低エネルギーRIビームを使ったαクラスター状態研究
Studying α-cluster states with low-energy RI beams

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Studying α clusters

Yamaguchi's message: "Let's study α clusters in non-4*n* *nuclei*"

What would be the efficient way of studying α-cluster levels?

- Basic idea: To study α cluster system, it should be effective to use α particle as the probe.

e.g.)

1. X(α, γ)Y; α capture, often also important in astrophysics.

but the cross section is usually too low for an RI beam.

2. X(α, α)X; resonant elastic scattering. States of X+α compound nucleus is observed as resonances.

3. α-transfer reaction X(^{6}Li,*d*)X+α.

4. Trojan Horse Method X(^{6}Li,*d*α)X

- Still many studies on 4n nuclei (^{8}Be, ^{12}C, ^{16}O, …) are in the main stream. Unique studies can be performed with RI beams.

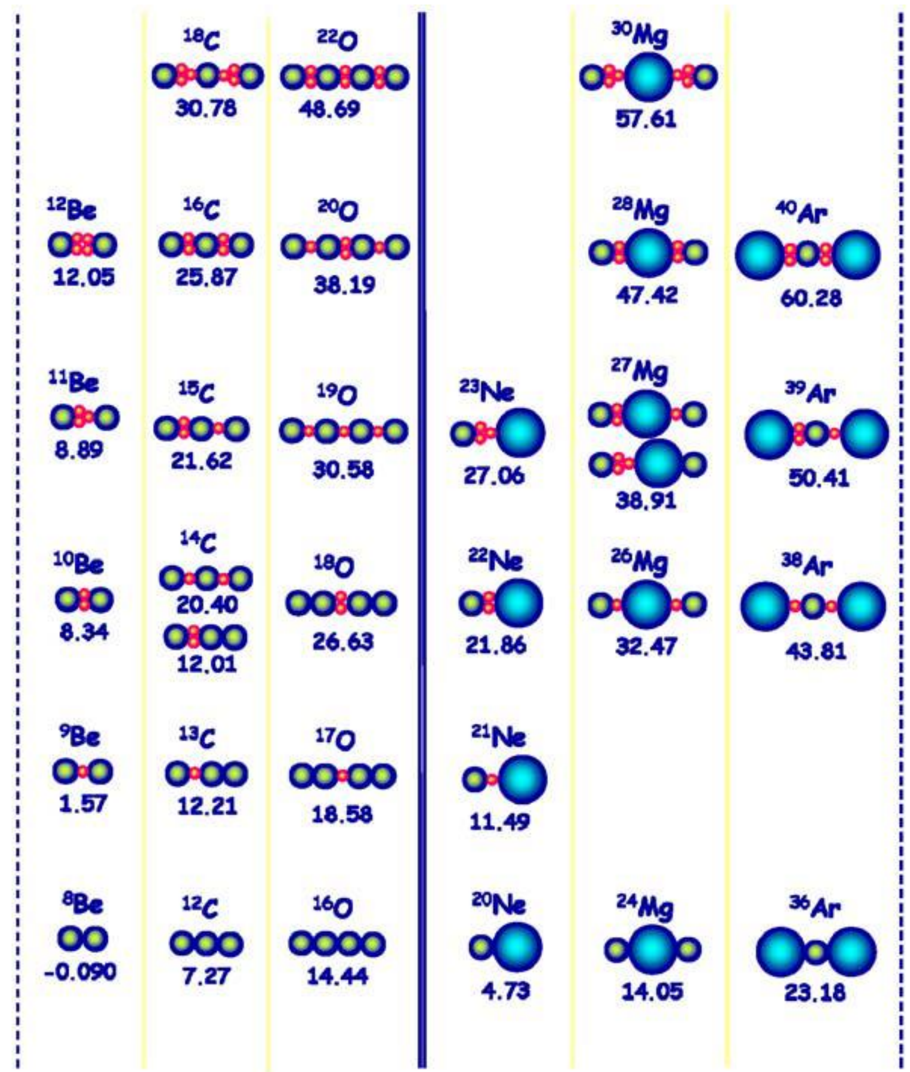
Why non-4n nuclei?

- ^{8}Be(⇔2α)…unbound
  ^{9}Be(⇔2α+n)…stable

neutron is the glue between 2α?

- Cluster structure could be realized in n-rich nuclei…extended Ikeda diagram *[W. von Oertzen et al. Physics Reports 432 (2006) 43–113.]*

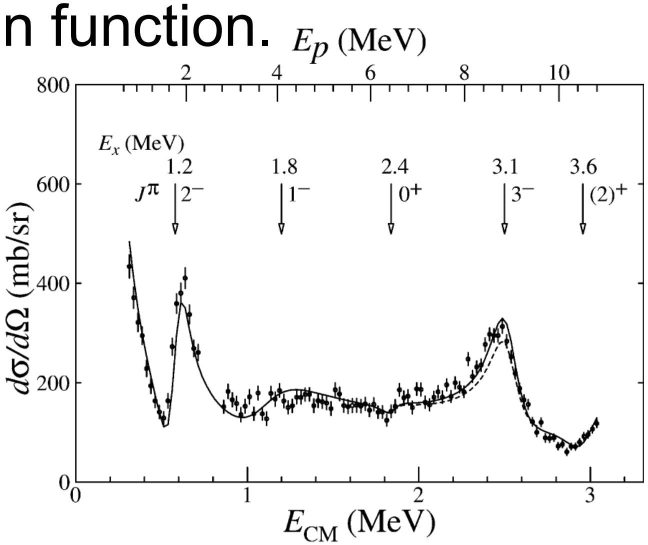
Experimental information is still not sufficient for them.



量子多体系の物理; n核子相関

Resonant elastic scattering

- Elastic scattering
  - ◆At energies far below Coulomb barrier…Simply Rutherford scattering. Cross section is higher at low energies and angles.
  - ◆At higher energies… interference of Coulomb and nuclear potential … "resonances" can be observed in the excitation function.



T. Teranishi et al. / Physics Letters B 556 (2003) 27–32

量子多体系の物理; n核子相関

One striking method…TTIK

- W.W. Daenick and R. Sherr (1963) “thick target method” ^{12}C(p,p).
- A. Artemov et al., (1990)

Thick-Target with Inverse Kinematics

^{12}C beam into thick helium (α) target

Effective method of study of α-cluster states

K. P. Artemov, O. P. Belyanin, A. L. Vetoshkin, R. Wolskj, M. S. Golovkov, V. Z. Gol’dberg, M. Madeja, V. V. Pankratov, I. N. Serikov, V. A. Timofeev, V. N. Shadrin, and J. Szmider

I. V. Kurchatov Institute of Atomic Energy

(Submitted 15 February 1990)
Yad. Fiz. **52**, 634–639 (September 1990)

For study of states with a large reduced α width the method of measurement of the excitation function of elastic scattering of α particles is proposed, but in a geometry which is the reverse of the traditional experimental arrangement. The targets are helium gas which is simultaneously a moderator for the primary beam of heavy ions and an absorber which shields the detector from the direct beam. The advantages of the method are obvious in those cases in which in the usual experimental arrangement the need arises of using gas targets or targets of rare isotopes or of measurements at an angle 180°. To check the method we have carried out a comparison with the known $\alpha + {}^{12}$C interaction. New results are obtained in the interaction ^{15}N $+ \alpha$.

