Search for α condensed states in ^{20}Ne and ^{24}Mg

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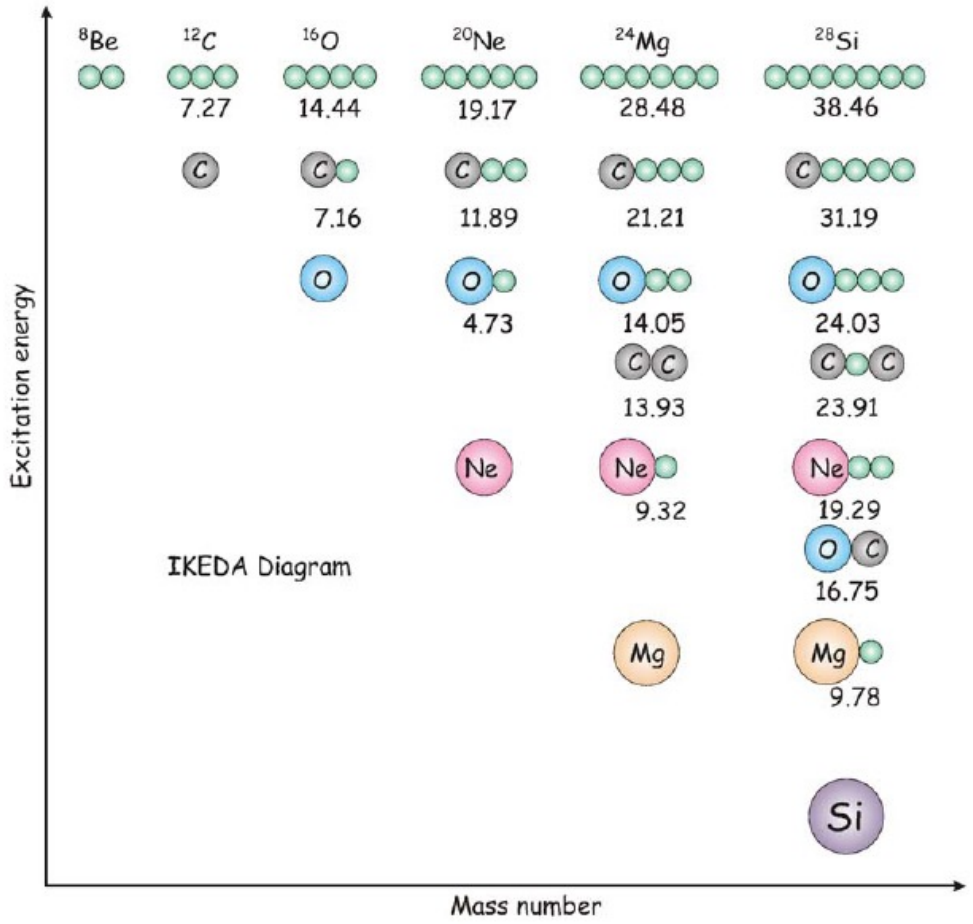
Cluster States in N = 4n Nuclei

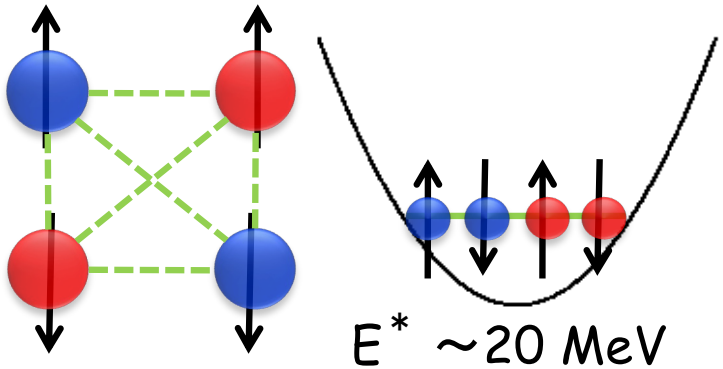
α clustering is an important concept in nuclear physics for light nuclei.

α cluster structures emerge near the α-decay thresholds in N = 4n nuclei.



The most tightly bound light cluster

α particle (quartet)



E^* ~20 MeV stiff

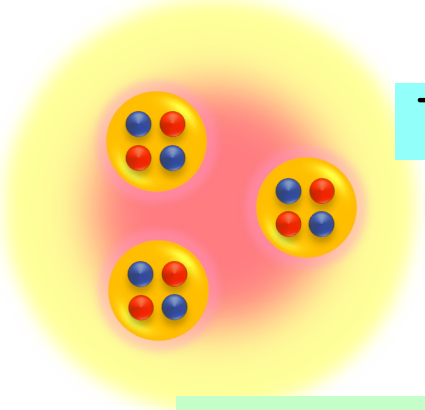
The most elemental subunit in nuclear cluster structures.

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

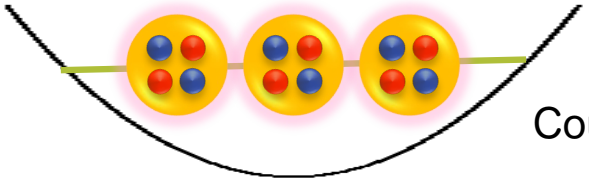
Alpha Condensed States

α clusters might condense into the lowest s orbit as BEC.

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



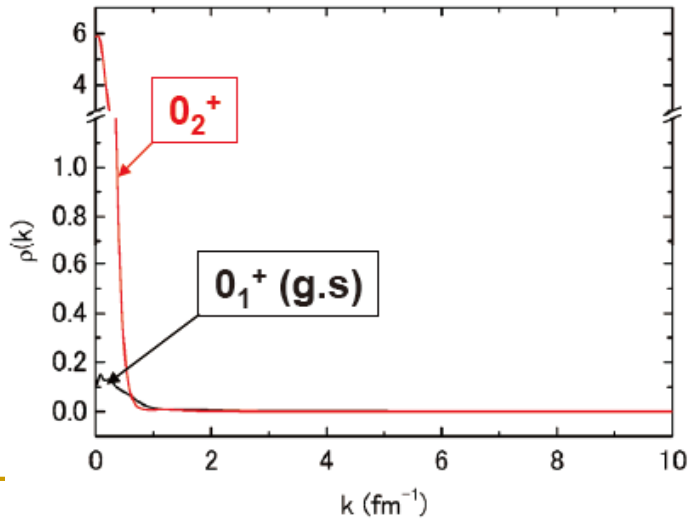
The 0^+_2 state in $_{12}C$ is the most well–known example.



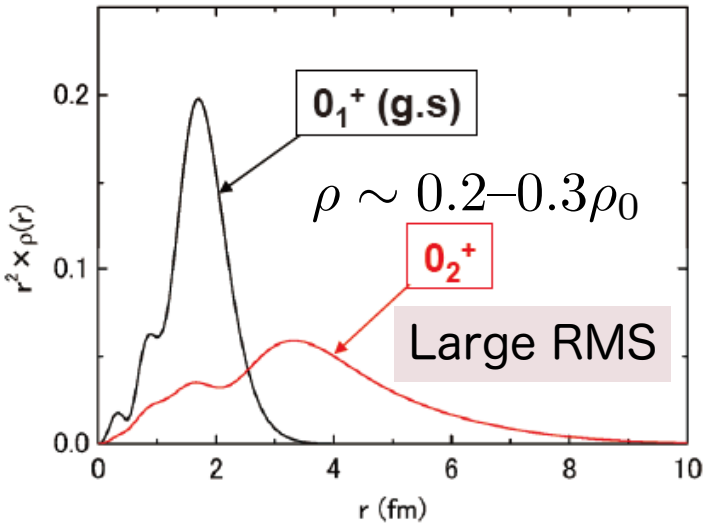
Courtesy of Y. Funaki

A new conformation of dilute nuclear matter.

Sharp momentum distribution



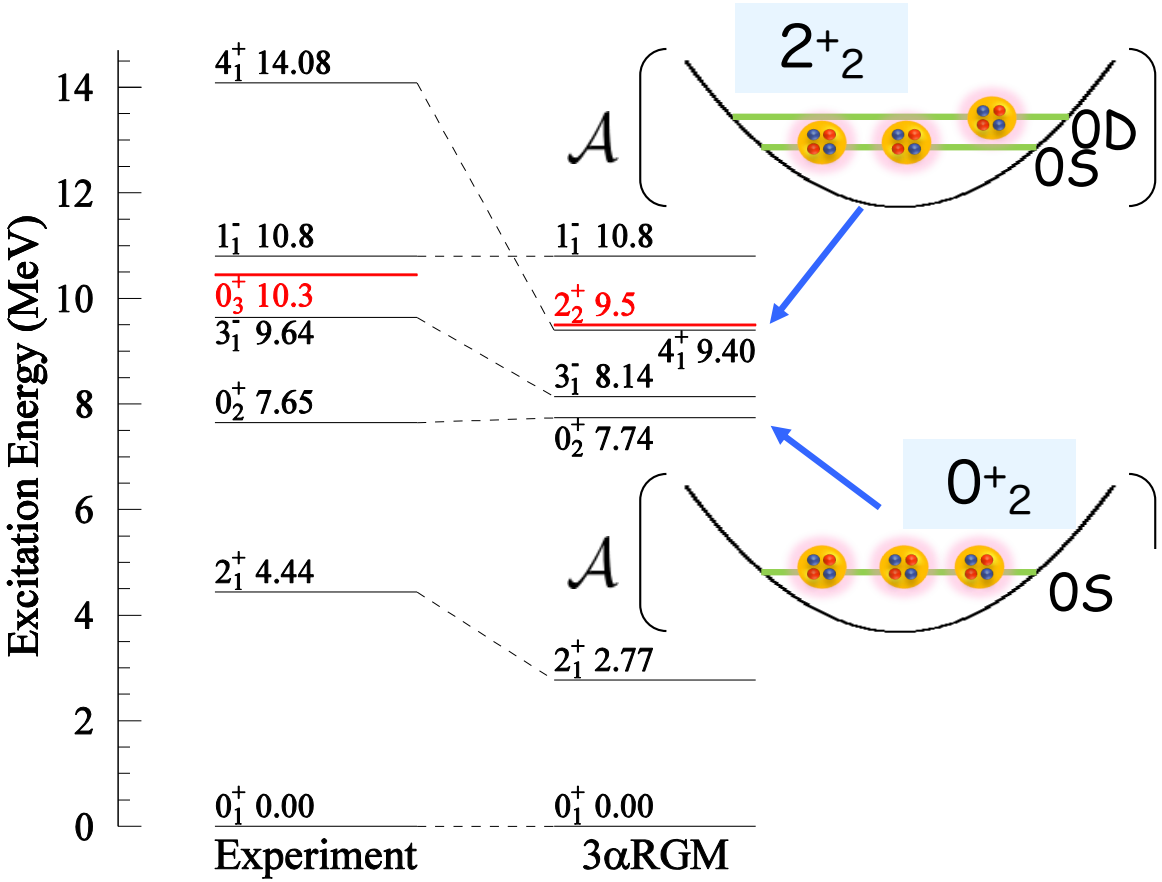
Dilute matter distribution

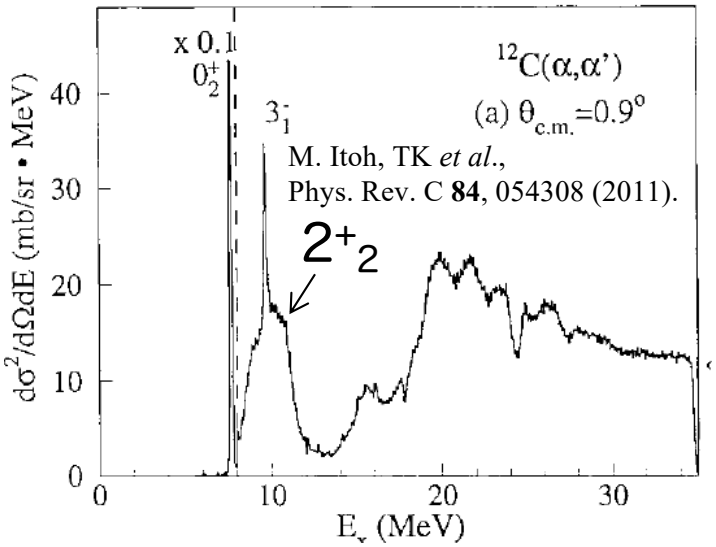


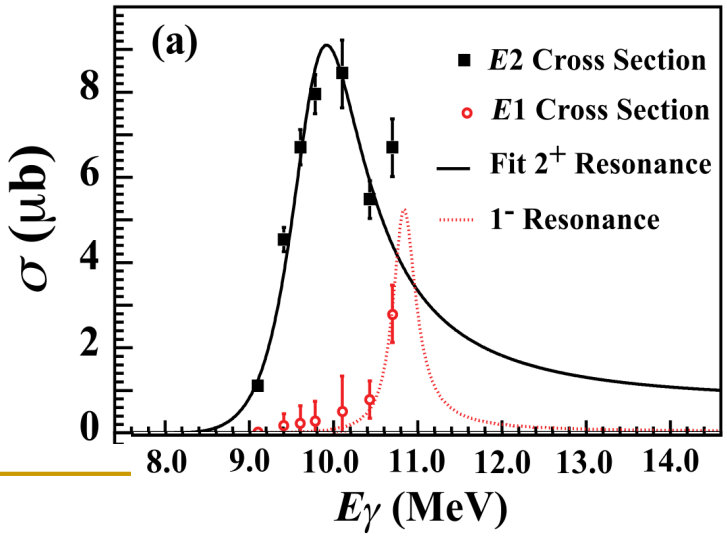
T. Yamada and P. Schuck, Eur. Phys. J. A 26, 185 (2005).

2^+_2 state in ^{12}C

A 2^+ excited state of ACS in ^{12}C is predicted at $E_x \sim 9.5$ MeV.





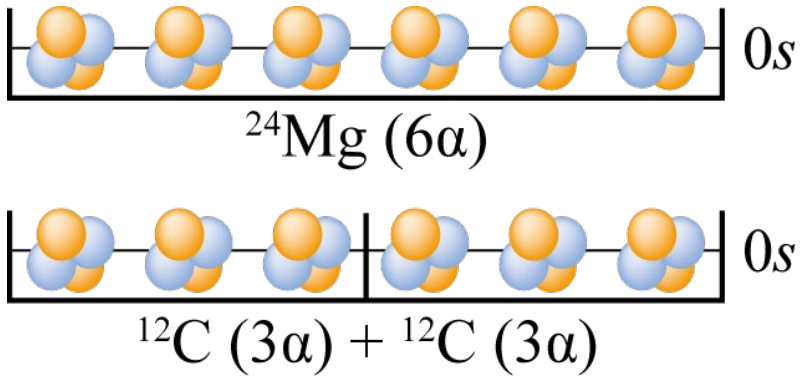


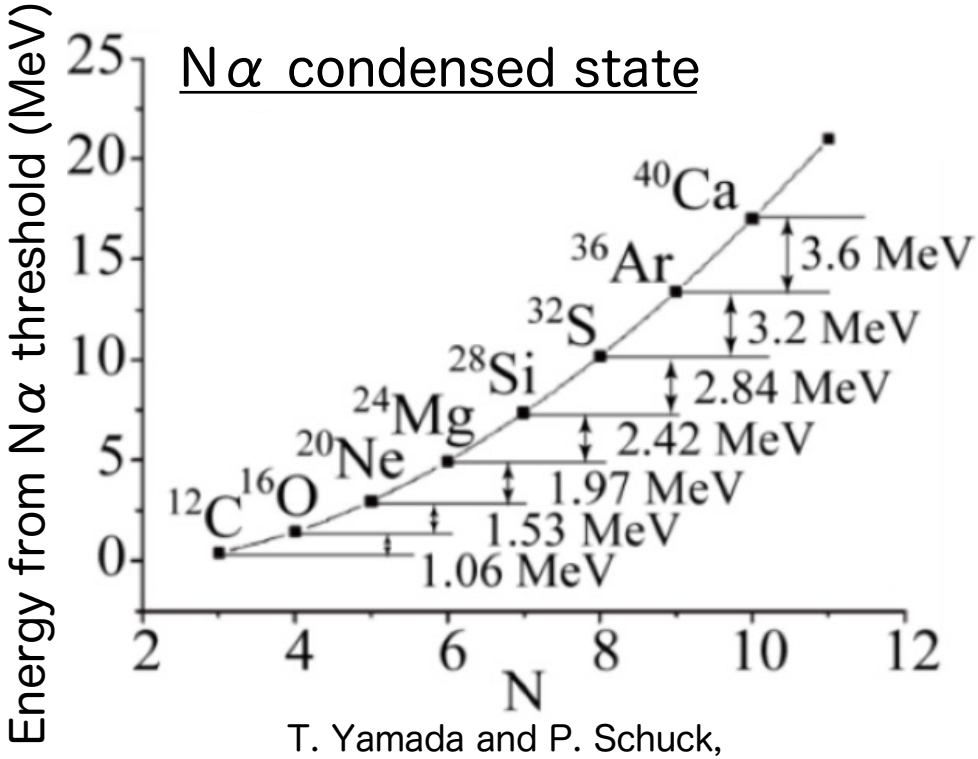
Existence of the 2^+_2 state is strong evidence of ACS in ^{12}C.

