α共鳴散乱による不安定核クラスター状態の研究
Study on cluster states in unstable nuclei with α-resonant scattering

Nuclear astrophysics/CRIB group members)
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McMaster (Canada), CIAE, IMP (China), Chung-Ang, Ehwa, SNU (Korea), INFN Padova/Catania (Italy), IOP(Vietnam) and others.

Overview

Interests: Clusters emerging in unstable (non-4n) nuclei

Method: RI Beam+α resonant scattering

Facility: "CRIB", the low-energy RI beam separator of CNS, the University of Tokyo.

Experiments:

- ^{7}Li+α/^{7}Be+α

  Astrophysical (α,γ) reactions and α–cluster structure in ^{11}B/^{11}C.

  Alpha resonances were observed. *Publication: H. Yamaguchi et al., Phys. Rev. C (2011) and Phys. Rev. C (2013).*
- ^{10}Be+α: motivated by Suhara-En'yo calculation of linear cluster chain in ^{14}C. *H. Yamaguchi et al., Phys. Lett. B (2017).*
- ^{15}O+α: measured in 2015.
- ^{18}Ne+α: measured in 2016.

The beginning of the story (as for me)

-In 2007, I finished the development of the cryogenic gas target at CRIB, and obtained an intense ^{7}Be beam (2 x 10^{8} pps).

-Also in 2007, a paper on the ^{11}B (=^{7}Li+α) cluster structure was published by Kawabata-san (at CNS) et al., based on En'yo-san's theoretical paper (2007).

-Study of ^{11}B/^{11}C cluster levels could be done with the α-resonant scattering using low-energy stable/RI beams→ I made a proposal based on this idea.

-The idea to study clusters with α-resonant scattering was nothing new, but I initiated a series of measurements at CRIB, which I introduce you today.

PHYSICAL REVIEW C **75**, 024302 (2007)

Negative parity states of ^{11}B and ^{11}C and the similarity with ^{12}C

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(Received 2 November 2006; published 8 February 2007)

The negative parity states of ^{11}B and ^{11}C were studied based on the calculations of antisymmetrized molecular dynamics (AMD). The calculations reproduced well the experimental strengths of Gamov-Teller (GT), $M1$, and monopole transitions. We especially focused on the $3/2^-_3$ and $5/2^-_2$ states for which GT transition strengths were recently measured. The weak $M1$ and GT transitions for $3/2^-_3$ in ^{11}B and ^{11}C are described by a well-developed cluster structure of $2\alpha+t$ and $2\alpha+{}^3$He, respectively, while the strong transitions for $5/2^-_2$ is characterized by an intrinsic spin excitation with no cluster structure. It was found that the $3/2^-_3$ state is a dilute cluster state, and its features are similar to those of ^{12}C(0^+_2) which is considered to be a gas state of 3α clusters.

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$2\alpha + t$ cluster structure in ^{11}B

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The method…TTIK

- W.W. Daenick and R. Sherr (1963) "thick target method" $^{12}C(p,p)$.
- K.P. 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

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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 $^{15}N + \alpha$.

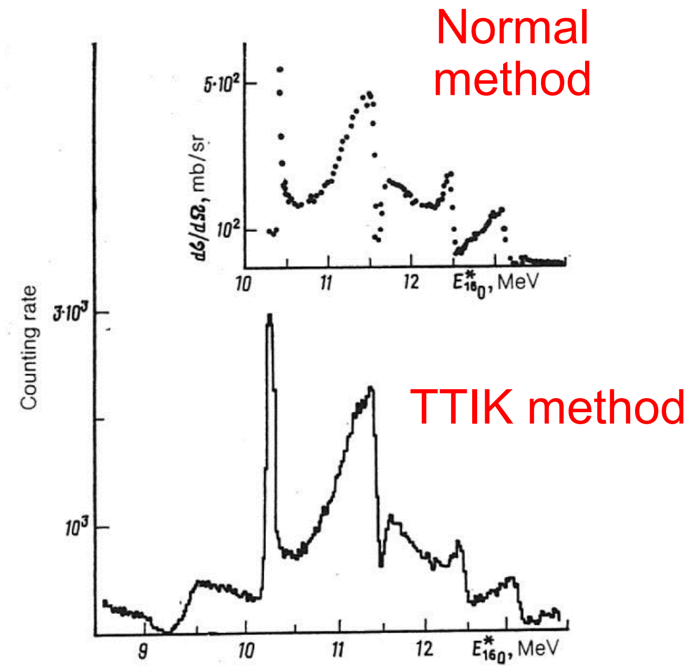
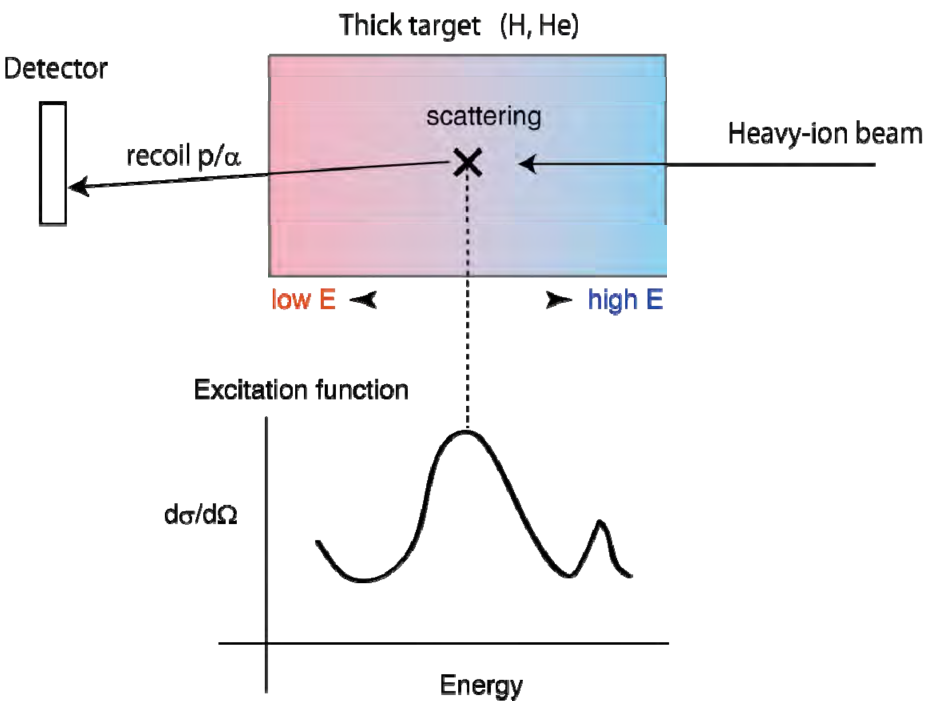


FIG. 1. Spectrum of α particles obtained in interaction of ^{12}C ions with initial energy 28 MeV with helium. The detection angle is 0°. In the insert we have given the excitation function for elastic scattering of α particles by carbon from Ref. 4. The detection angle is 158.8°.

The thick-target method in inverse kinematics (TTIK)

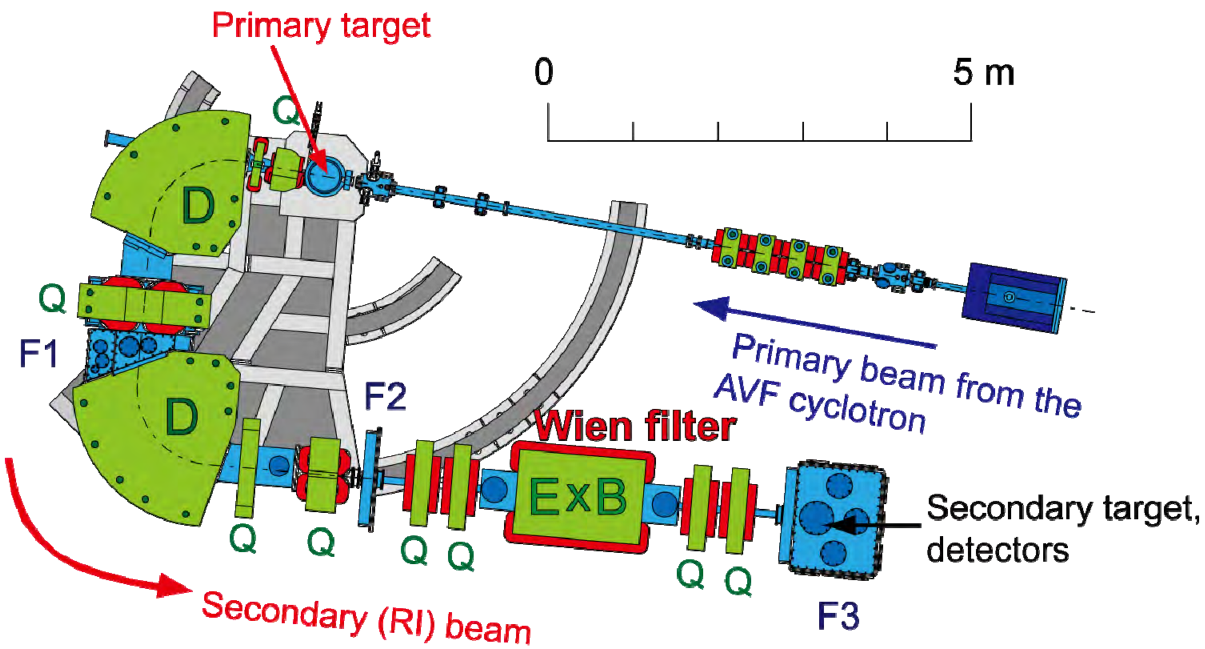
Measurement of resonant scattering



- Inverse kinematics… measurement is possible for short-lived RI which cannot be used as the target.
- Simultaneous measurement of the excitation function for certain energy range.(Small systematic error, no need to change beam energy.)
- The beam can be stopped in the target…measurement at θ_{cm}=180 degrees (where the potential scattering is minimal) is possible.