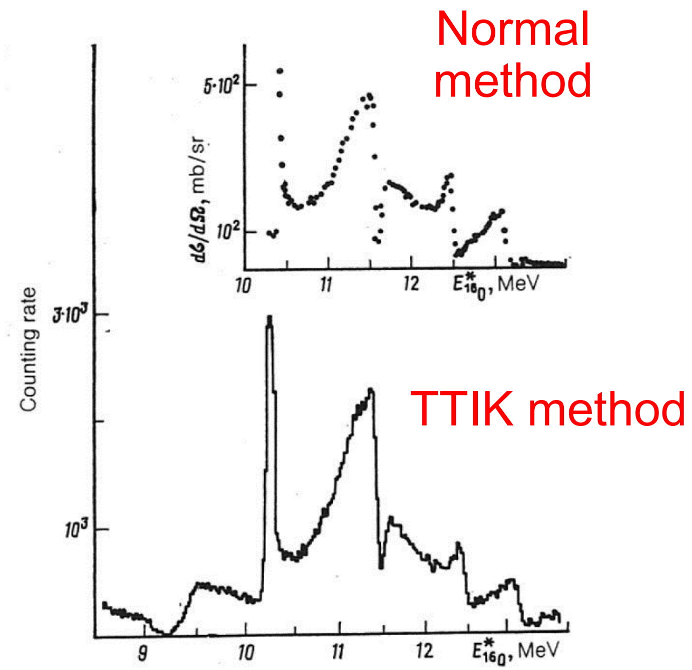


FIG. 1. Spectrum of α particles obtained in interaction of ^{12}C ions with initial energy 28 MeV with helium. The detection angle is 0°. In the insert we have given the excitation function for elastic scattering of α particles by carbon from Ref. 4. The detection angle is 158.8°.

Another method: (^{6}Li,*d*) transfer reaction

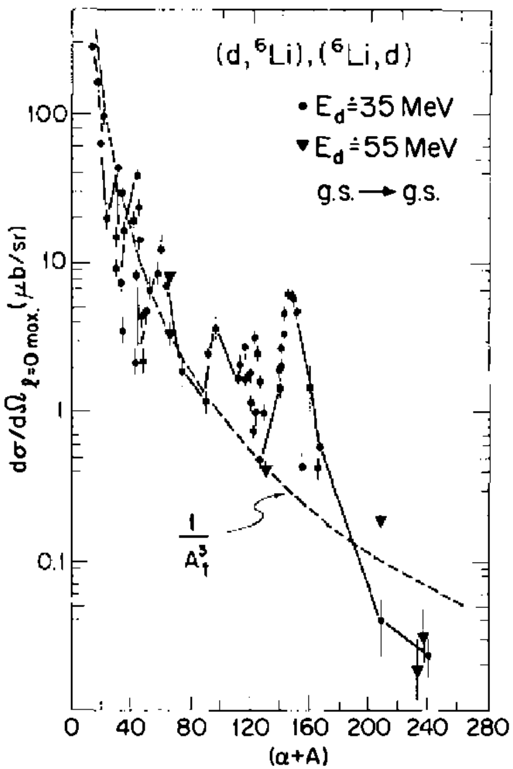
- 4-nucleon transfer reaction with minimum mass.
- Can be a simulation of astrophysical (α,γ) reaction.
  - ◆ ^{6}Li⇒d+α …requires 1.47 MeV (reaction Q value becomes lower than (α,γ) .)
- (α,α)…
  - ◆ Simple R-matrix calculation can be applied, direct information on Γ_{α}, large cross section
  - ◆ Coulomb scattering dominates at low energies and only Γ_{α} can be obtained (no Γ_{γ}).

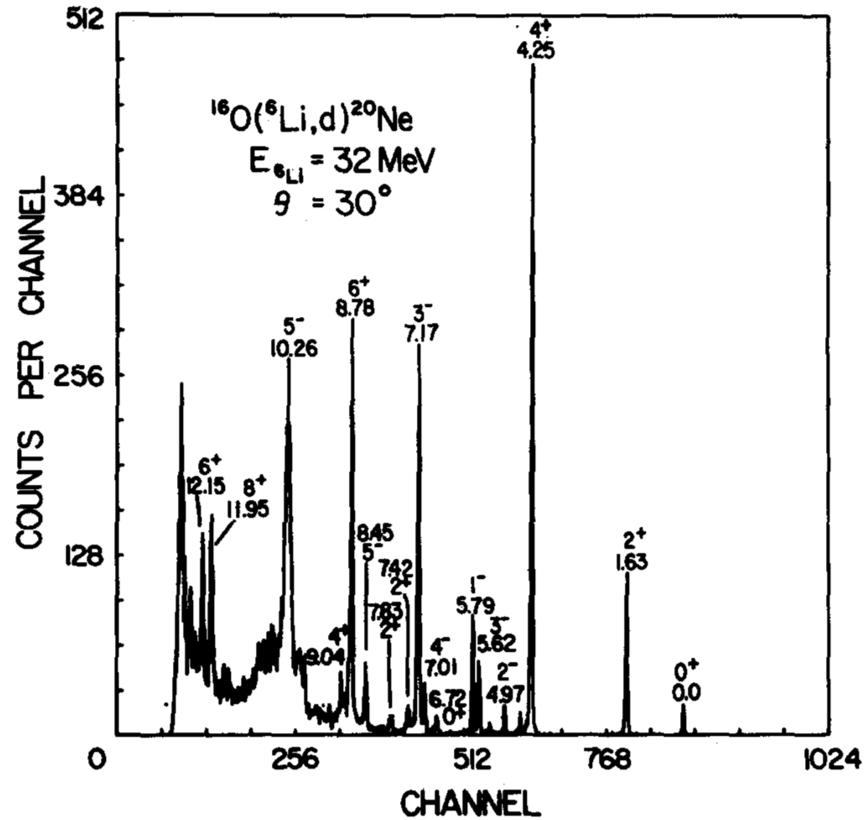
⇔

- (^{6}Li, d)…
  - ◆ Needs analysis such as DWBA, smaller cross section [but, larger than (α,γ)].
  - ◆ Information on resonances near the α threshold can be obtained.

(^{6}Li,*d*), previous studies

- A-dependence
  Becchetti (1978).