W. R. Zimmerman et al., Phys. Rev. Lett. **110**, 152502 (2013).

ACS in Heavier N = 4n Nuclei

- ✓ AC might affect symmetry energy of dilute nuclear matter.
- ✓ If AC emerges in nuclear matter, ACS should exist in heavier nuclei.
- ✓ ACSs in A < 40 nuclei are theoretically predicted by alpha cluster model, it is not trivial....





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

Nα condensed states should decay via lighter α condensed states.

ACS in Heavier N = 4n Nuclei

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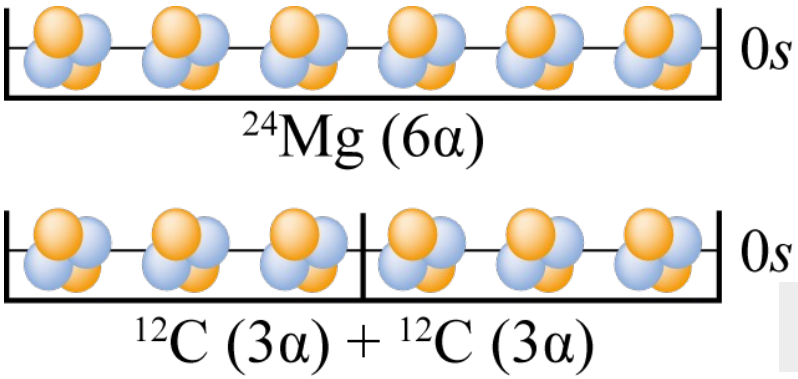

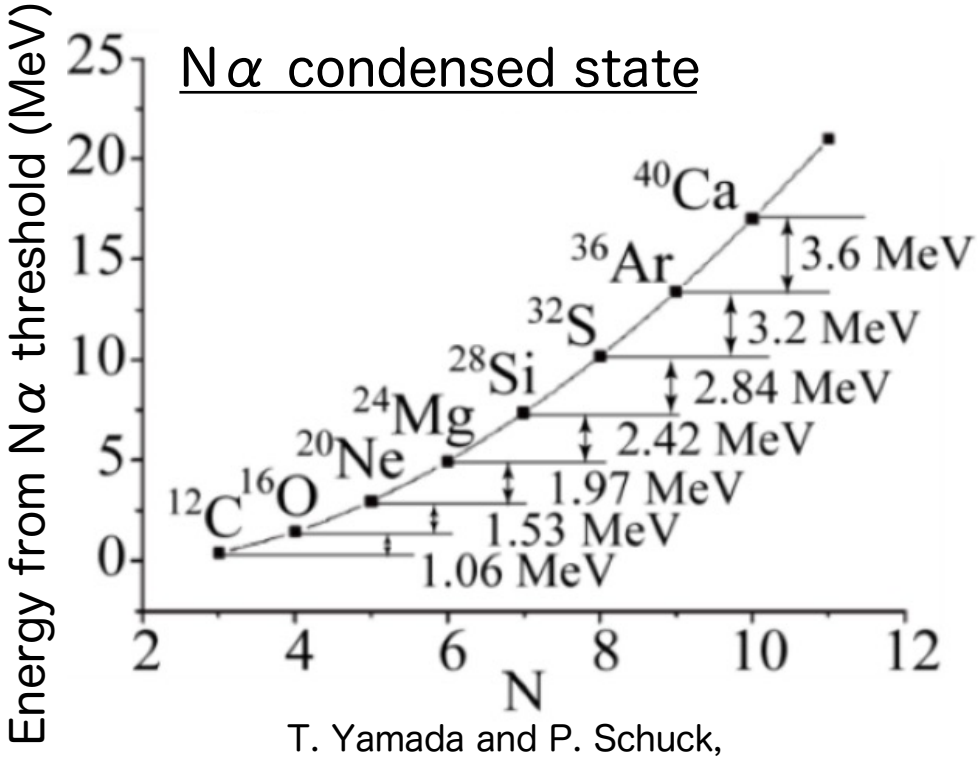

T. Yamada and P. Schuck,
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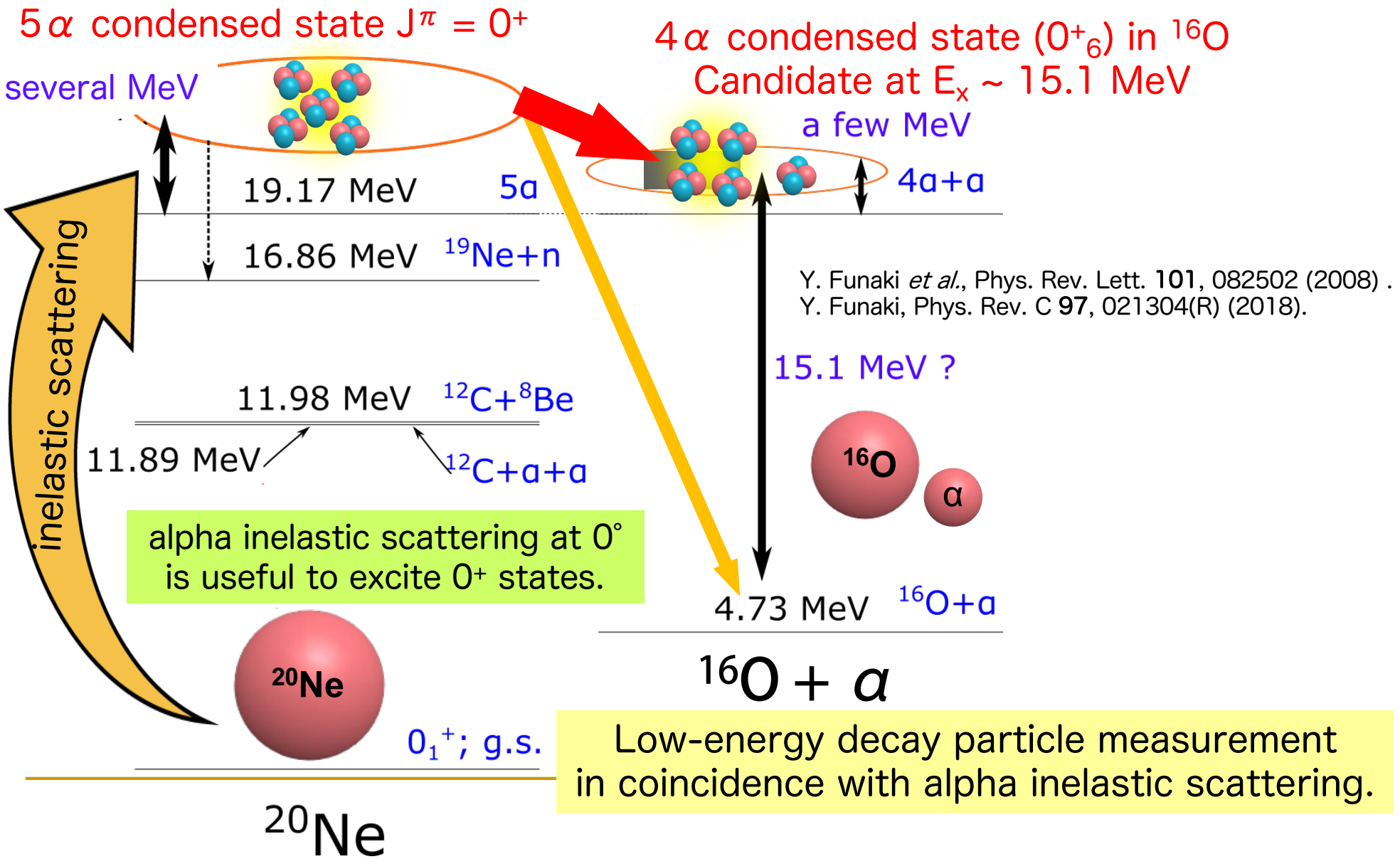
Nα condensed states should decay via lighter α condensed states.

We searched for ACSs in ^{20}Ne and ^{24}Mg.

Alpha Condensed State in ^{20}Ne

ACS decays via ACS in lighter nuclei by emitting low-energy α particles

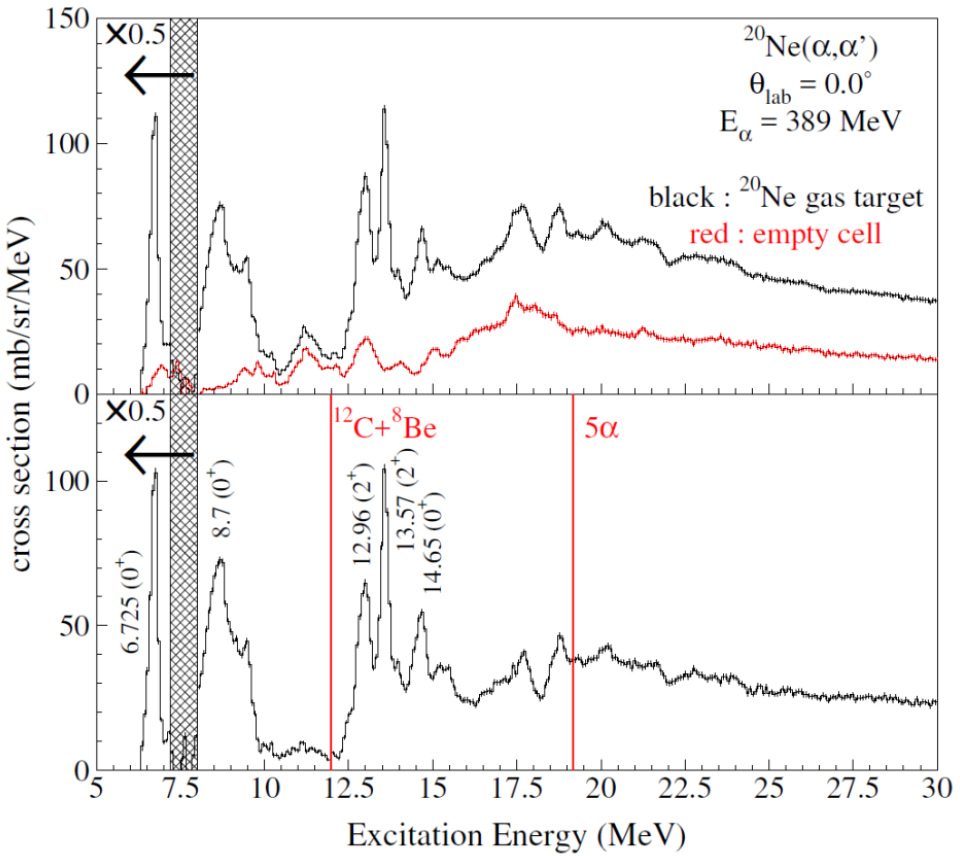


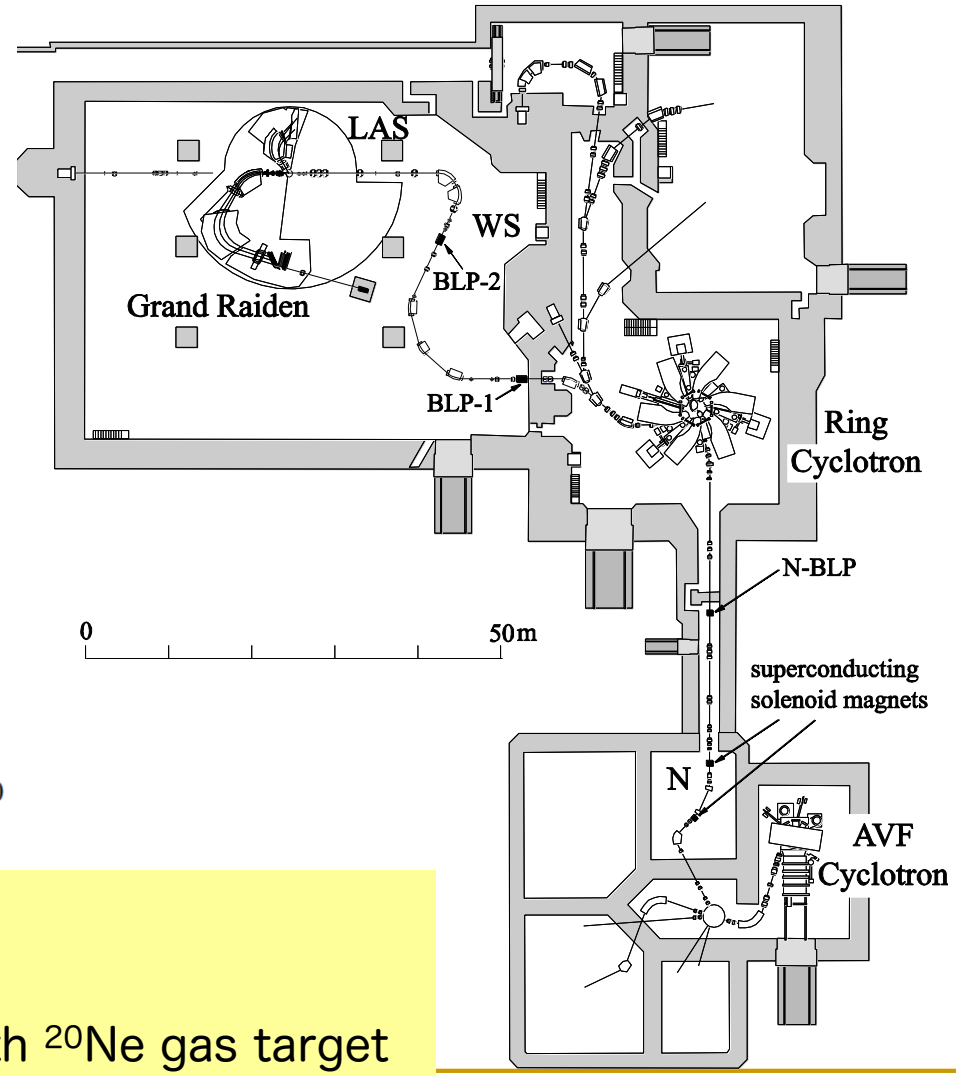
alpha inelastic scattering at 0° is useful to excite 0+ states.

