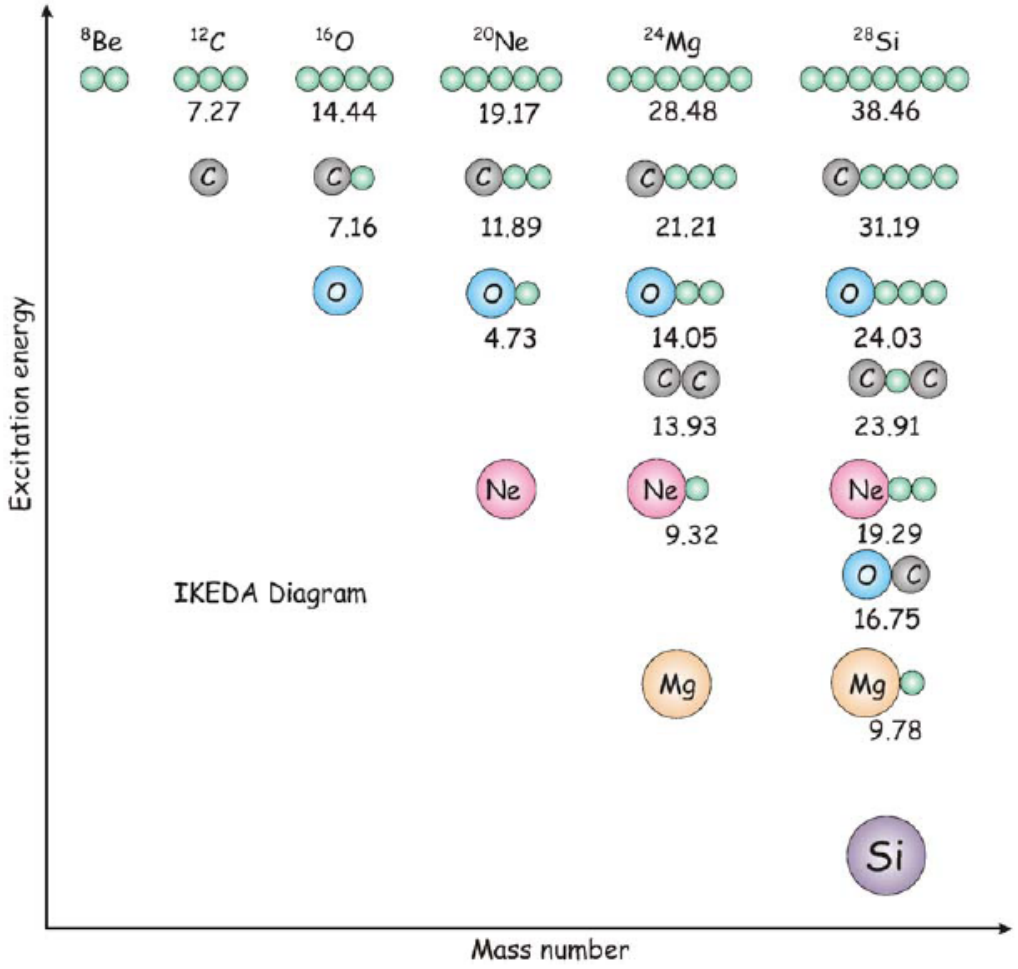
Cluster States in N = 4n Nuclei

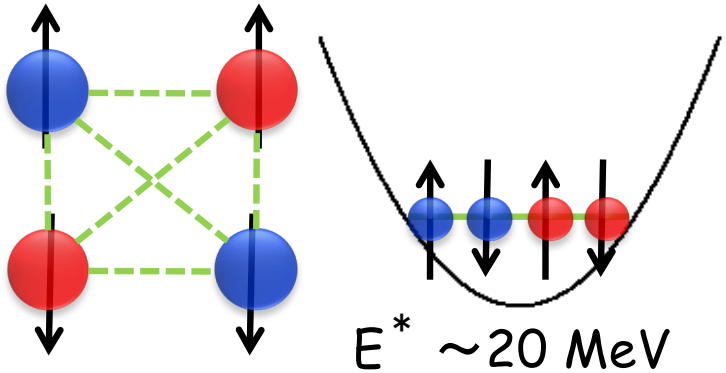
a clustering is an important concept in nuclear physics for light nuclei.

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)