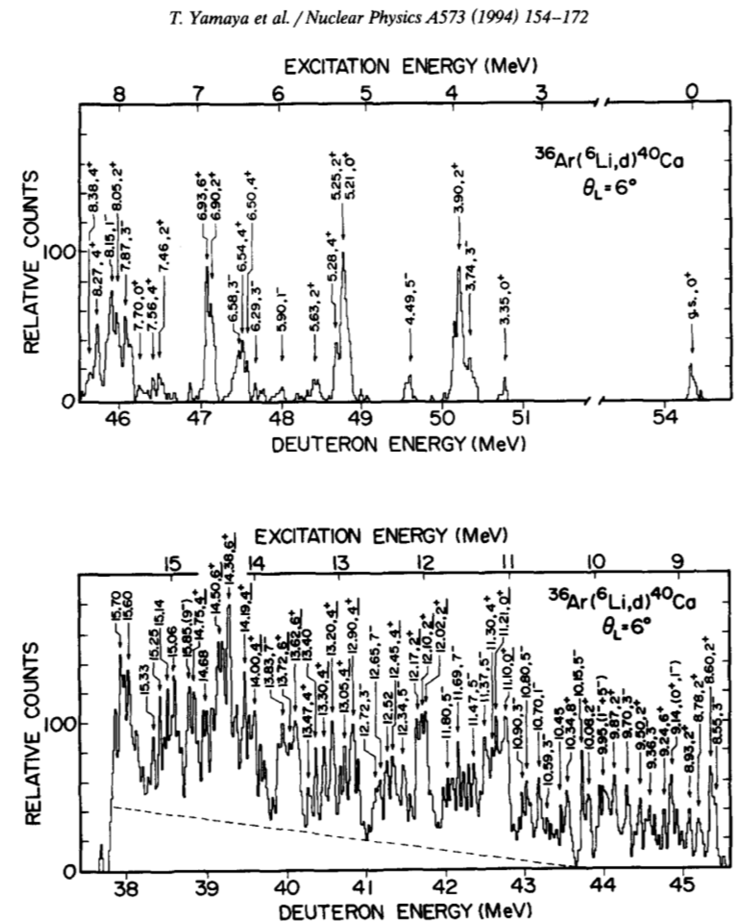


^{16}O(^{6}Li, d) @32MeV
Anantaraman et al. (1979).

(^{6}Li,*d*), previous studies

- Higher-mass example: Yamaya et al., (measured at RCNP) using 50 MeV ^{6}Li beam and enriched ^{36}Ar gas target.
- 38-55 MeV deuterons were detected.
- Cross section was 10-100 μb/sr (at peaks).
- Dense resonant structure at high excitation energy.

Not so easy to perform a similar experiment with low-intensity RI beam…



α-resonant scattering performed at CRIB

1. $^{7}Li+\alpha$ (^{11}B), 3 -body cluster, neutrino process

2. $^{7}Be+\alpha$ (^{11}C), mirror nucleus of ^{11}B, supernovae nucleosynthesis

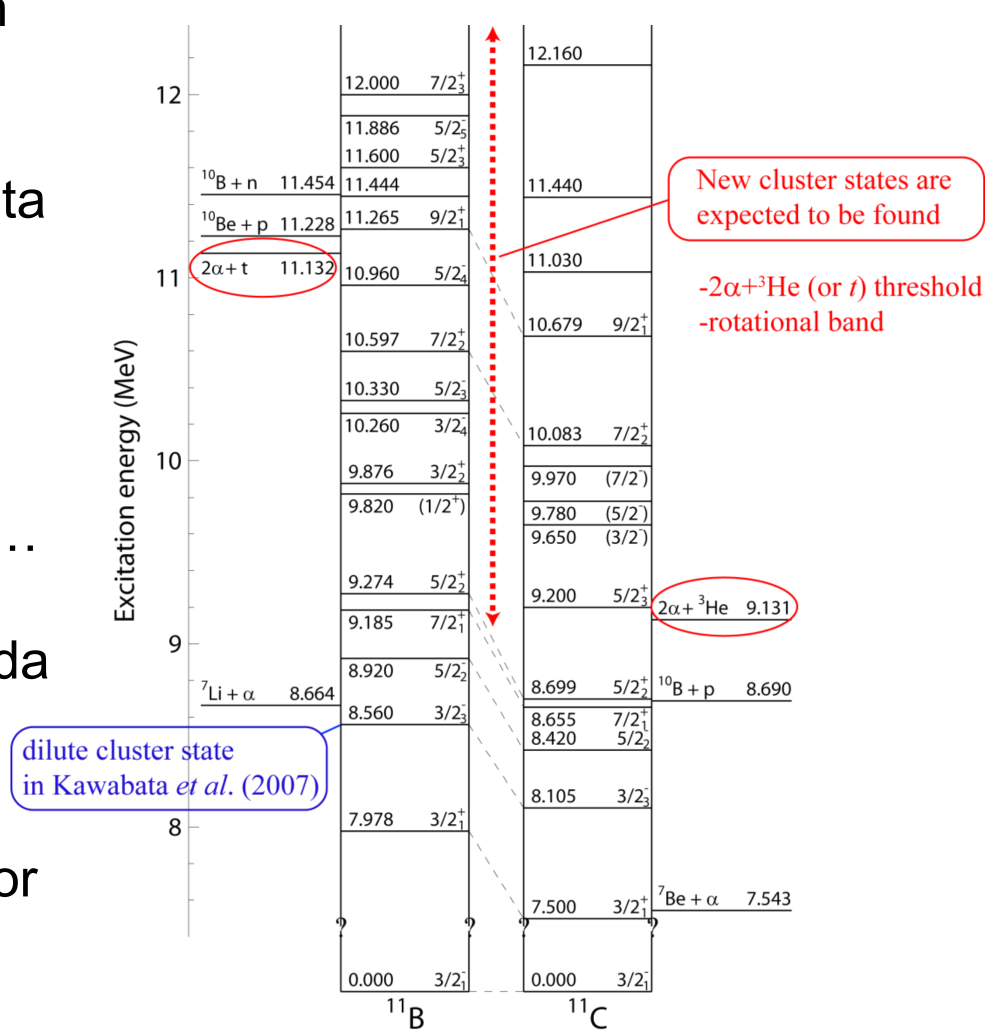
3. $^{10}Be+\alpha$ (^{14}C), Linear-chain levels

4. $^{30}S+\alpha$ (^{34}Ar), astrophysical $^{18}F(\alpha, p)$ reaction

5. $^{15}O+\alpha$ (^{19}Ne), Comparison with ^{20}Ne cluster, astrophysical $^{18}F(p, \alpha)$ reaction

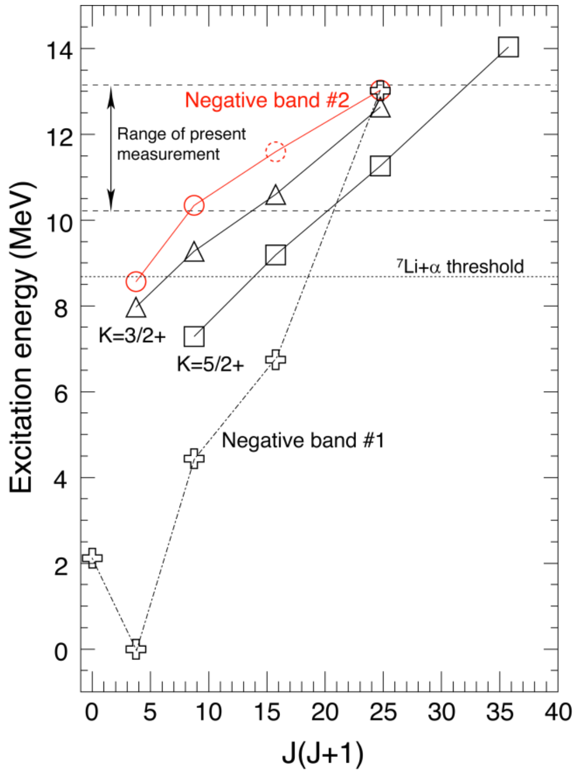
^{7}Be/^{7}Li for cluster structure

- $2\alpha+t$ / $2\alpha+{}^{3}$He cluster state in ^{11}B/^{11}C, similar to the dilute cluster structure in ^{12}C: Y.K. En'yo (2007), T. Kawabata *et al*. (2007). ⇒ A rotational band is expected in higher excited energy region (N.Soic et al., 2004).
- Near the $2\alpha+{}^{3}$He(t) threshold… cluster-condensed state with $J^{\pi}=1/2^{+}$ is expected (T. Yamada *et al*.), but not found yet.
- α width ⇔ spectroscopic factor of α-cluster configuration ⇔ evidence of cluster structure



