Present and Future in experimental nuclear cluster physics

Takahiro KAWABATA
Department of Physics, Kyoto University

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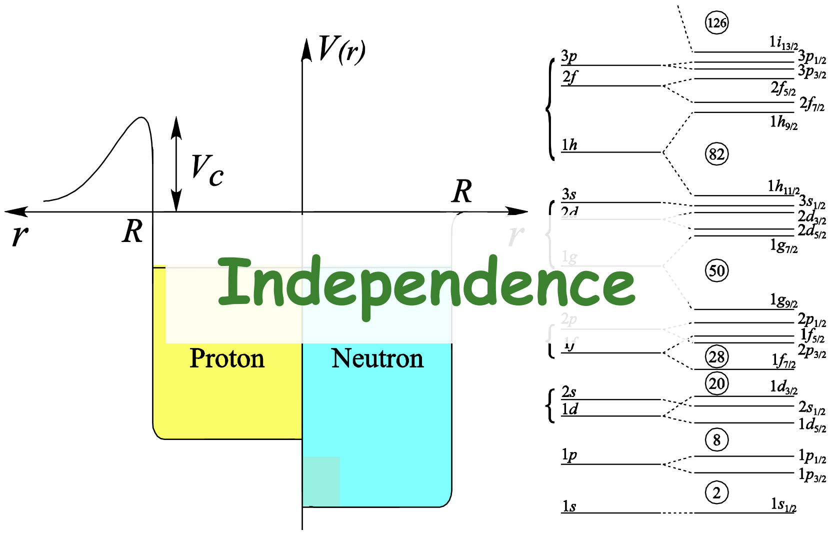
- Cluster Correlation
  - E0 strength and cluster excitation
  - Alpha inelastic scattering
- Dilute Cluster State
  - ^{12}C case ~ Hoyle state ~
  - Heavier nuclei
    - Normal vs Inverse Kinematics
- Cluster Structure in unstable nuclei
  - New experiment using MAIKo active target
- Summary

Introduction

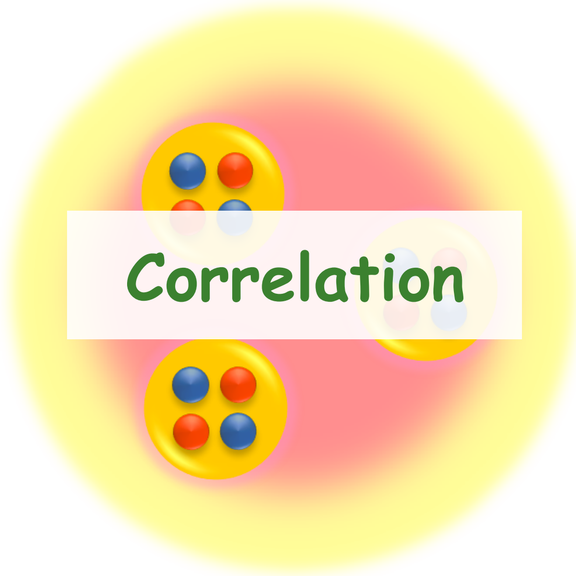
Two different pictures of Nuclear Structure

Shell Model | **SU(3) Limit** | **Cluster Model**



Independence

Multi-hω Configuration



Correlation

S. P. orbit in the mean-field potential.
Magic numbers (2, 8, 20, ...).
Describes well S. P. excited states.

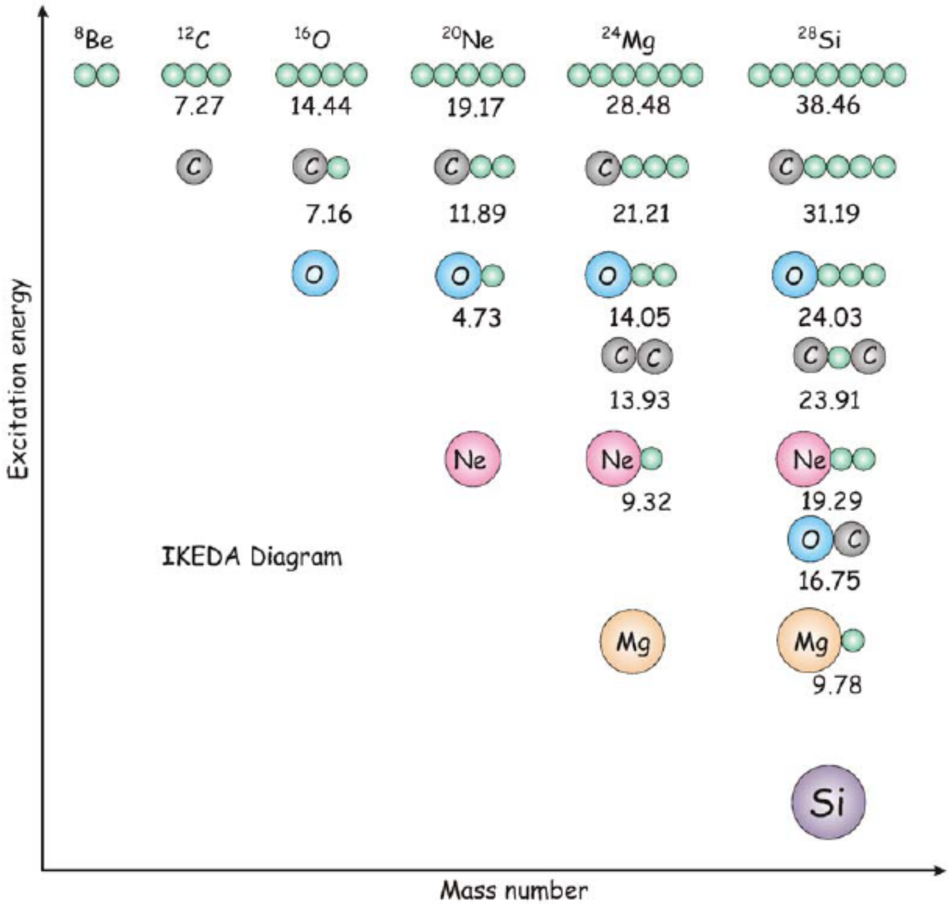
Strong correlation between nucleons.
Cluster consists of several nucleons.
Clusters are weakly bound.

It is important to study appearance and disappearance of the cluster correlation for better understanding of "Atomic Nucleus".

Cluster States in N = 4n Nuclei

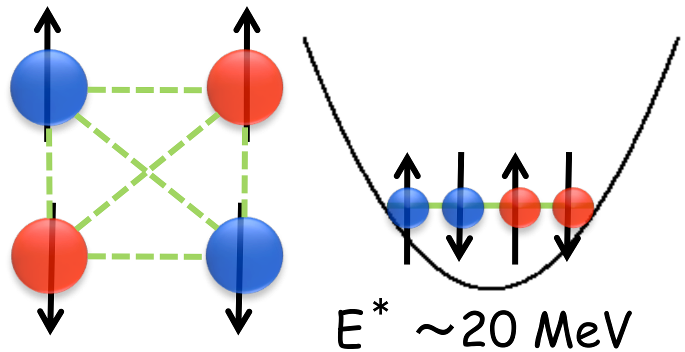
α clustering is an important concept in nuclear physics for light nuclei.

α 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

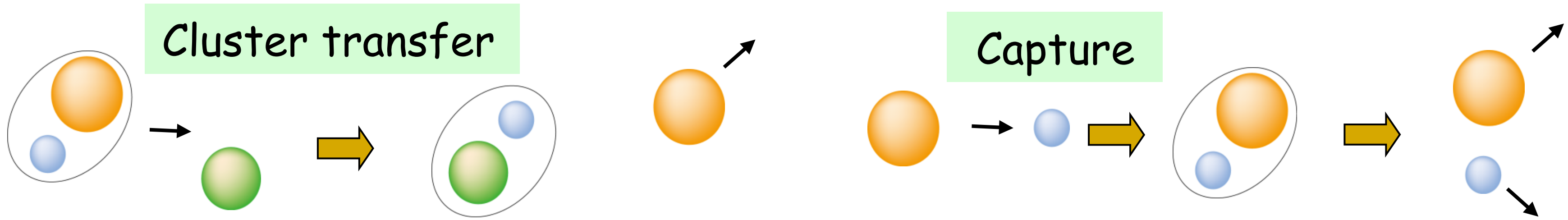
stiff

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.

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 a 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).

Isoscalar E0 transition:
ΔL=0, ΔS=0, ΔT=0

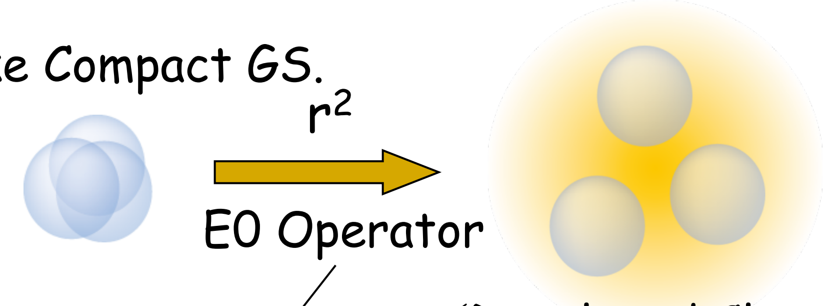
$$B(E0;IS) = \left|ME(E0;IS)\right|^2$$

$$ME(E0;IS) = \left\langle J_f \left\| \sum_{i=1}^{A} r_i^2 \right\| J_i \right\rangle = \int_0^\infty \left(\rho_t^p + \rho_t^n\right) r^4 dr$$

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.



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 a cluster structure.

Inelastic Alpha Scattering

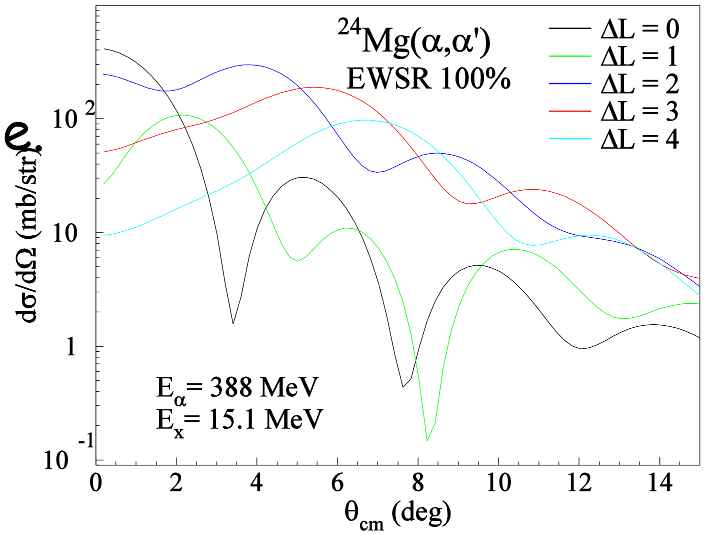
Inelastic a scattering is a good probe for nuclear excitation strengths.

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

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

  - Folding model gives a reasonable description of dσ/dΩ.
- Relatively large cross section.
- High resolution measurement is possible.
- Selectivity for the ΔT = 0 and natural-parity transitions.
- Multiple decomposition analysis is useful to separate ΔJ^{π}.

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

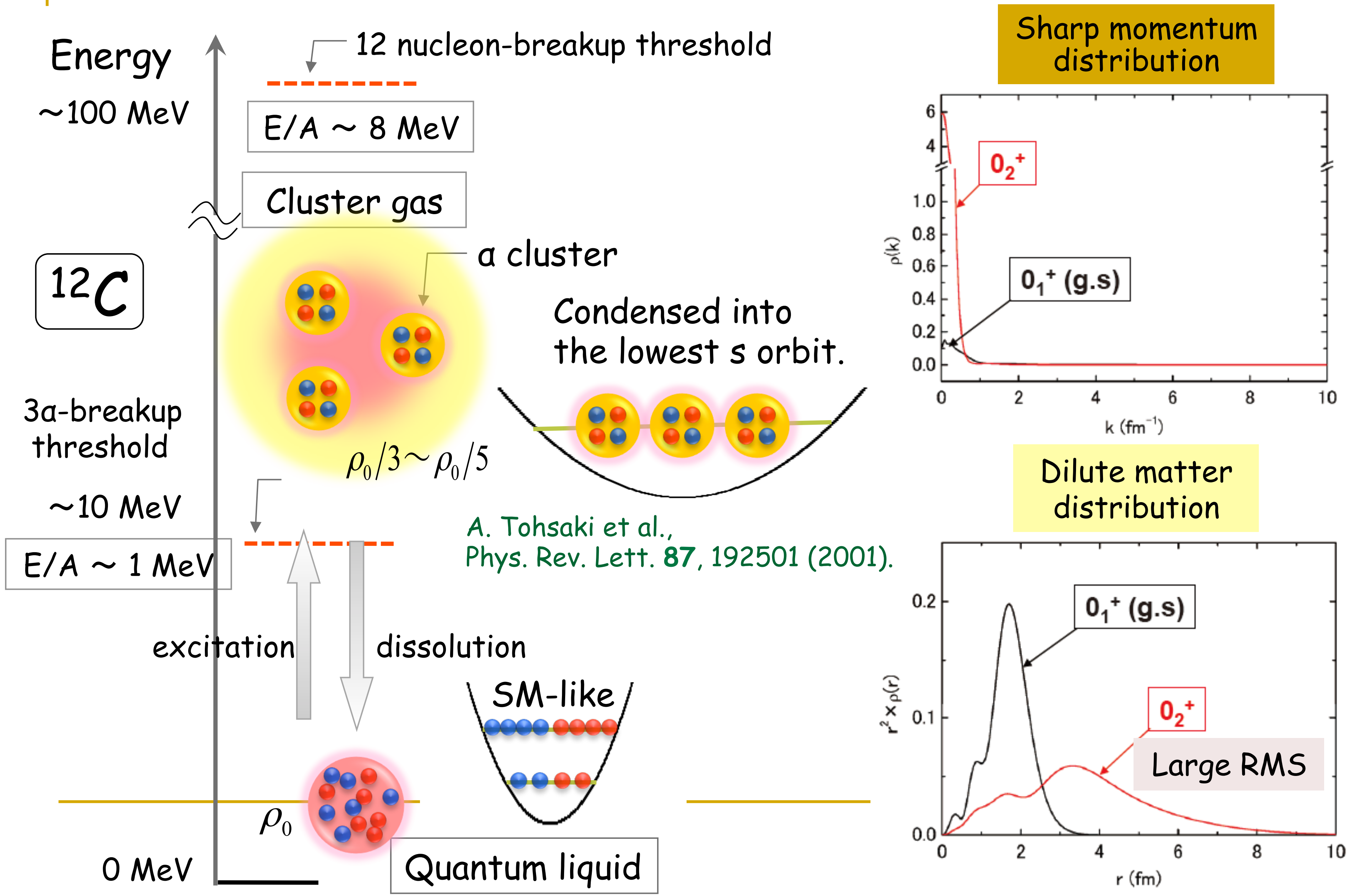


We measured inelastic a scattering to extract IS E0 strengths and to examine cluster structures in light nuclei.