Low-energy decay particle measurement in coincidence with alpha inelastic scattering.

Experiment at RCNP

Experiment was performed at RCNP, Osaka University.





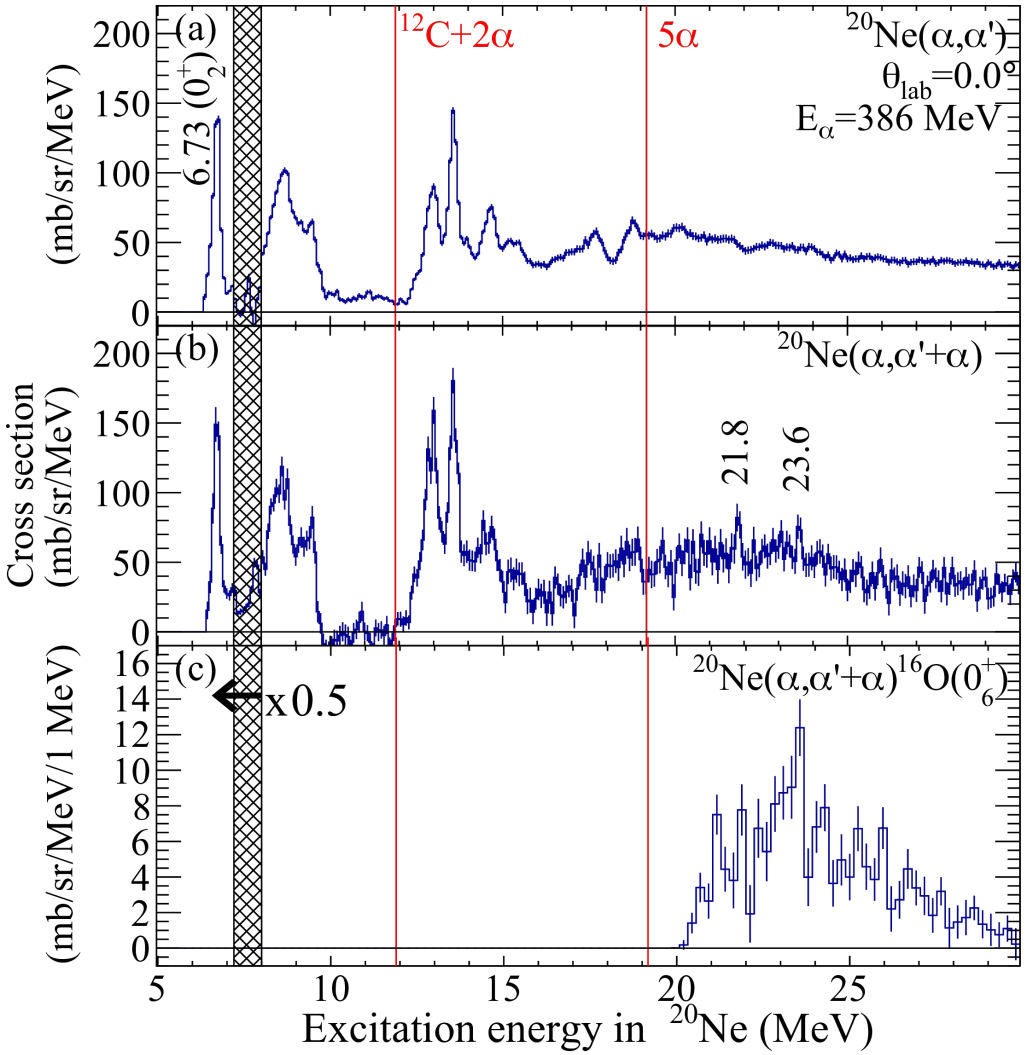
RCNP-E402

S. Adachi, Y. Fujikawa, TK et al

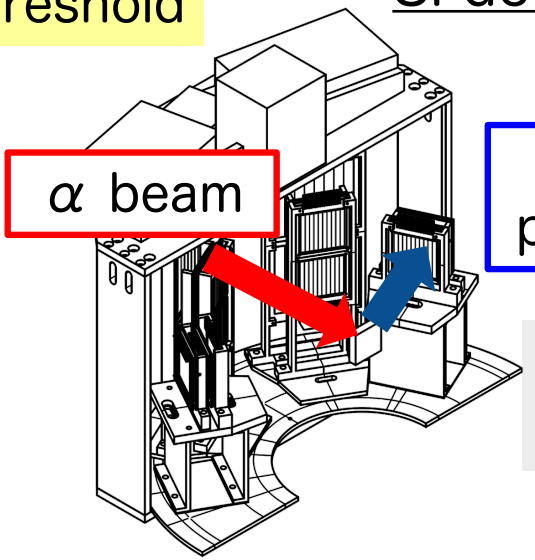
(α, α'+α) @ 400 MeV θ_{lab}= 0° with ^{20}Ne gas target

Decay to the 4α condensed state

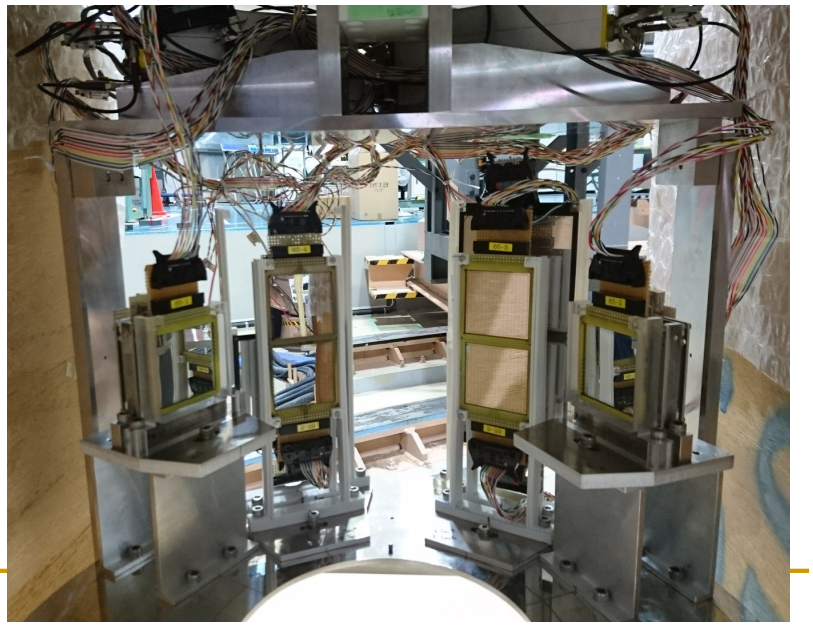
Region of Interest: 1—5 MeV above 5α threshold



Si detector array



6 segments
Solid Angle 4%



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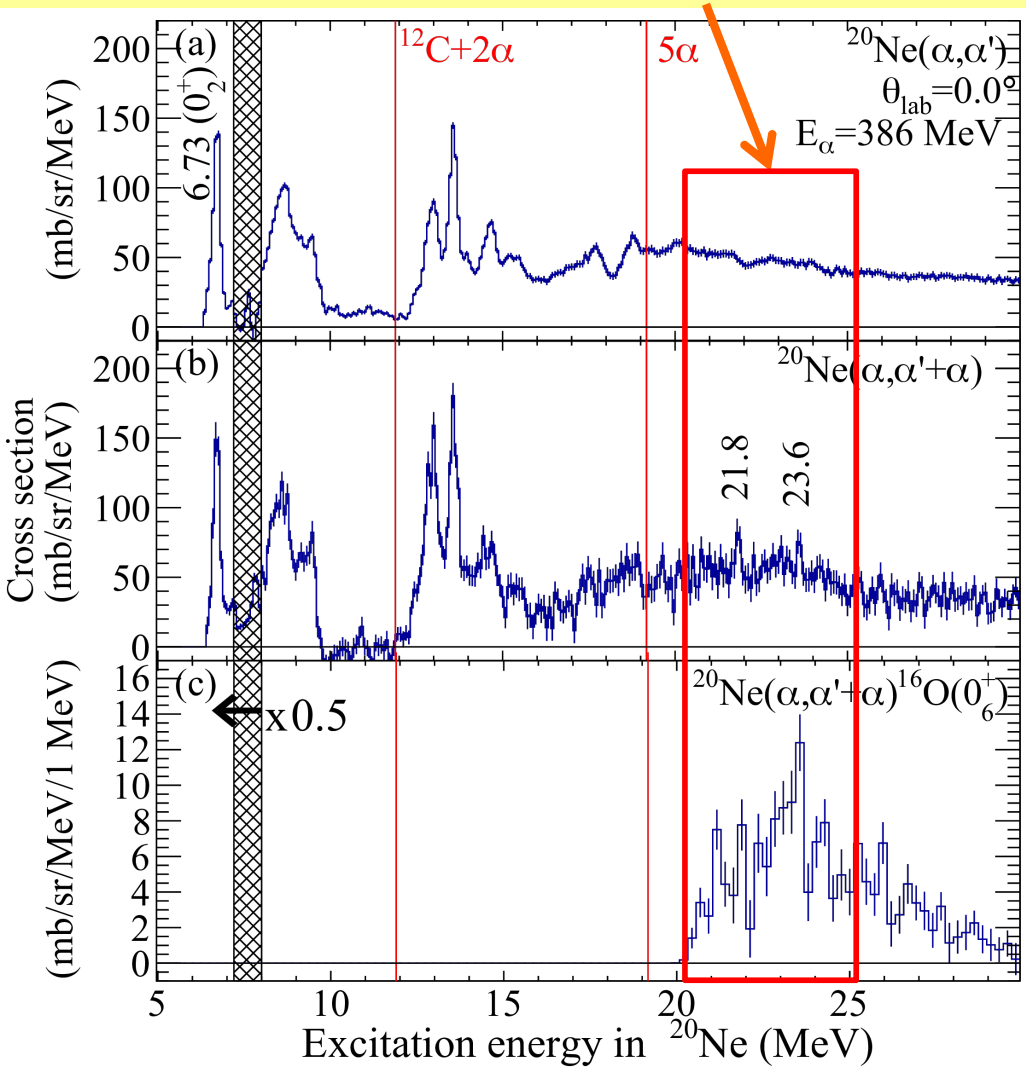

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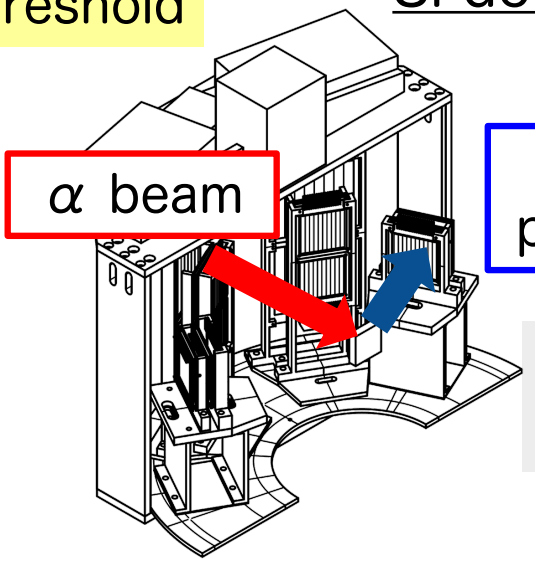

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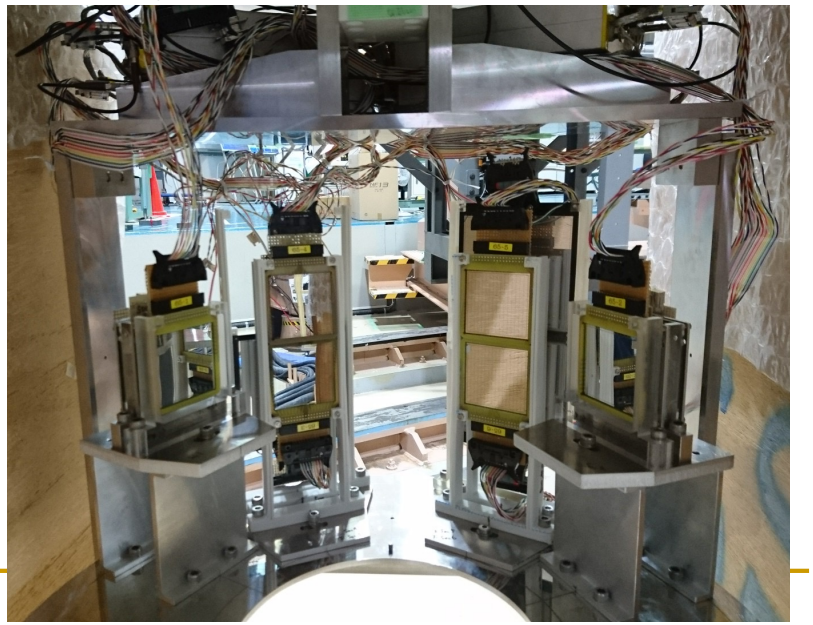

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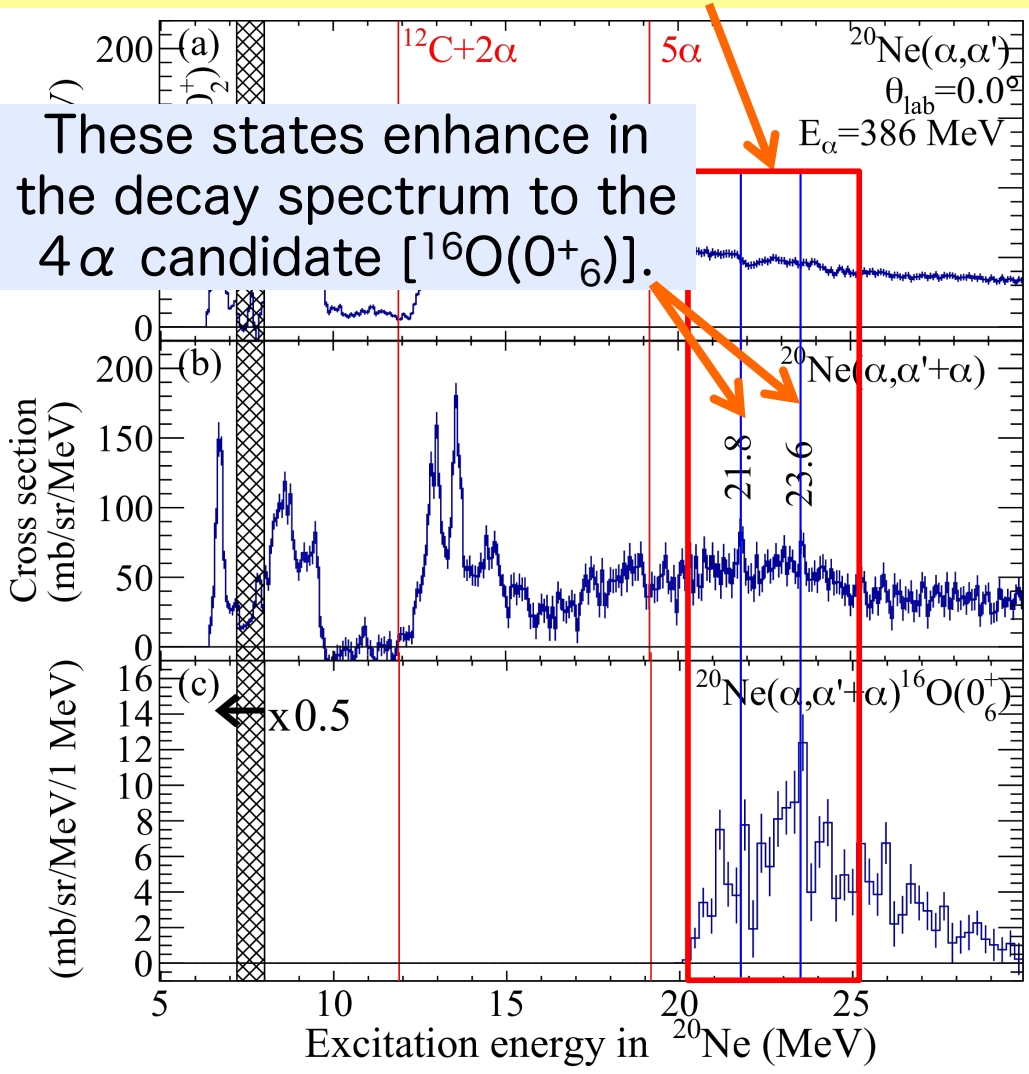