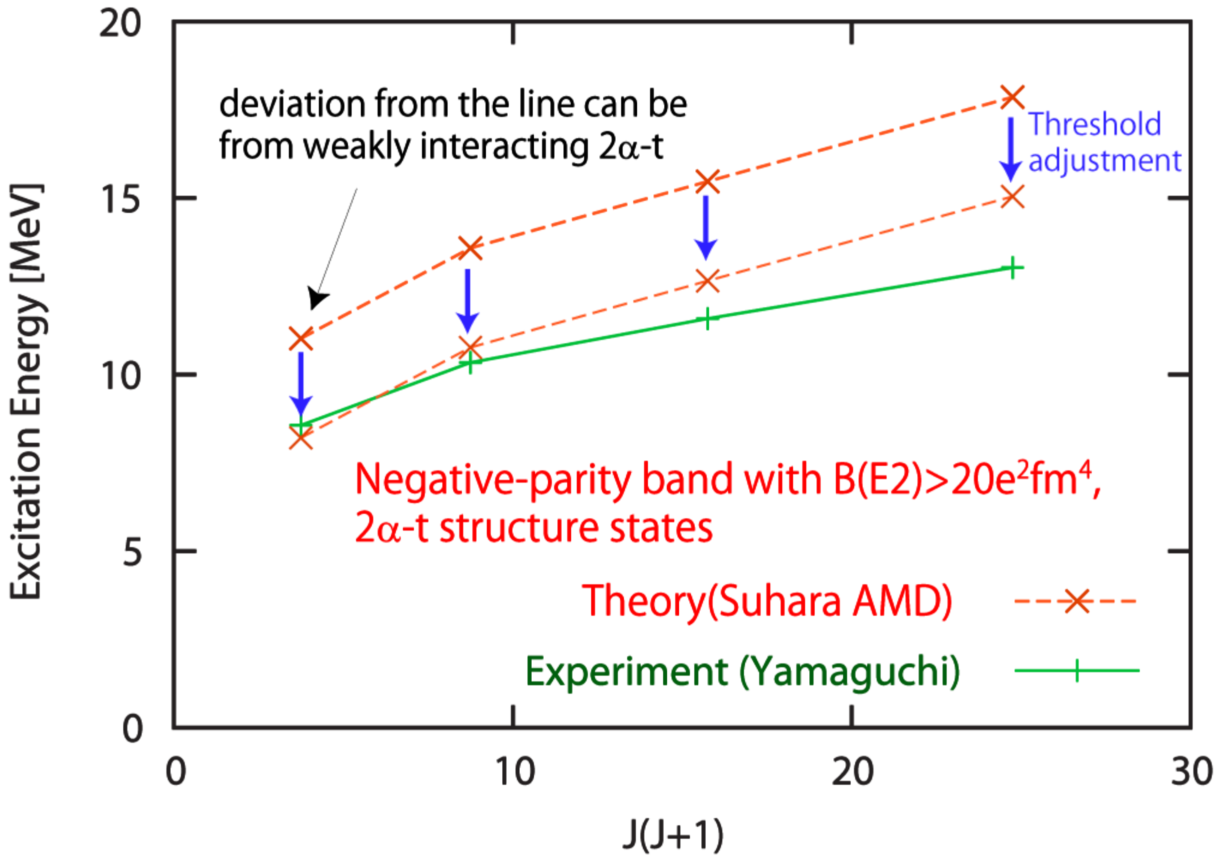
^{7}Li+α; result on the cluster band

- Newly proposed a negative parity band.
- It may not be a simple rotational band, but corresponds to a 2α-t structure [AMD Calc. by Suhara & En'yo]



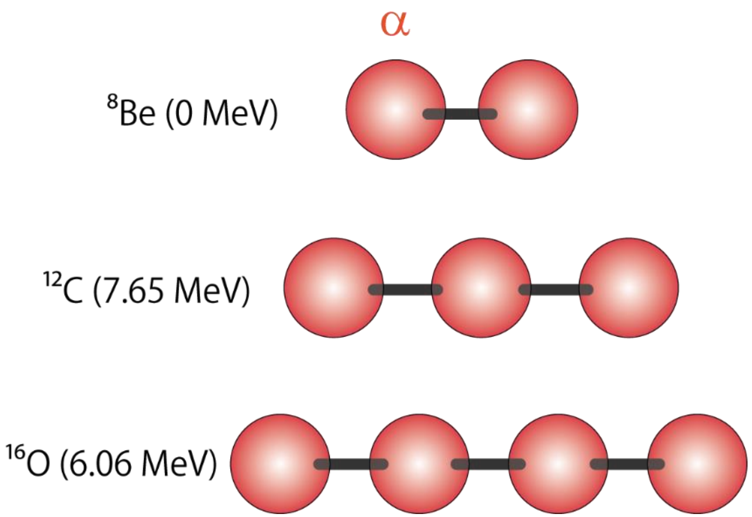
Interpretation of the new negative-parity band

Suhara & En'yo PRC (2012)



Morinaga (1956) and linear chain

- Discussed on 4n-nuclei based on the alpha particle model
- Predicted linear-chains in ^{12}C, ^{16}O, etc., from their high momenta of inertia.

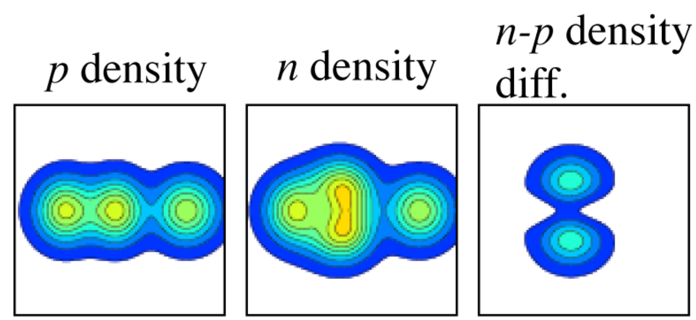


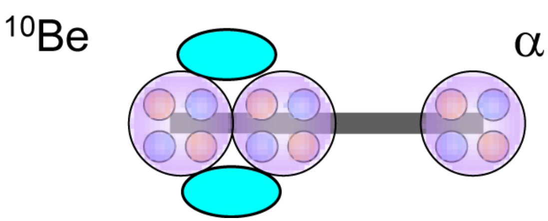
- It was shown in later studies that the Hoyle state is NOT a linear-chain state.