Dilute Cluster States

as a Precursor of Dilute Nuclear Matter

Cluster Gas-like States in ^{12}C



Questions

- How do we confirm the dilute gas like structure of the Hoyle state?
  - ✓ Radius of the Hoyle state.
  - ✓ Decay particle correlation.

- Do similar states exist even in heavier nuclei?
  - ✓ Precursor of the dilute nuclear matter.

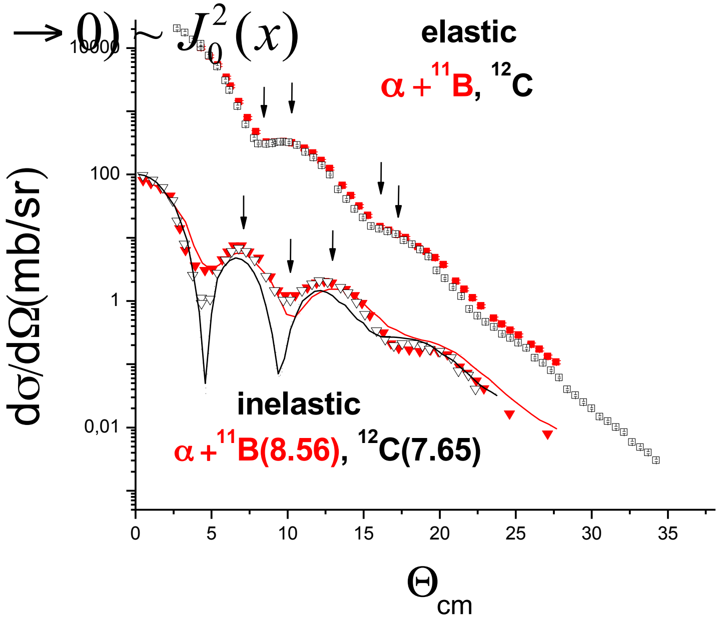
Radius of the Hoyle State

Diffraction Pattern might reflect the radius.

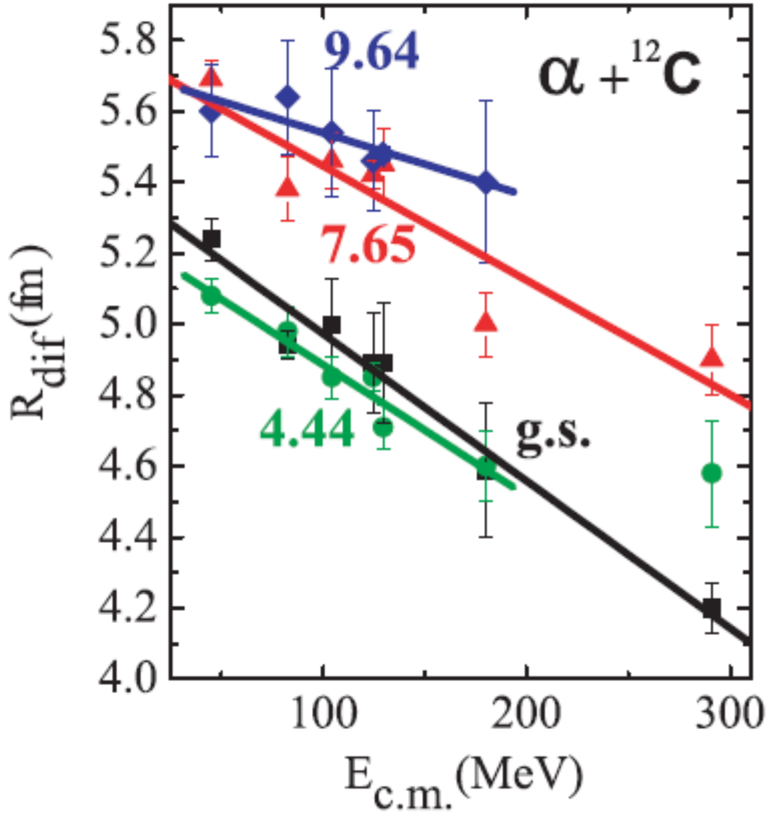
$$\frac{d\sigma}{d\Omega}(el) \sim \left|\frac{J_1(x)}{x}\right|^2$$

$$x = qR_{dif}$$

$$\frac{d\sigma}{d\Omega}(0 \rightarrow 0) \sim J_0^2(x)$$



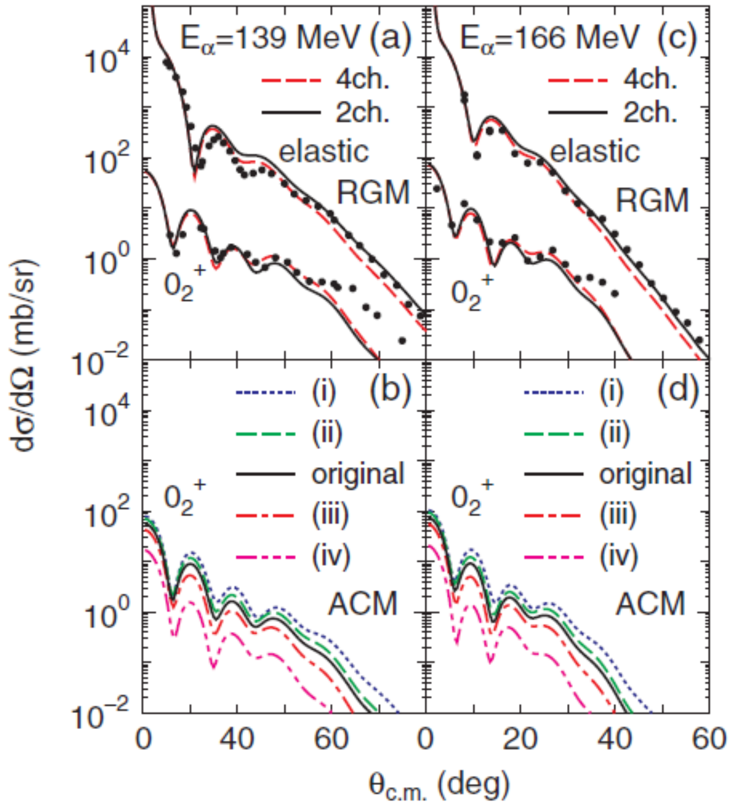
$$R_{rms}^{e.s.} = R_{rms}^{g.s.} + \left[R_{dif}^{in} - R_{dif}^{el}\right]$$



A. N. Danilov et al.,
Phys. Rev. C **80**, 054603 (2009).

Radius of the Hoyle State

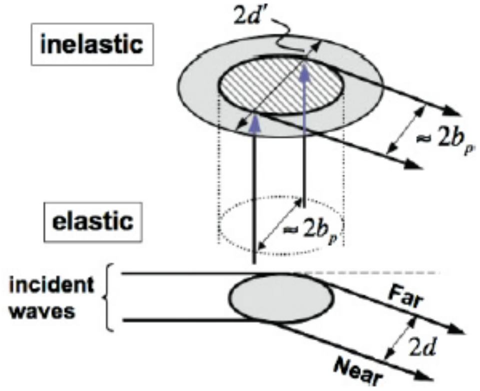
Transition density is overlap between the ground and excited states.
→ Cut off by the smaller state.

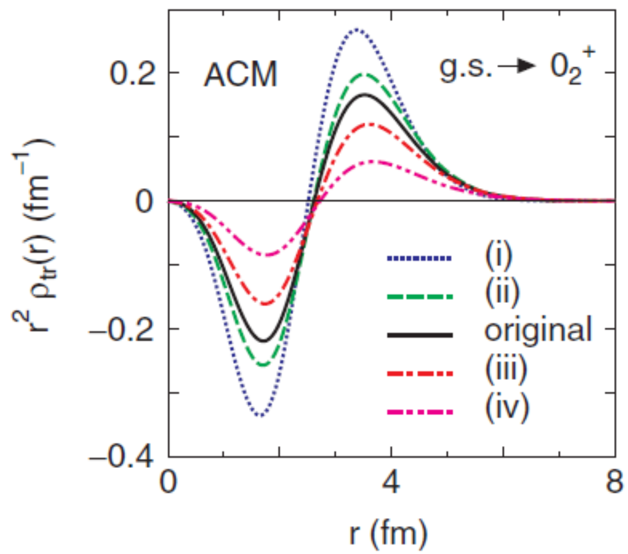


Original	(i)	(ii)	(iii)	(iv)
4.60	3.92	4.36	5.05	6.18

R_{rms} (fm)

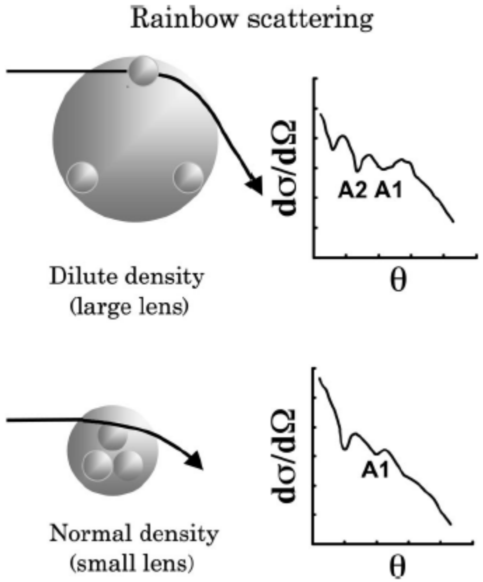
M. Takashina et al., Phys. Rev C **74**, 054606 (2006).
M. Takashina, Phys. Rev. C **78**, 014602 (2008).

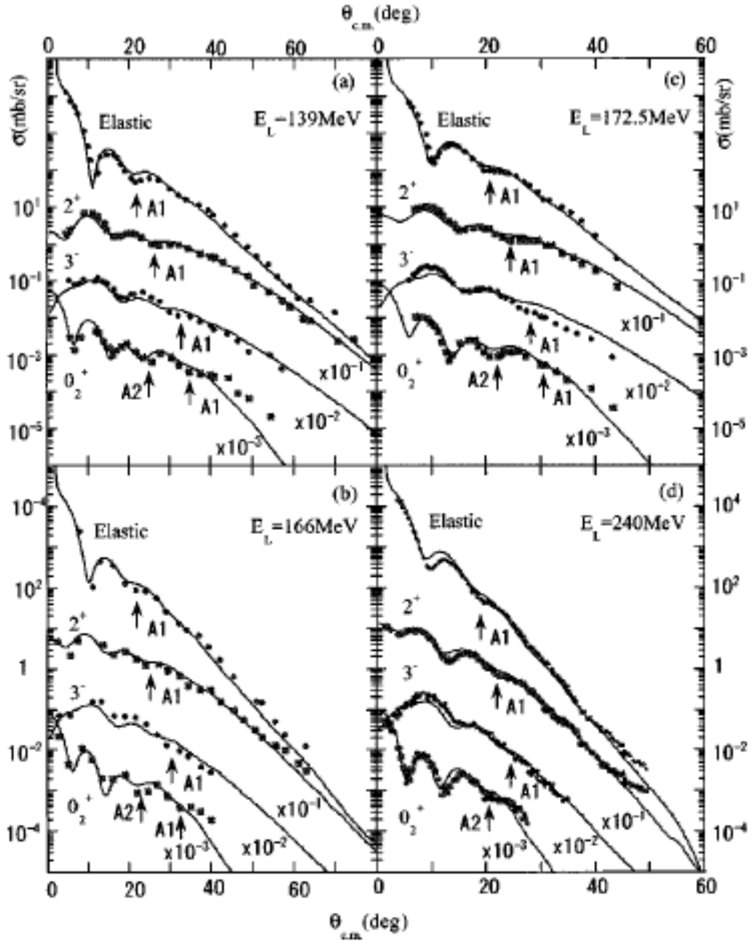




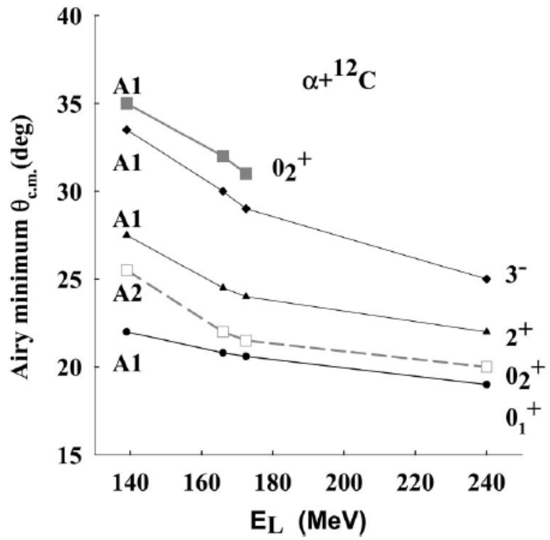
Radius of the Hoyle State

Rainbow scattering ???





S. Ohkubo and Y. Hirabayashi, Phys. Rev C 70, 041602 (2004).



Scattering Radius

Controversial situation was clarified on the basis of the partial wave analysis.