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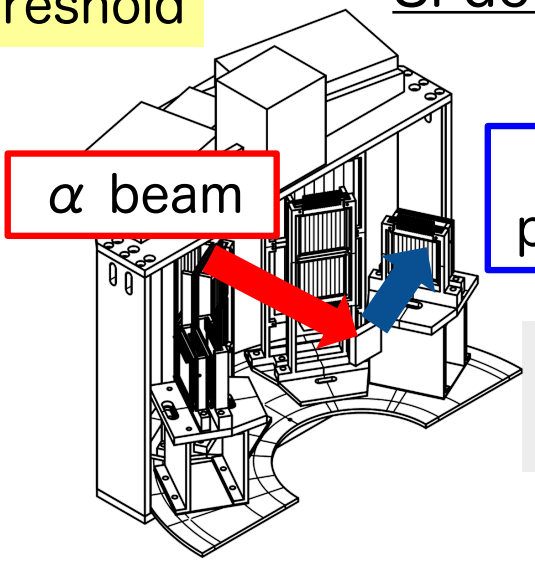

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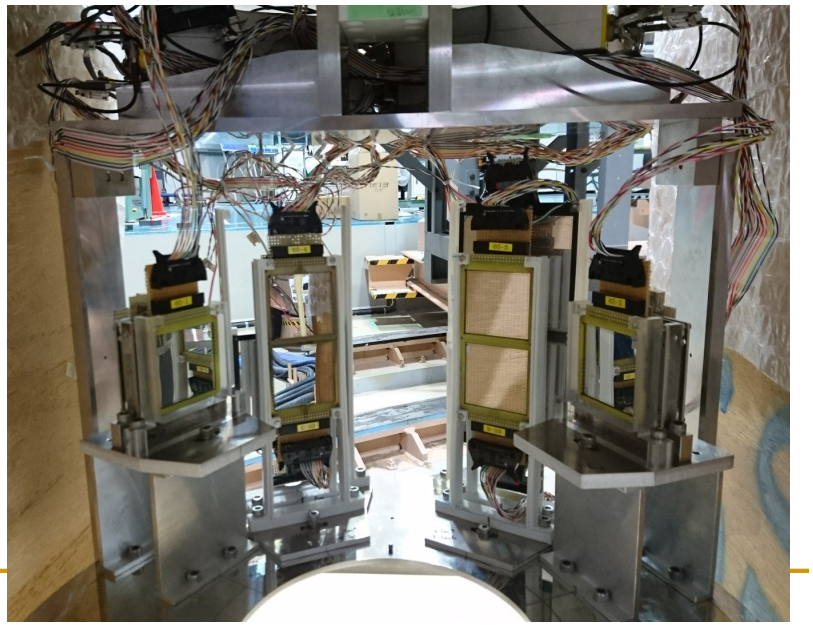

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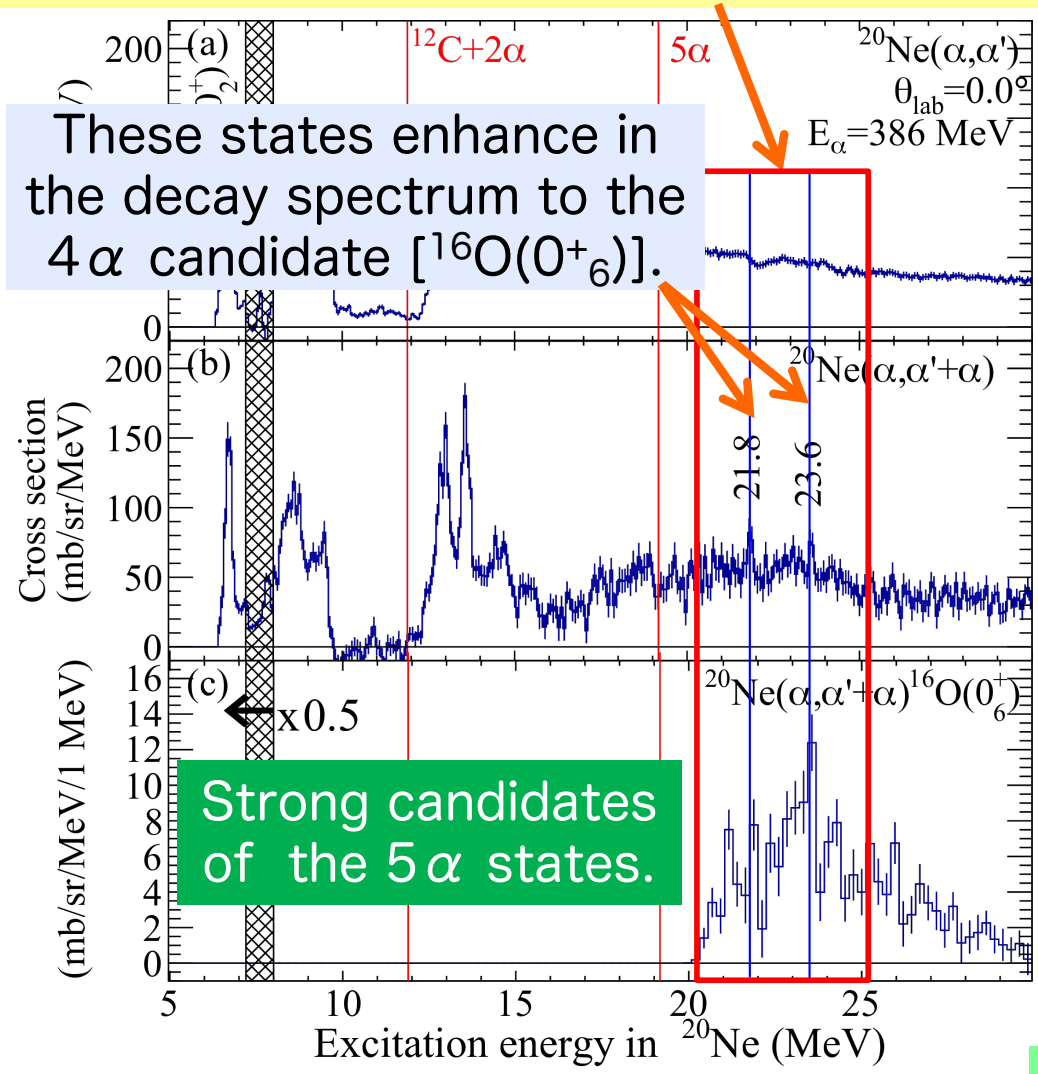
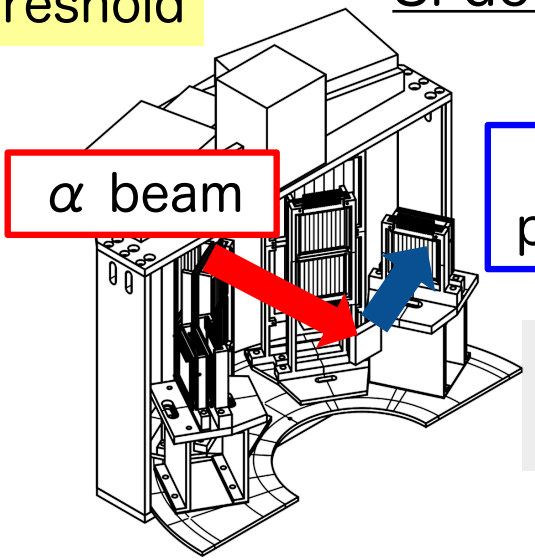


These states enhance in the decay spectrum to the 4α candidate [^{16}O(0^+_6)].

Strong candidates of the 5α states.

Si detector array



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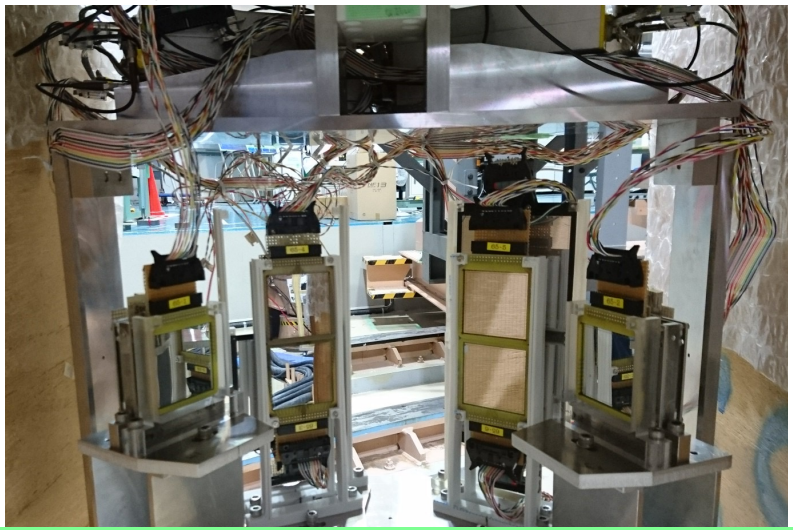


Need large solid angle for decay-particle measurement.

However, statistics was poor...

Alpha Condensed State in ^{24}Mg

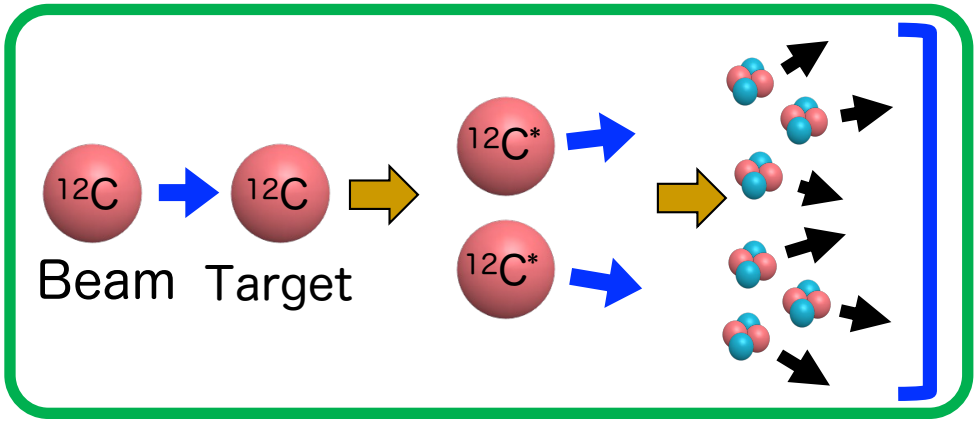
Heavy-ion beam boosts decay particles to forward angles.

Search for ACS in ^{24}Mg

$^{12}C + {}^{12}C$

$\rightarrow {}^{24}Mg(6\alpha;\ ACS)$

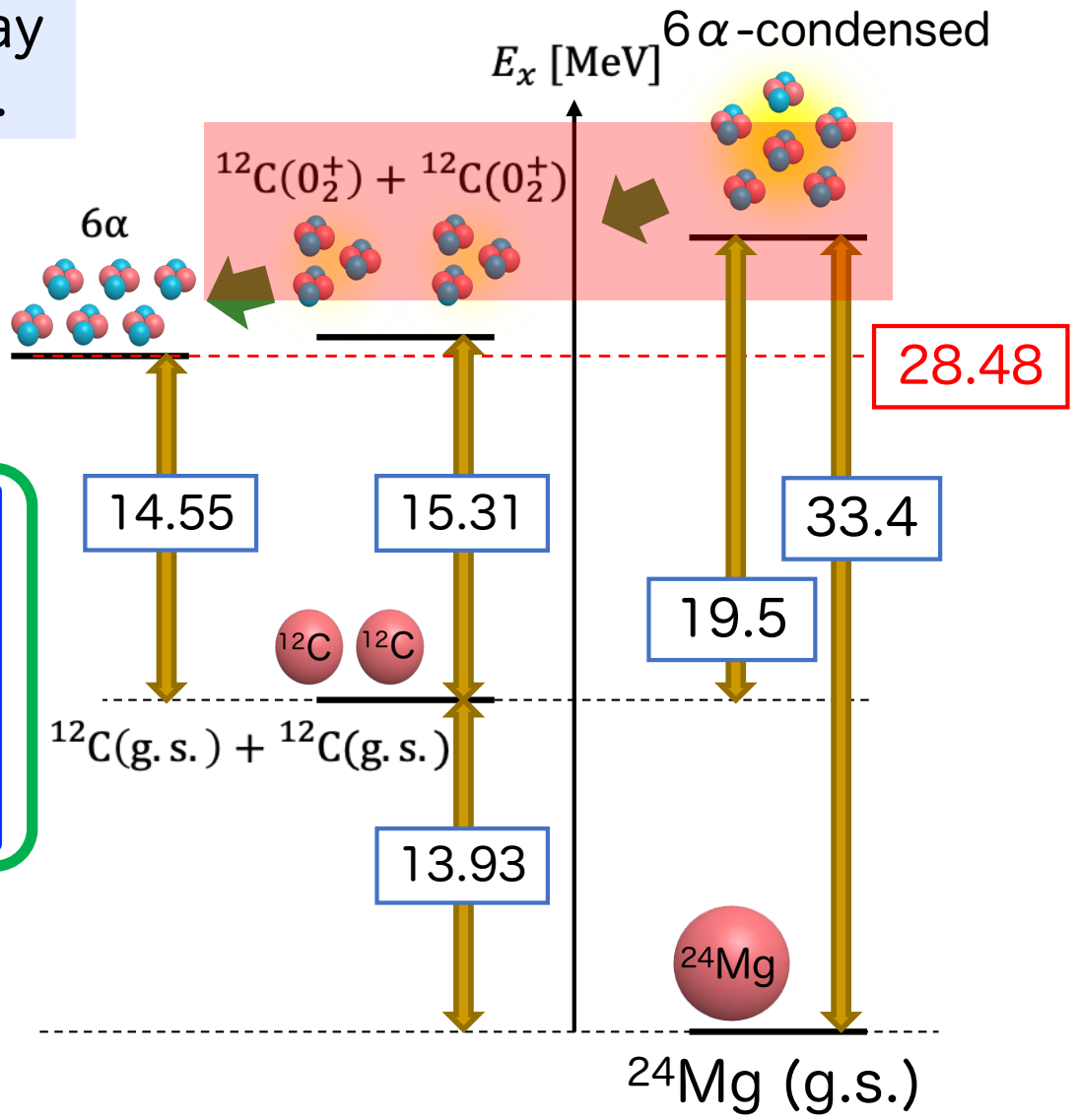
$\rightarrow {}^{12}C(0^+_2) + {}^{12}C\ (0^+_2) \rightarrow 6\alpha$



$^{12}C + {}^{12}C$ Energy scan

E_{beam} = 35.0—50.0 MeV

E_{cm} = 17.5—25.0 MeV



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$^{12}C + {}^{12}C$

$\rightarrow {}^{24}Mg(6\alpha$; ACS)