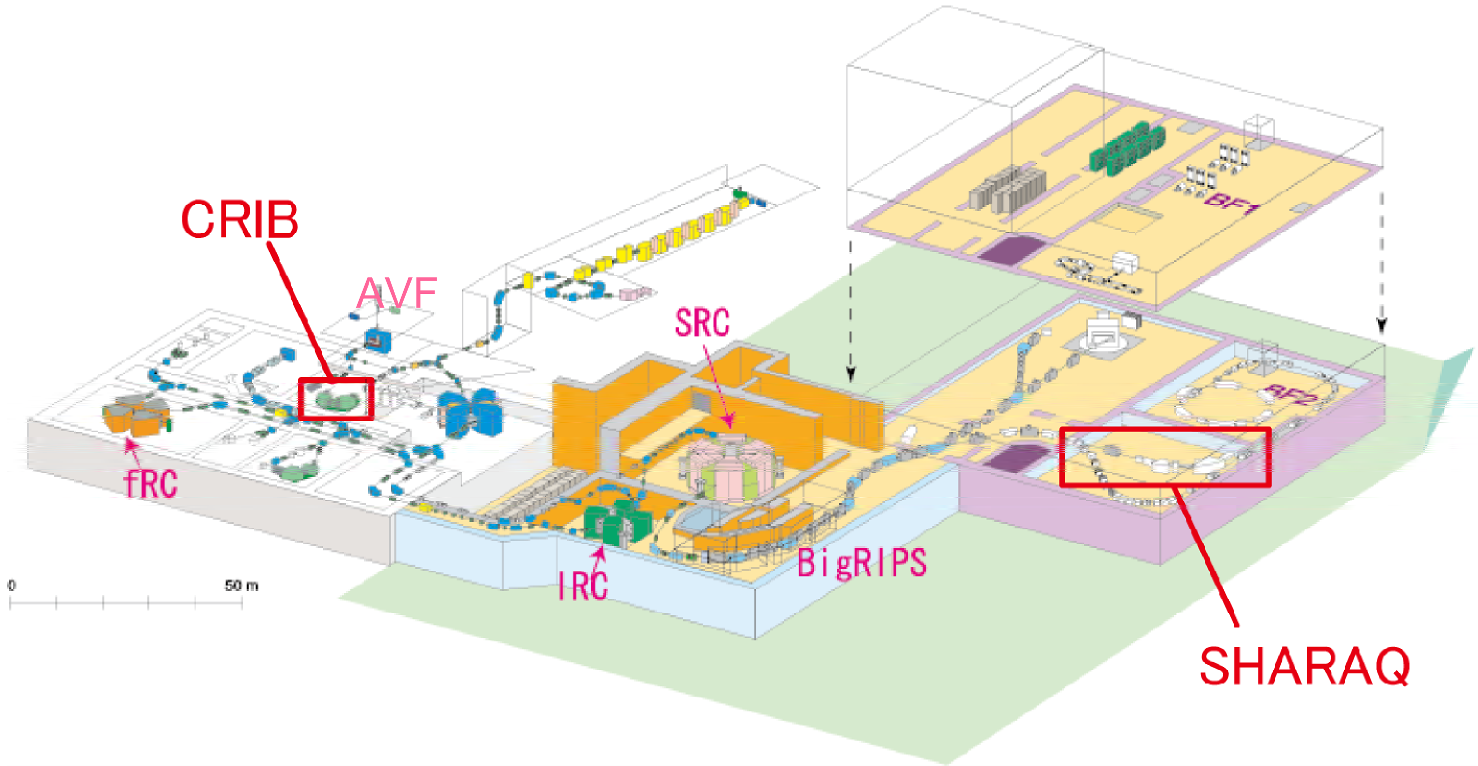
CRIB

- CNS Radio-Isotope Beam separator , operated by CNS (Univ. of Tokyo), located at RIBF (RIKEN Nishina Center).
  - Low-energy(<10MeV/u) RI beams by in-flight method.
  - Primary beam from K=70 AVF cyclotron.
  - Momentum (Magnetic rigidity) separation by “double achromatic” system, and velocity separation by a Wien filter.
  - Orbit radius: 90 cm, solid angle: 5.6 msr, momentum resolution: 1/850.



CRIB in RIBF

- AVF alone, operation cost ~1/10 of BigRIPS.
- Ion source / AVF/ CRIB…have been developed under CNS-RIKEN collaboration (joint venture).

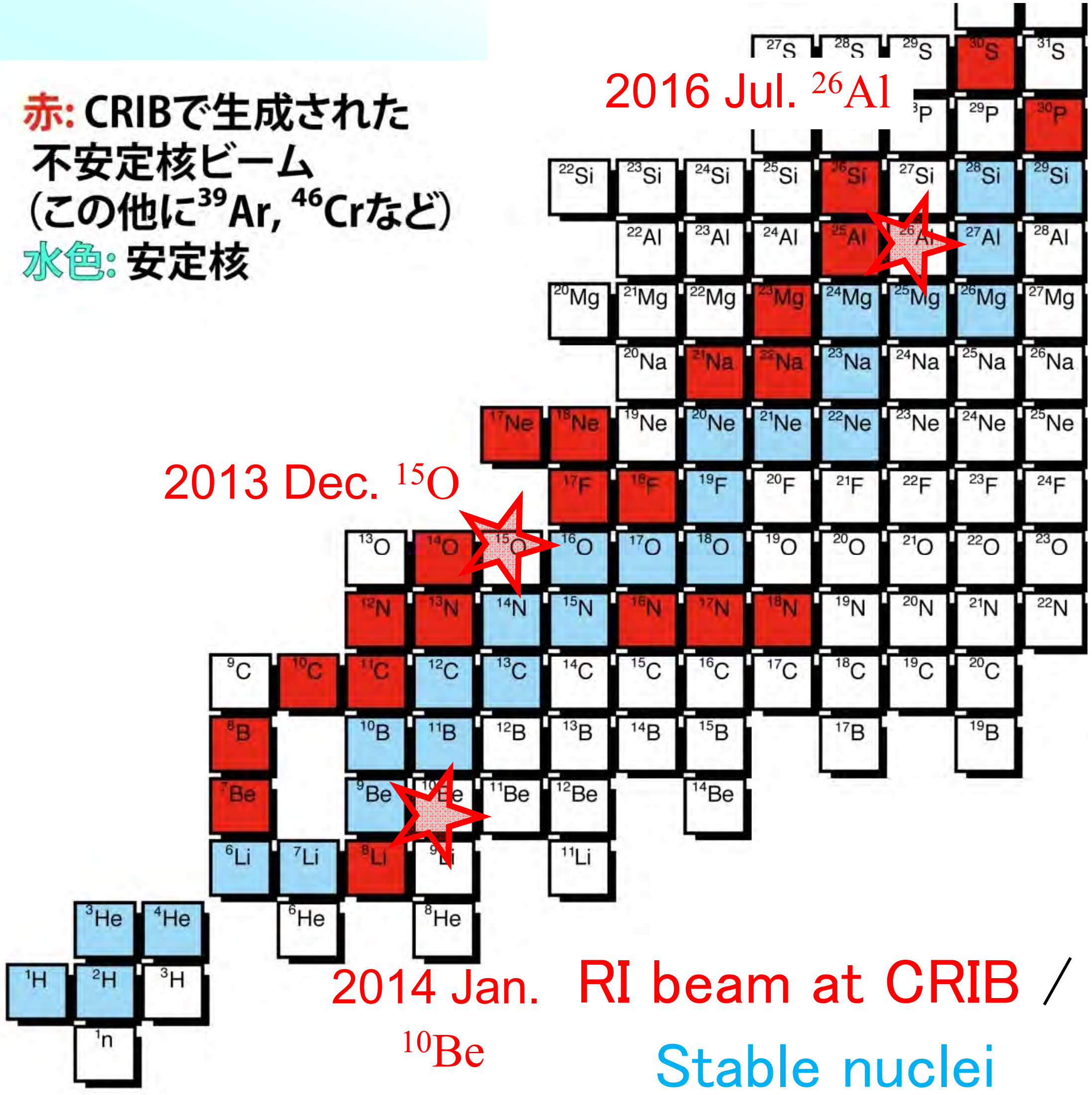


Low-Energy RI beam Productions at CRIB

2-body reactions such as (p,n), (d,p) and (^{3}He,n) in inverse kinematics are mainly used for the production….large cross section

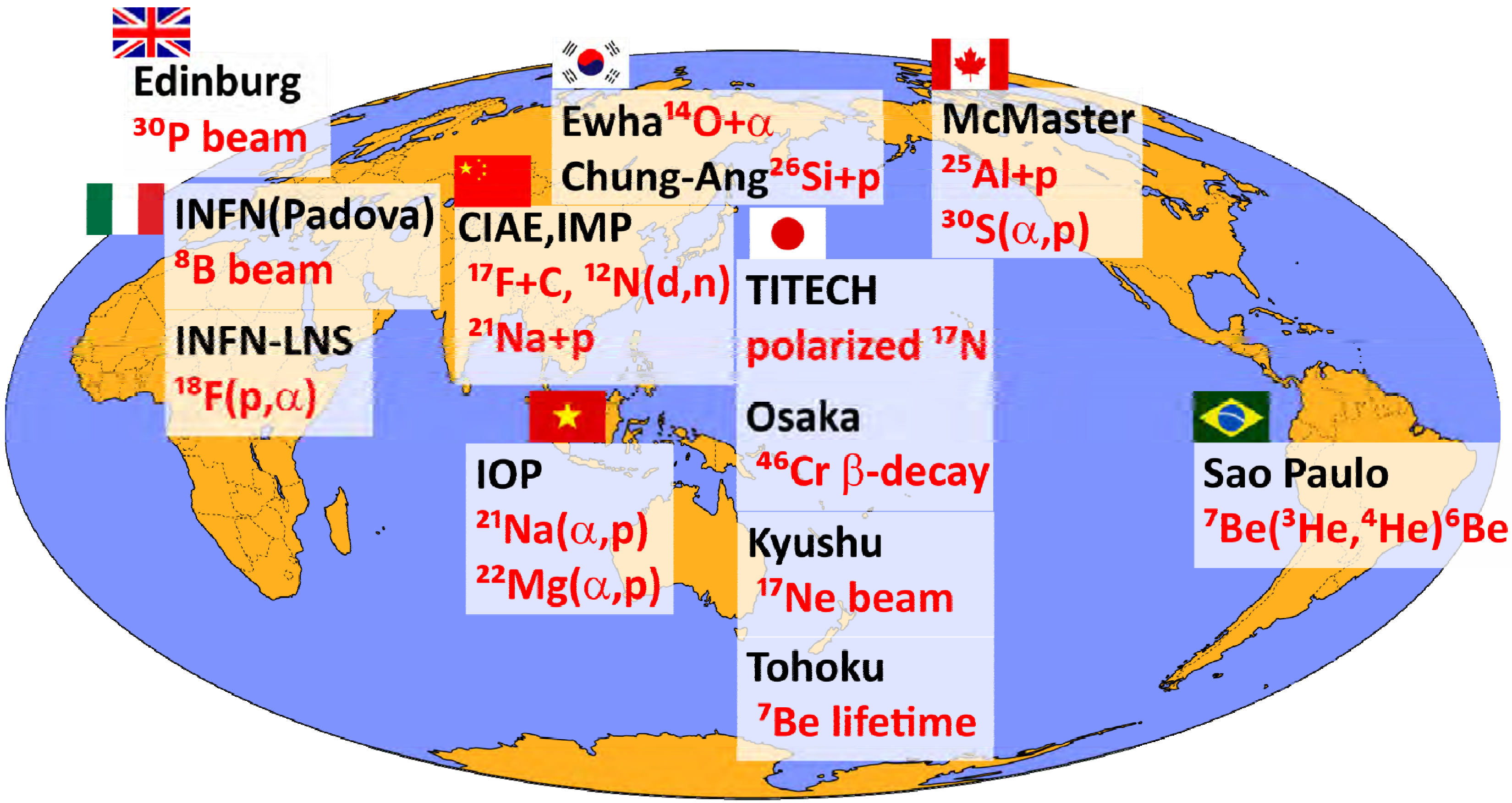
Many RI beams have been produced at CRIB: typically 10^4-10^6 pps

Low energy & low mass; very suitable for α cluster studies.