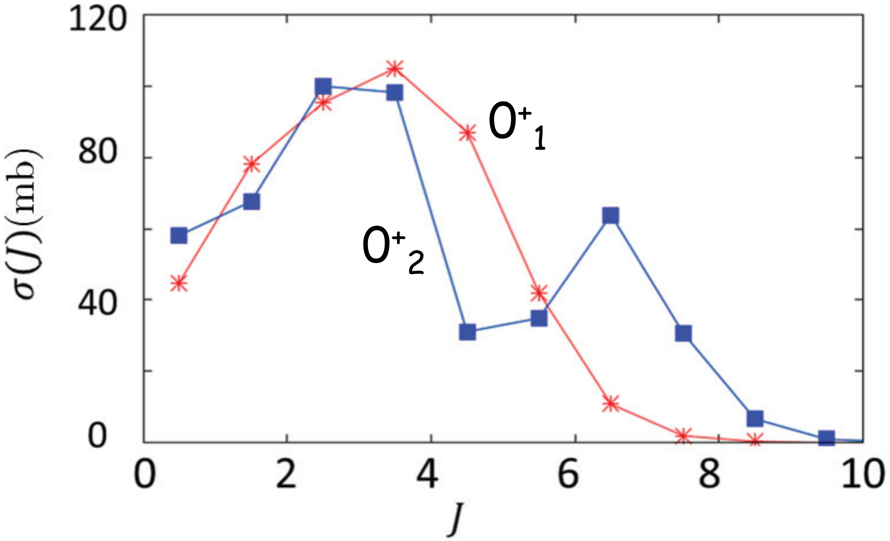
Scattering radius $R_{SC} = \frac{\bar{L}}{k}$

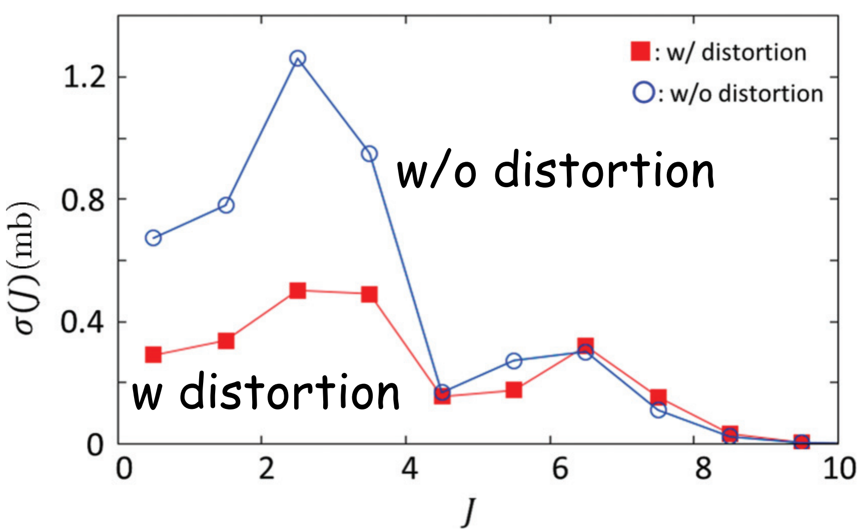
$$\bar{L} = \sqrt{\frac{\sum_{JL} \hat{L}^4 \sigma(JL)}{\sum_{JL} \hat{L}^2 (JL)}}$$

M. Tomita et al.,
Phys. Rev C 89, 034619 (2014).

Matter radius $\bar{r} = \sqrt{\frac{\int dr\, r^4 \rho(r)}{\int dr\, r^2 \rho(r)}}$

$$\hat{L}^2 = J(2J+1)$$



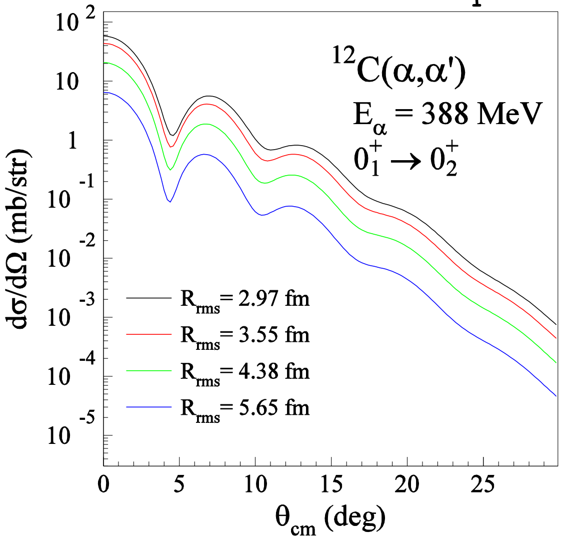


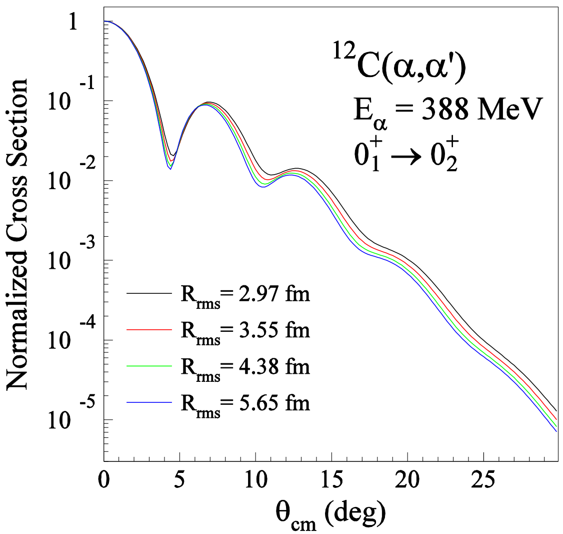
	E_x (MeV)	$\bar{L}$	R_{sc} (fm)	$\bar{r}$ (fm)
0^+_1	0.00	4.69	2.65	2.40
0^+_2	7.65	6.13	3.46	3.47

	$\bar{L}$	R_{sc} (fm)	$\bar{r}$ (fm)
With Distortion	6.13	3.46	3.47
No distortion	5.46	3.09	3.47

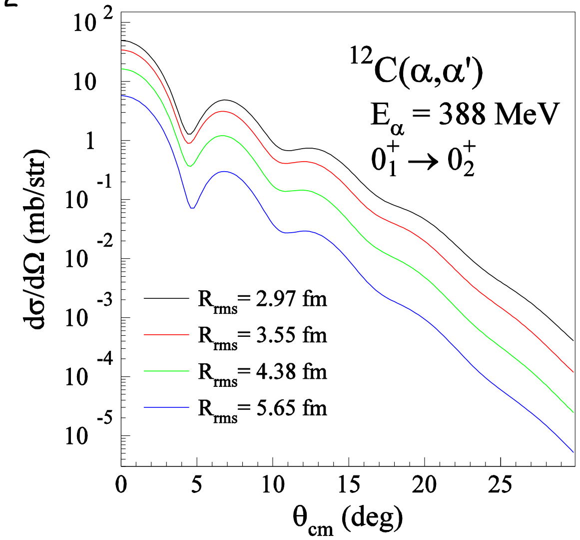
Inelastic Alpha Scattering

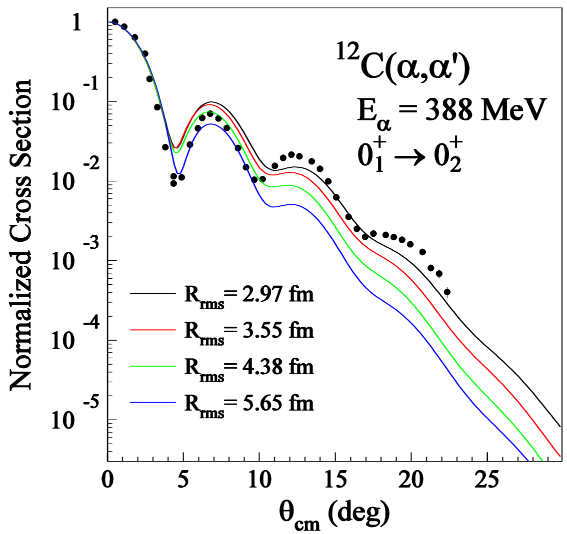
Same distortion for 0^+_1 and 0^+_2



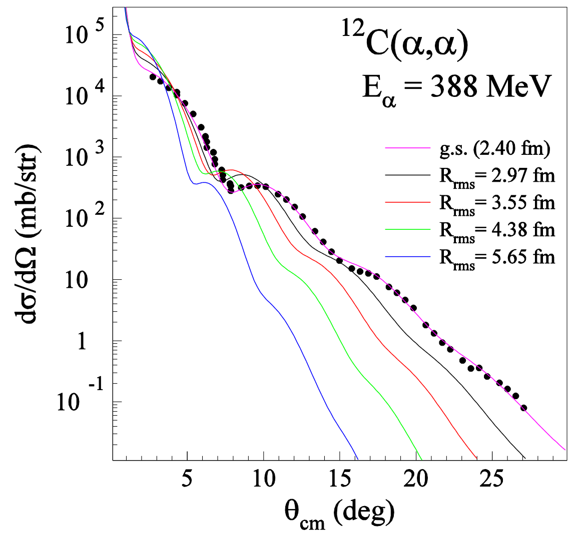


Different distortion for 0^+_1 and 0^+_2





The distorting potentials should be different between the *normal* and *dilute* states.



Distorting potential enhances differences between the normal and dilute states.

Anguler dist. exhibits the signature... but the accurate calculation is required.

3α Decay of the Hoyle state

Decay mode of the Hoyle state is still controversial

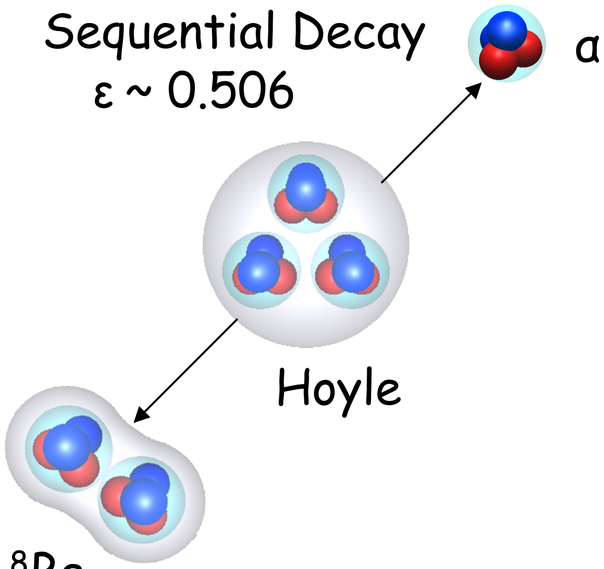
Three decay mechanisms

- ✓ Sequential decay through ^{8}Be + α channel (SD)
- ✓ Direct decay to 3α particles with equal energies (DDE)
- ✓ Direct decay to 3α particles with uniform phase-space distribution (DDΦ)

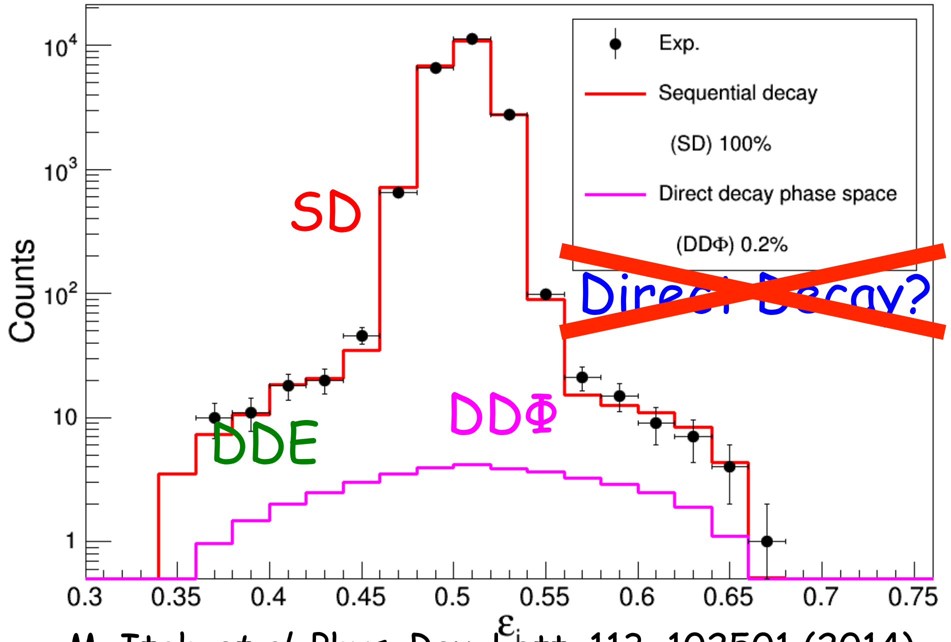
Dilute gas-like state might prefer direct decay to sequential decay

Key observable: "ε" Highest normalized energy among three decay-α particles

Sequential Decay
ε ~ 0.506



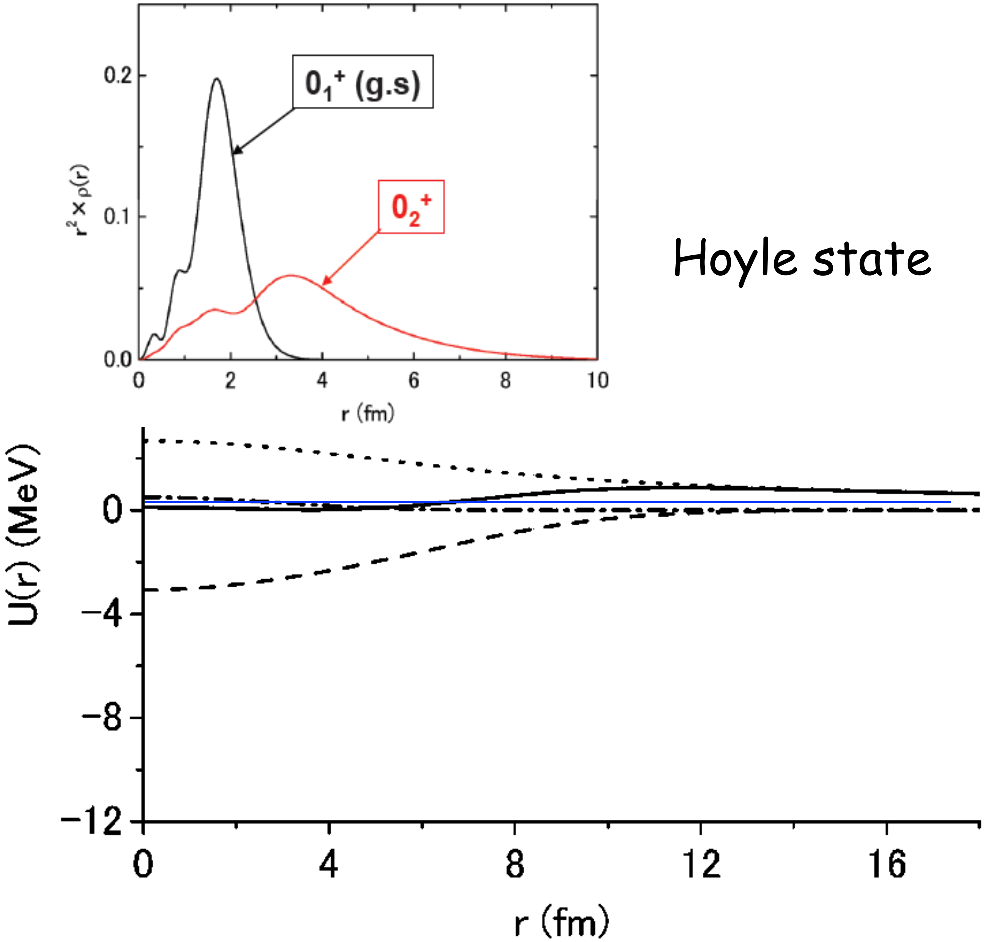
Direct decay < 0.2% (95%C.L.)



M. Itoh *et al*, Phys. Rev. Lett. 113, 102501 (2014)

Single particle potential

a particle is confined by the Coulomb barrier.



Hoyle state

Particle decay of the Hoyle state reflects just tail of the wave function far from the pocket.

Decay particles should not carry much information inside the Hoyle state.

We need a new strategy.
HBT interference???