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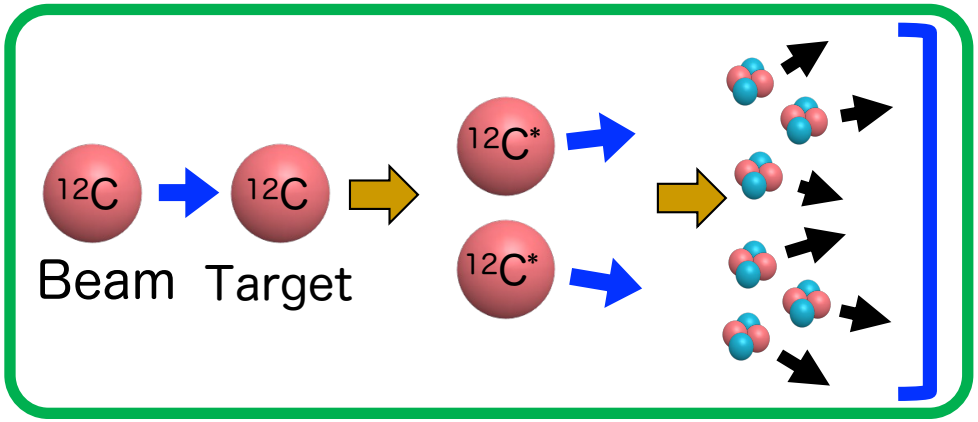

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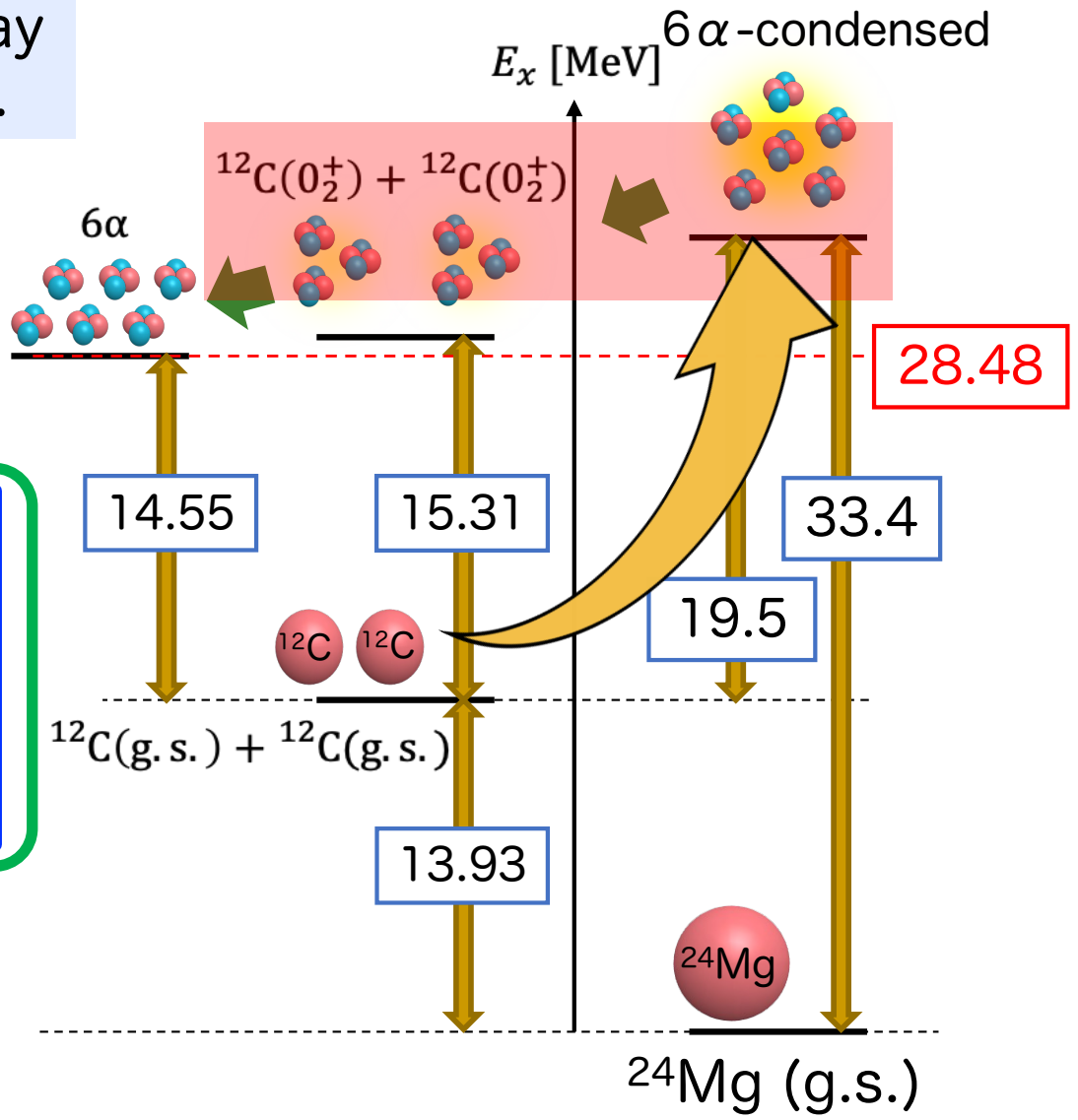
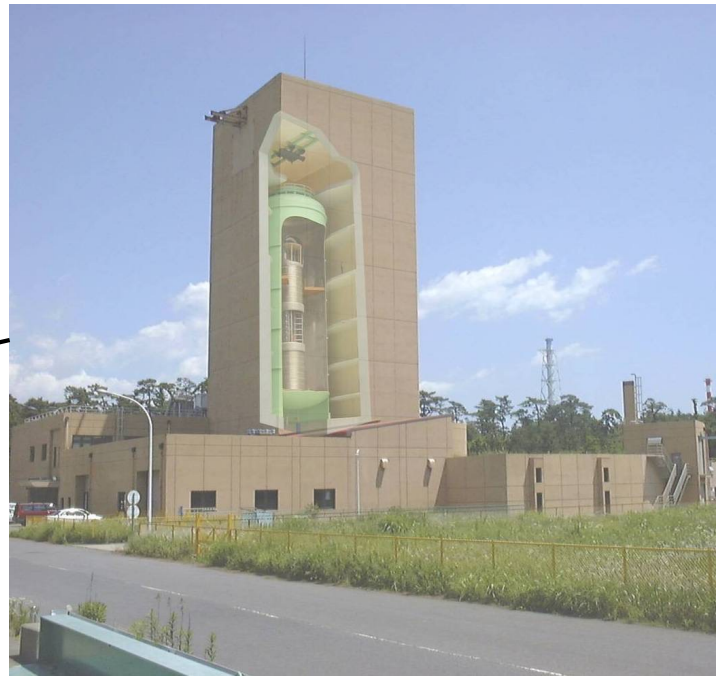


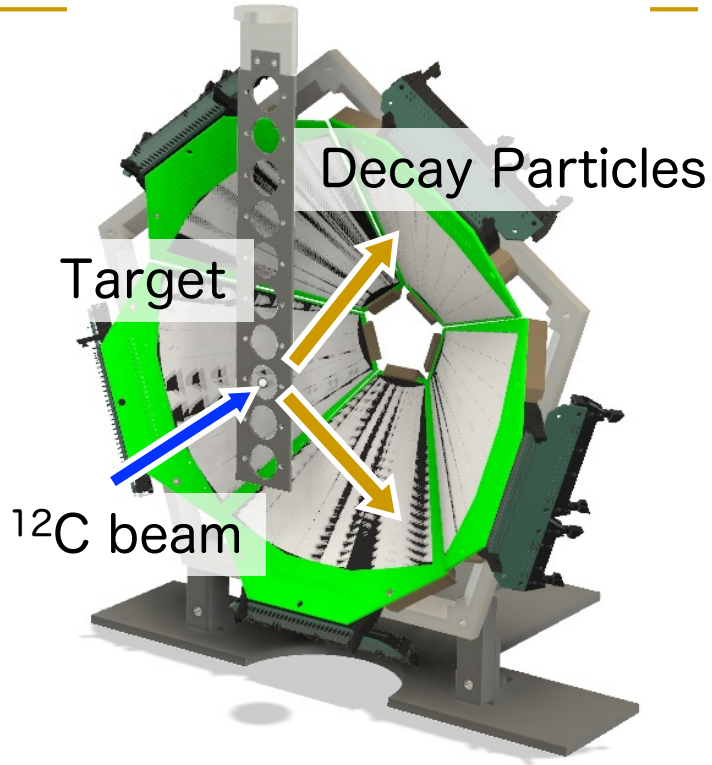
Experiment at JAEA

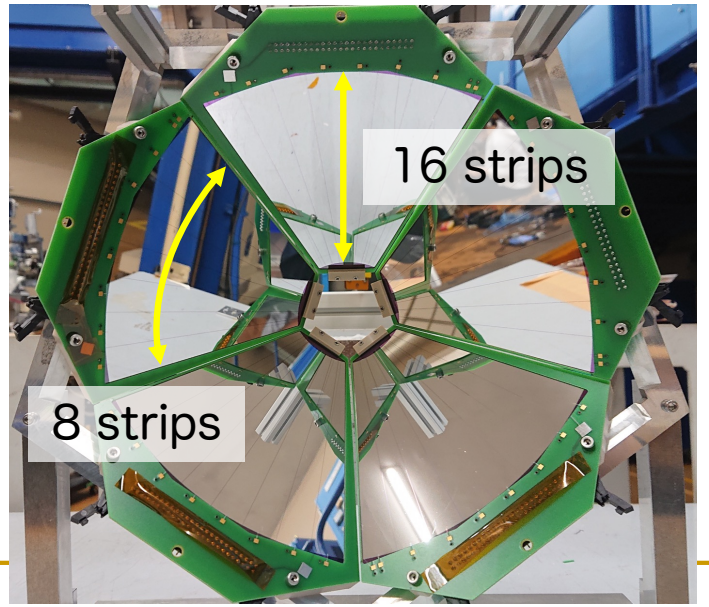
- $^{12}C + {}^{12}C$ scattering @ $E_{\mathrm{beam}} = 35.0 - 50.0\ \mathrm{MeV}$
  - JAEA Tokai 19 MV Tandem Accelerator, R5 beam line
  - Heavy ion induced reaction
    → Decay particles are boosted to forward angle
  - Target: ^{nat}C 100 ug/cm^2



Si detector array: SAKRA

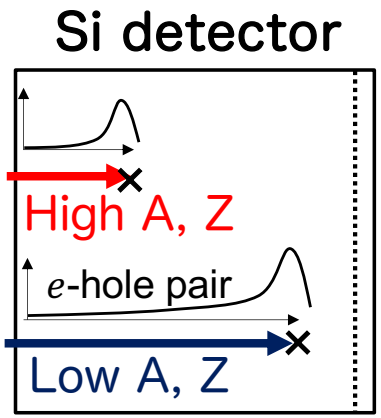
- Design MMM Si sensor from Micron Semiconductor × 5
  - Thickness: 500 um
  - Double sided readout
    - Front (Ohmic) : 8 strips (radial)
    - Rear (Junction): 16 strips (ring)
  - Large angular acceptance
    - R = 33—135 mm, θ = 60°
- Special configuration for PSA
  - Neutron Transmutation Doping Si
    →Good uniformity of the crystal
  - Rear (ohmic) side injection
    →Better separation in PID

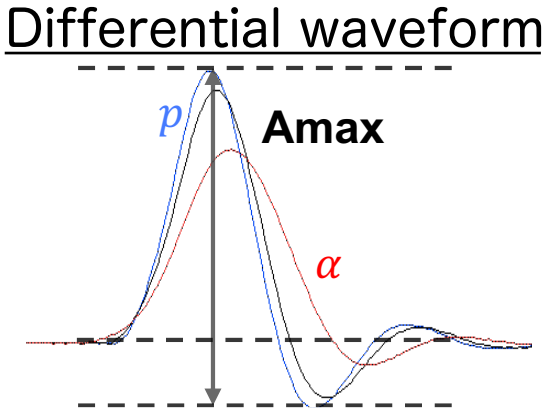


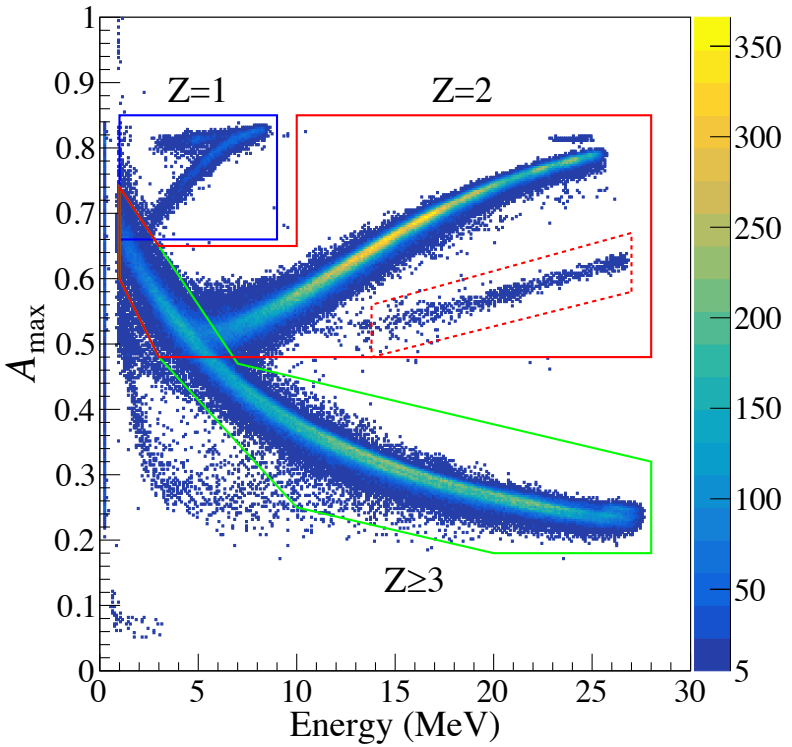


Particle Identification (PID)

- Distribution of electron-hole pair depends on A and Z of incident particle
  - → Pulse shape depends on incident particle
- PID parameter : A_{max}
  - Amplitude of the differential waveform
  - A_{max} vs Energy
    - Reasonable PID
      - p/α separation : 2 MeV~
      - α/C separation : 5 MeV~