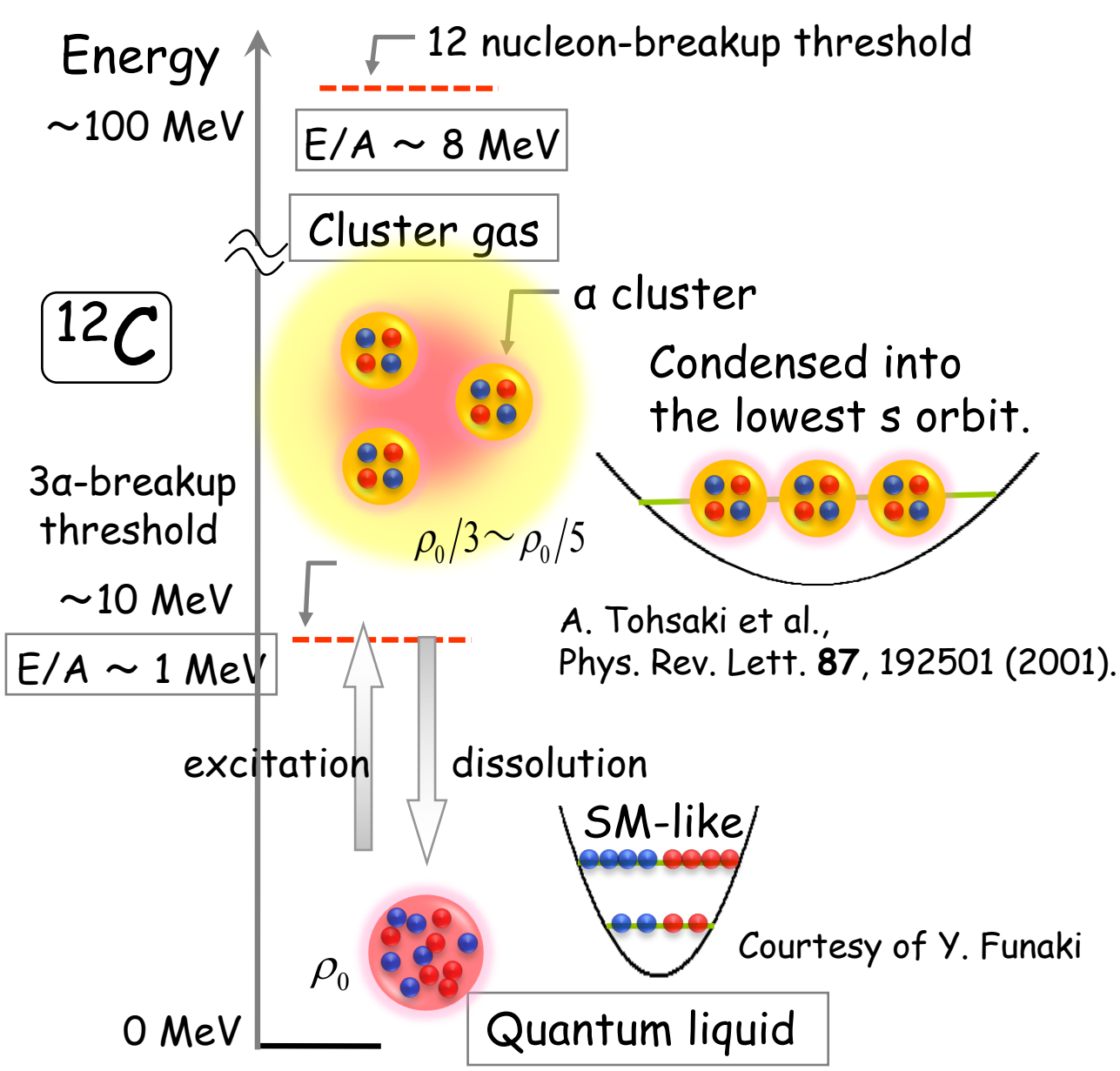
E^* ~20 MeV

stiff

The most elemental subunit in nuclear cluster structures.

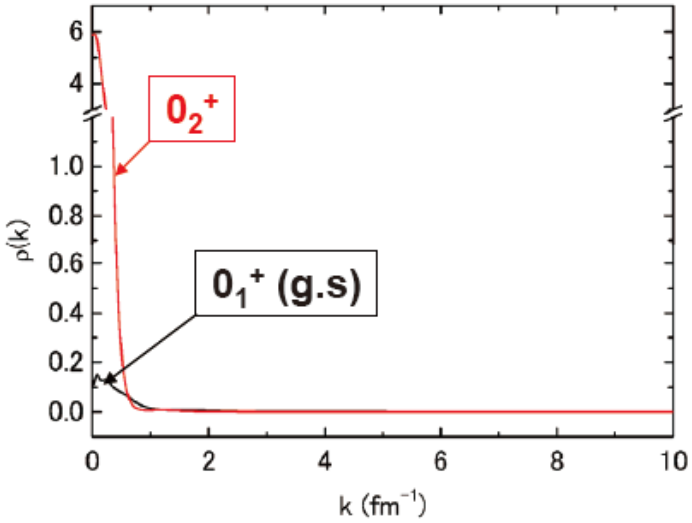
The 0^+_2 state at E_x = 7.65 MeV in ^{12}C is a famous 3α cluster state.

Alpha Condensed States in ^{12}C

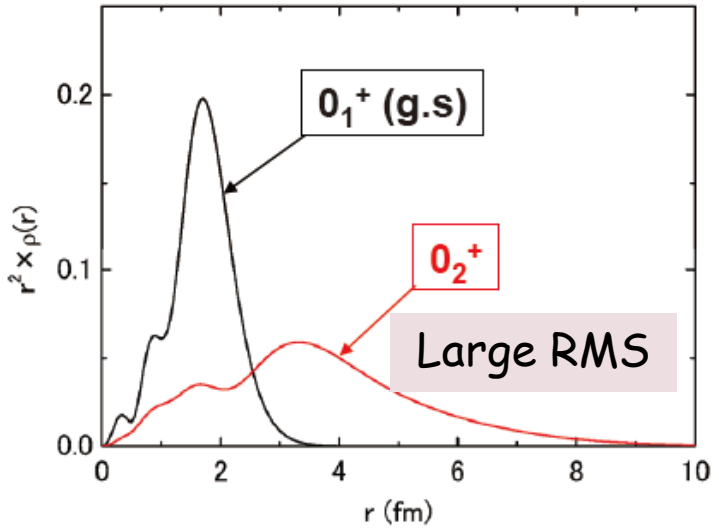


A. Tohsaki et al.,
Phys. Rev. Lett. **87**, 192501 (2001).

Sharp momentum distribution



Dilute matter distribution



Maybe, a new conformation of dilute nuclear matter.