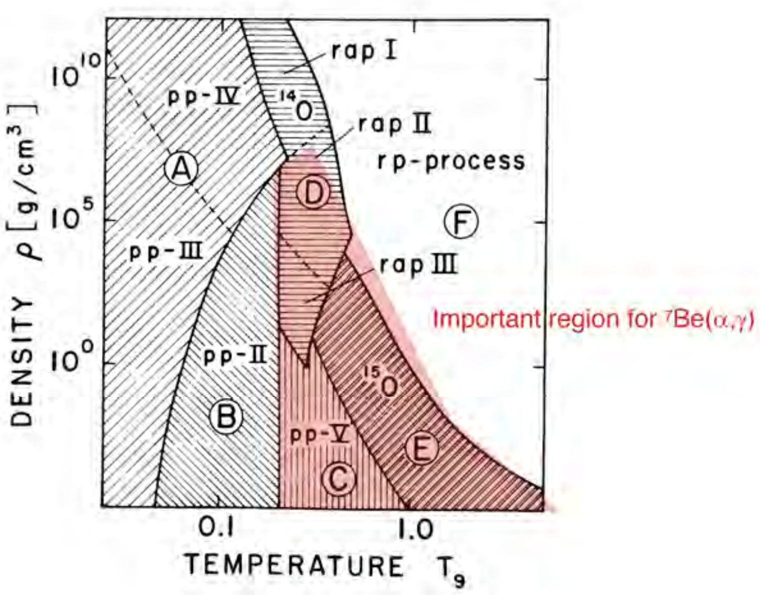
International collaborations at CRIB

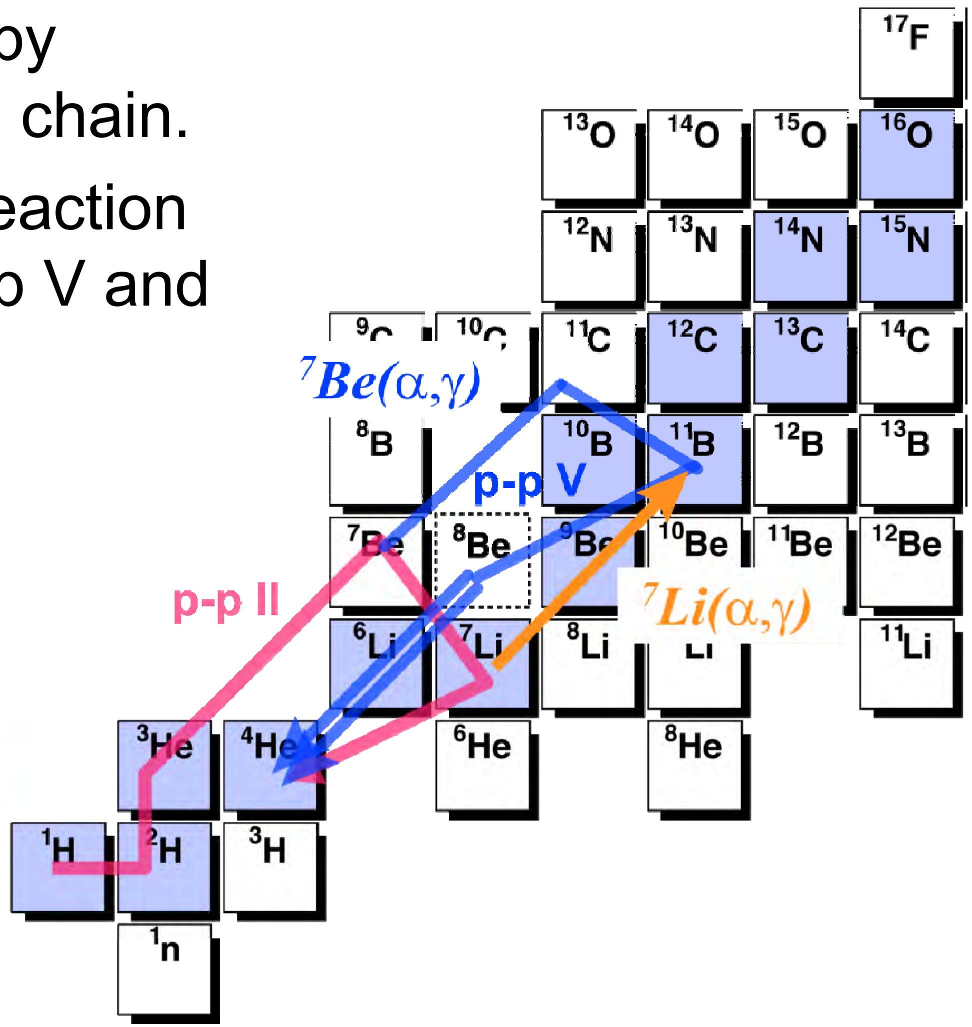
- CRIB experiments performed in 2007-2011, by collaborated members of CNS and other institutes:



^{7}Li(α,γ) and ^{7}Be(α,γ) in the p-p chains

- ^{7}Li…mainly destroyed by ^{7}Li(p,α)^{4}He in the p-p II chain.
- ^{7}Be(α,γ)…one of the reaction in the hot p-p chain (p-p V and "rap" processes).





^{7}Li/^{7}Be(α,γ) experimental study

- ^{7}Li(α,γ) and ^{7}Be(α,γ) were directly measured only at low-lying resonances:
  - *Paul et al., Phys. Rev.* ***164*** *(1967) 1332.*
  - *Hardie et al., Phys. Rev. C,* ***29*** *(1984)1199.*

  ^{7}Be(α,γ): only two resonances at E_r<1 MeV are included in the NACRE evaluation.

E_r	J^π	$\omega\gamma$ (eV)	Γ_α (eV)	Γ_γ (eV)	Ref	
0.560	$3/2^-$	0.331±0.041	11±7	0.350±0.056	HA84	I
0.877	$5/2^-$	3.80±0.57	12.6±3.8	3.1±1.3	HA84	I

- Resonant reaction dominates the reaction rate. Higher resonances may contribute at supernova temperature (>1 GK).
- We studied higher-lying resonances by the resonant elastic scattering method, ^{7}Li(α,α) and ^{7}Be(α,α) at CRIB to obtain information on the resonances (energy, width, spin and parity).

Nuclear Cluster

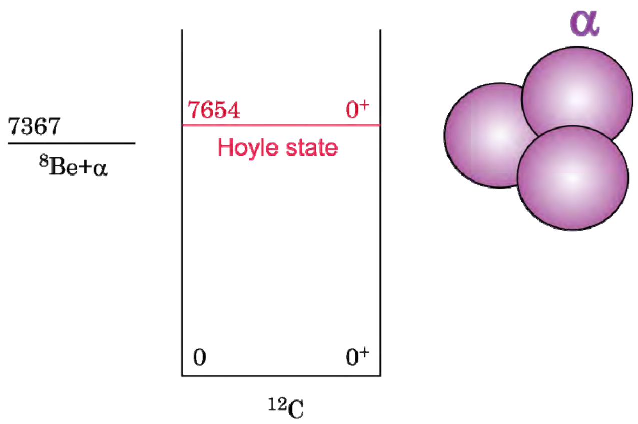
- Low-mass nuclei often have α-cluster states (large Γ_α).
- Those states may greatly enhance alpha-induced reaction rates. (Integrated resonant reaction cross section

  $\propto \Gamma_\alpha \Gamma_x / \Gamma$.)

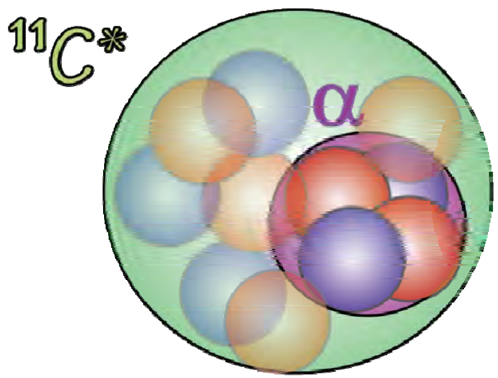
Hoyle state is a famous example.

- Those states should be observed as strong resonances by resonant elastic scattering.

^{7}Be+α…cluster structure in ^{11}C can be studied.



Alpha-cluster structure

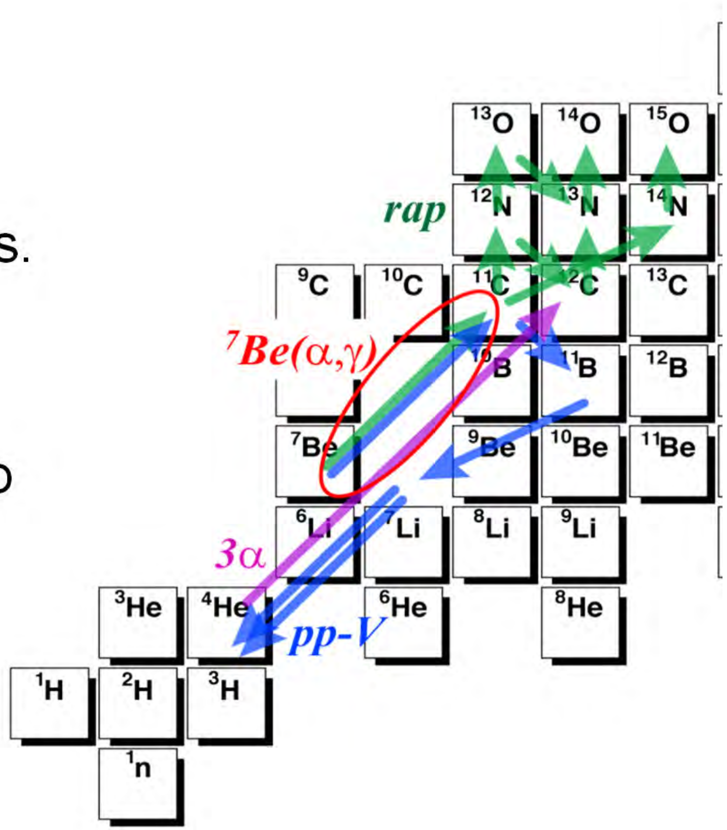


^{7}Li+α/ ^{7}Be+α study

- ^{7}Li(α,γ)^{11}B …important at high-T, as a production reaction of ^{11}B (the ν-process in core-collapse supernovae).
- ^{7}Be(α,γ)^{11}C … one reaction in the hot *p-p* chain, relevant at high-T.