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

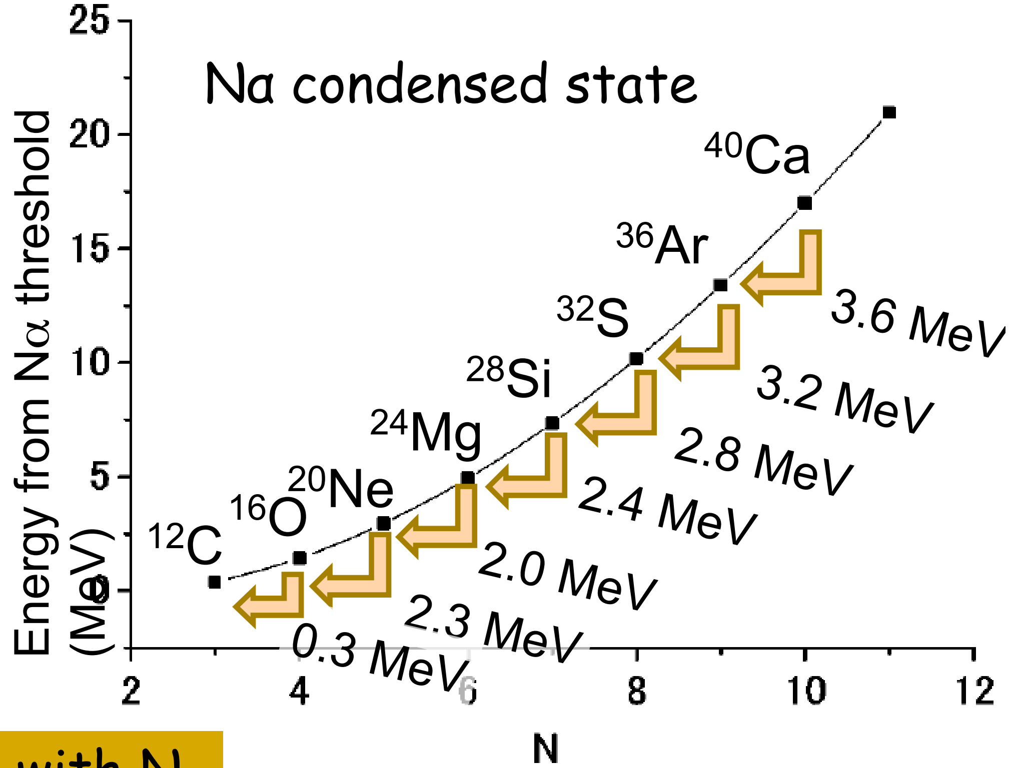
α Condensed States in Heavier Nuclei

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).

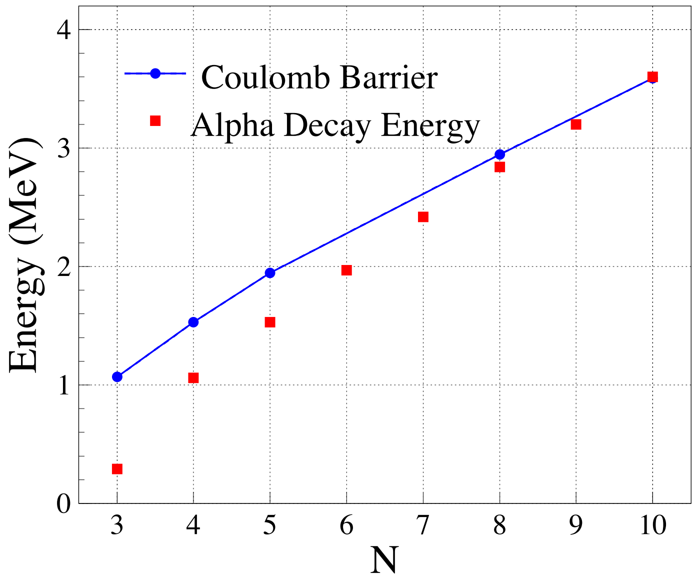
If such nα condensed states are formed, they should sequentially decay into lighter α condensed states by emitting α particles.

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

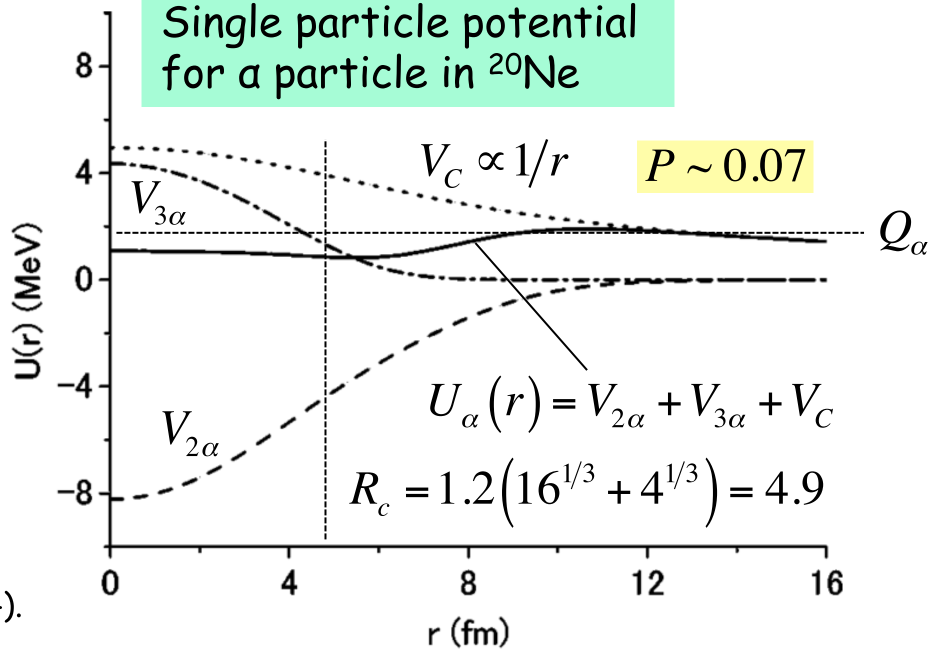
Low-Energy α Particle Emission

Coulomb barrier might disturb low-energy α particle emission.

Penetrability: $$P = \exp\left(-\frac{2}{\hbar}\int_a^b dr\sqrt{2m\left(V(r)-E\right)}\right)$$



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

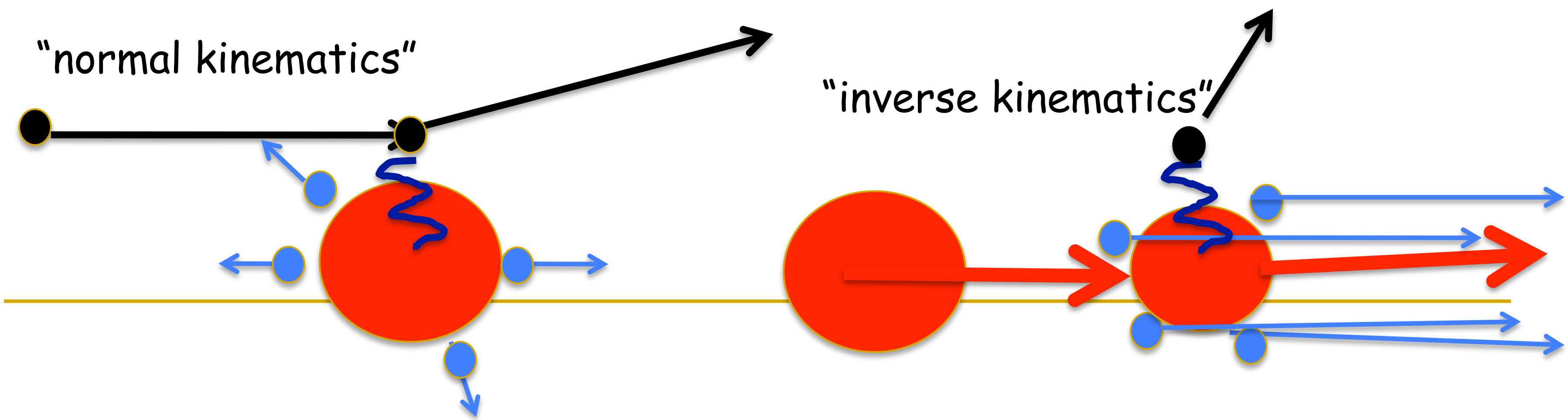


Dilute nature suppresses Coulomb barrier.

Penetrability is still low, but low-energy α emission could be a signature of the Nα condensed states owing to the large overlap between them.

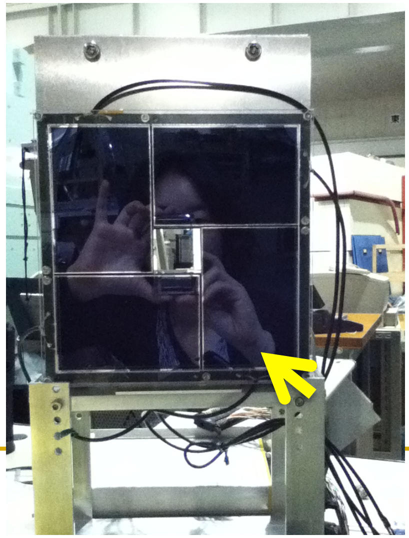
Inverse vs Normal Kinematics

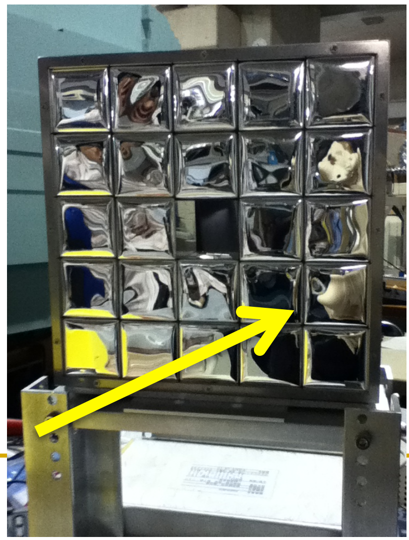
- Inverse Kinematics
  - ☺ Easy to cover large angular acceptance for decaying particles
  - ☹ Incident particle and decaying particle has the same p/A and p/z. This makes background at forward angles
  - ☹ Difficult to determine E_x
- Normal Kinematics
  - ☺ Easy to determine E_x and J^π
  - ☹ Difficult to cover large angular acceptance

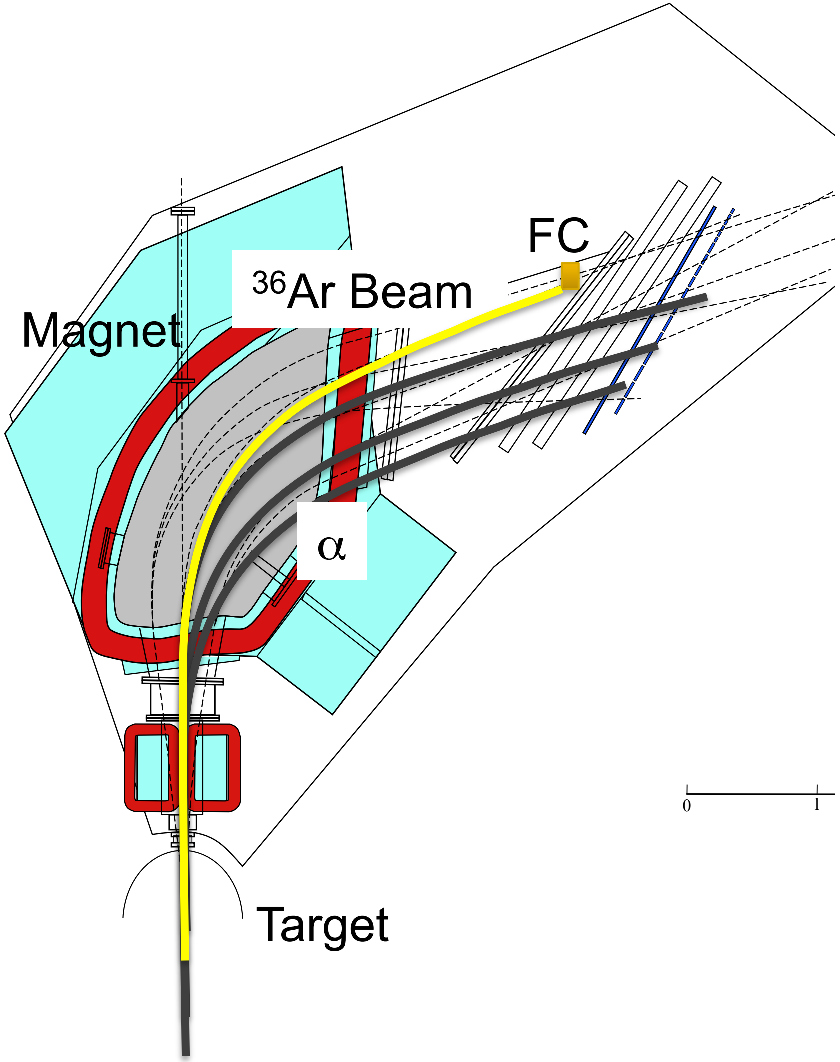


Inverse Kinematic Measurement at RCNP

- E391 (H. Akimune et al.)
  - LAS at 0 degree.
  - ±50 mr × ±50 mr (±3deg × ±3 deg)
  - $\delta p/p$ = 30 %
- Segmented Hodoscopes at FP
- Si/CsI array in SC

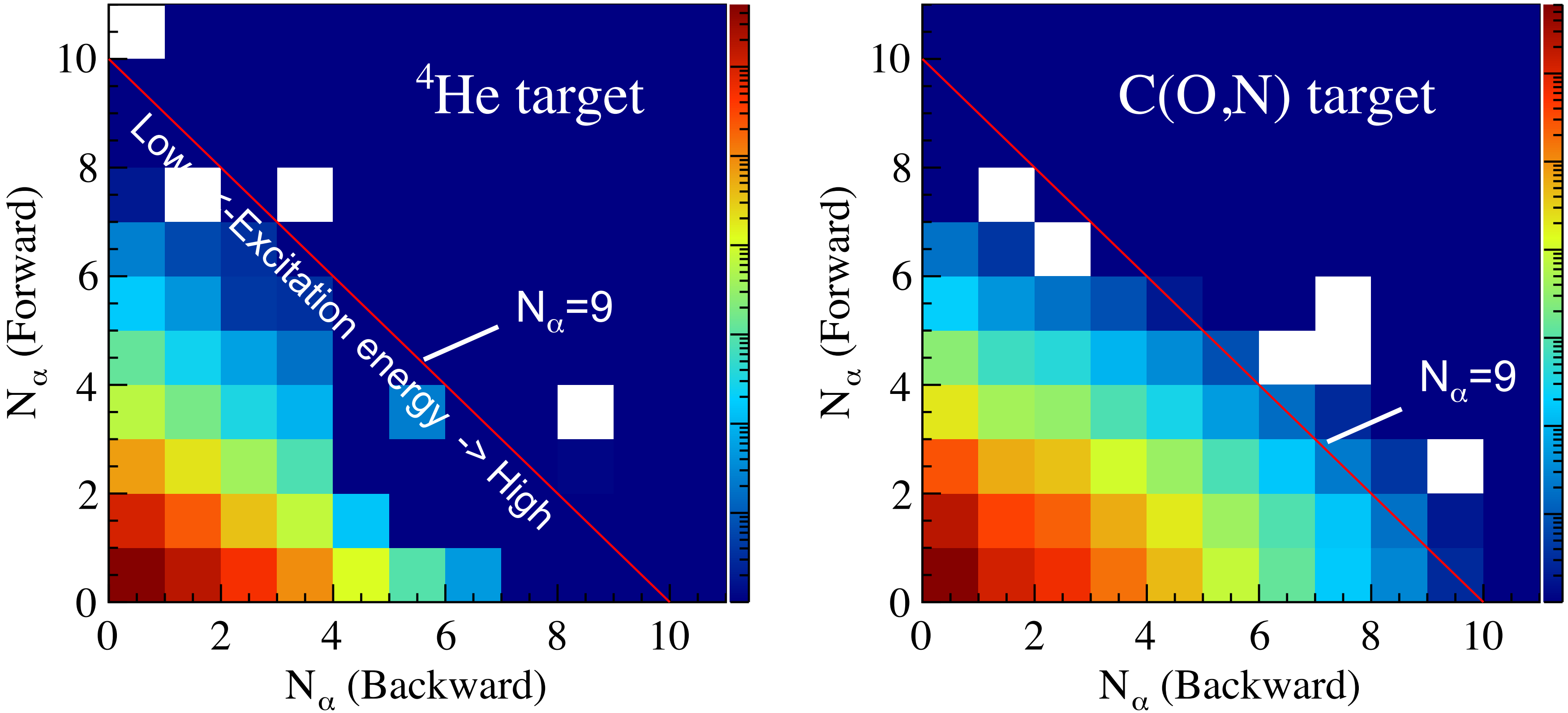






Multiplicity of alpha particles

RCNP E391 (H. Akimune et al.)