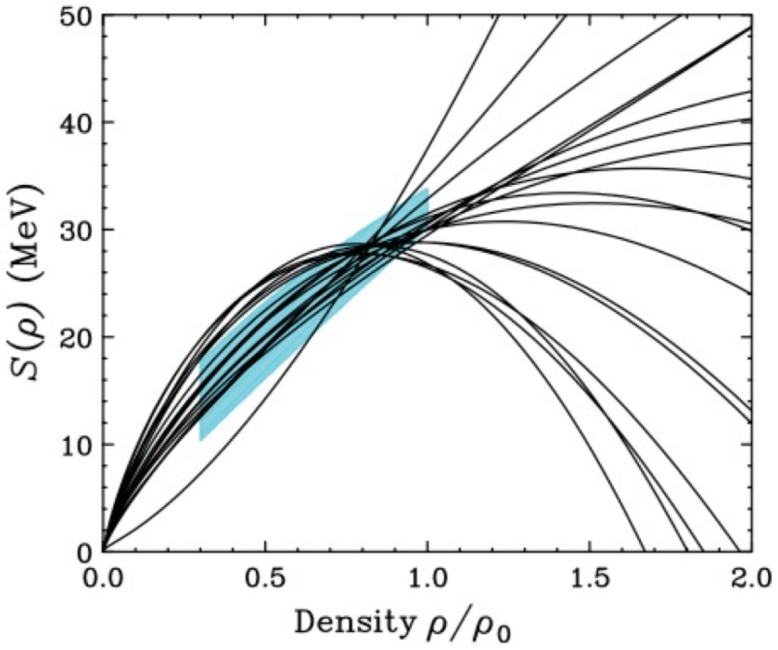
ACS and Symmetry Energy

If a condensed states universally exist in various nuclei ….

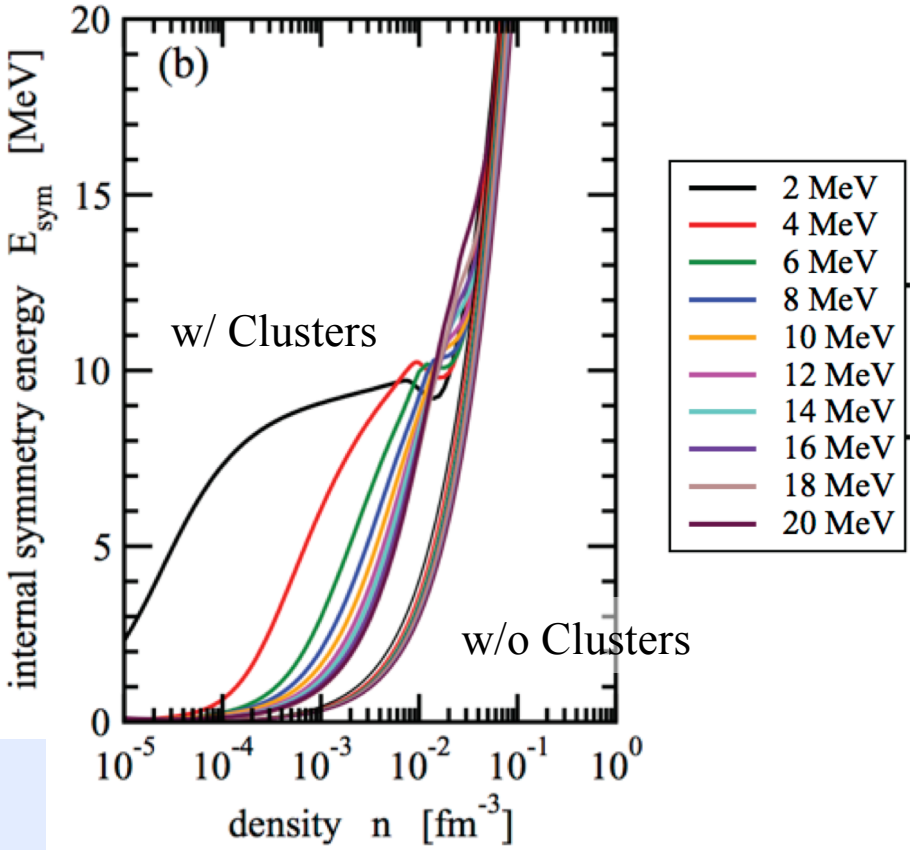
→ Establish a condensed phase as a conformation of the dilute nuclear matter

→ 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.