⇒ Needs information on higher lying resonances.

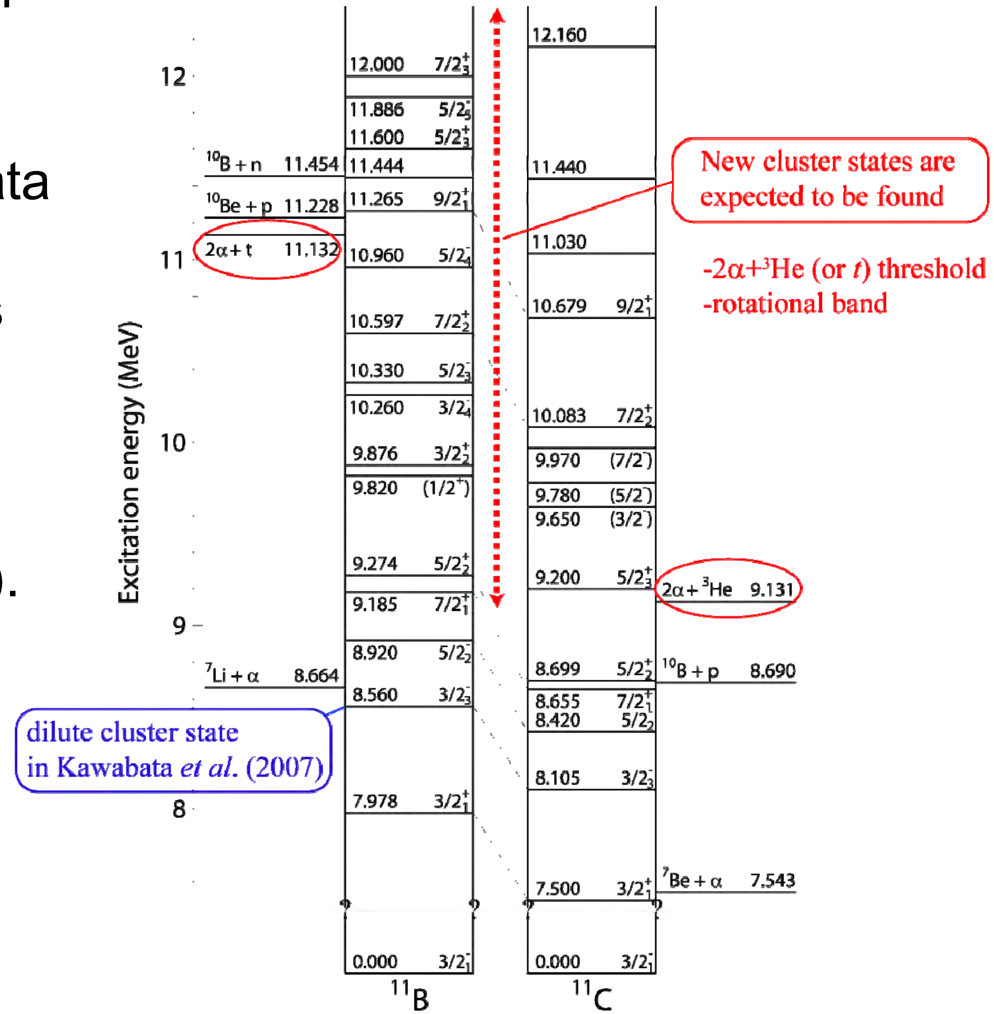
- α-cluster structure in ^{11}B/^{11}C :
  - 2α+*t* / 2α+^{3}He cluster states are known to exist *En'yo (2007), Kawabata et al. (2007)*.
  - Several "bands" which have a feature of α-cluster structure could be formed. We can study the band and cluster structure more in detail.



Exotic 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 with negative parity was expected in higher excited energy region

  (c.f. positive parity bands observed by N. Soic et al., 2004).



^{7}Li(α,γ) ; interests

- T<< 1 GK; ^{7}Li(p,α)^{4}He (p-p chain).^{7}Be(α,γ)^{11}C($\beta^+\nu$)^{11}B is more important.
- High temperature: triple-α should be fast, but ^{7}Li(α,γ) may play important roles in some environments:

◆ ^{7}Li /^{11}B ratio in core-collapse supernovae

…the ν-process *T. Yoshida et al., PRL (2006),*

G.J. Mathews et al., PRD (2012).

^{11}B is produced mainly through the ^{7}Li(α,γ)^{11}B reaction. (Some are via ^{12}C.)

The number ratio of ^{7}Li/^{11}B can be sensitive to the neutrino hierarchy through neutrino mixing parameter, θ_{13}.

◆ Boron production in inhomogeneous big-bang nucleosynthesis.

PRL **96,** 091101 (2006) PHYSICAL RE

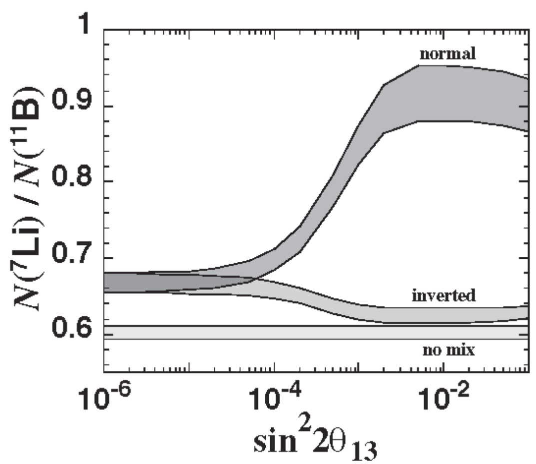
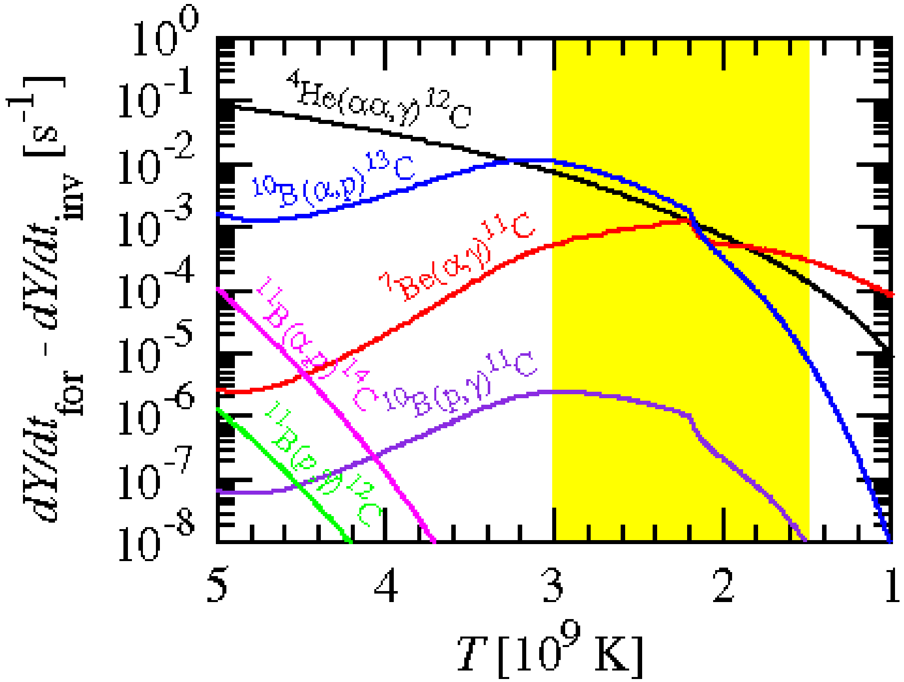


FIG. 3. The number ratio of ^{7}Li/^{11}B with the relation of $\sin^2 2\theta_{13}$. The shaded ranges include the uncertainties of neutrino energy spectra deduced from the calculations using three sets of neutrino temperatures and total neutrino energies (see text).

$^{7}Be(\alpha,\gamma)$ and other low-mass (α,p)

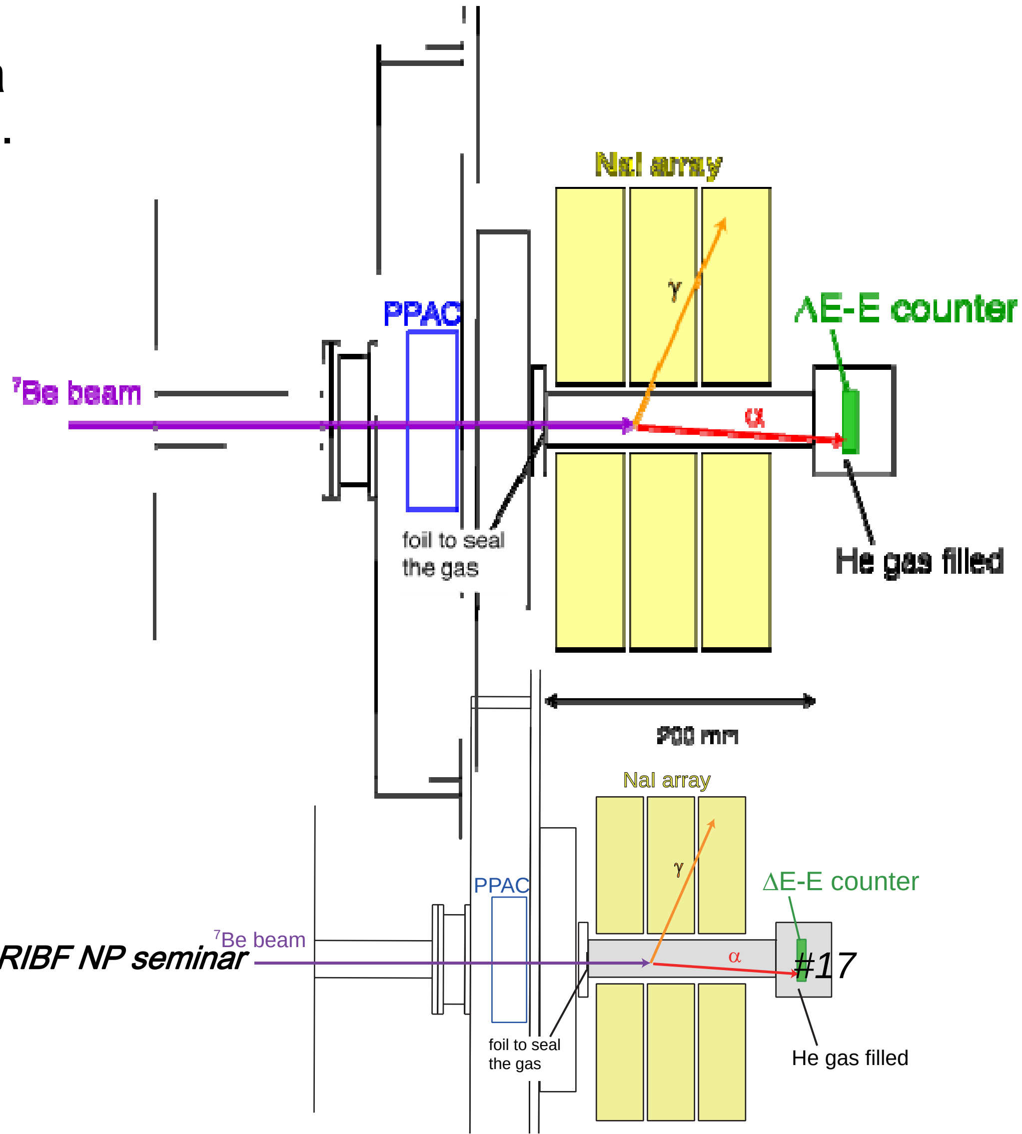
νp-process calculation (T_9>1) shows considerable contribution by $^{10}B(\alpha,p)^{13}C$ and $^{7}Be(\alpha,\gamma)^{11}C$ as much as the triple-alpha process.