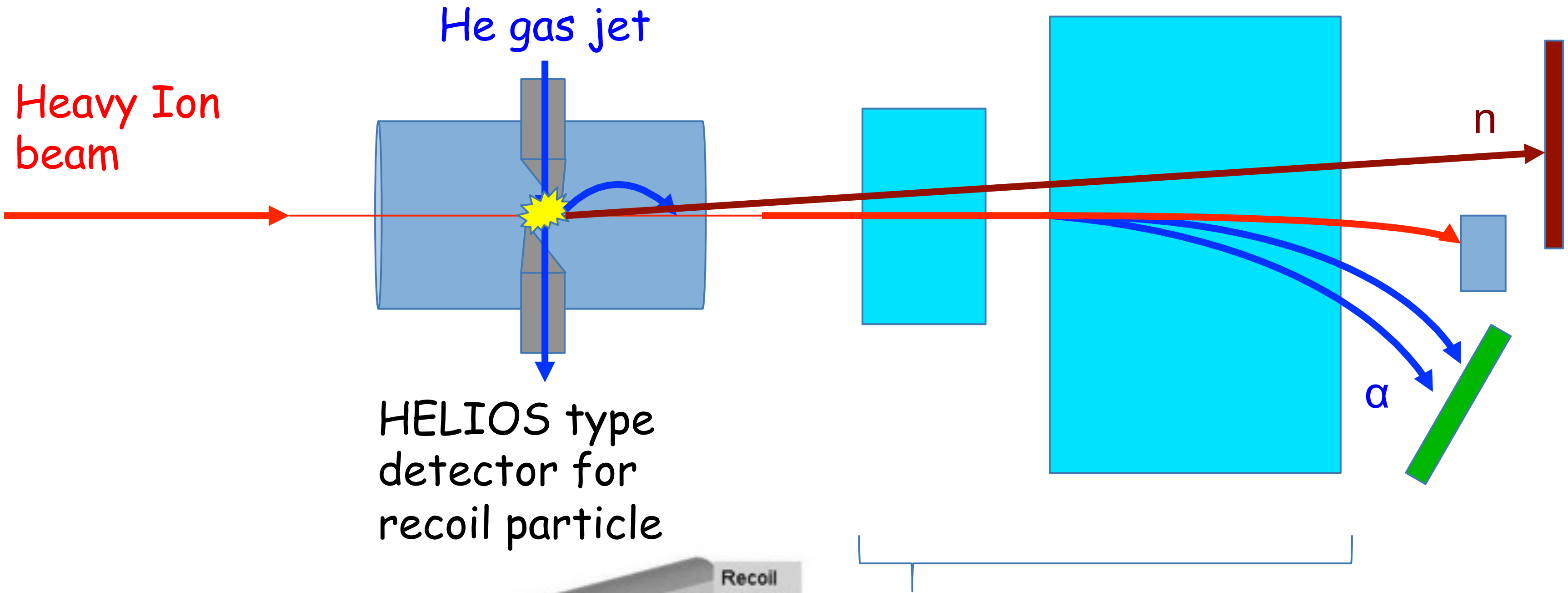


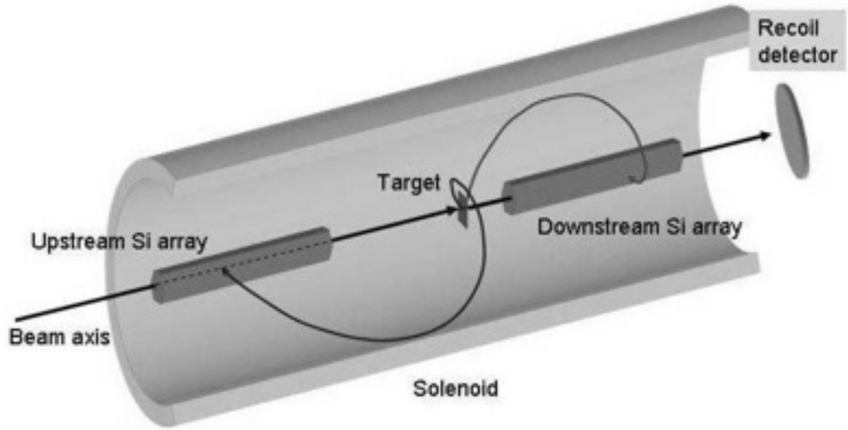
High multiplicity events were observed.
Analysis is still going on.

Future Perspective

M. Itoh et al.

HELIOS type detector as a recoil particle detector to determine E_x.

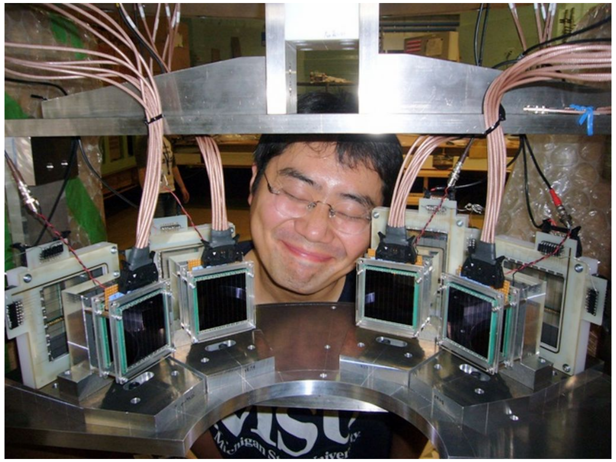


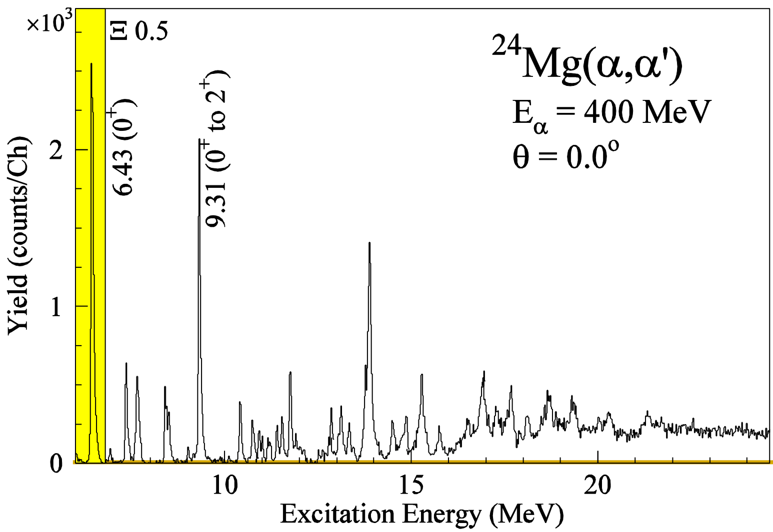


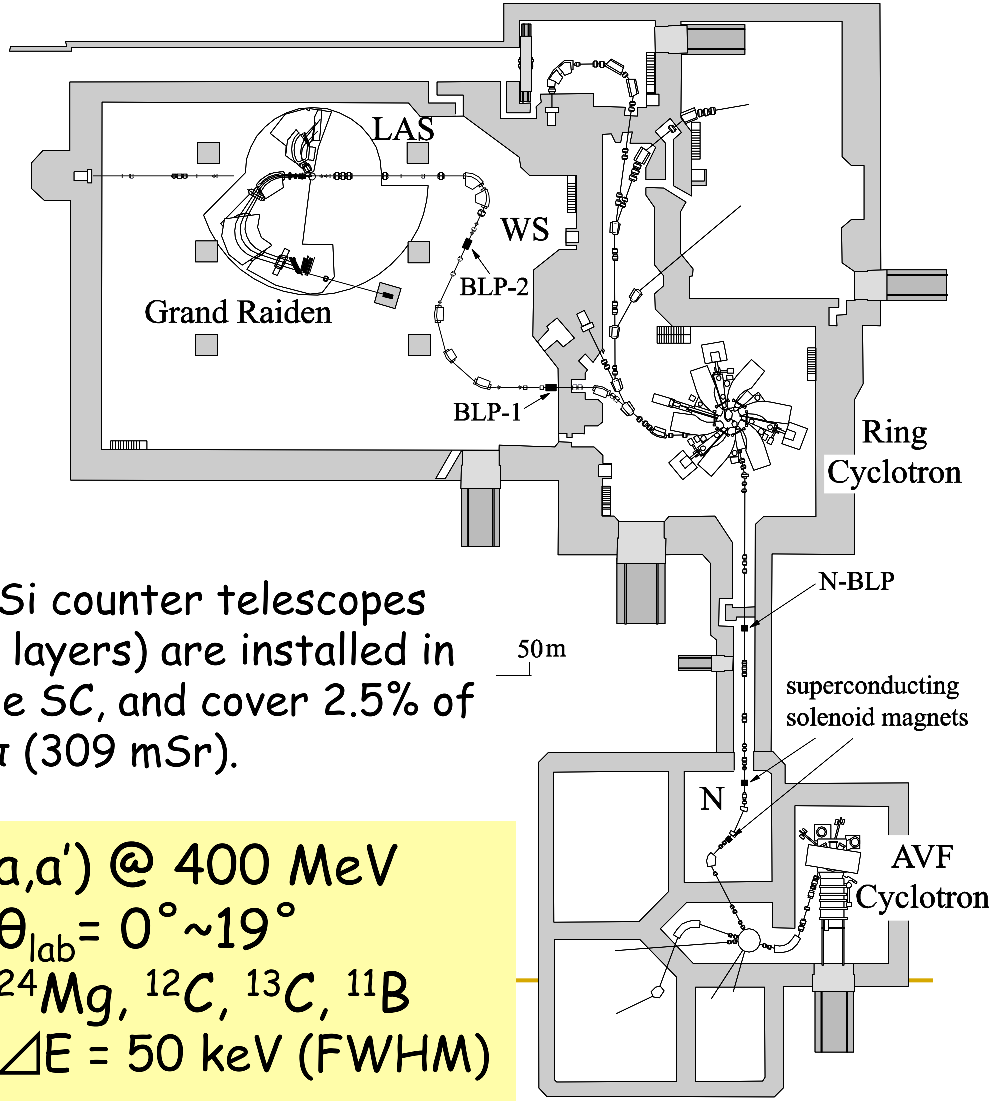
Large acceptance spectrometer to detect decay α particles

Normal Kinematic Measurement at RCNP

Background-free measurement at extremely forward angles





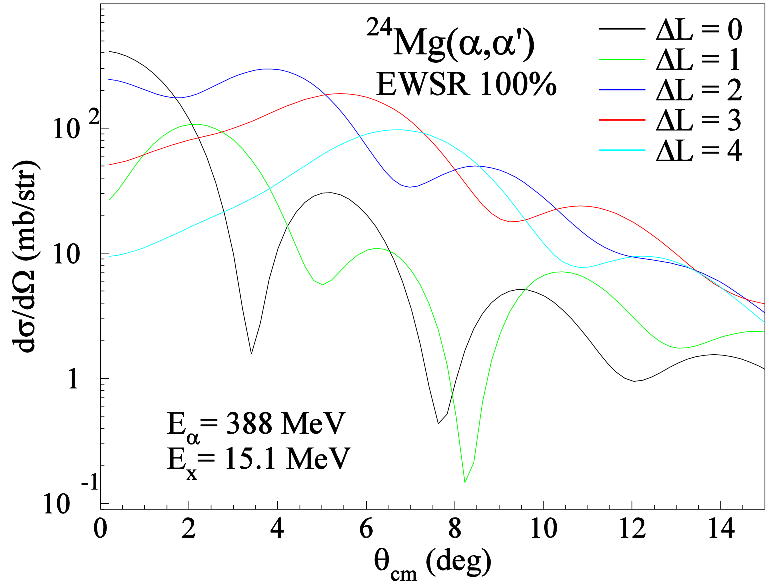


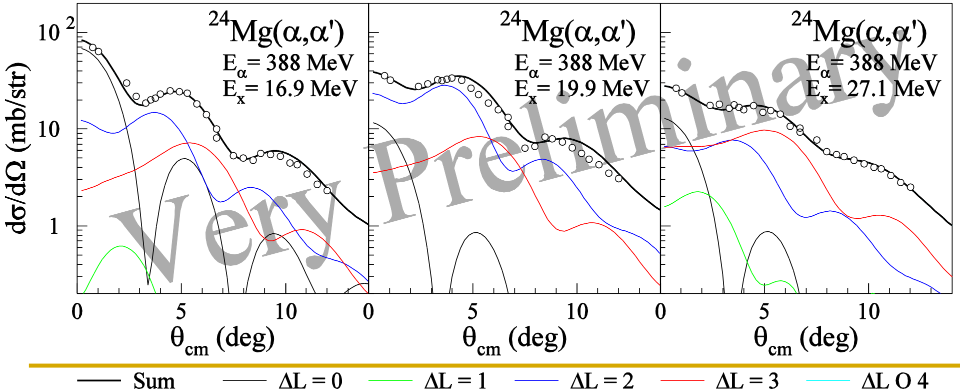
4 Si counter telescopes (5 layers) are installed in the SC, and cover 2.5% of 4π (309 mSr).