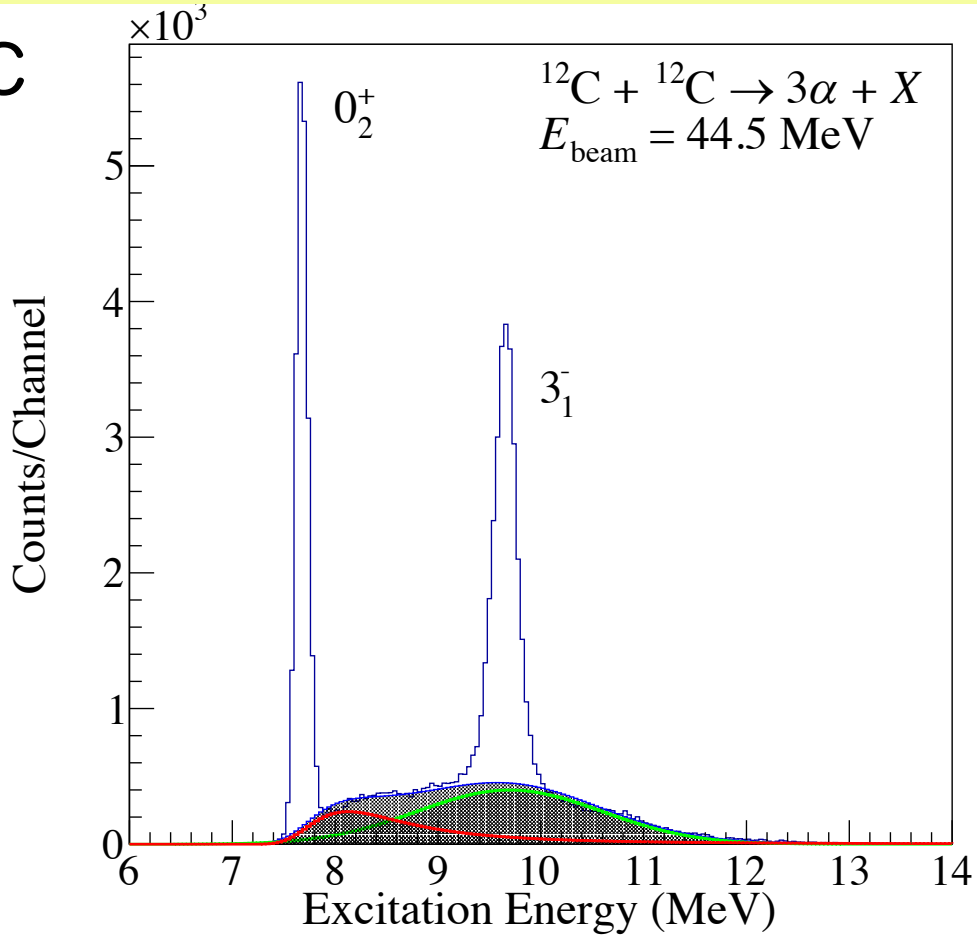




Invariant Mass of 3α Particles

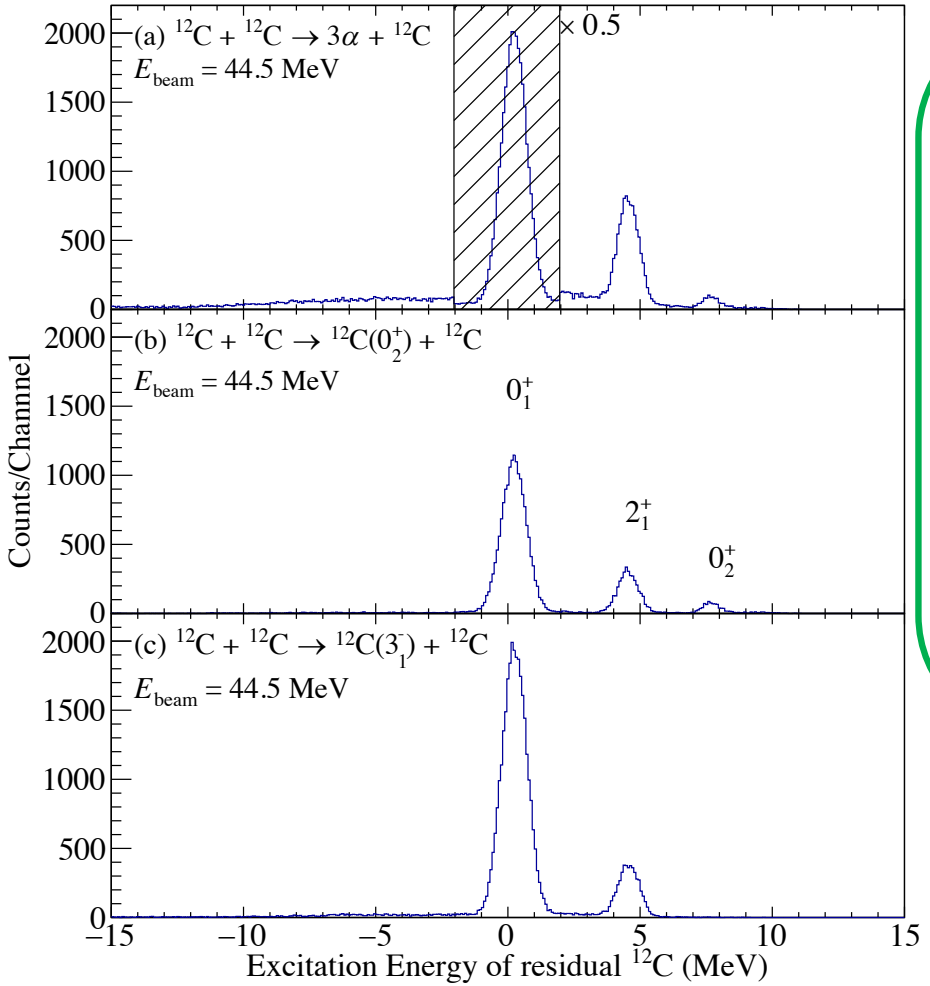
Excitation-energy spectrum of ^{12}C
was successfully obtained from 3α invariant mass.

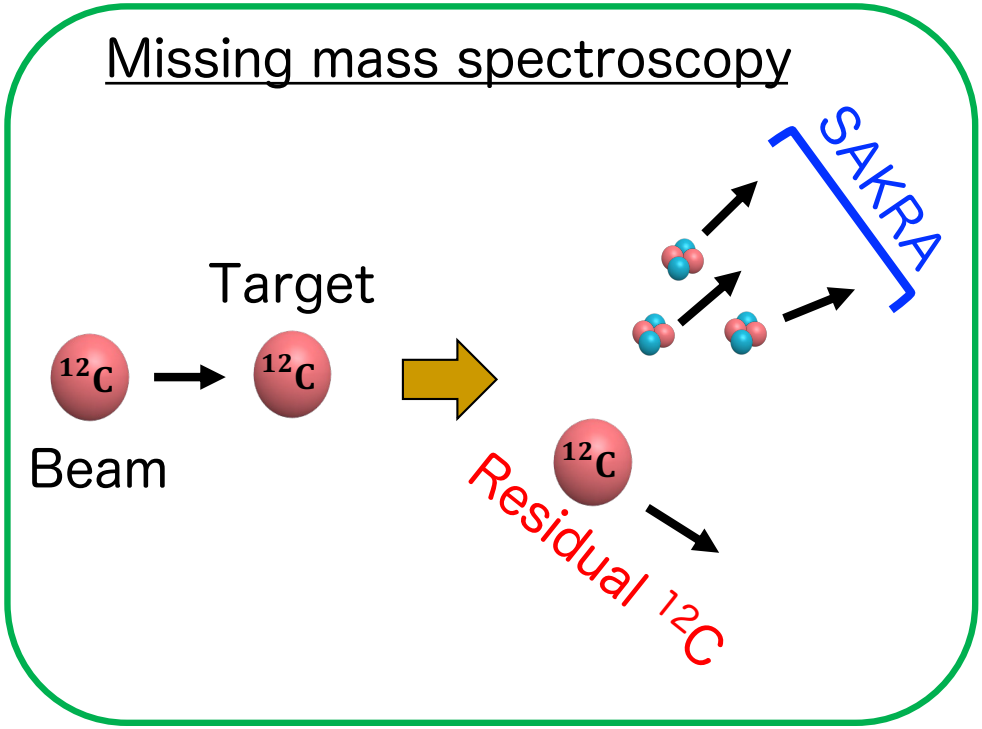
- Two discrete states in ^{12}C
  - 0^+_2: 7.65 MeV
  - 3^-_1: 9.64 MeV
- Continuous spectrum below the peaks
  - Broad 0^+_3 and 2^+_2 states in ^{12}C (green)
  - Backgrounds due to wrong PID events (red)
  - Accidental events are negligible.



Missing mass spectroscopy for residual ^{12}C

Excitation-energy spectra of residual ^{12}C nuclei were also obtained.

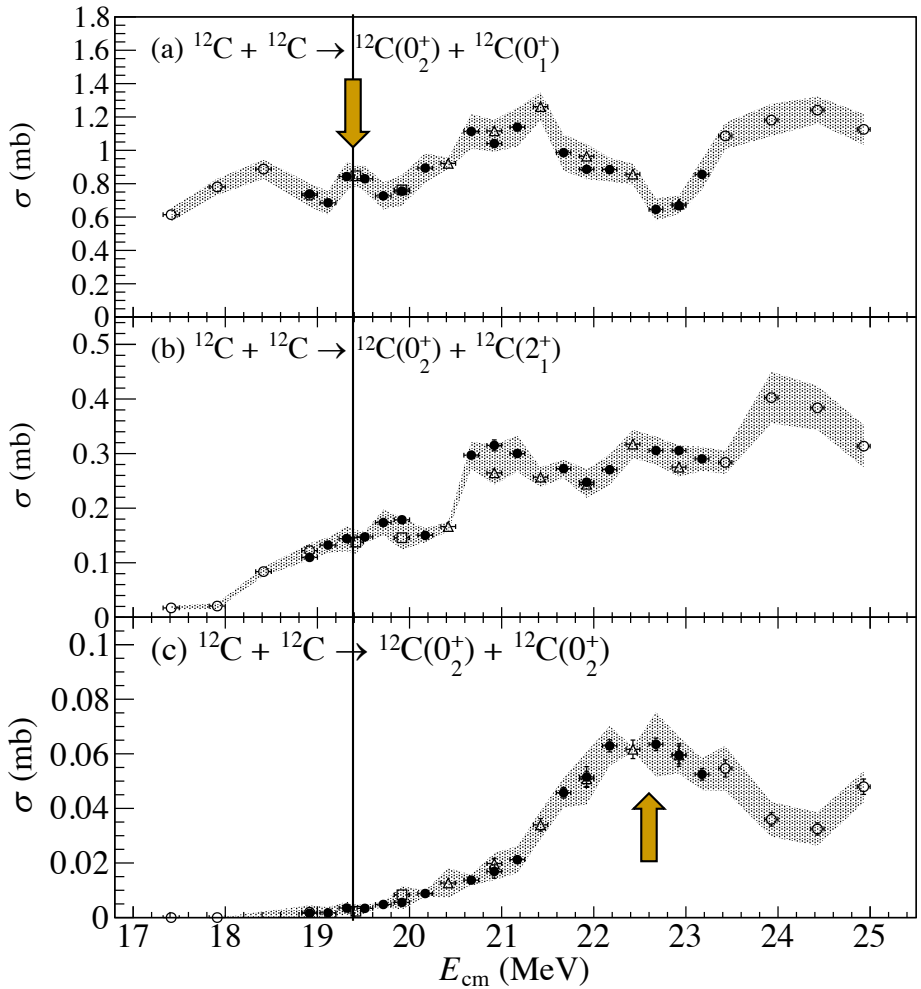




Reaction channels were unambiguously identified.

Exclusive E_x function

Exclusive E_x functions for $^{12}C + {}^{12}C \rightarrow {}^{12}C(0^+_2) + {}^{12}C(0^+_1, 2^+_1, \text{or } 0^+_2)$



Narrow peak at E_{cm} ~19,4-MeV in $^{12}C(0^+_2) + {}^{12}C(0^+_1)$.

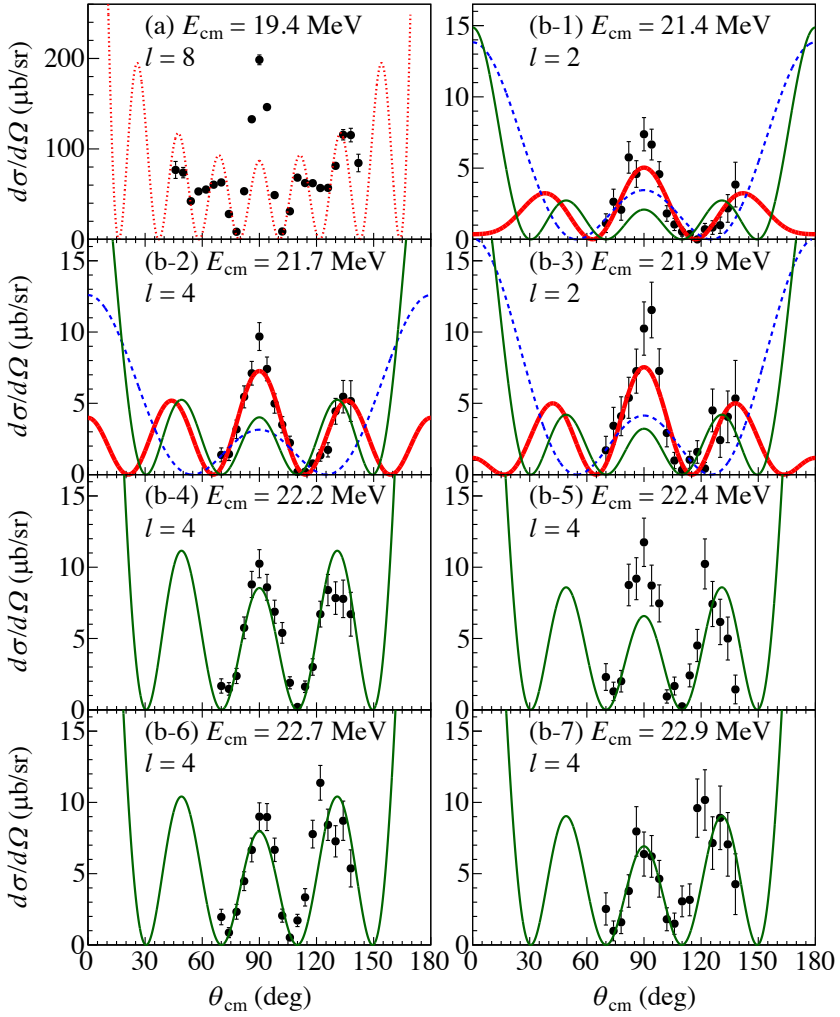
- Close to the theoretical energy of the 6α ACS.
- Suppressed in $^{12}C(0^+_2) + {}^{12}C(0^+_2)$ by the Coulomb barrier due to small decay energy.

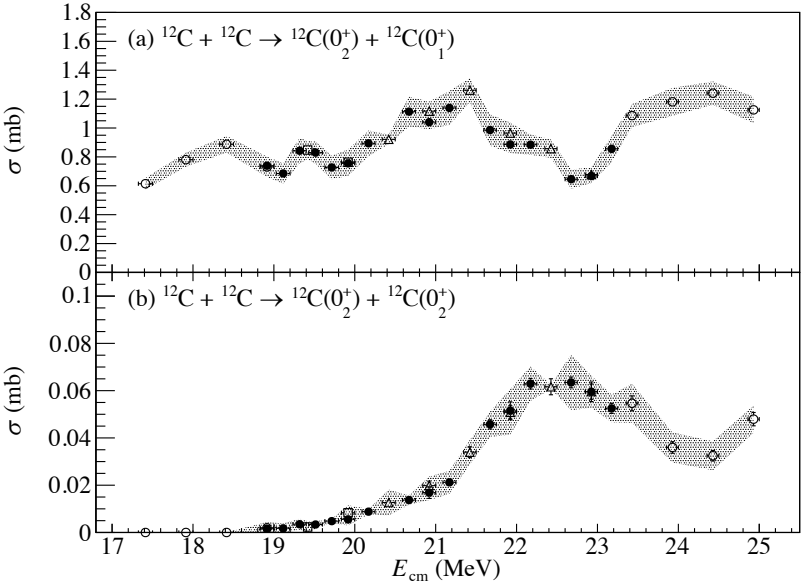
Broad bump at E_{cm} ~ 22.6 MeV in $^{12}C(0^+_2) + {}^{12}C(0^+_2)$.

- Excited state of the 6α-condensed state like the broad 2^+_2 state in ^{12}C ?

Angular Distributions

Angular distributions were analyzed to determine the spin and parity.