S. Wanajo et al., Astrophys. J (2010)

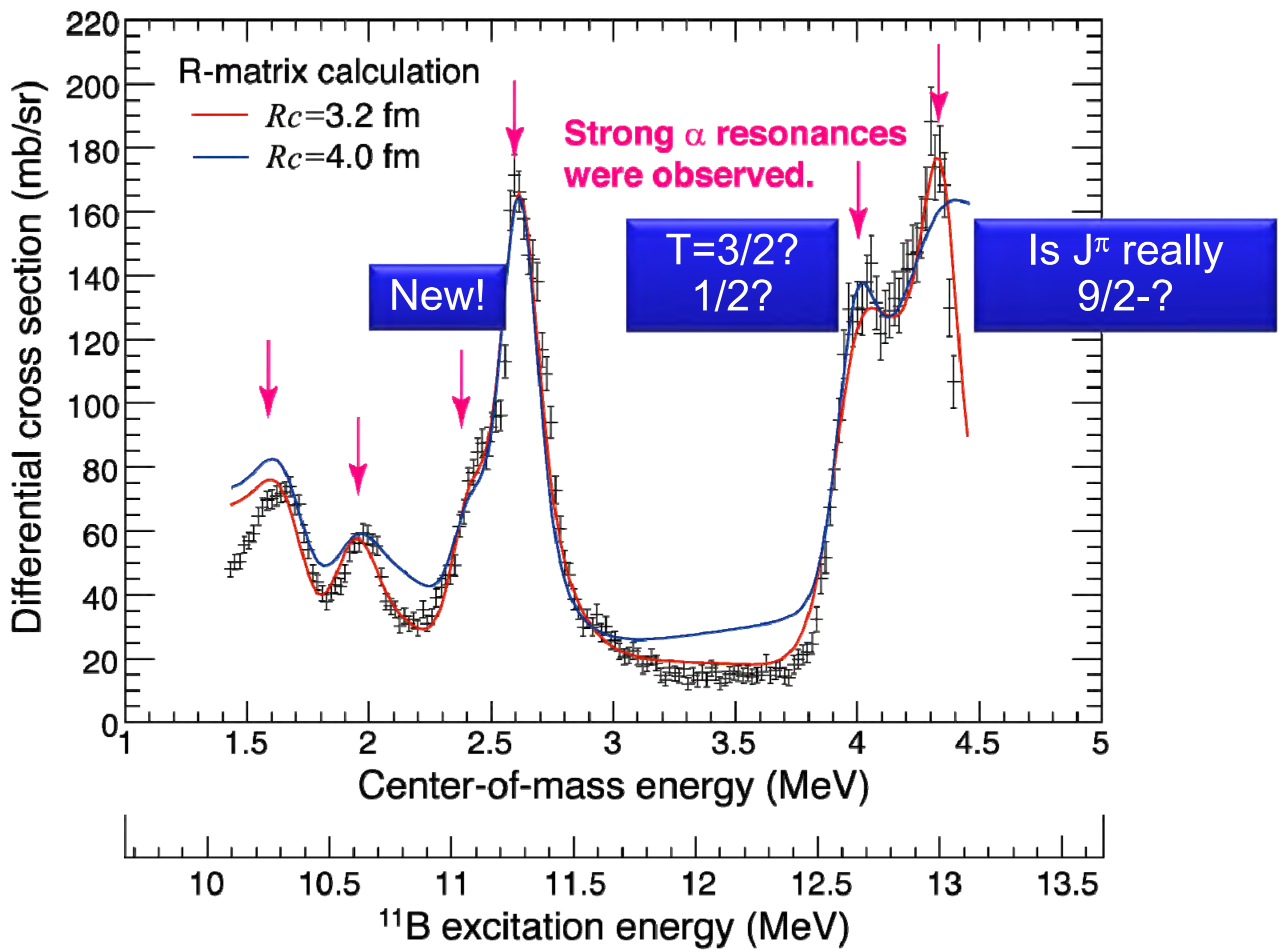
Setup for ^{7}Li/^{7}Be+α

- Thick target method with inverse kinematics …An efficient method to measure excitation function.
  - ^{7}Be beam is monitored by a PPAC (or an MCP detector).
  - ^{7}Be beam stops in a thick helium gas target (200 mm-long, 1.6 atm).
  - Recoiled α particles are detected by ΔE-E counter (10 μm and 500 μm Si detectors) at forward angle.
  - NaI array for γ-ray measurement (to identify inelastic events).



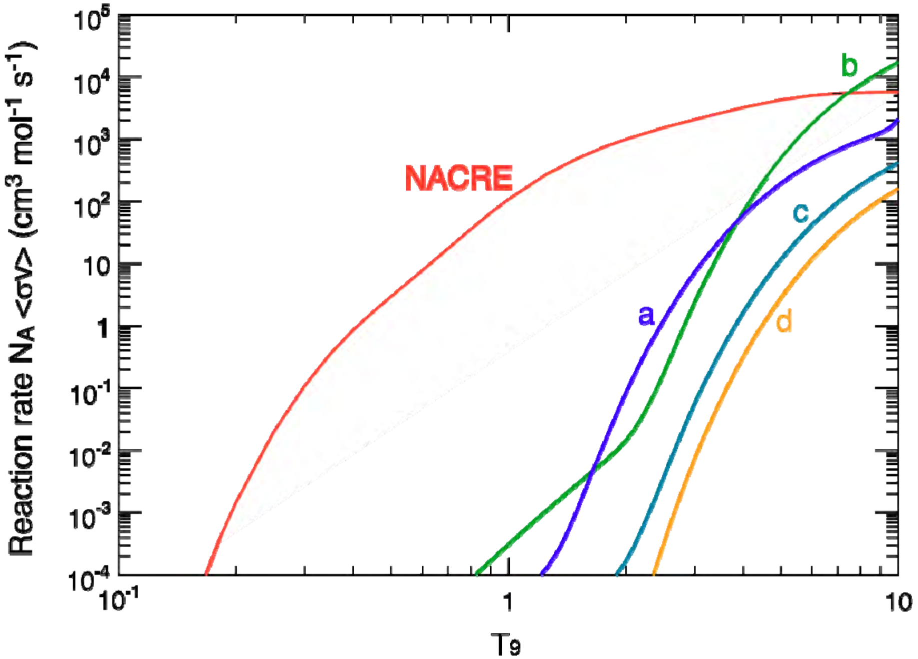
^{7}Li+α result

- Strong alpha resonances were successfully observed, and we determined the α widths (Γ_α). *H. Yamaguchi et al., Phys Rev. C (2011).*



^{7}Li+α; results

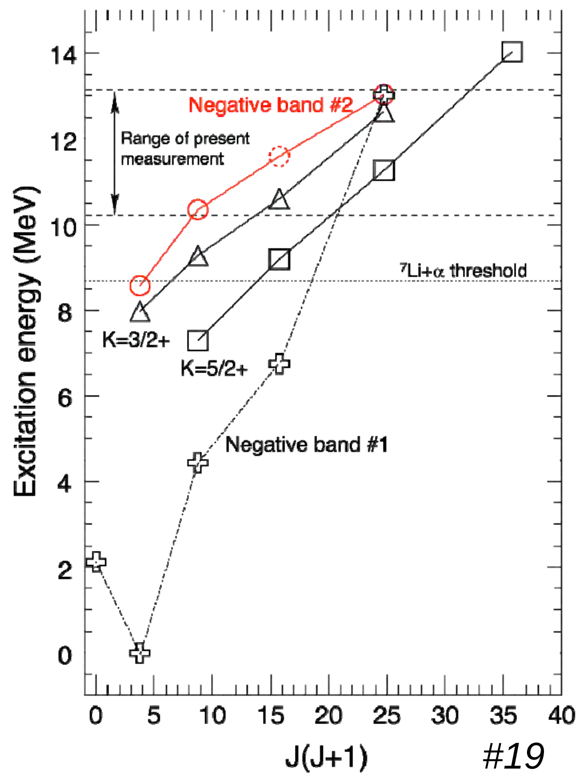
- Resonant reaction rates for the observed resonances are compared with NACRE evaluation (including resonances below 11 MeV).



Conclusion: No need to modify NACRE evaluation (for T_9<5).