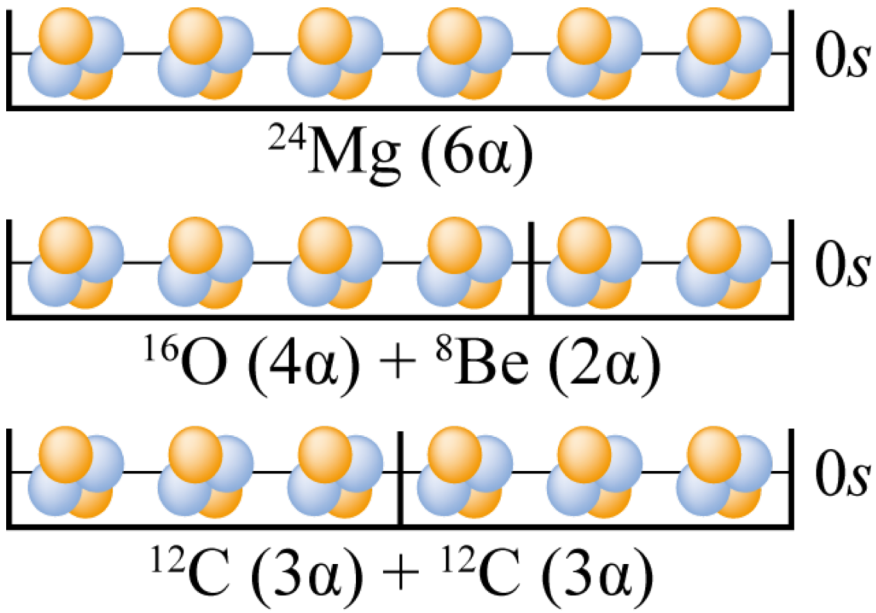
S. Typel *et al.*, Phys. Rev. C 81, 015803 (2010).

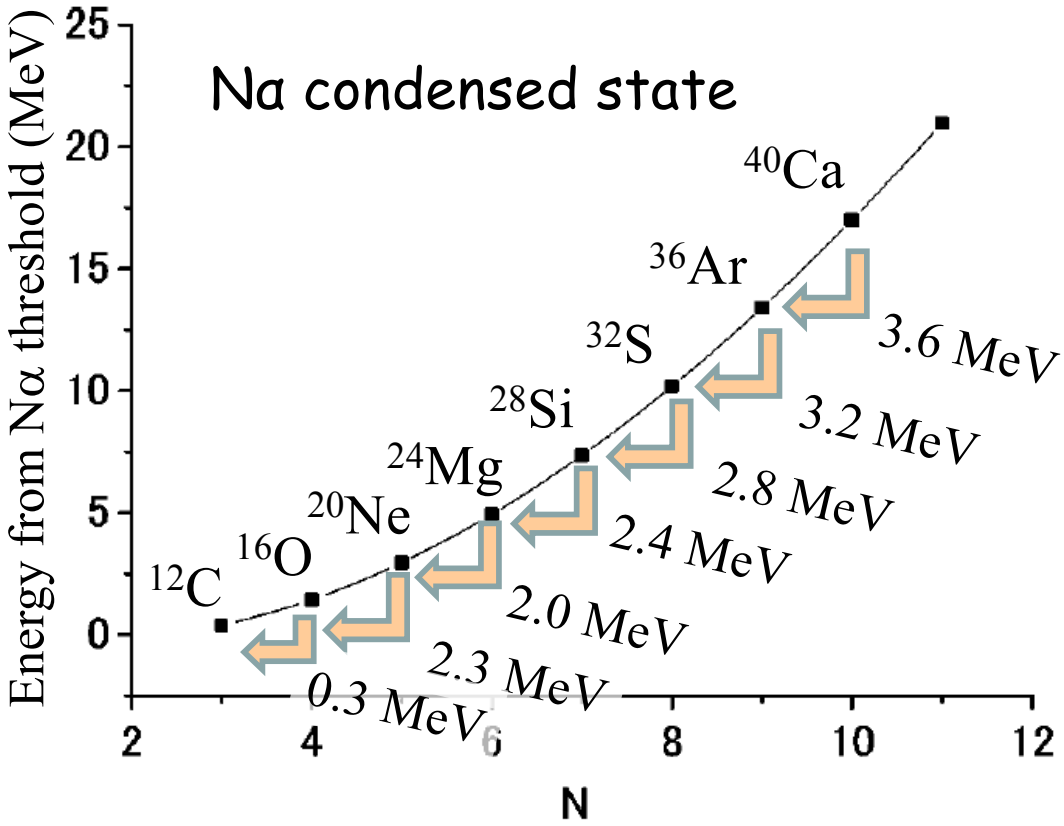
α Condensed States in Heavier N = 4n Nuclei

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

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

α condensed state should have a large overlap with those in lighter nuclei.