$^{10}Be+\alpha$

- Linear-chain cluster levels in ^{14}C were predicted in Suhara & En'yo (2010,2011).
- Asymmetric, $^{10}Be+\alpha$ configuration …likely to be observed with $^{10}Be+\alpha$ alpha-resonant scattering.
- May form a band with $J^{\pi}=0^+,2^+,4^+$ a few MeV above α-threshold.
- Scattering of two 0^+ particles…only l-dependent resonant profile.

Suhara & En'yo, PRC 2010 and 2011:

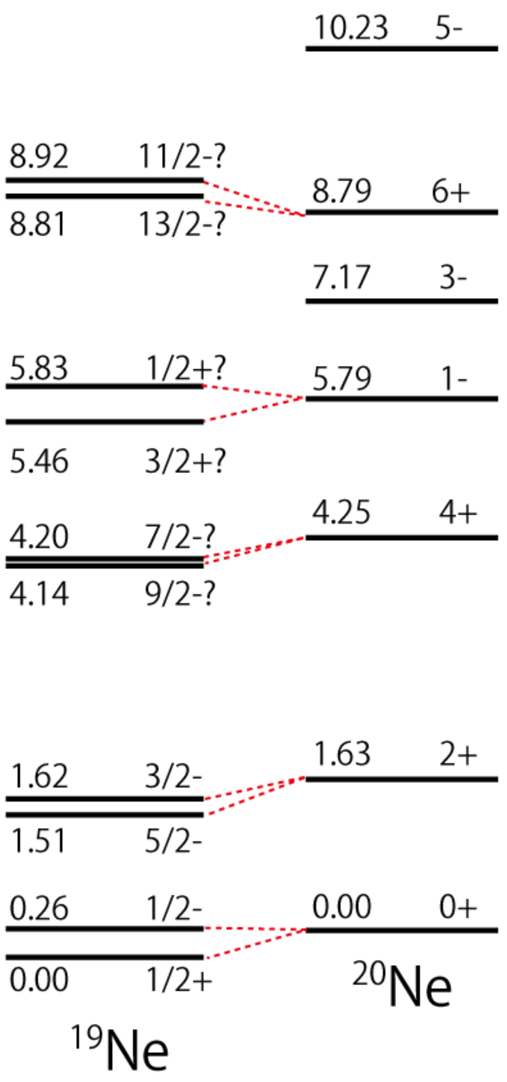




^{15}O+α study

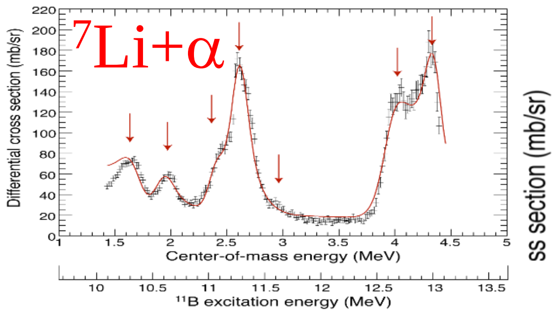
- Rotational band in ^{20}Ne
  - ◆positive ($0^+,2^+,\ldots$)& negative(1^-, $3^-,\ldots$)
  - ◆Corresponding states in doublets expected in ^{19}Ne, which should also have α-cluster feature.

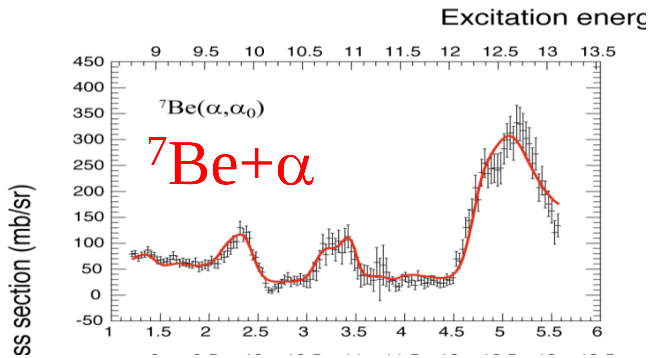
  Nemoto & Bando, PTP (1971).
  - ◆Many parameters still unknown.
- ^{15}O+α resonant elastic scattering…these levels can be selectively observed.

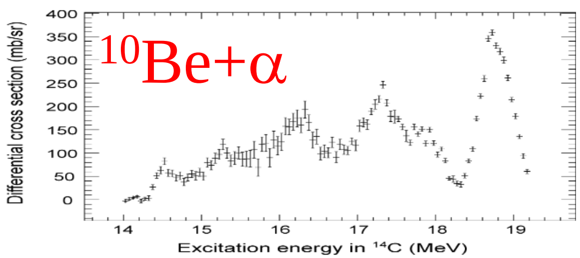


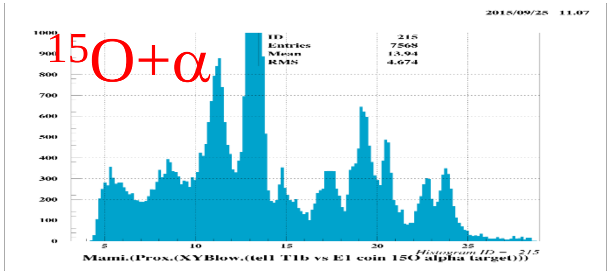
Summary of alpha resonant scattering

•Many resonances above the α particle threshold are observed in each measurement:





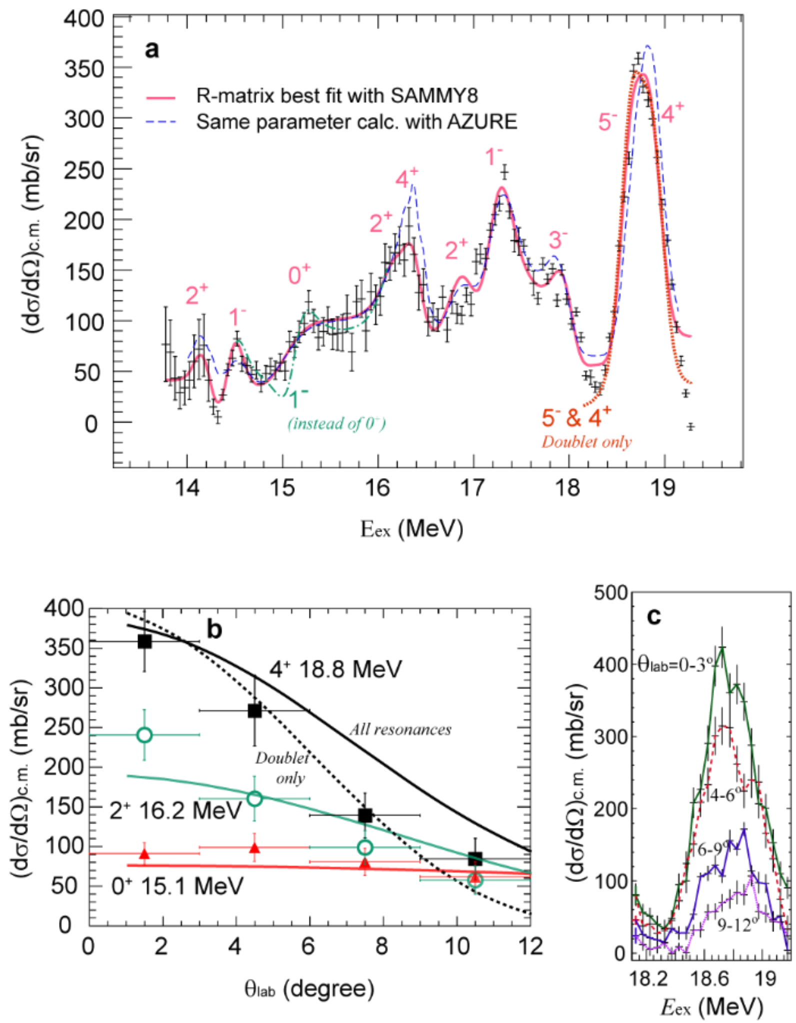




•New rotational bands were suggested, compared with AMD calculations (published for the first two projects.)

Hot result: ^{10}Be+α Excitation function

- The excitation function we obtained for 13.8-19.2 MeV exhibits many resonances.
- R-matrix analysis performed, and some of the resonance parameters (E, J^{π}, Γ_{α}) were determined.

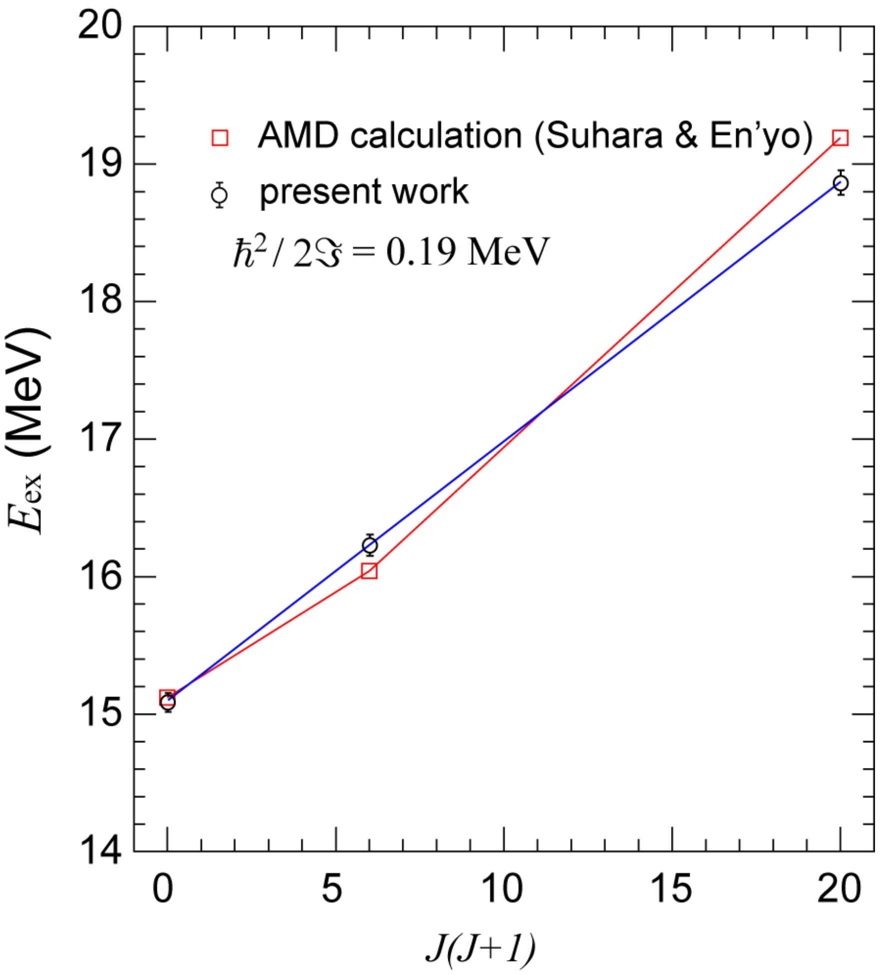


Rotational Band

The set of resonances we observed (0+, 2+, 4+) is proportional to *J(J+1)* …
consistent with a view of rotational band.

Also perfectly consistent with the theoretical prediction.

Is this real or accidental?



Summary of alpha resonant scattering

What's achieved:

Now we are able to study α-cluster states in non-4n nuclei with a good selectivity. Not only the level energies, but we also the spin-parities and alpha widths are obtained by R-matrix analysis. The level spacing in a rotational band is another good measure to discuss cluster levels, comparing with the theory.

What's not achieved:

The spin-parities are not always uniquely determined. Limited precision for the alpha widths, for both experimental and theoretical aspects.

It is difficult to conclude if an observed resonance corresponds to a theoretical prediction or not.

Future prospects (at RIBF)

Alpha resonant scattering…main issue is the beam energy.

- CRIB…very suitable machine (<10 MeV/u).
- RIPS…feasible if beam energy can be degraded.

Isobaric analog resonances of the $N = 21$ nucleus ^{35}Si [N. Imai et al., *Phys. Rev. C, 085 034313 (2012)*] … used degraded beam (63MeV/u → 4.4 MeV/u).

- OEDO (CNS future project)… energy-degraded (~10 MeV/u) beam after BigRIPS will be available.
- SLOWRI...low-energy beam available, but reacceleration necessary?

Alpha transfer reaction…higher beam energy is acceptable (though the cross section is lower and >100MeV/u is not favored). Beam intensity is another key issue.

New scheme:Trojan Horse Method

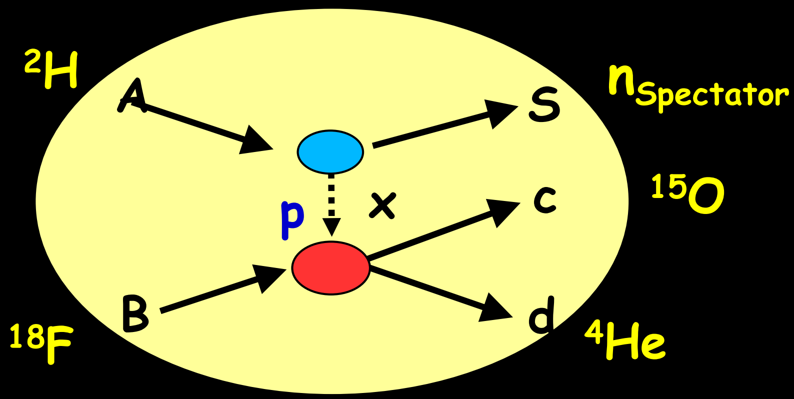
- Trojan Horse Method (THM)…simulate 2-body reaction with 3-body quasi-free reaction.
  - ◆Resonant elastic scattering: X(α,α)X
  - ◆THM: X(^{6}Li, dα)X

- First Trojan Horse Method + RI beam experiment in the world…performed at CRIB, *S. Cherubini et al., PRC (2015)*…[See next slides]. This was for (p,α) reaction study.