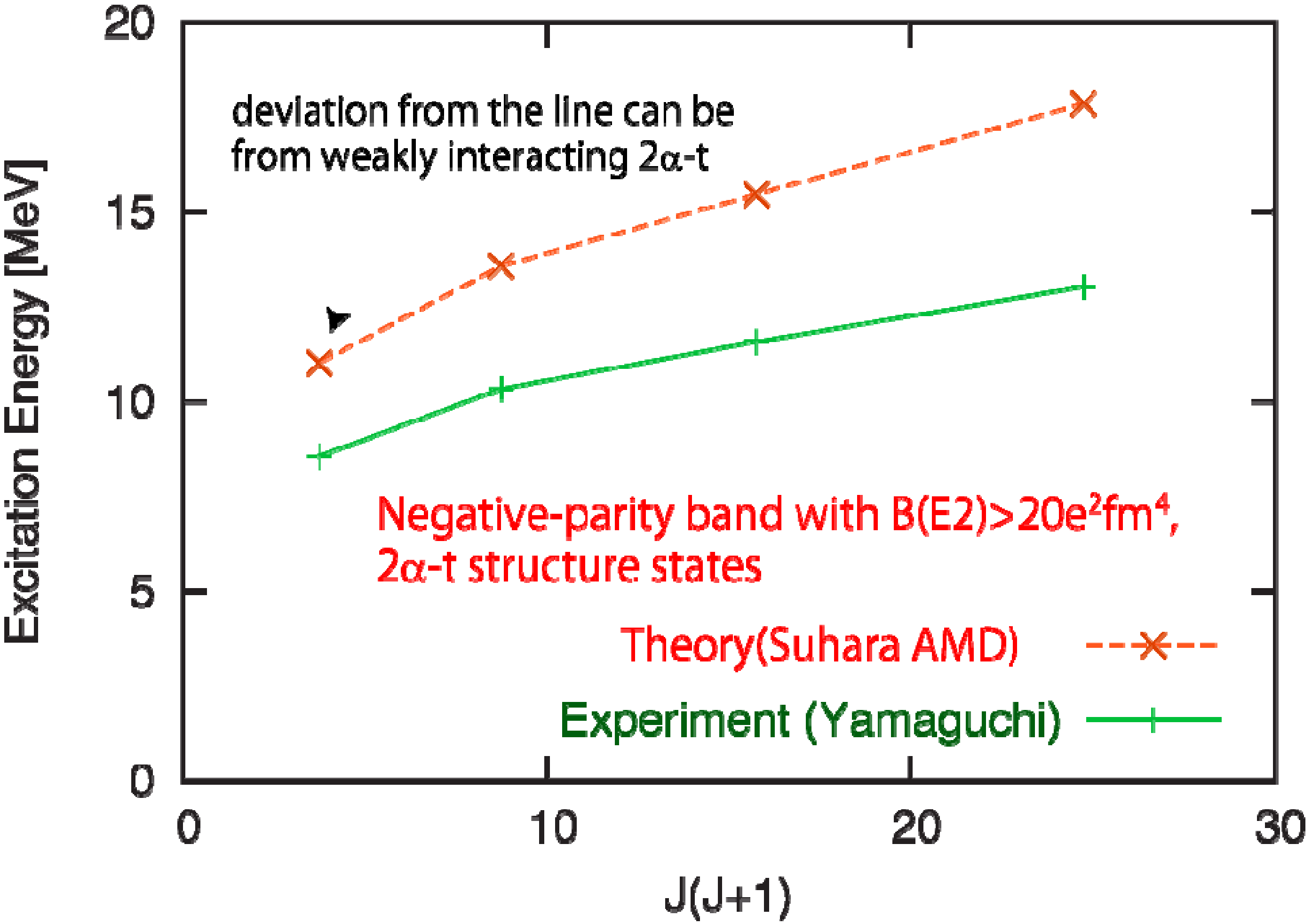
•Newly proposed a negative parity band.

•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)



Interpretation of the new negative-parity band

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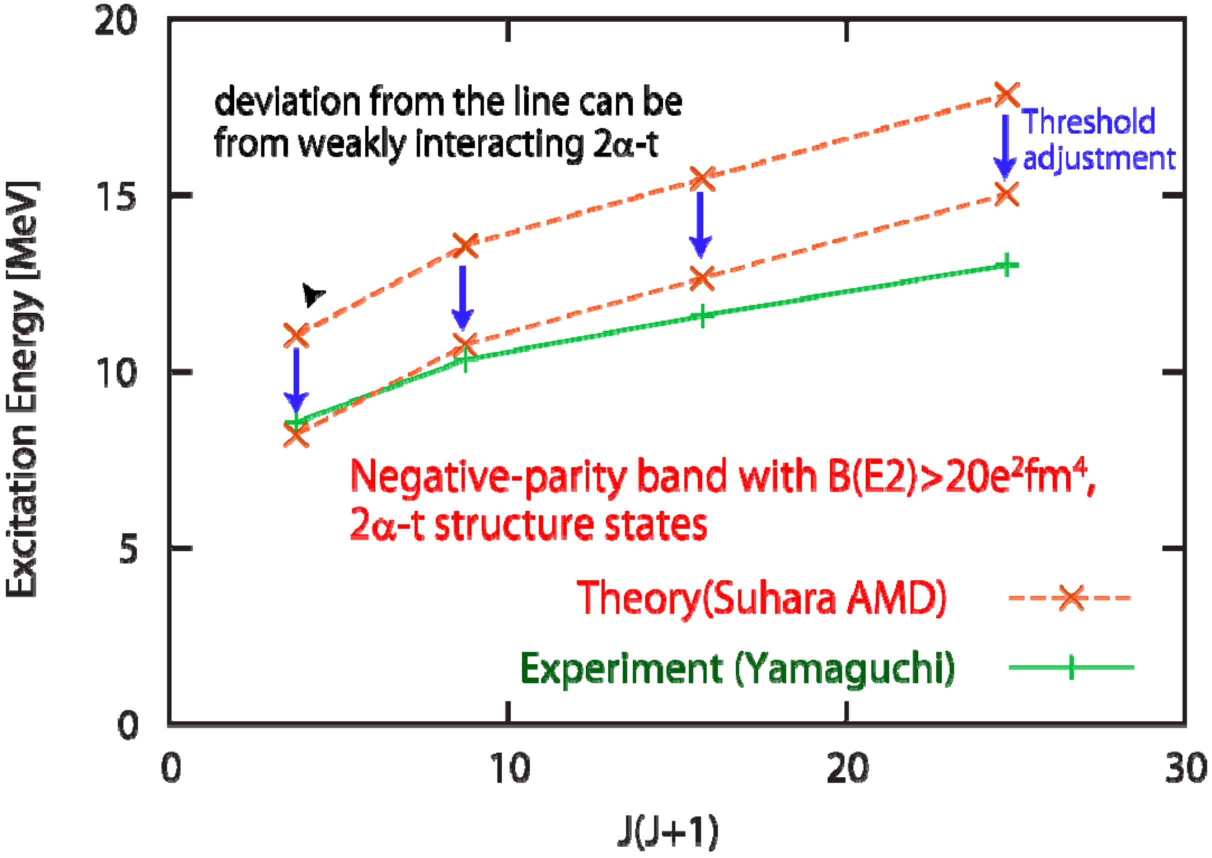
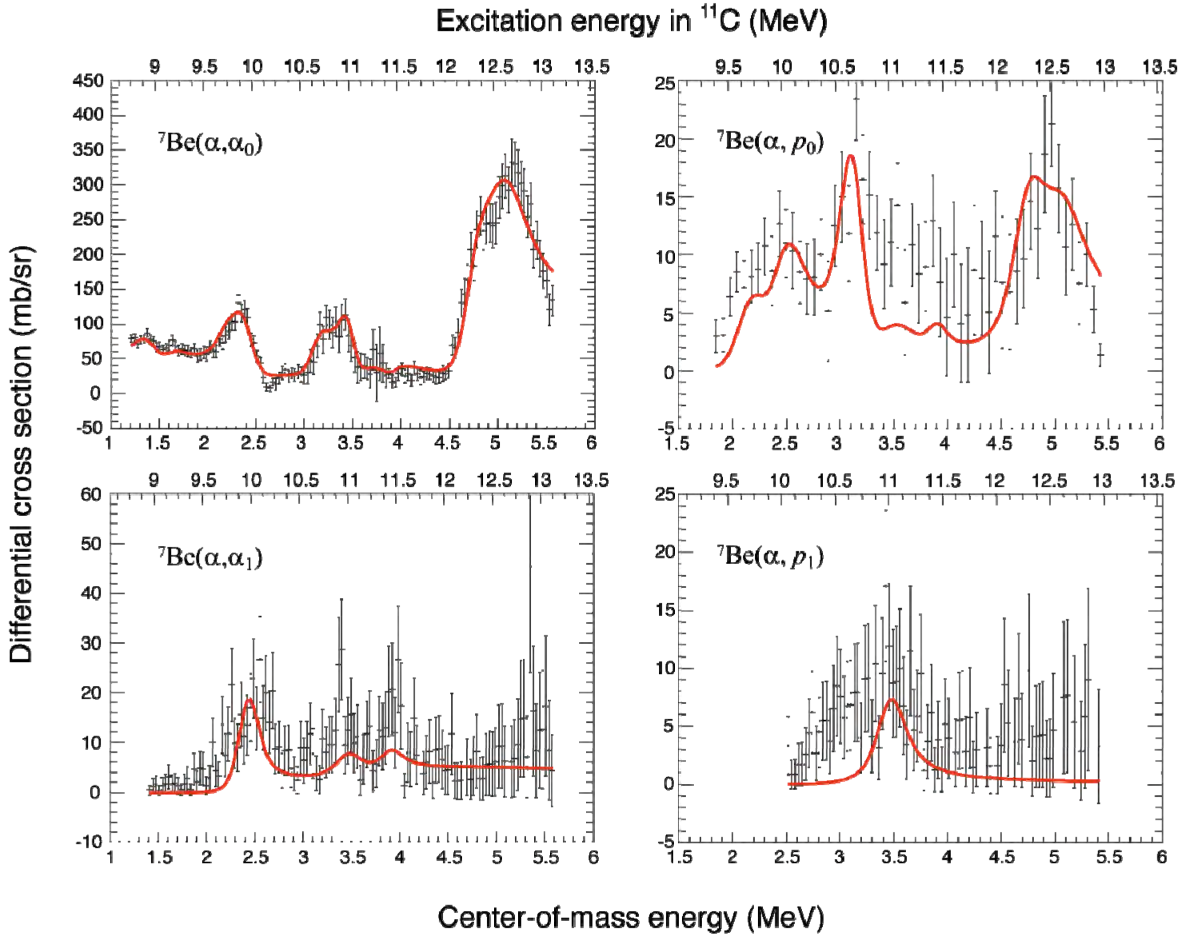