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

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

Previous Work – RCNP E308 –

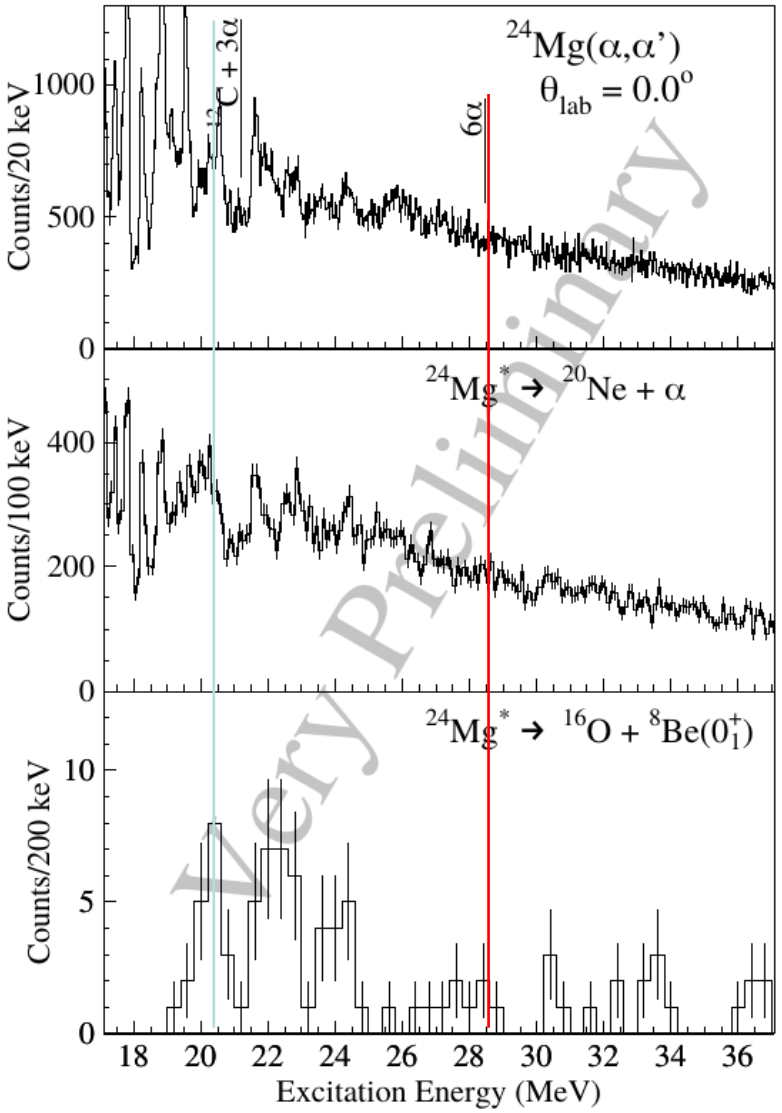
^{24}Mg(α,α'+α) θ = 0 deg, $E_α$ = 400 MeV

- ✓ Sensitivity to 0^+ states
- ✓ ^{8}Be emission channel
  - Several peaks around the 3α threshold
  - Low statistic around the 6α threshold

- ✓ Small solid angle (3%) of the decay-particle detector
  - Size of sensors
  - Distance from the target for TOF measurement for PID
- ✓ Long shutdown of RCNP

^{12}C + ^{12}C Resonance Scattering @ JAEA

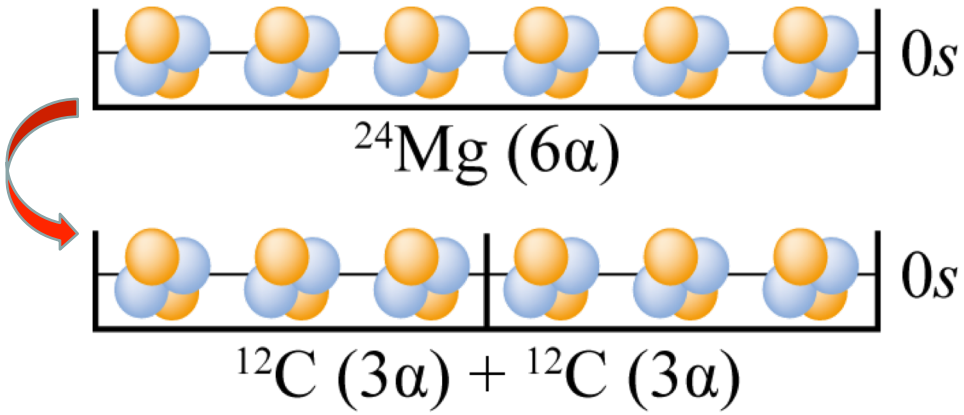
- ✓ Forward emission of decay particles
- ✓ Large Si sensors and PID with machine learning technique



T. Kawabata *et al.*,
J. Phys.: Conf. Ser. 436, 012009 (2013).

$^{12}C + {}^{12}C \rightarrow {}^{12}C(0^+_2) + {}^{12}C(0^+_2)$

6α condensed state should decay to a condensed states in lighter nuclei.



0^+_2 state in ^{12}C
"Established" 3α condensed state.

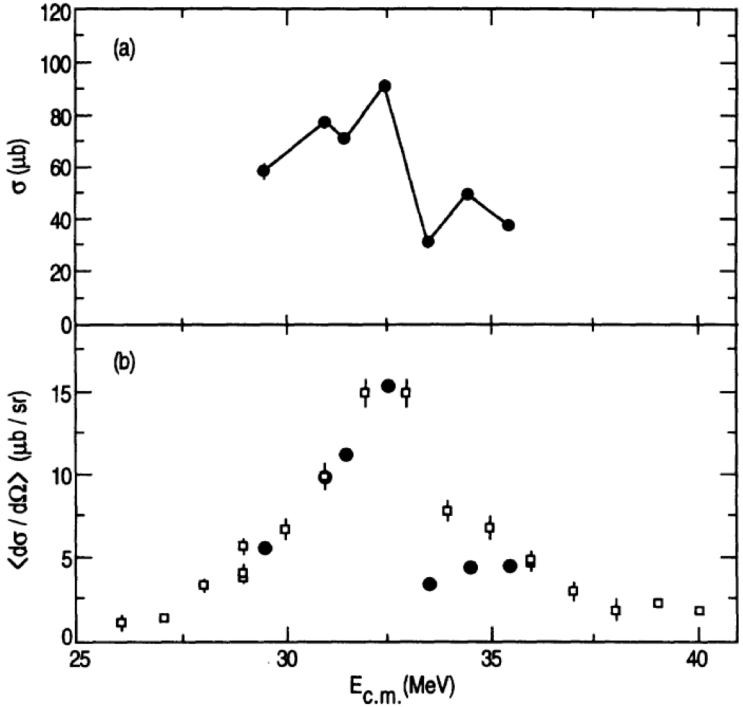
Decay to 6α particles at the end.
Invariant mass spectroscopy of
3α × 2 particles.