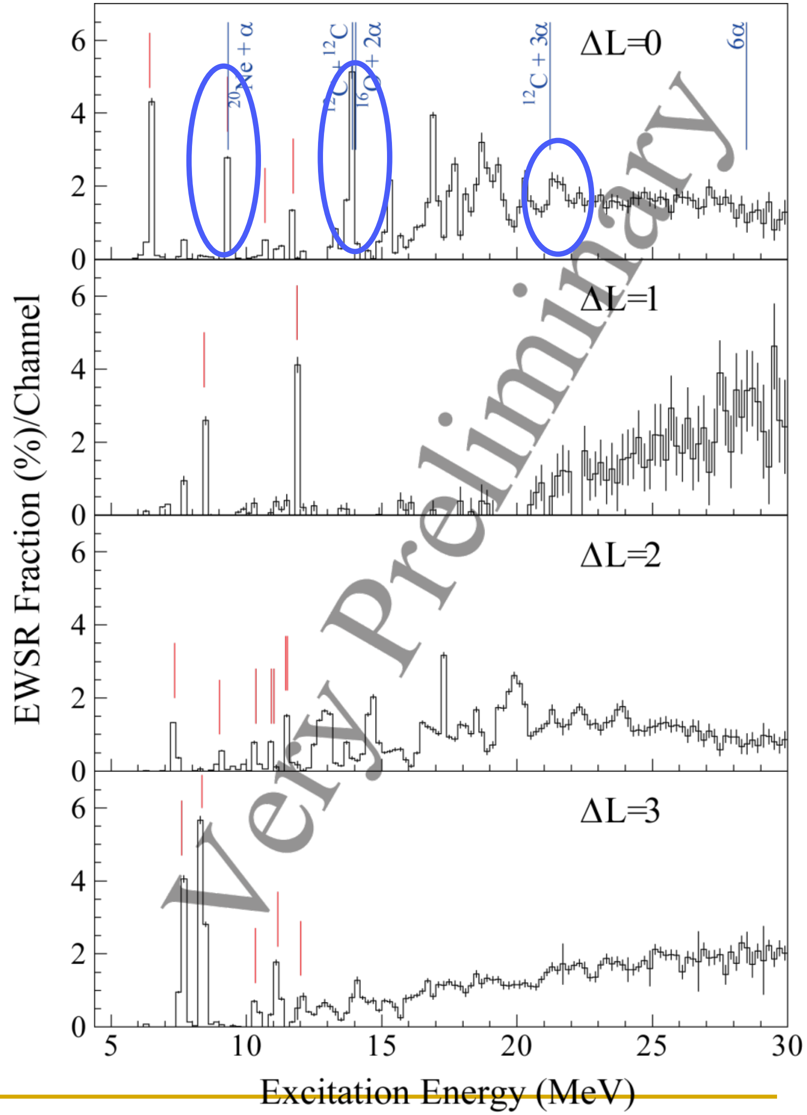
(a,a') @ 400 MeV
θ_{lab}= 0°~19°
^{24}Mg, ^{12}C, ^{13}C, ^{11}B
⊿E = 50 keV (FWHM)

Multipole Decomposition Analysis

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



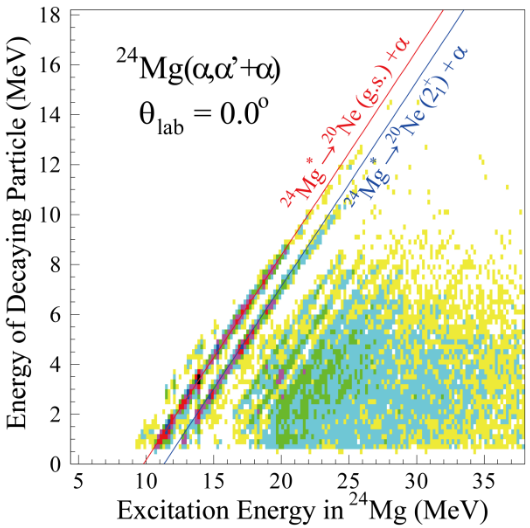


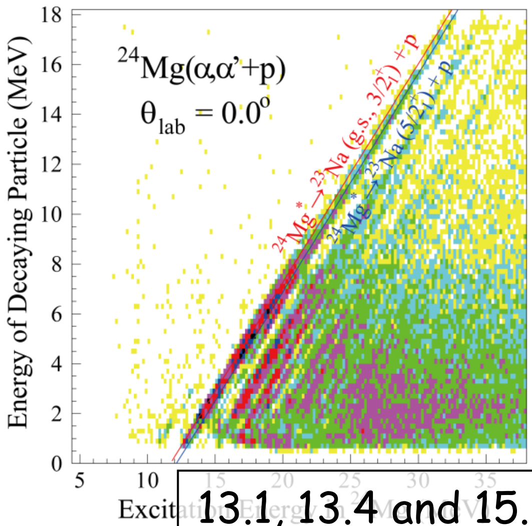


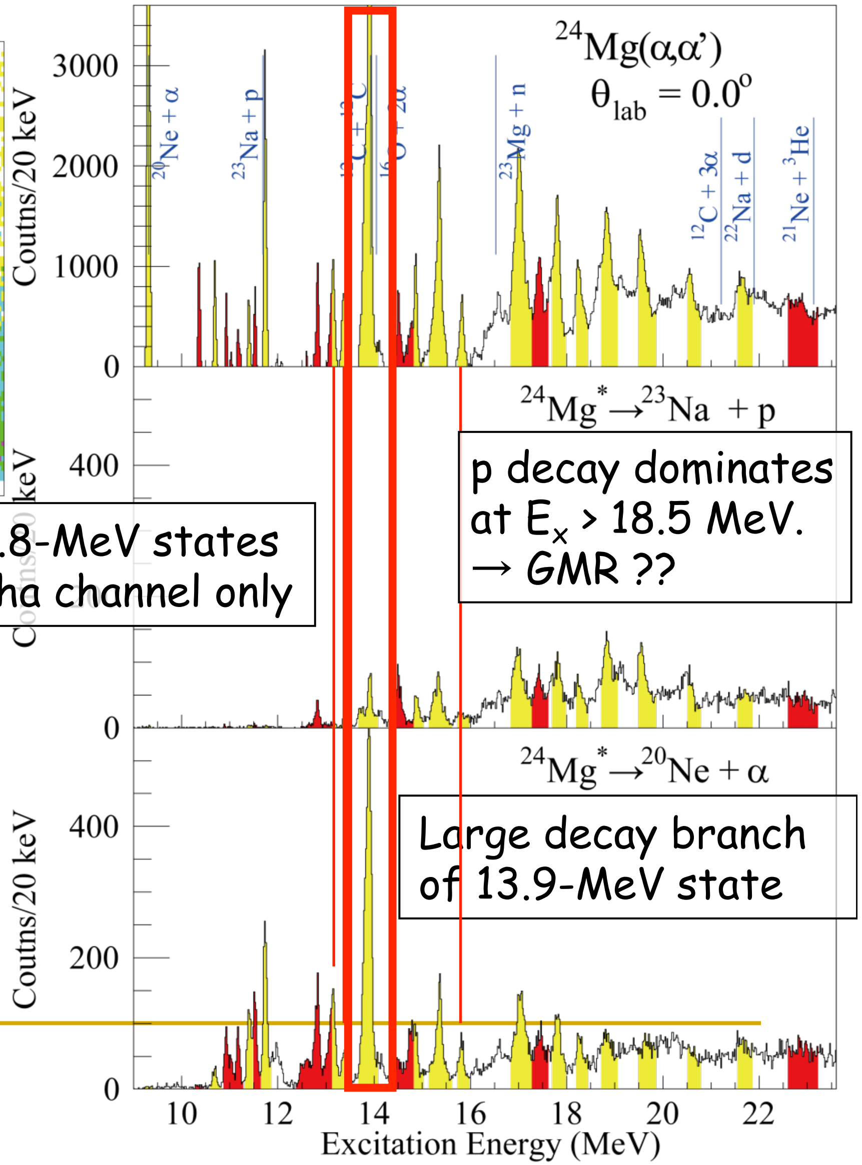
Fine structure in ΔL=0 strengths was observed.

Decay Particle Measurement

Decay to the proton and alpha emission channels were identified.







13.1, 13.4 and 15.8-MeV states decay to the alpha channel only

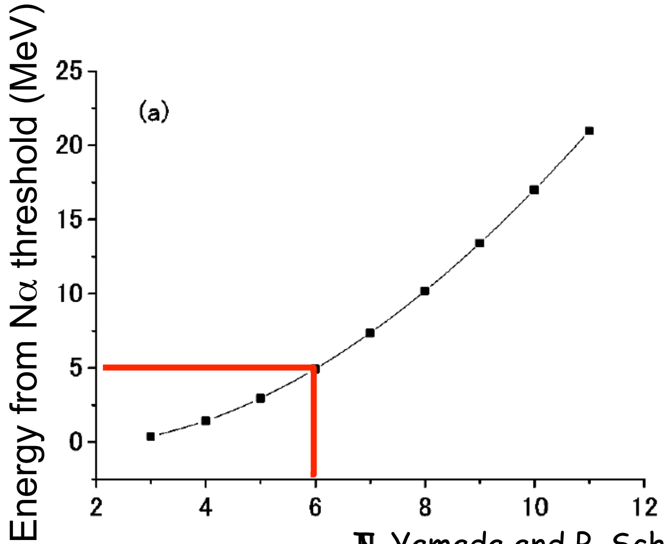
p decay dominates at E_x > 18.5 MeV.
→ GMR ??

Large decay branch of 13.9-MeV state

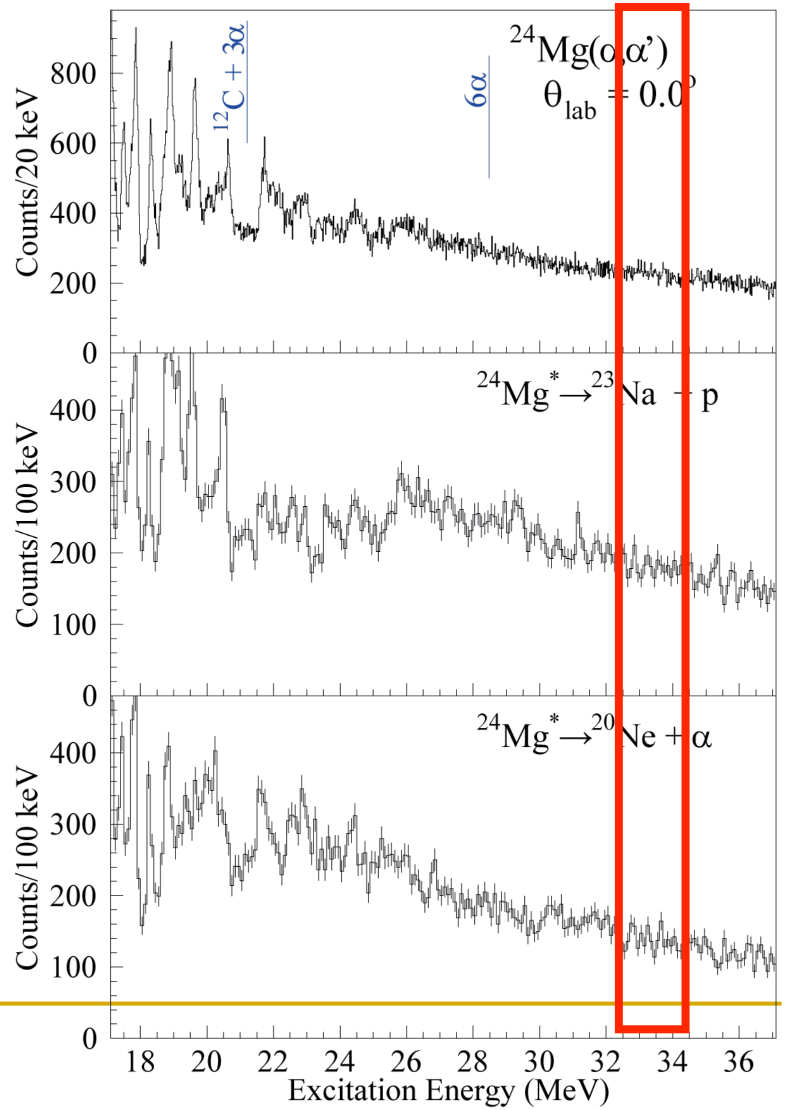
- Proton and alpha decay channels are separated.
- 13.1, 13.4 and 15.8-MeV states decay to ^{20}Ne only.
- 0^+ state at 13.9 MeV near the ^{12}C + ^{12}C and ^{16}O + 2a thresholds has a large decay branch to ^{20}Ne.

Highly Excited Region

6α condensed state was searched for in the highly excited region.



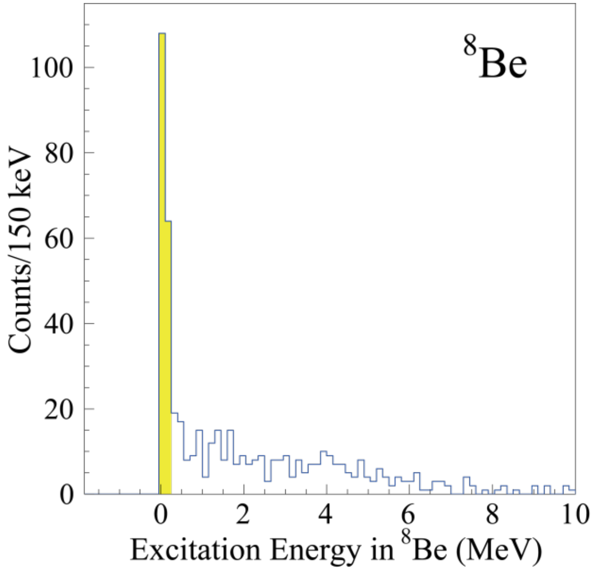
T. Yamada and P. Schuck, Phys. Rev. C **69**, 024309 (2004).

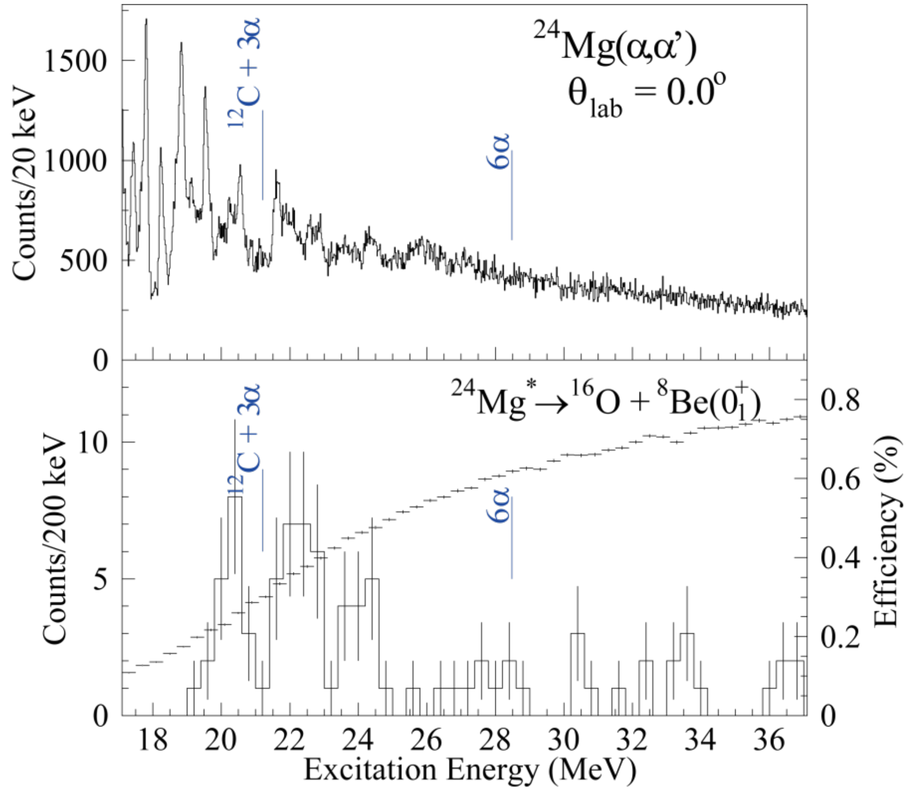


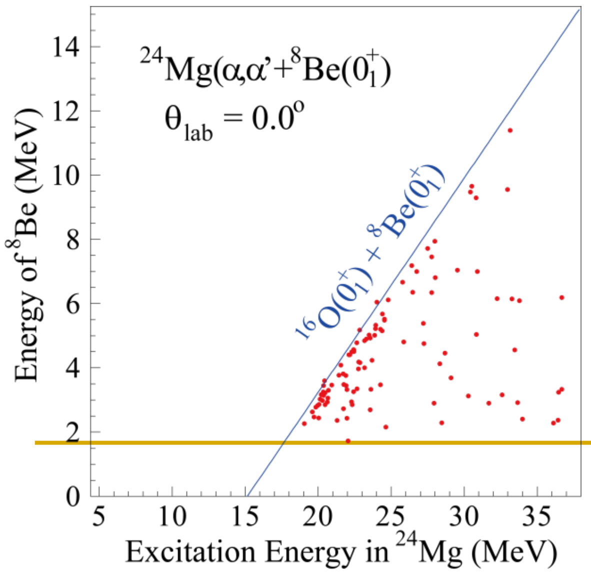
- 6α condensed state is expected at 5 MeV above the 6α threshold.
  - E_x ~ 28.5 + 5 = 33.5 MeV
- No significant structure suggesting the 6α condensed state.
  - Several small structures indistinguishable from the statistical fluctuation.
    → Need more statistics.