- No real experiment of the THM elastic scattering has been performed yet, but in principle we can access resonances below Coulomb barrier (The feasibility must be studied).

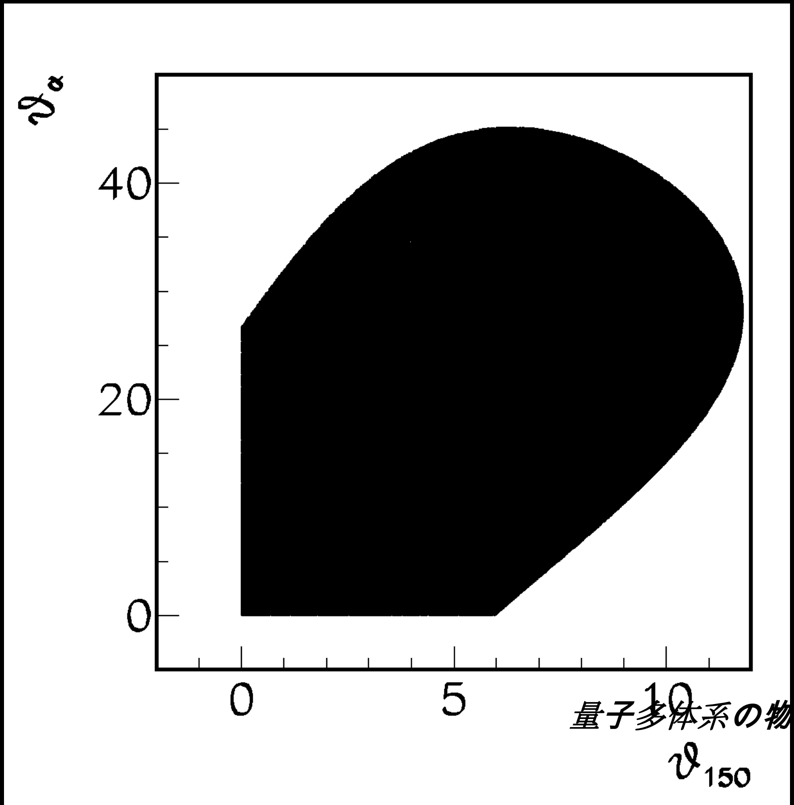
THM measurement: ^{18}F(p,α) ^{15}O via ^{2}H(^{18}F,α ^{15}O)n

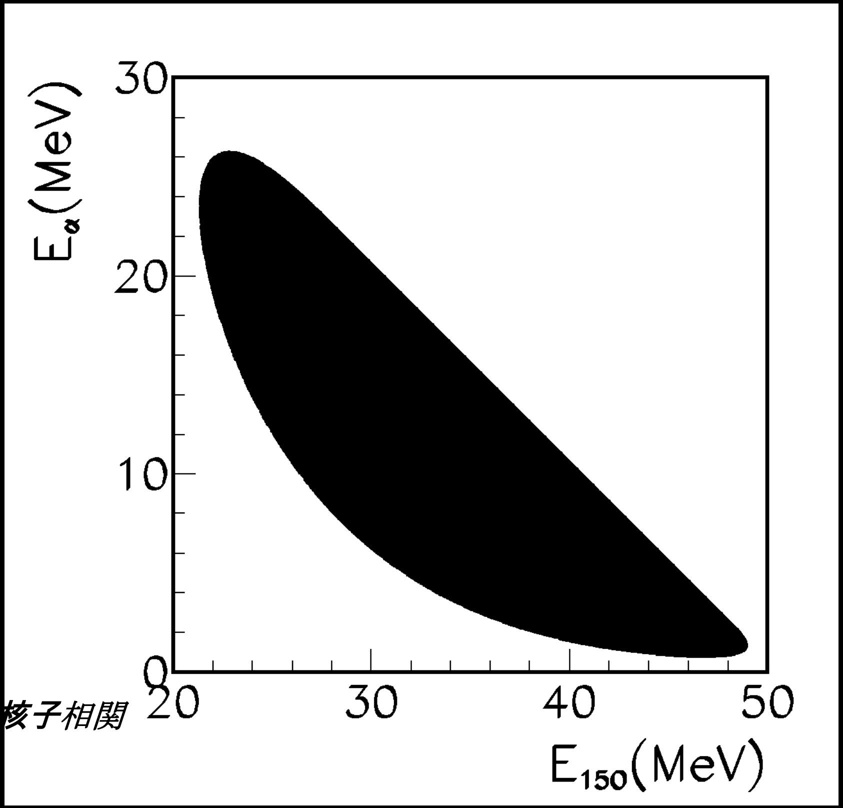
Kinematics



^{2}H(^{18}F,α ^{15}O)n

E(^{18}F) = 50 MeV





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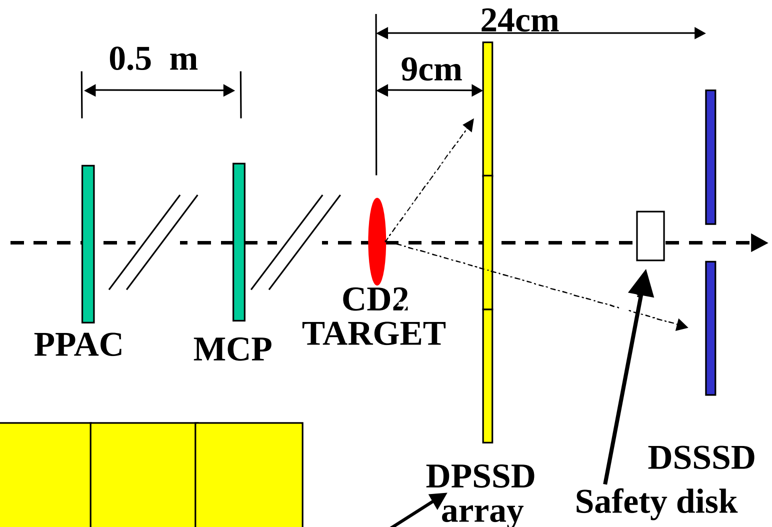
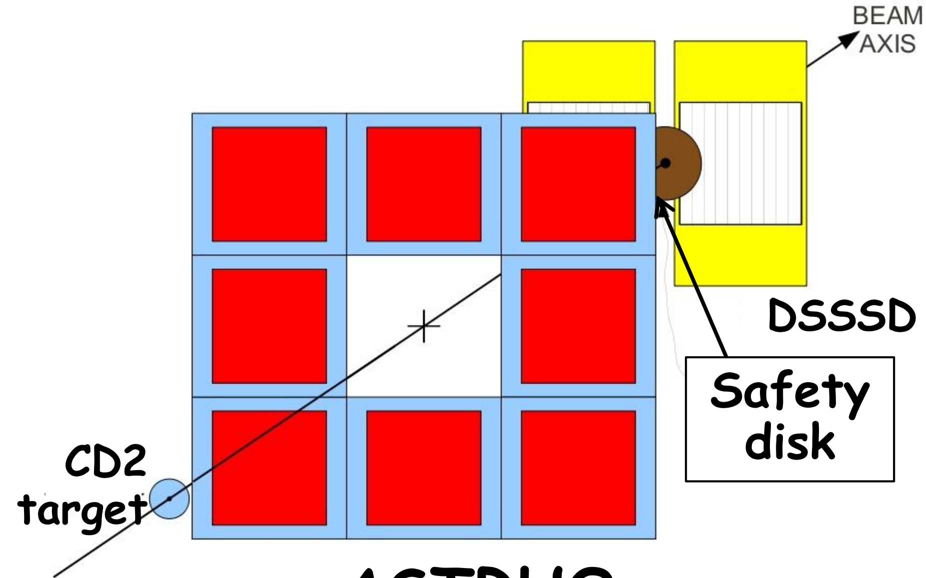
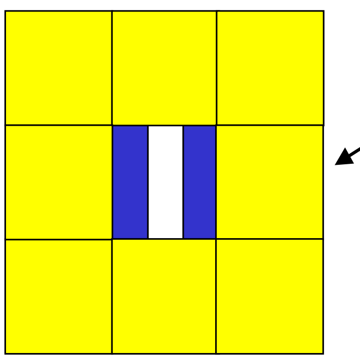
EXPERIMENTAL SETUP