Previous measurement @ ANL

$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}(0^+_2) + {}^{12}\mathrm{C}(0^+_2) \rightarrow 6\alpha$

$\mathrm{E_{cm}} = 26 - 40$ MeV ($\mathrm{E_x} = 45.5 - 59.5$ MeV)

Higher reaction energy than
the 6α condensed state ($\mathrm{E_x} \sim 33.4$ MeV)

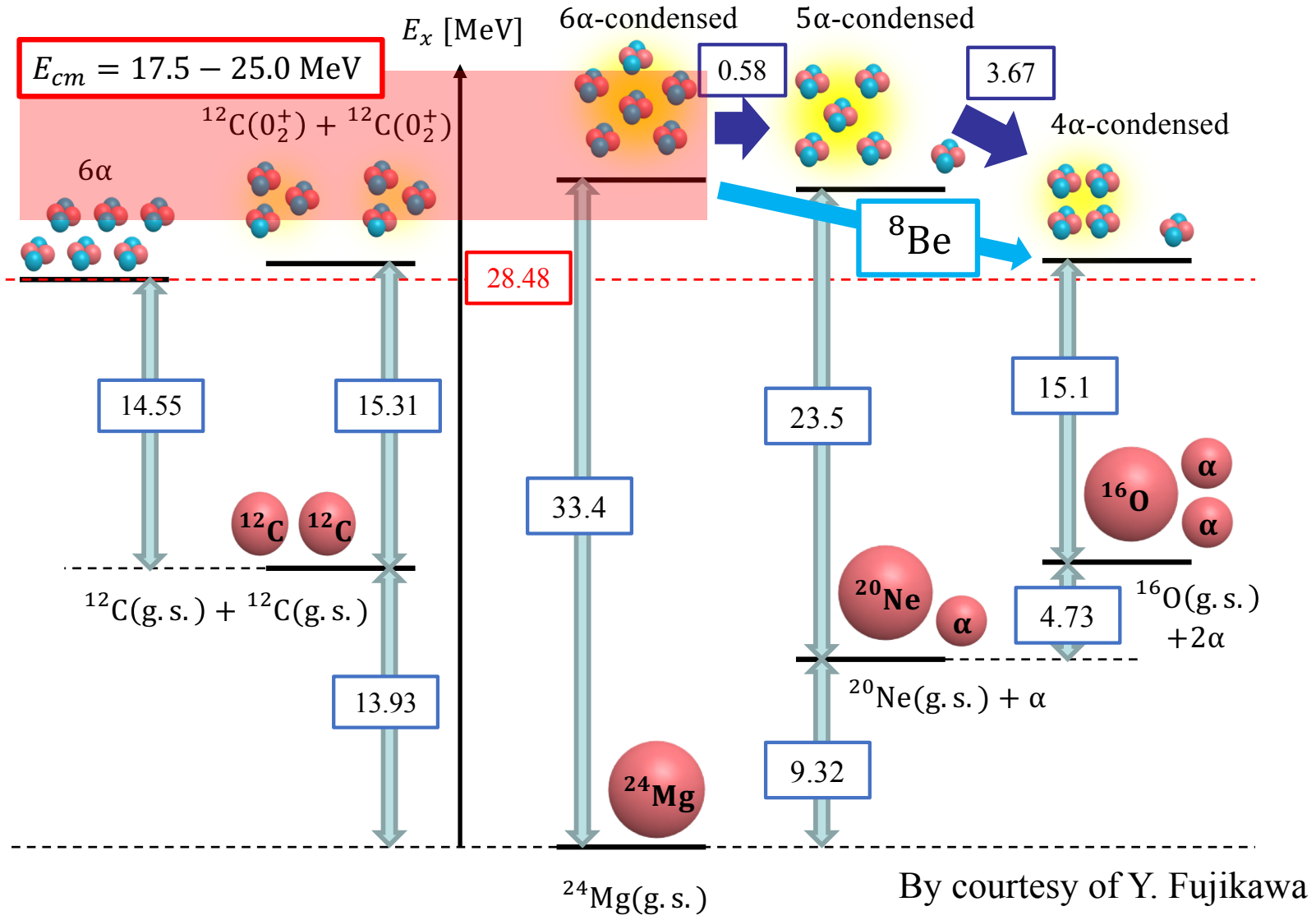


A. H. Wuosmaa *et al.*, Phys. Rev. C **50**, 2909 (1994).

New measurement at
E_{cm} = 17.5—25.0 MeV
Y. Fujikawa, K. Sakanashi, T. K. et al.

Energy Diagram in the 6α System

Beam energy of E_{12C} = 35—50 MeV corresponds to
the CM energy E_{cm} = 17.5—25 MeV and
the excitation energy of E_x = 31.4—38.9 MeV in ^{24}Mg.