^{8}Be Emission Events

$^{8}Be(0^{+}_{1})$ emission events were indentified from 2α emission events by E_x in ^{8}Be.



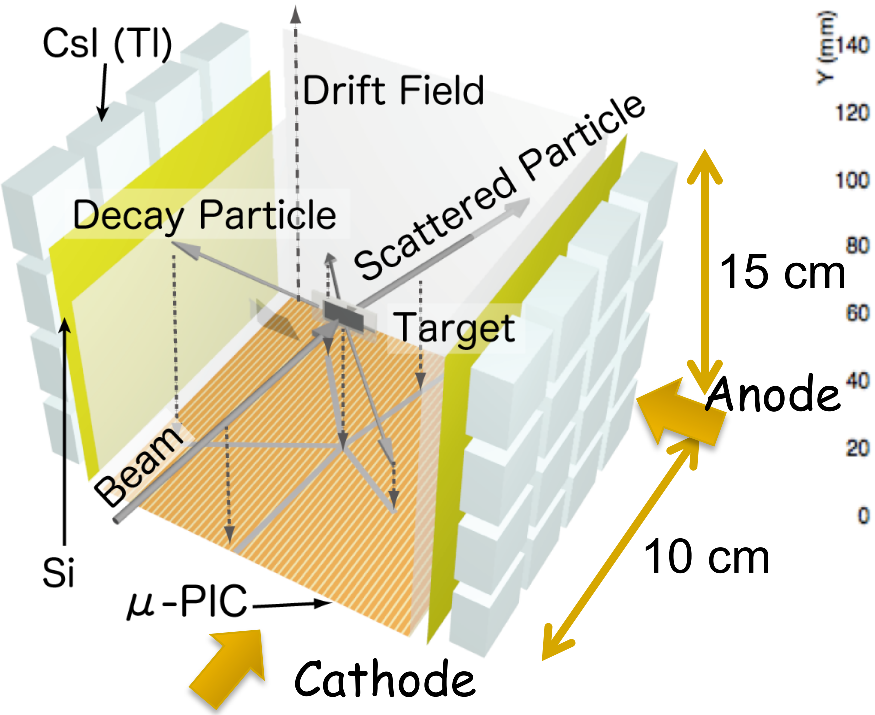


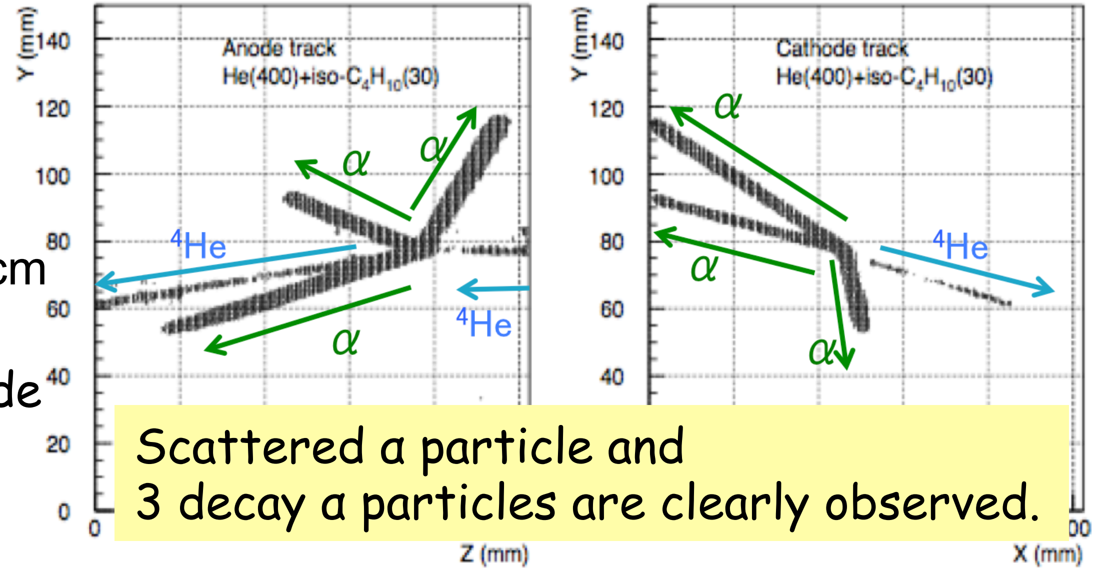


- Several states at 20.5, 22.0, and 24.3 MeV were observed near the ^{12}C+3α threshold.
- Possible structures were seen above the 6α threshold although statistically poor .
  → Need more statistics.

Future Perspective

MAIKo TPC is developed by the Kyoto-RCNP group.
It will be installed at the target position of Grand Raiden.





Scattered a particle and
3 decay a particles are clearly observed.

- Beam: ^{4}He @ 12.5 MeV/u
- Gas: He(93%) + iC_4H_{10}(7%) @430 hPa

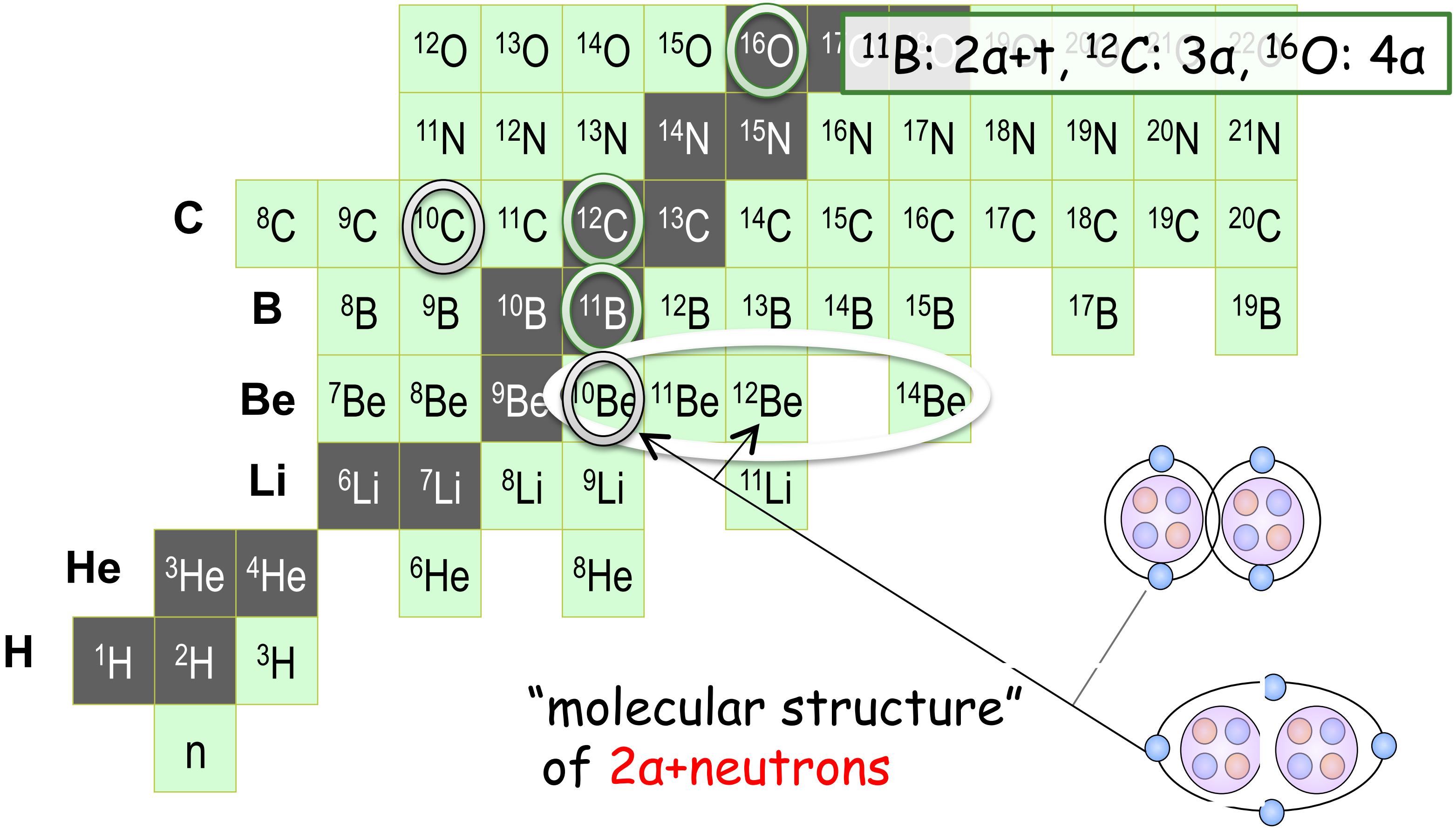
- Detect low-energy decay particles with large angular coverage.
- Introduce μ-PIC + GEM for multiplication and detection of electrons.

dΩ for previous detector: 309 mSr
dΩ for MAIKo: ~ 4π

MAIKo will gain solid angle by a factor of
$(0.3/4\pi)^6 \sim 5 \times 10^6$ for 6a measurement.

Cluster Structure in unstable nuclei

Cluster Structures in unstable nuclei

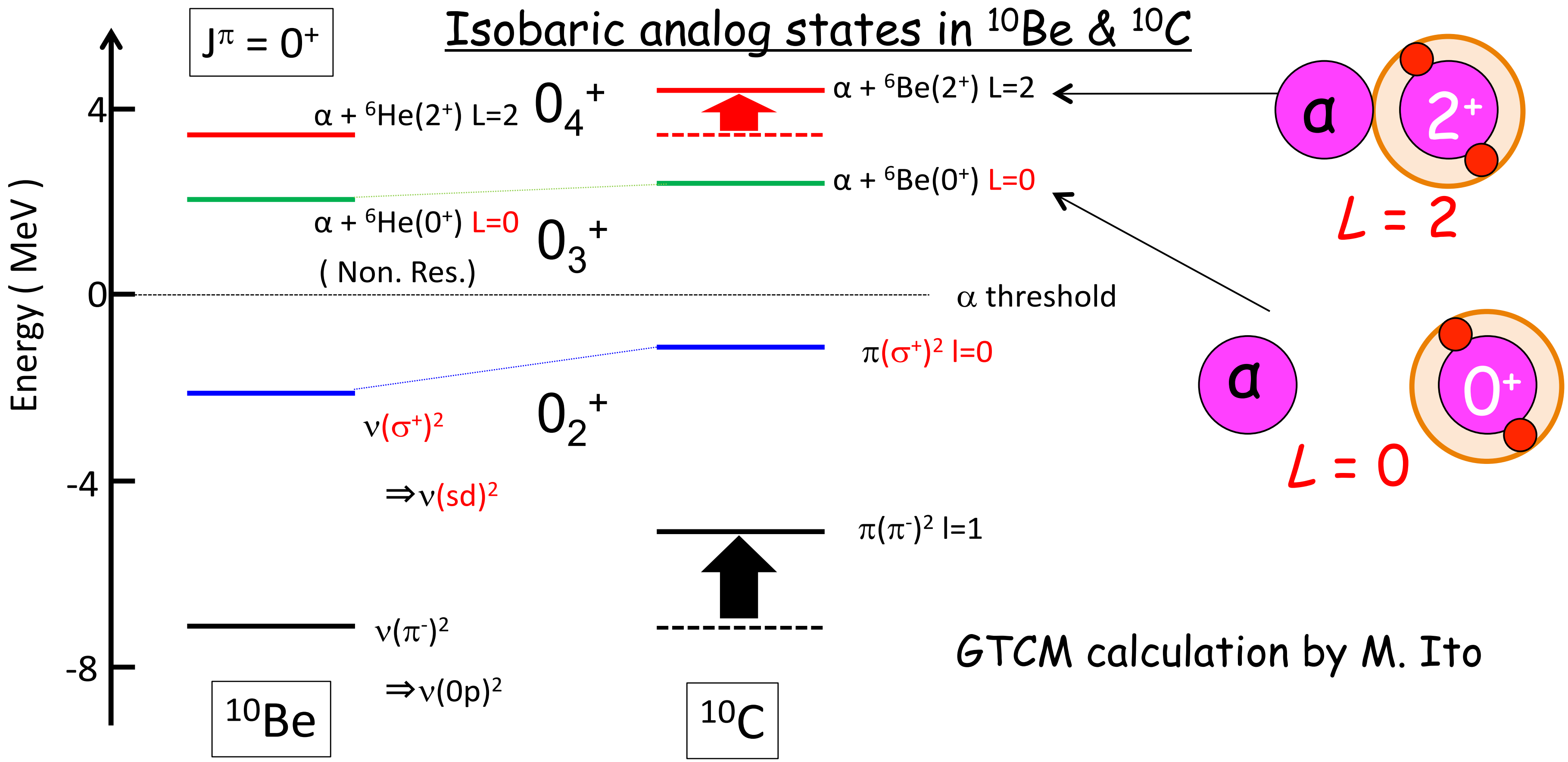


Can proton-rich nuclei also form a molecular structures?

We propose a study of the mirror symmetry of clustering in ^{10}C and ^{10}Be.