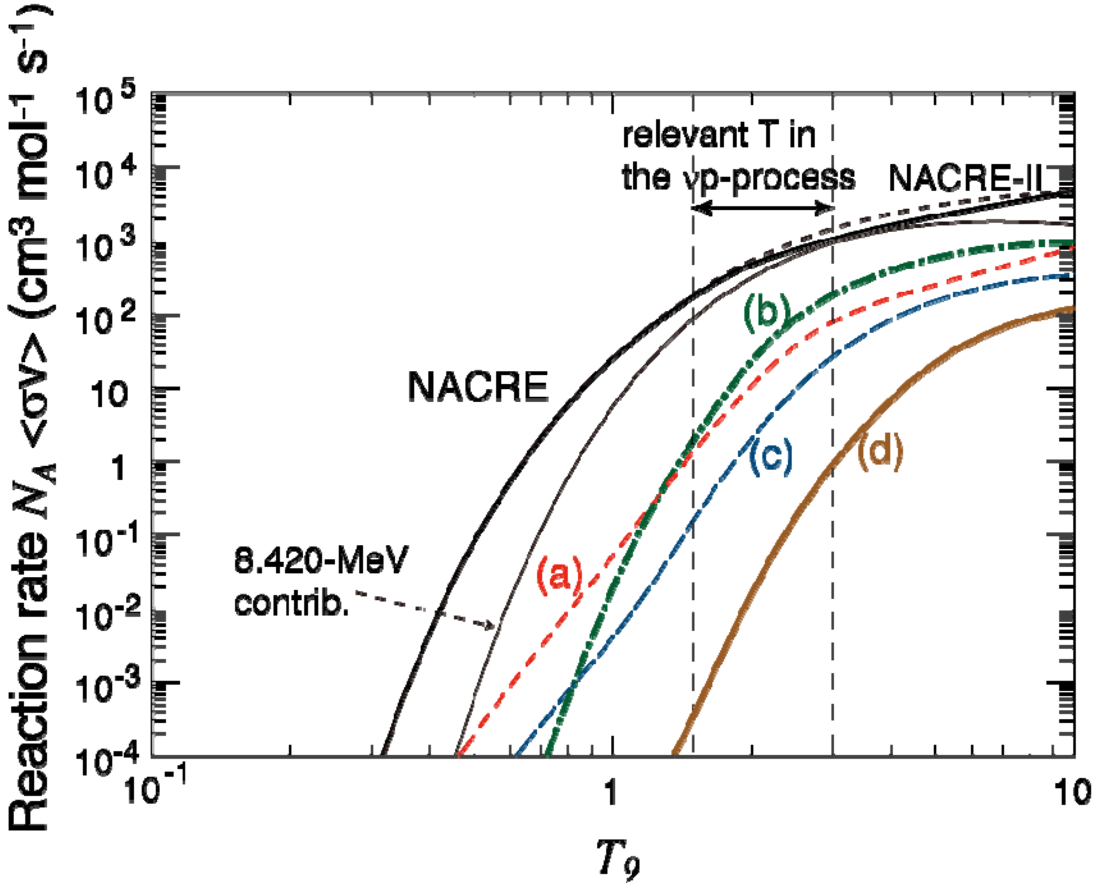
^{7}Be+α Excitation functions

- 4 excitation functions… new information on resonant widths, spin, and parity. *H. Yamaguchi et al., PRC (2013).*



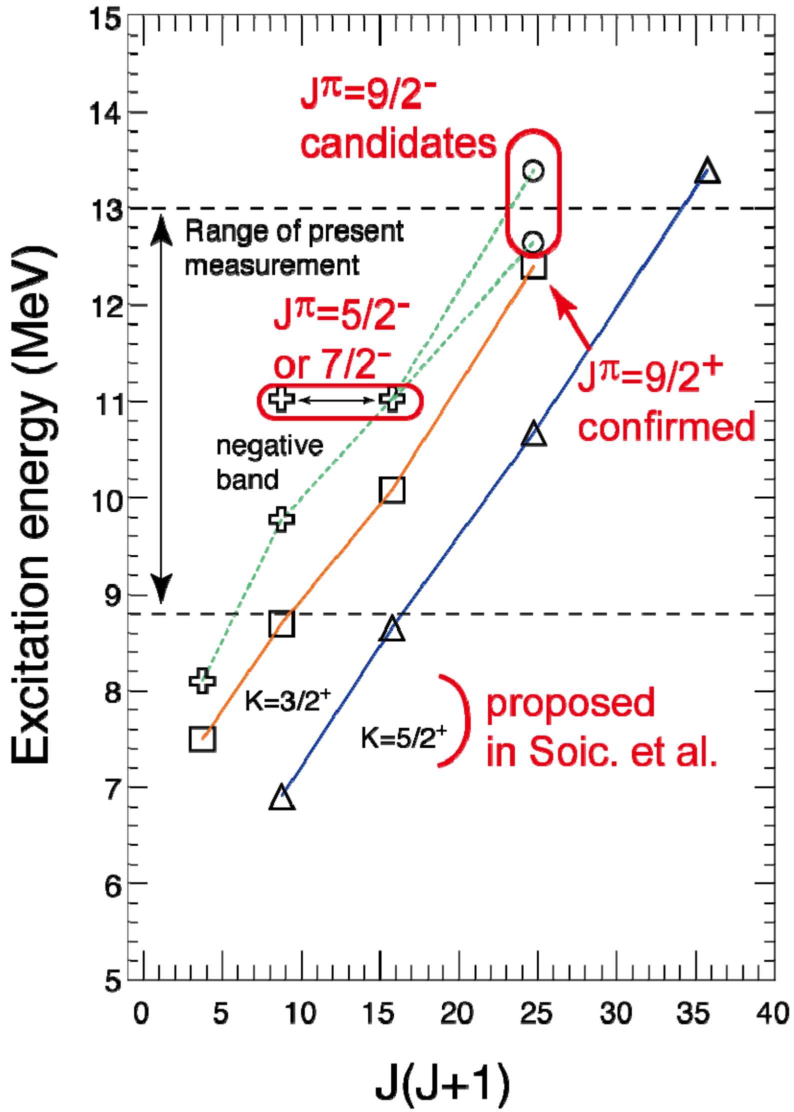
Resonant contribution to $^7Be(\alpha,\gamma)$

- Small but not negligible contribution compared to lower-lying states (~10%).



(Rotational) bands in ^{11}C

- 2 rotational bands ($K=3/2^+,5/2^+$) were suggested in Soic et al. (2004).
- $J^\pi=9/2^+$ was assigned for the resonance at 12.4 MeV, and it can be the member of $K=3/2^+$ band.
- A negative-parity band is proposed.



^{10}Be+alpha

- The main topic of today.

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Experimental investigation of a linear-chain structure in the nucleus ^{14}C

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^{7}Li/^{7}Be+α; level parameters

E_{ex} (MeV)	J^{π}	l	Γ_{α} (keV)		Γ_{w} (keV)	γ_{α}^{2} (MeV)		
			This study	Ref. [18]		This study	Ref. [9]	Ref. [13]
10.24	$3/2^-$	2	4 (<9)		72	0.089	0.227	0.05
10.34	$5/2^-$	2	19 ± 4		94	0.32		0.09
10.60	$7/2^+$	3	10 ± 3	30	15	1.1	0.640	0.084
11.06 ± 0.04	$5/2^+$ ($3/2^+$, $7/2^+$, $9/2^+$)	3	32 ± 20		41	1.25		
11.29	$9/2^+$	3	35 ± 4		63	0.89		
(11.59)[a]	($7/2^-$)	4	270 ($\Gamma_n = 580$)		(7)			
12.63 ± 0.04	($3/2^+$ [6], $5/2^+$, $7/2^+$, $9/2^+$ [22])[b]	3	33–400[c]	275	330	0.20–1.3		
13.03	$9/2^-$	4	140^{-80}_{+110}		58	2.5		

[a]The values $3/2^+$ and $9/2^+$ were suggested in previous studies, while four spins are possible from our measurements alone.
[b]This resonance should not be regarded as a single-state resonance.
[c]Depends on J. See also Table II.

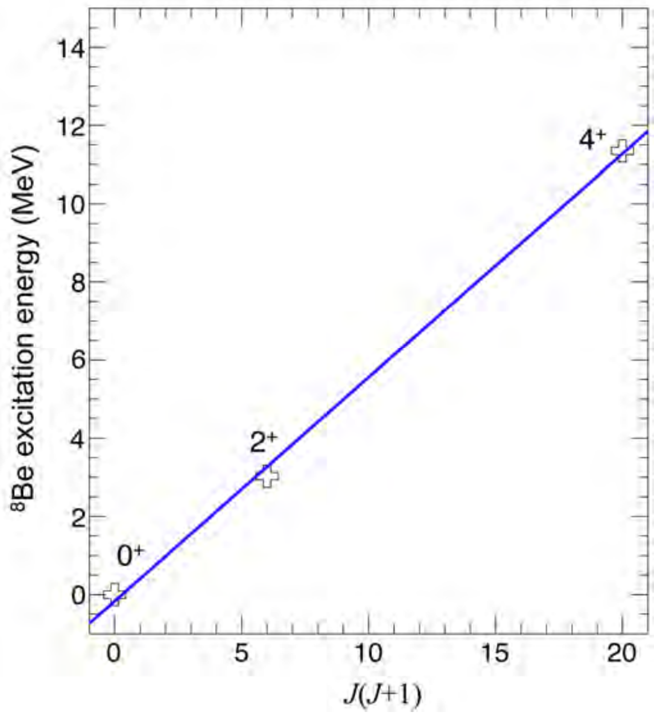
Γα were obtained

E_{ex} (MeV)	J^{π}	$l_{\alpha0}$	$\Gamma_{\alpha0}$ (KeV)	Γ_{p0} (KeV)	$\Gamma_{\alpha1}$ (KeV)	Γ_{p1} (KeV)	Γ_{tot} [38] (KeV)	$\Gamma_{W\alpha}$ (KeV)
8.90	($9/2^+$)	3	8					6.4
9.20	$5/2^+$	3	13				500	21
9.65	($3/2^-$)	0	20	50			210	1310
9.78	($5/2^-$)	2	19	100			240	450
9.97	($7/2^-$)	2	153 ±55	35	30		120	580
10.083	$7/2^+$	3	25	230			230	90
10.679	$9/2^+$	3	58 ±36	110			200	230
11.03	($5/2^-$)	3	130 ±83	25	45	120	300	360
11.44	($3/2^+$)	1	80	30	150		360	2680
12.40	$9/2^+$	3	460 ±150	90			1000–2000	1100
12.65	($7/2^+$)	3	420 ±178	110			360	1270

Early evidences of cluster structure

- High binding energy of ^{4}He, ^{12}C, ^{16}O, …
- ^{8}Be
  - ◆Strong 2α decay with a short li
  - ◆0 MeV (0+), 3.03 MeV (2+), 11.35 MeV(4+) levels…rotational
  - ◆Large momentum inertia.
- ^{12}C: Hoyle state

  Difficult to form with usual reactio



Alpha particle model

- 1930's: alpha particle model was invented, which treats alpha particle as a subunit of nucleus. (⇔ independent particle model) *Bethe & Bacher (1936) etc. [cf. shell model: 1949]*
- Successful in reproducing binding energies of 4n-nuclei (^{8}Be, ^{12}C, ^{16}O,…) and others.
- Already had a concept of triangular-shaped ^{12}C.