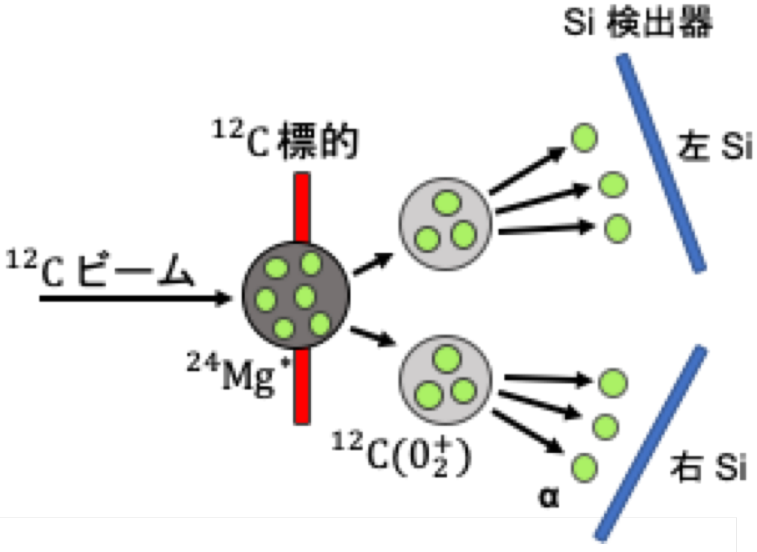


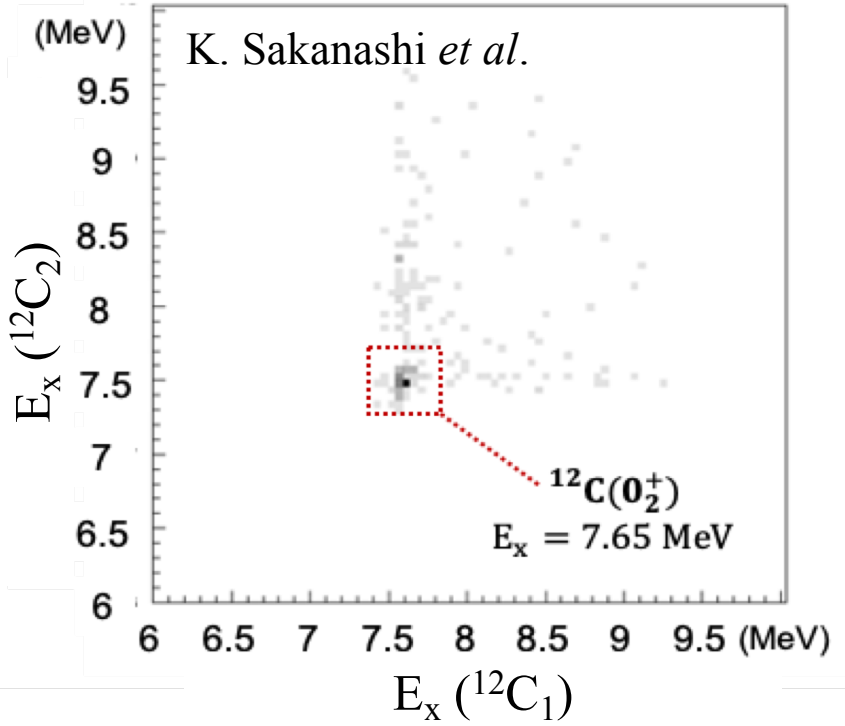
By courtesy of Y. Fujikawa

Test Measurements @ RCNP

^{12}C Beam at E_{12C} = 57 MeV accelerated by the AVF cyclotron bombarded a ^{nat}C target.

Si sensors:
- ✓ Two sensors at left and right.
- ✓ 50 mm x 50 mm
- ✓ 10 strips in vertical direction
- ✓ Detection efficiency of 6α: 2%





$^{12}C + {}^{12}C \rightarrow {}^{12}C(0^+_2) + {}^{12}C(0^+_2)$ events were successfully identified.

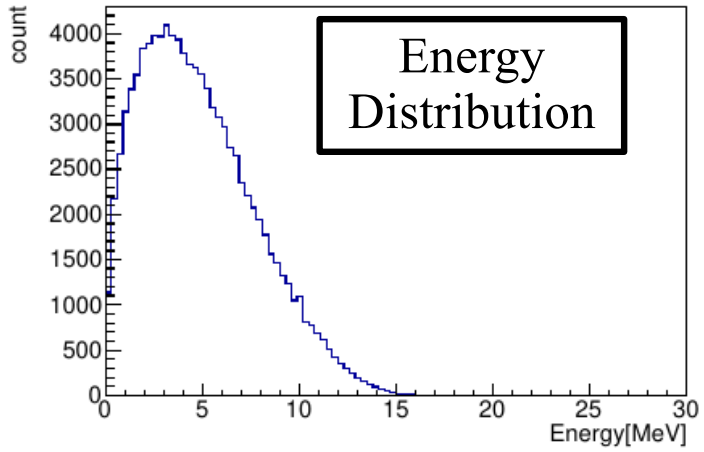
More statistics and energy scan are needed.