Mirror system of ^{10}C & ^{10}Be

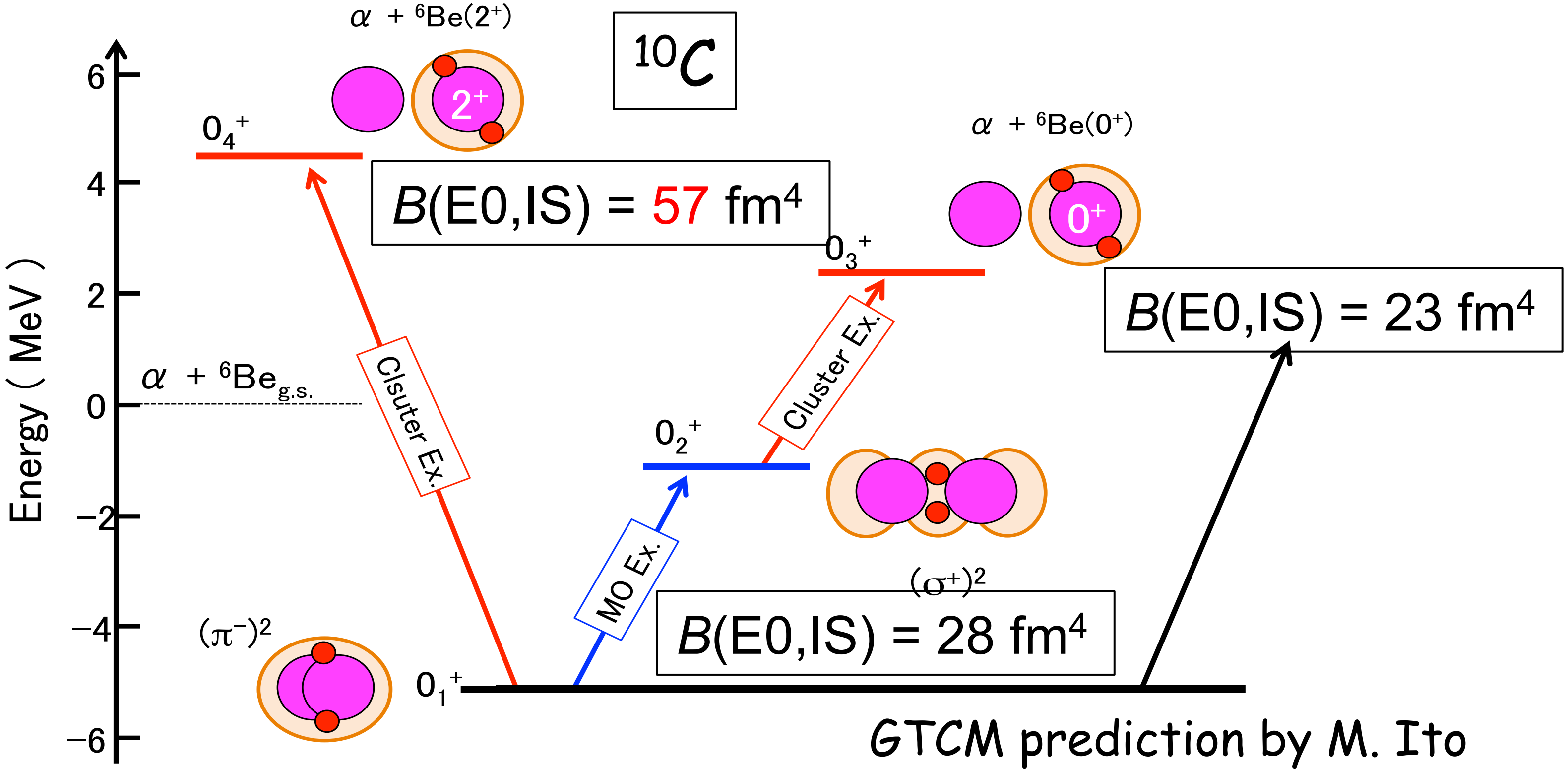
Mirror system provides a insight to cluster structures.



- Energy shift will be observed in 0_4^+ states (α+^{6}He/^{6}Be with *L=2*).
  → *Thomas-Ehrman shift (TES)* of "cluster structures"
- T-E shift will unveil the inner structures of the clusters.

Monopole excitations in ^{10}C

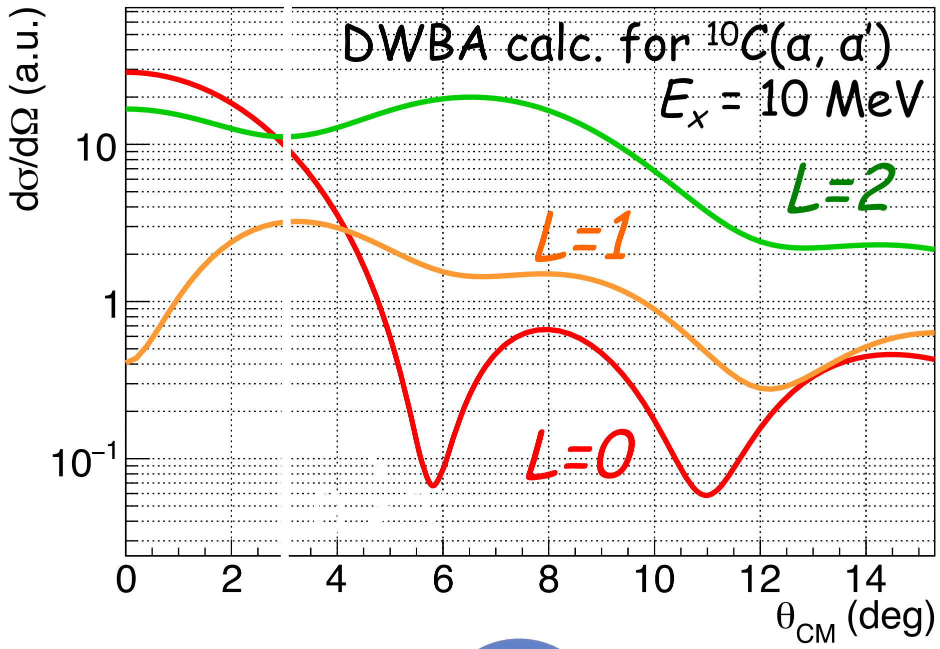
Monopole strength is a key parameter to pin-down cluster structure.

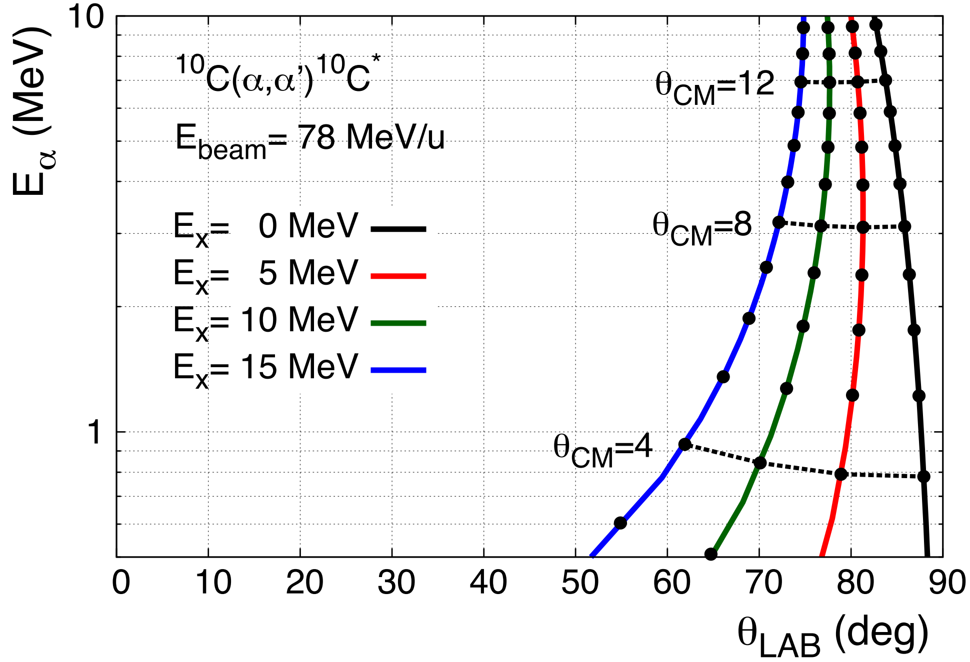


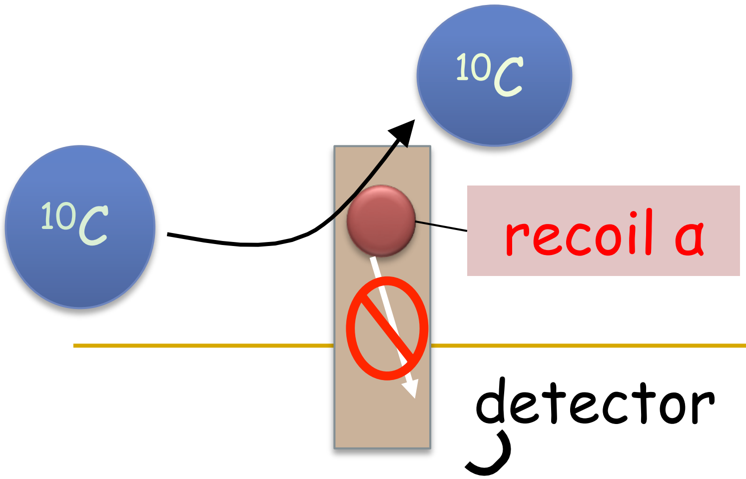
- *B*(E0,IS) is enhanced for cluster excitations.
- B(E0, IS) reflects the cluster structures.
- Measure *B*(E0,IS) systematically by $^{10}C(\alpha, \alpha')$ scattering.

Challenges in inverse kinematics

Measure the *B*(E0,IS) by missing mass spectroscopy with ^{10}C beam.







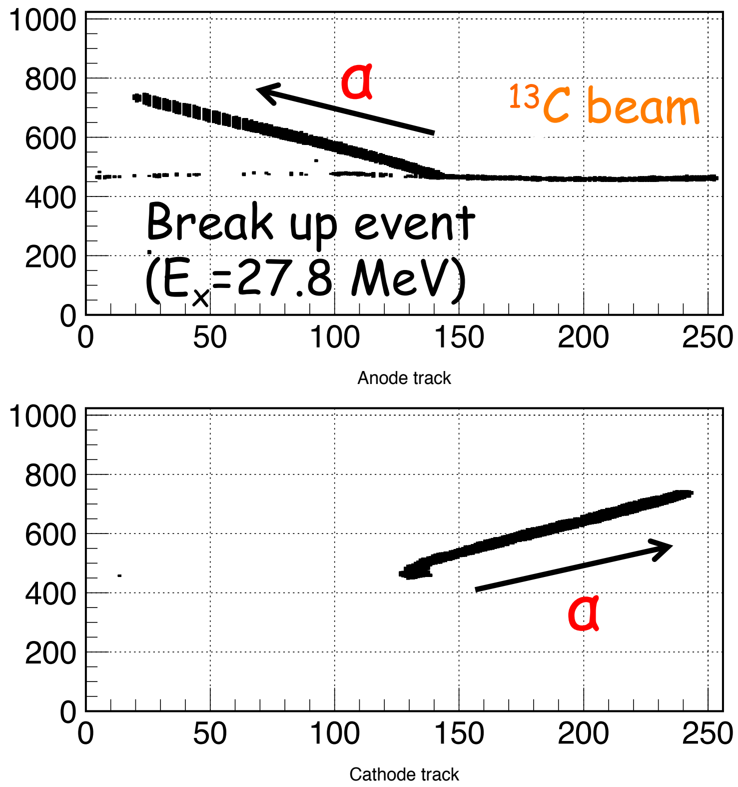
Measurement @$\theta_{CM} > 3°$

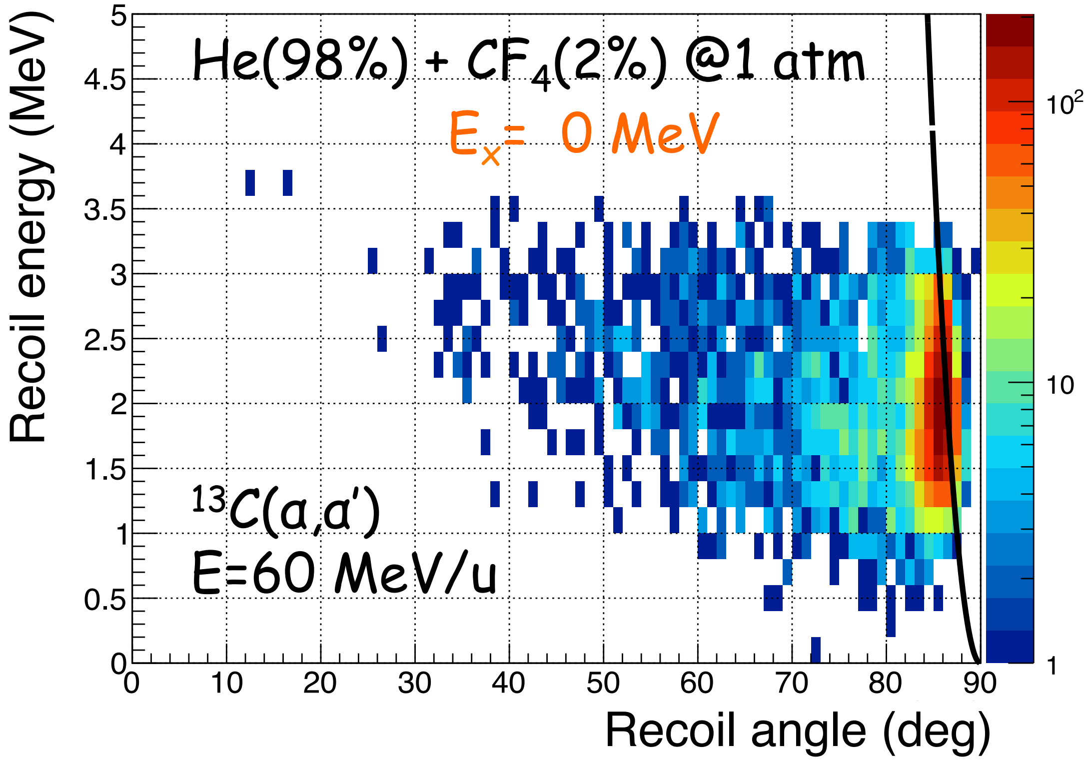
- ✓ $E_{\alpha} > 0.5$ MeV
- ✓ $60° < \theta_{LAB} < 90°$

MAIKo is suitable
for the present measurement.

MAIKo test experiment

$^{13}C(\alpha,\alpha')$ @60 MeV/u → Similar kinematics to $^{10}C(\alpha,\alpha')$.





- Recoil trajectory was reconstructed by Hough transform method.
- TPC self trigger → Sensitivity down to 1 MeV.
- Clear correlation from elastic scattering was observed.
- The gas pressure will be reduced to detect ~0.5 MeV recoil α.

Summary

- Cluster Correlation
  - E0 strength and cluster excitation
  - Alpha inelastic scattering
- Dilute Cluster State
  - ^{12}C case ~ Hoyle state ~
  - Heavier nuclei
    - Normal vs Inverse Kinematics
- Cluster Structure in unstable nuclei
  - New experiment using MAIKo active target