ASTRHO



ASTRHO:
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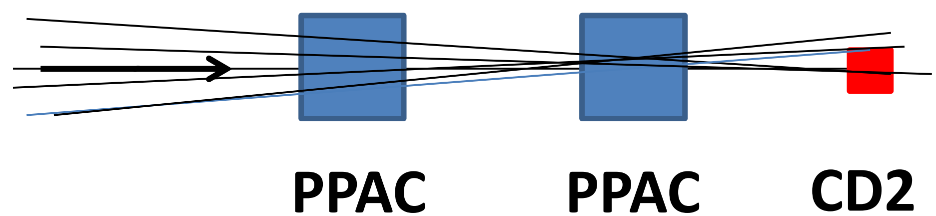
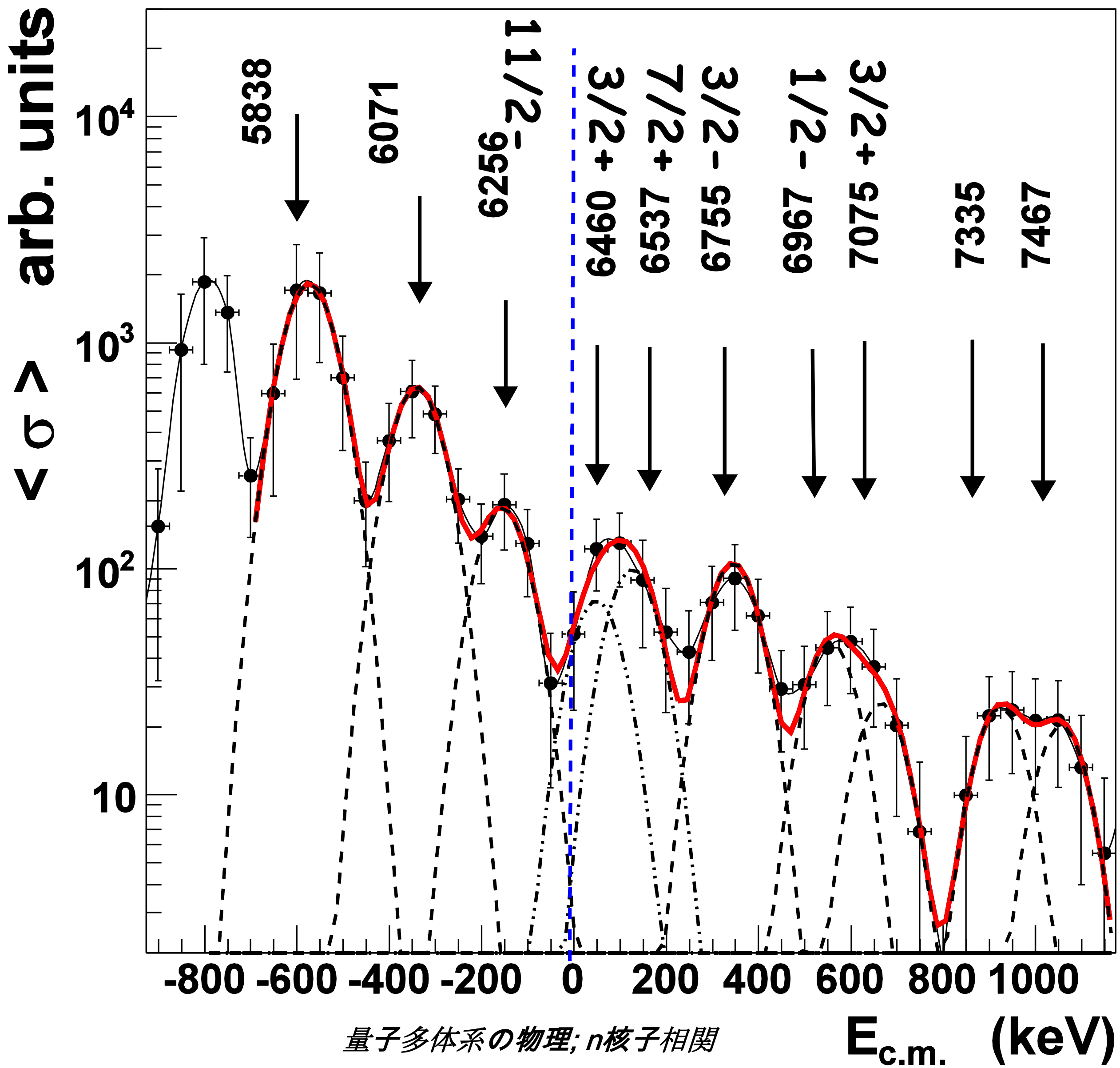


Beam track reconstruction

THM(=barriers free) CROSS SECTION



Summary

My message: **"Let's study α clusters in non-4*n* *nuclei*"**

- Alpha resonant scattering is a striking method for the

α-cluster structure study.

- Several studies performed so far at CRIB:

1. ^{7}Li+α (^{11}B), 3 -body cluster, neutrino process
2. ^{7}Be+α (^{11}C), mirror nucleus of ^{11}B, supernovae nucleosynthesis
3. ^{10}Be+α (^{14}C), Linear-chain levels (, BBN nucleosynthesis).
4. ^{30}S+α (^{34}Ar), astrophysical ^{18}F(α, p) reaction
5. ^{15}O+α (^{19}Ne), Comparison with ^{20}Ne cluster, astrophysical ^{18}F(p, α) reaction

Competitive situation with foreign experimental groups (e.g. Charissa collaboration), but CRIB/OEDO has an advantage in the low-energy RI beam.

- α–transfer,THM…other methods to study α-clusters with direct α particle probe. Studies to test the feasibility are needed. Beam intensity might be an issue.