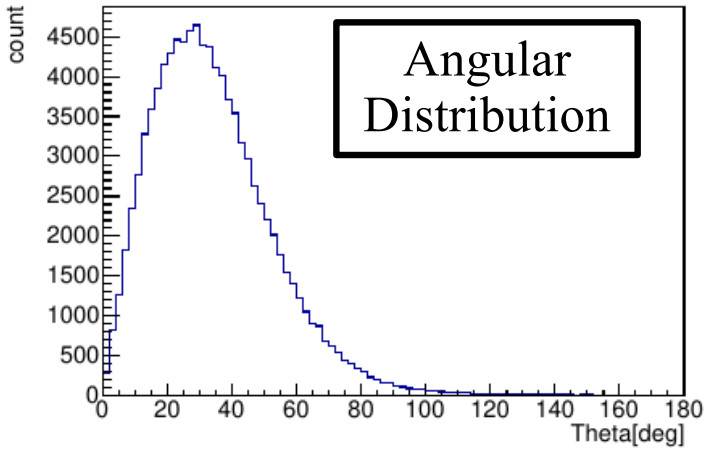
Physics experiments should be proposed.
→ Electrostatic accelerator facility is preferable for energy scan.

Monte Carlo Simulation

$^{12}C + {}^{12}C \rightarrow {}^{12}C(0^+_2) + {}^{12}C(0^+_2) \rightarrow 6\alpha$ at E_{12C} = 35 MeV
α particles are emitted around θ = 30 deg and E_α = 3 MeV

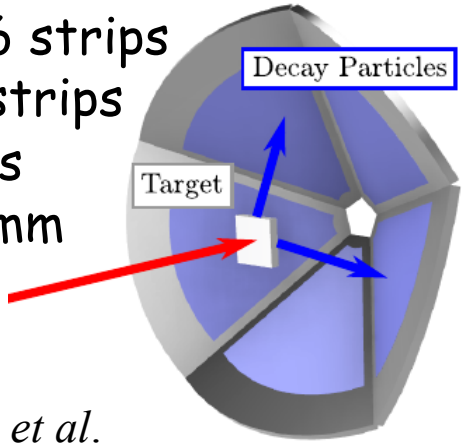
$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}(0^+_2) + {}^{12}\mathrm{C}(0^+_2) \rightarrow 6\alpha$$



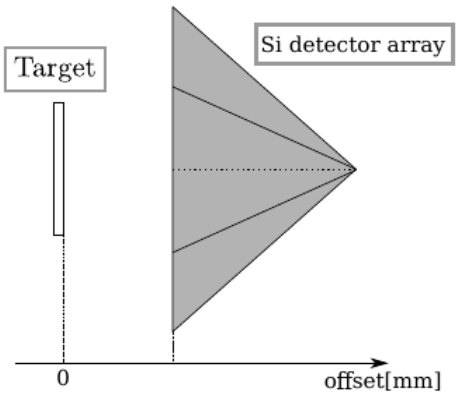


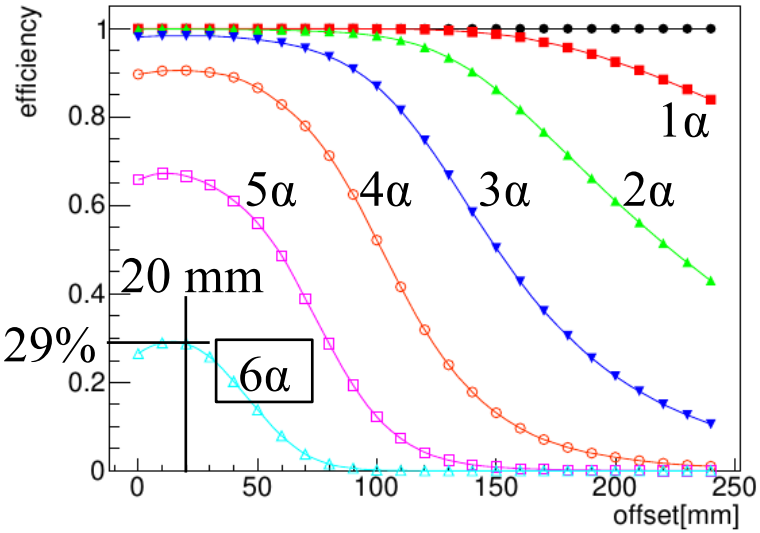
Detector layout is optimized to detect 29% of 6α events at 20 mm from the target.

NTD Si
- Front: 16 strips
- Rear: 8 strips
- 5 sensors
- R = 135 mm



Side View





Y. Fujikawa,
K. Sakanashi *et al.*

Yield Estimation

Beam Energy

E_{12C} = 35—50 MeV → 1-MeV step

E_{12C} = 38—40 MeV → 0.2-MeV step

Yield

Reaction Cross Section: 1 μb/sr

Detection Efficiency: 29%

Beam Intensity: 1 pnA

Target thickness: 100 μg/cm^2

→ 0.11 cps

Beam Time Requirement:

Detector Development: (PID with machine learning)	4 days
Physics Run:	7 days
Total:	11 days

Beam time of 11 days have been approved at the tandem accelerator in JAEA, Tokai.

Schedule:

June 2020	1 module test at Tandem Kobe.
Sep. 2020	1st full setup test at CYRIC, Tohoku.
??? 2021	Final detector test and Physics Run at JAEA

Summary

- ✓ Alpha condensed state is a new conformation of dilute nuclear matter.
- ✓ Alpha condensed states are expected to decay via the alpha condensed states in light nuclei.
- ✓ $^{12}C + {}^{12}C$ resonance scattering will be utilized to search for the alpha condensed state in ^{24}Mg.
  - A test measurement has been carried out.
  - Beam time at JAEA has been approved.
- ✓ A new particle detector is under construction.
  - The 1st sensor will be shipped by the end of May.