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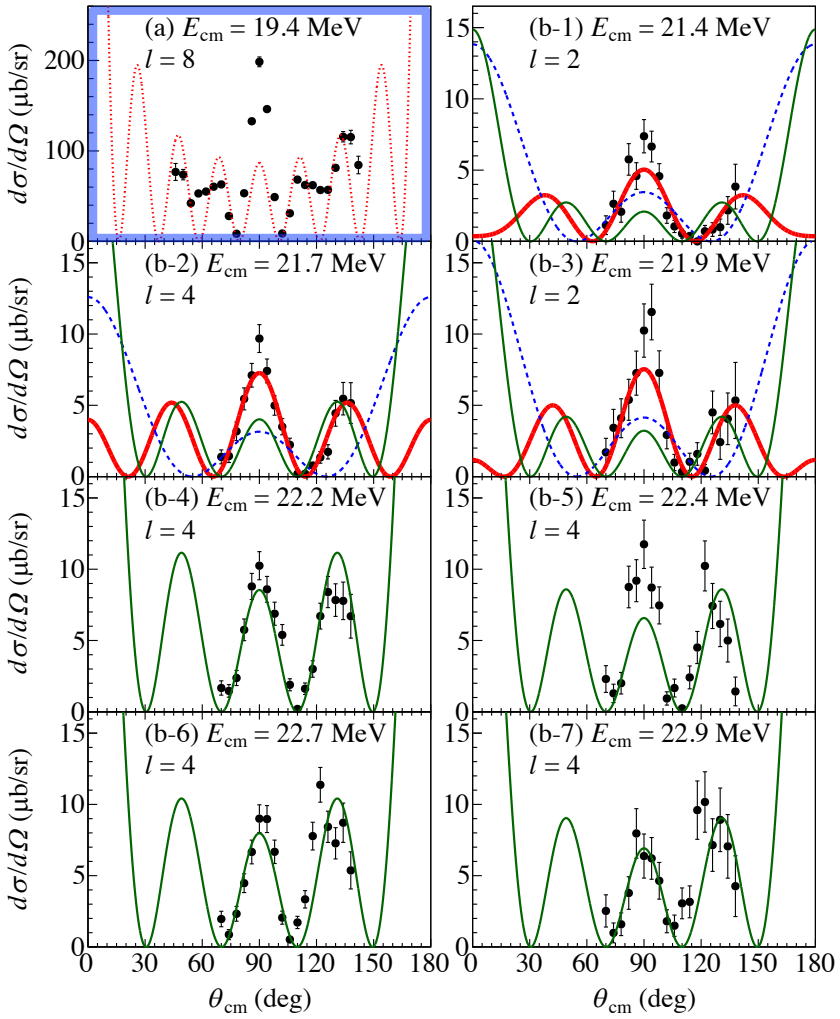

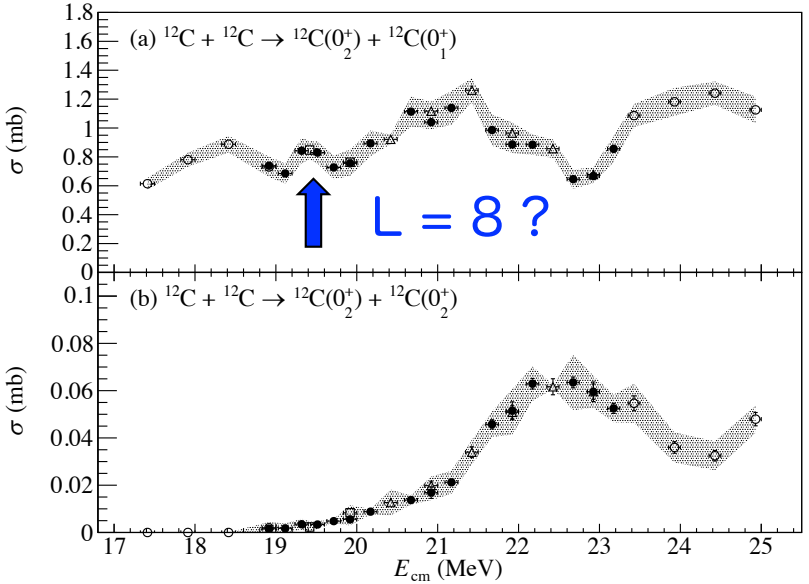

J^{π} at E_{cm} = 19.4 MeV is unclear due to continuous background.

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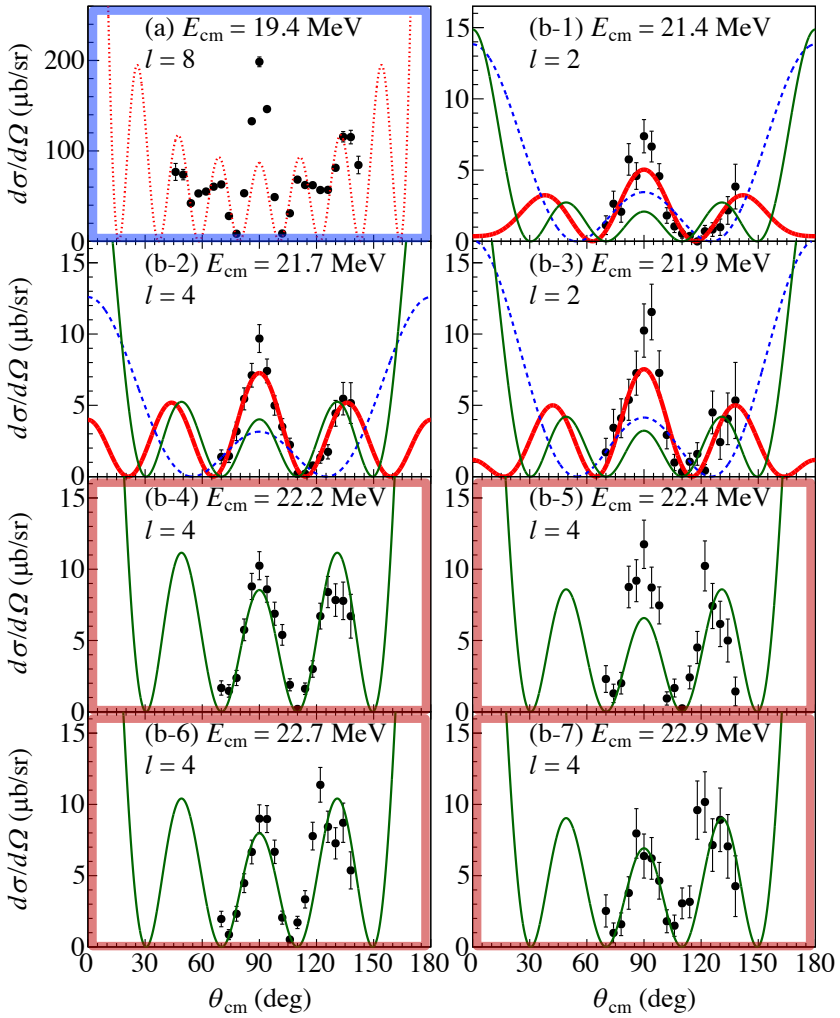

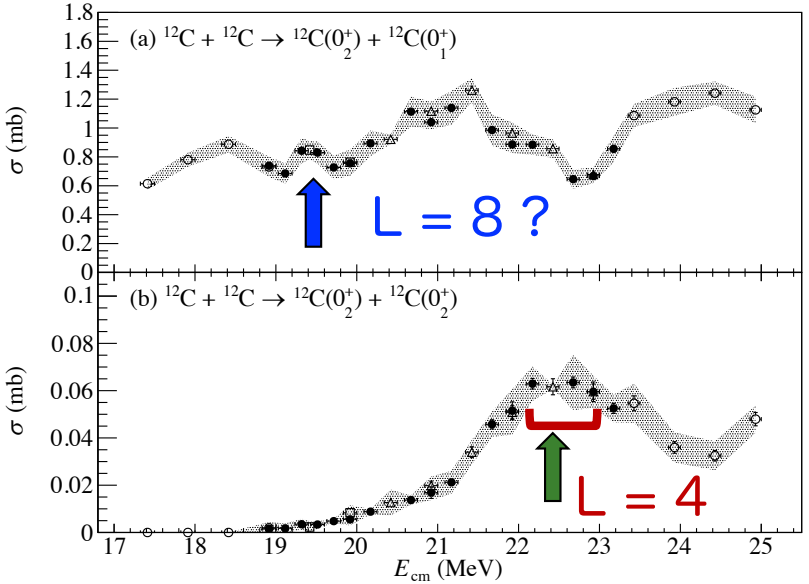

J^{π} at E_{cm} = 19.4 MeV is unclear due to continuous background.

Broad state at E_{cm} = 22.4 is $J^{\pi} = 4^+$.

Angular Distributions

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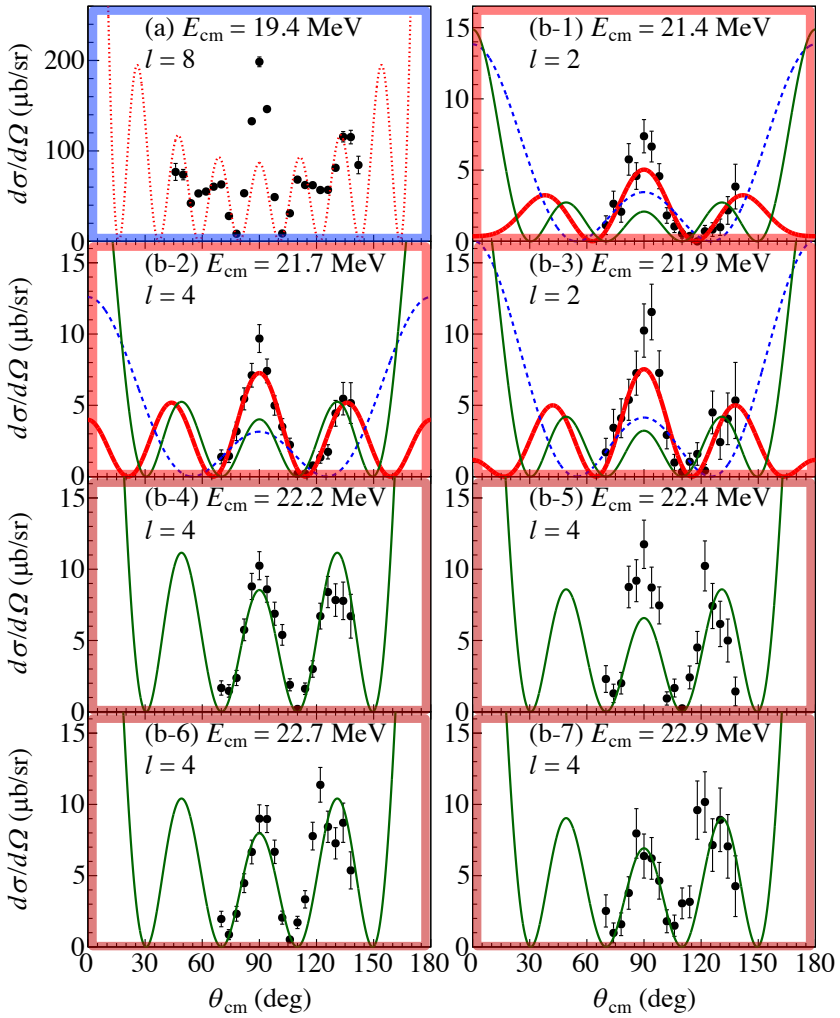
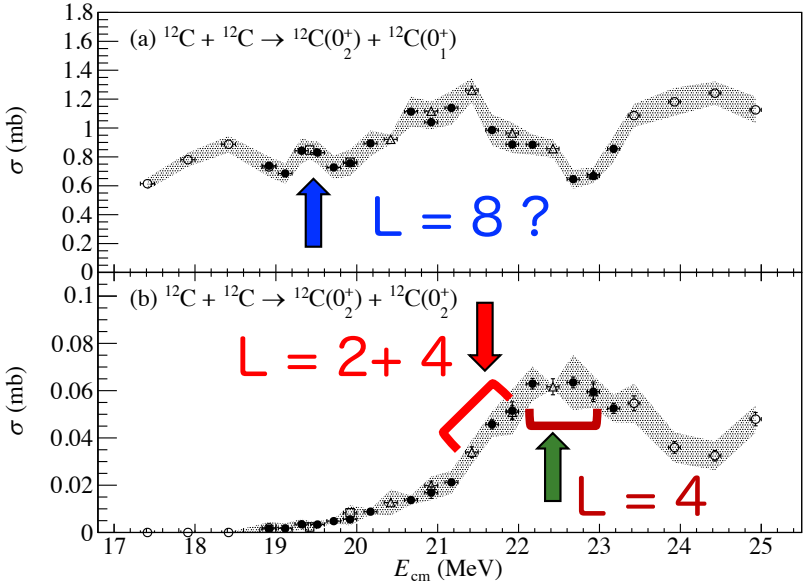




J^π at E_{cm} = 19.4 MeV is unclear due to continuous background.

Broad state at E_{cm} = 22.4 is $J^\pi = 4^+$.

$J^\pi = 2^+$ exists at low E_{cm} side of $J^\pi = 4^+$.

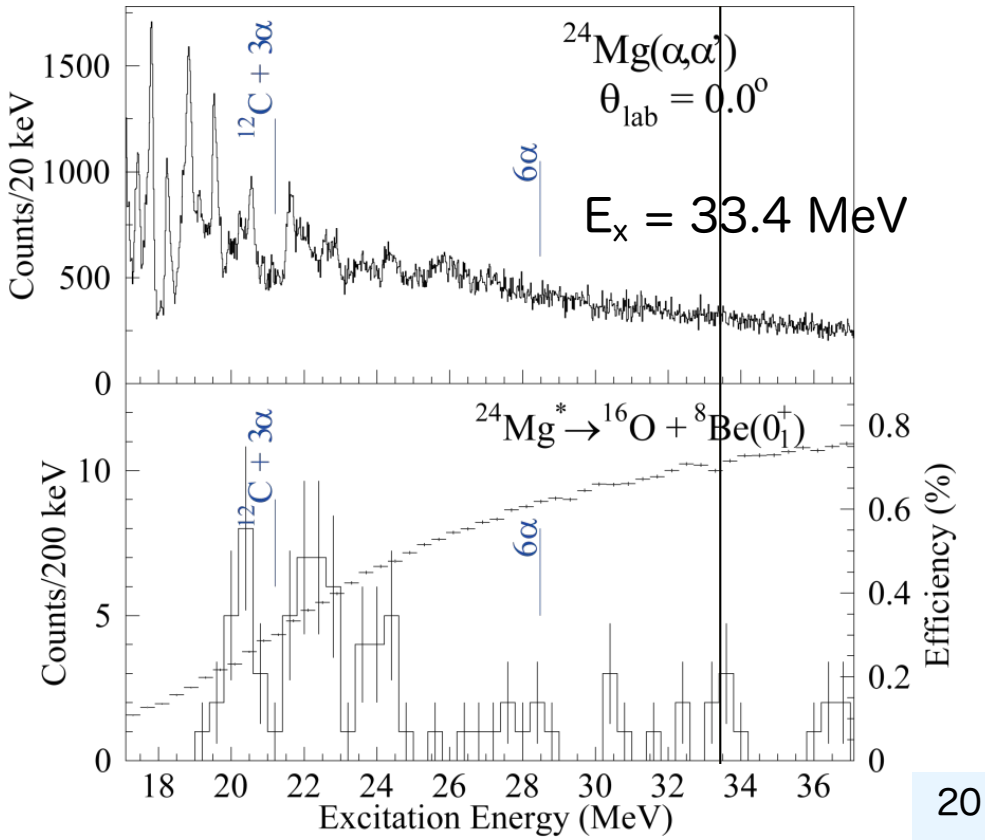
Excited states of 6α condensed state might be observed.

Y. Fujikawa, TK et al.,
Phys. Lett. B. 848, 138384 (2024).

Future Prospects

A candidate for the 6α condensed state was found at E_{cm} = 19.4 MeV [$E_x(^{24}Mg)$ = 33.4 MeV], but its spin and parity were not known.

$^{24}Mg(\alpha,\alpha'+X)$ might give an insight of J^{π}.



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

Old data on $^{24}Mg(\alpha,\alpha' + {}^{8}Be)$ implies a structure at E_x ~ 33.4 MeV in ^{24}Mg.

- ✓ J^{π} can be determined by the angular distribution of the cross section.
- ✓ However, statistically too poor due to small acceptance of the decay-particle detector ($\Delta\Omega/4\pi$ ~ 3%).
- ✓ New measurement with SAKRA ($\Delta\Omega/4\pi$ ~ 35%) might determine J^{π}.

$^{20}Ne(\alpha,\alpha'+X)$ measurement with SAKRA should be done as well.

Summary

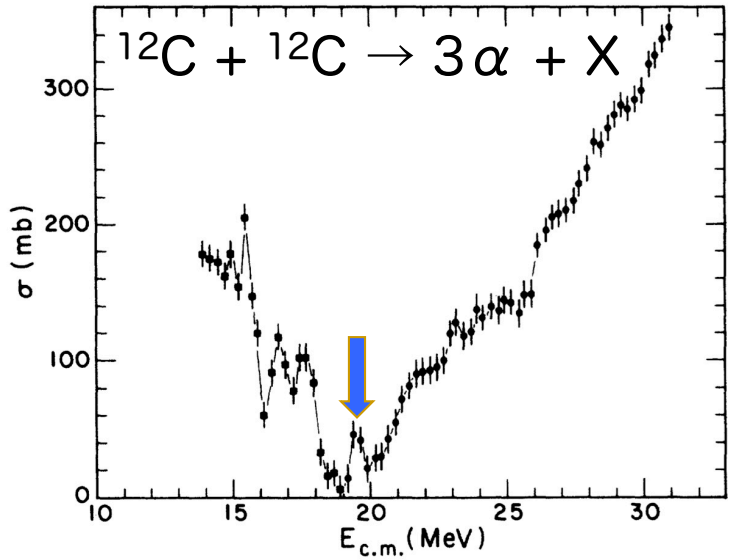
- Candidates for the Alpha condensed states in ^{20}Ne and ^{24}Mg were found.
  - Alpha inelastic scattering at RCNP.
    - Statistics too poor.
    - A new measurement with SAKRA will be done.
  - ^{12}C + ^{12}C scattering at JAEA Tandem facility.
    - SAKRA Si detector array worked well.
    - Exclusive E_x functions for $^{12}C + {}^{12}C \rightarrow {}^{12}C(0^+_2) + {}^{12}C(0^+_2, 0^+_1, \text{or } 2^+_1)$ were obtained.
    - The 2^+ and 4^+ states were found, but J^π of the candidate state are still unknown.
    - Alpha inelastic scattering will be proposed.

E_x function: $^{12}C + {}^{12}C \rightarrow {}^{12}C(0^+_2, 3^-_1) + X$

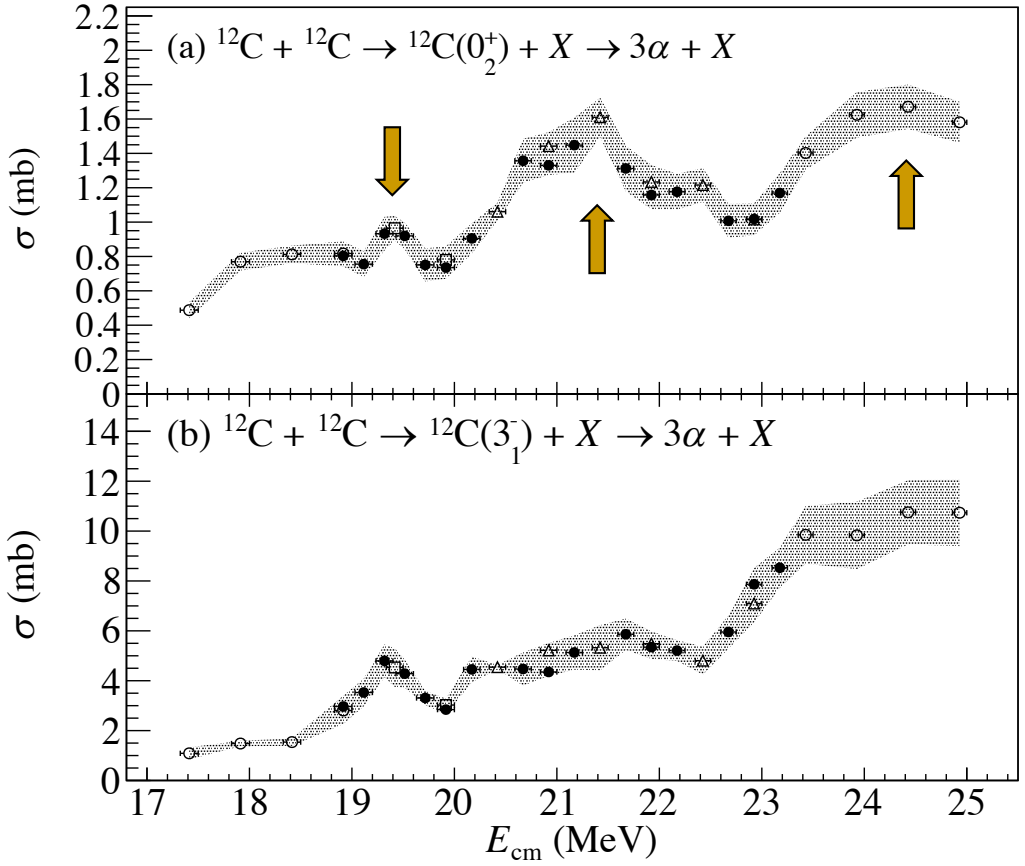
Inclusive cross sections for the $^{12}C + {}^{12}C \rightarrow {}^{12}C(0^+_2, 3^-_1) + X$ reactions at E_{cm} = 17.5--25 MeV were obtained.

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

- Broad structures at E_{cm} = 21.4 and 24.4 MeV
- A narrow peak at E_{cm} = 19.4 MeV
  - Close to the predicted 6α-condensed state.



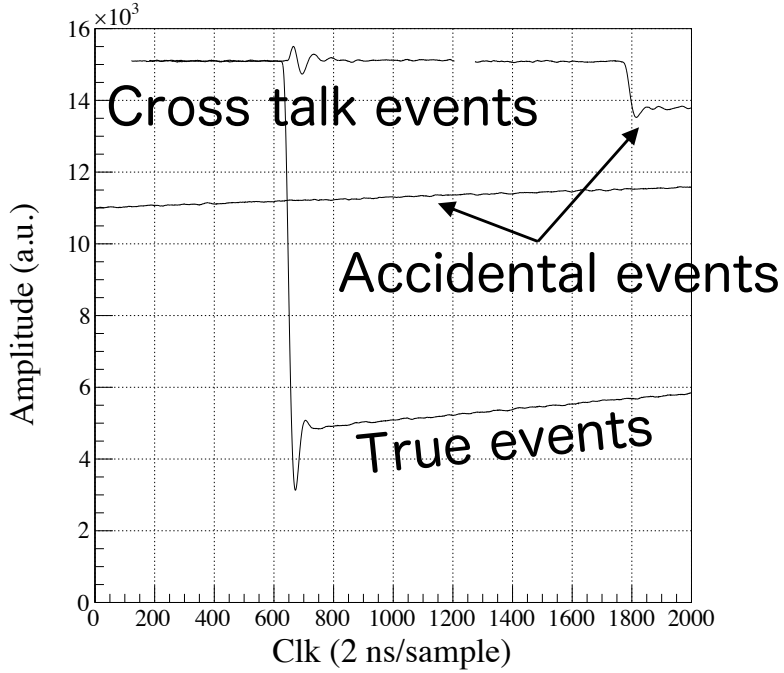
J. J. Kolata et al., Phys. Rev. C **21**, 579 (1980).

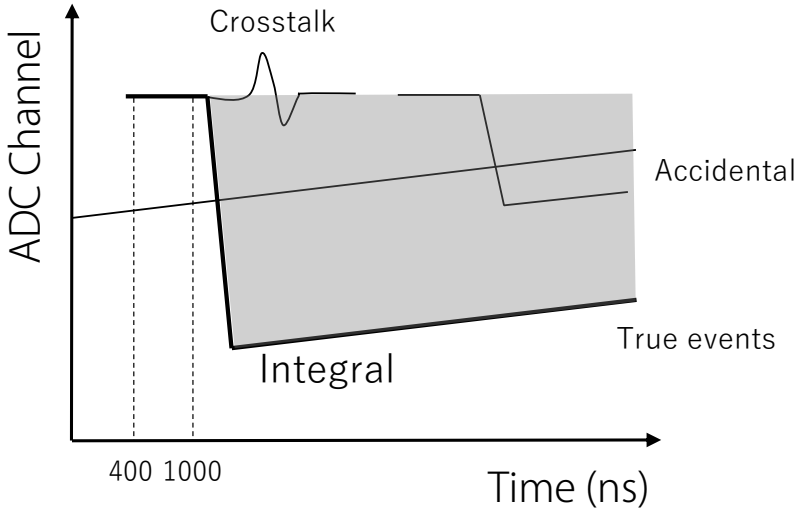


Similar structure was observed in the earlier indirect measurement.

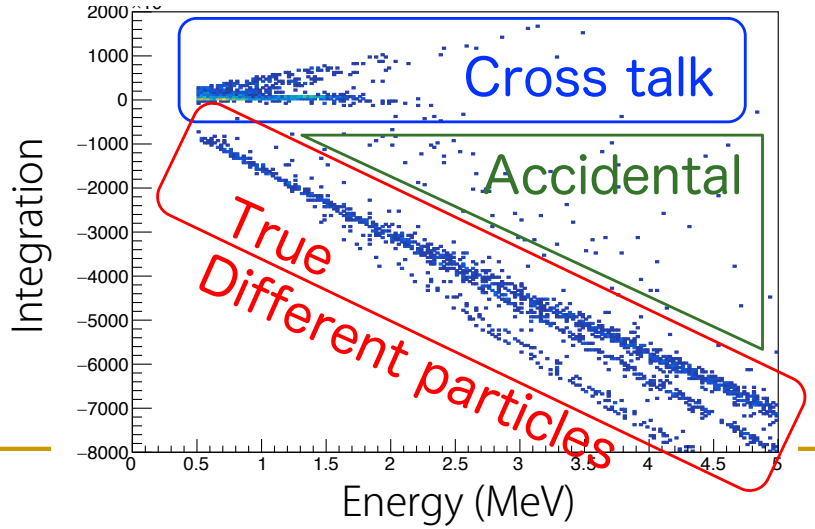
Pulse Shape Analysis (PSA)

Charge signals from SAKRA were processed
by MPR-16/32 and acquired by FADC V1730.





Background events due to cross talk and accidental events were successfully removed by integrating waver forms.



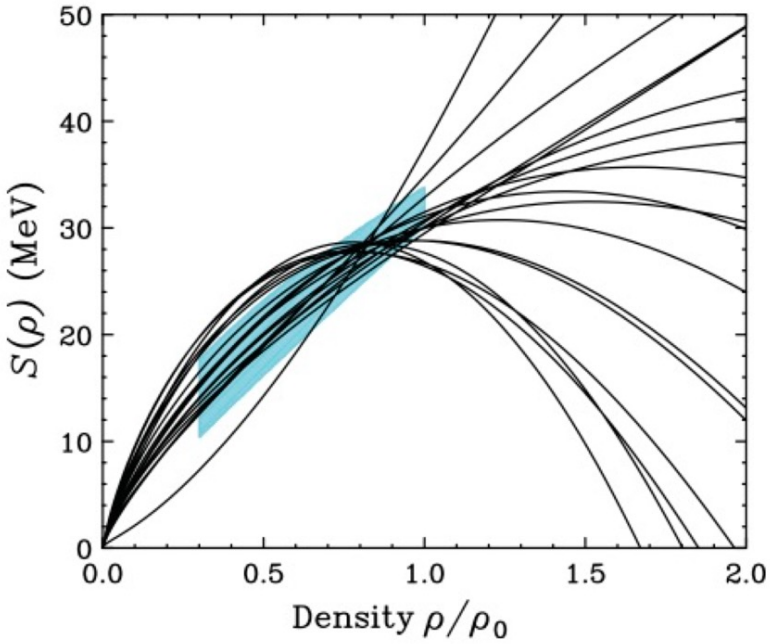
ACS and Symmetry Energy

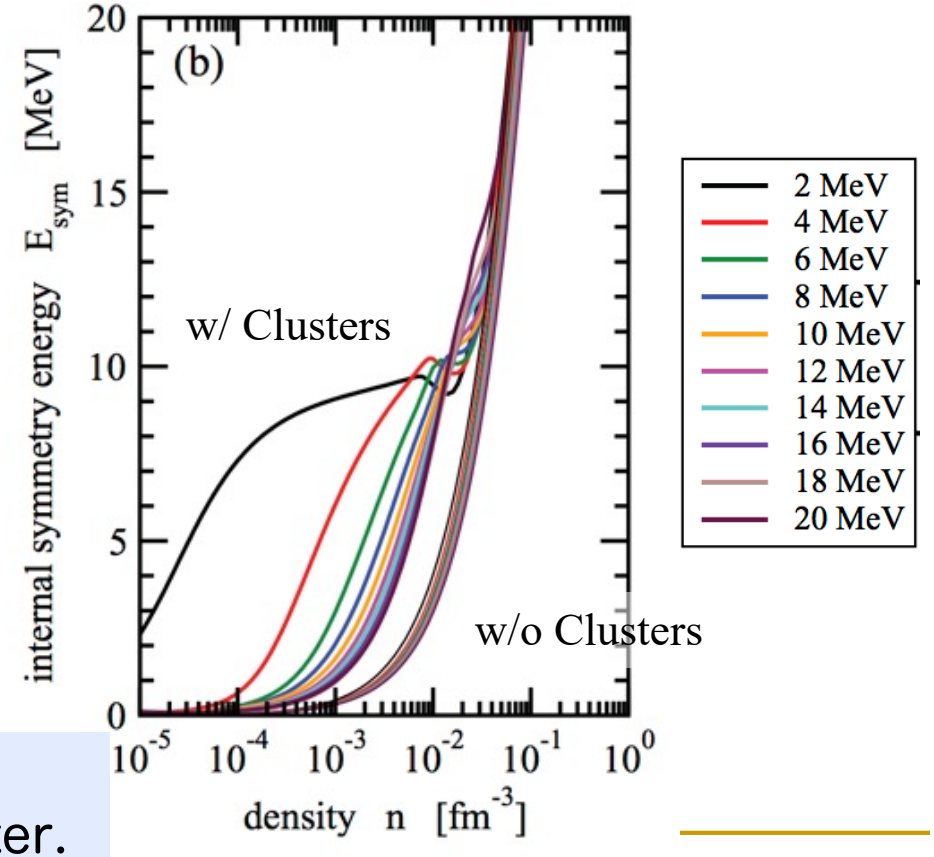
If α condensed states universally exist in various nuclei ….

→ Establish ACS 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).