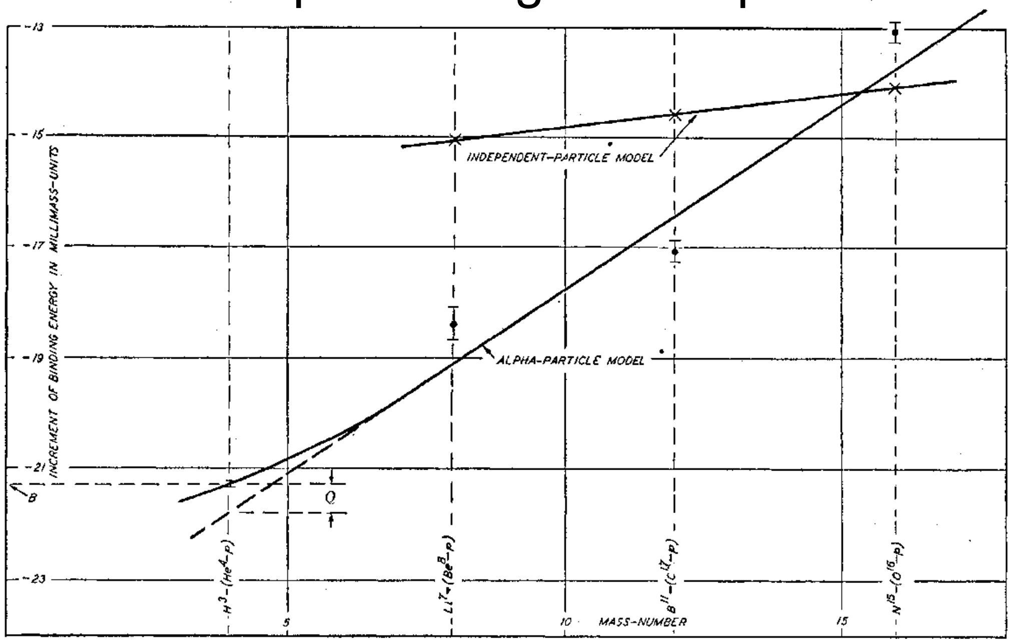
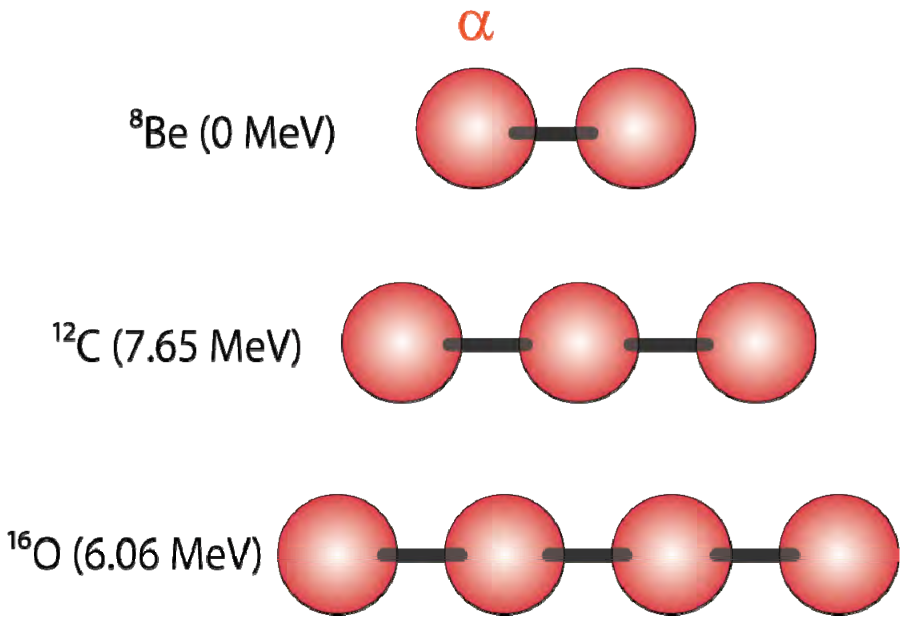


FIG. 4. Increments of binding energies for nuclei of $(4n-1)$ type. (The superscript to the carbon symbol should be 12.)

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.



Experimental evidence?

There had been several “experimental evidences” of linear chain states reported, but with rather weak reasoning, typically based on the high momentum of inertia.

Chevallier et al. (1967), E_x>17 MeV states in ^{16}O:

“The only conceivable structure with such a moment of inertia is of four α’s laid out in a string and rotating rigidly.”

is found to have the value

$$\mathcal{J} = 21M(O^{16})(F)^2 = 3M(O^{16})R(O^{16})^2,$$

where $M(O^{16})$ is the mass of O^{16} and $R(O^{16})$ the radius, taken as 2.64 F.

This is a rather large moment of inertia, about four times the moments of inertia of the bands with band heads at 6.05 and 11.26 MeV,[1] and it implies a very extended structure of the O^{16} nucleus in these states. The only conceivable structure with such a moment of inertia is of four α's laid out in a string and rotating rigidly. The distance between centers of adjacent α's in this configuration is found to be 4.1 F, close to the diameter of the α particle. A similar structure has been suggested by Morinaga[6] for a rotational band in Mg^{24}.

ACKNOWLEDGMENTS

Part of this work was carried out at the Max Planck Institut fur Kernphysik in Heidelberg and we would like to express our most sincere appreciation and gratitude for the hospitality and help extended to us by the laboratory in general and most particularly to Professor Gentner, Dr. Bock, and Dr. Zimmerer.

[6] H. Morinaga, Phys. Rev. 101, 254 (1956).

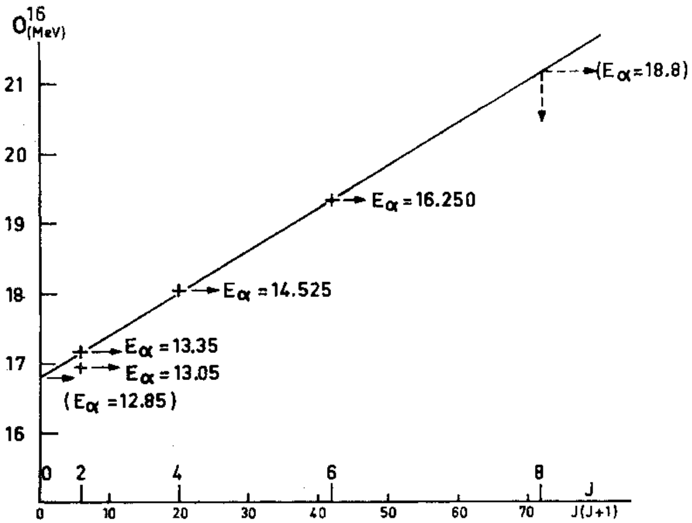


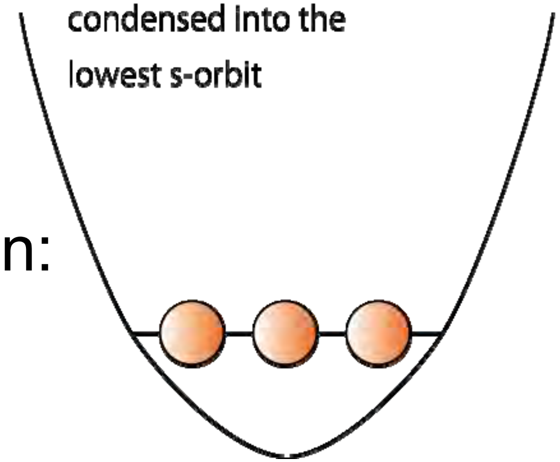
FIG. 14. The energies of the four established resonances on an $J(J+1)$ scale exhibiting a possible rotational-band structure of some of these levels.

Hoyle state was not the linear-chain state

- Horiuchi (OCM), Uegaki (GCM), Fukushima and Kamimura (RGM), En'yo (AMD), Neff and Feldmeier (FMD)…long research history of theoretical development, suggesting the Hoyle state is not a linear chain.
- Röpke et al., (1998), Tohsaki et al., (2001):

"α particle condensation in low-density nuclear matter"

α …boson, condensed into lowest s-wave state

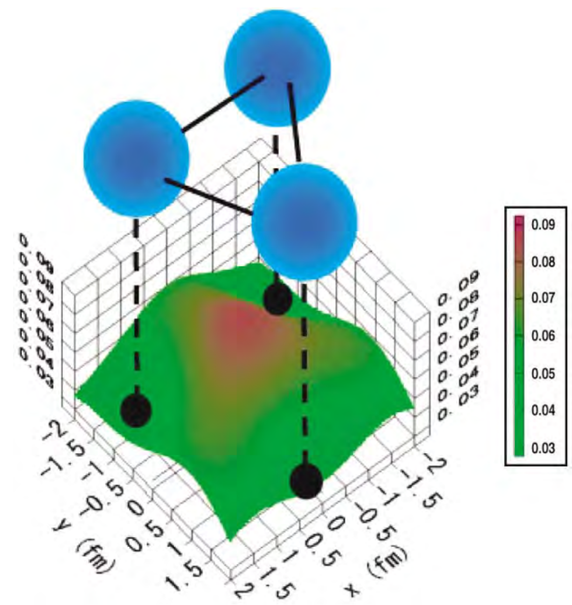


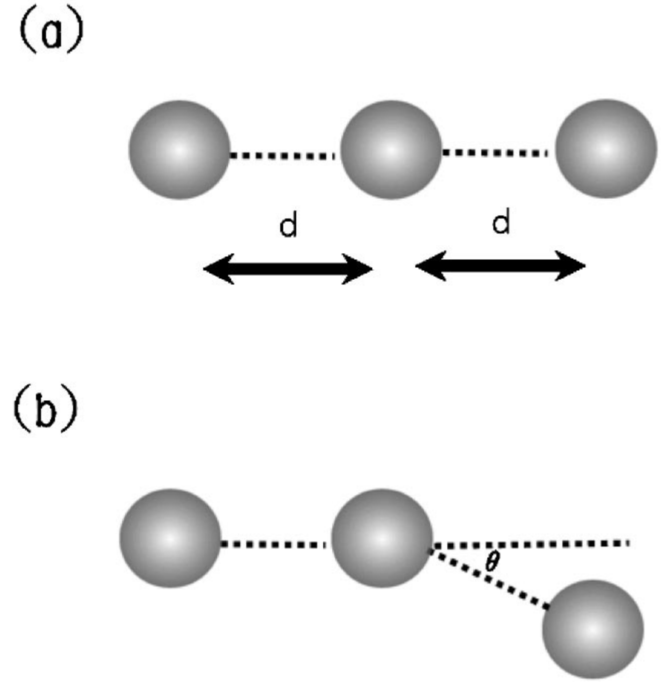
3 α particles are weakly interacting and having a broad spatial distribution: "dilute cluster state"

Clustering in carbon isotopes

^{14}C: half-life 5,730±40 years, famous for chronology

- ^{14}C…Itagaki (triangular shape), Oertzen (prolate deformation).
- ^{16}C…stabilized depending on d, θ?





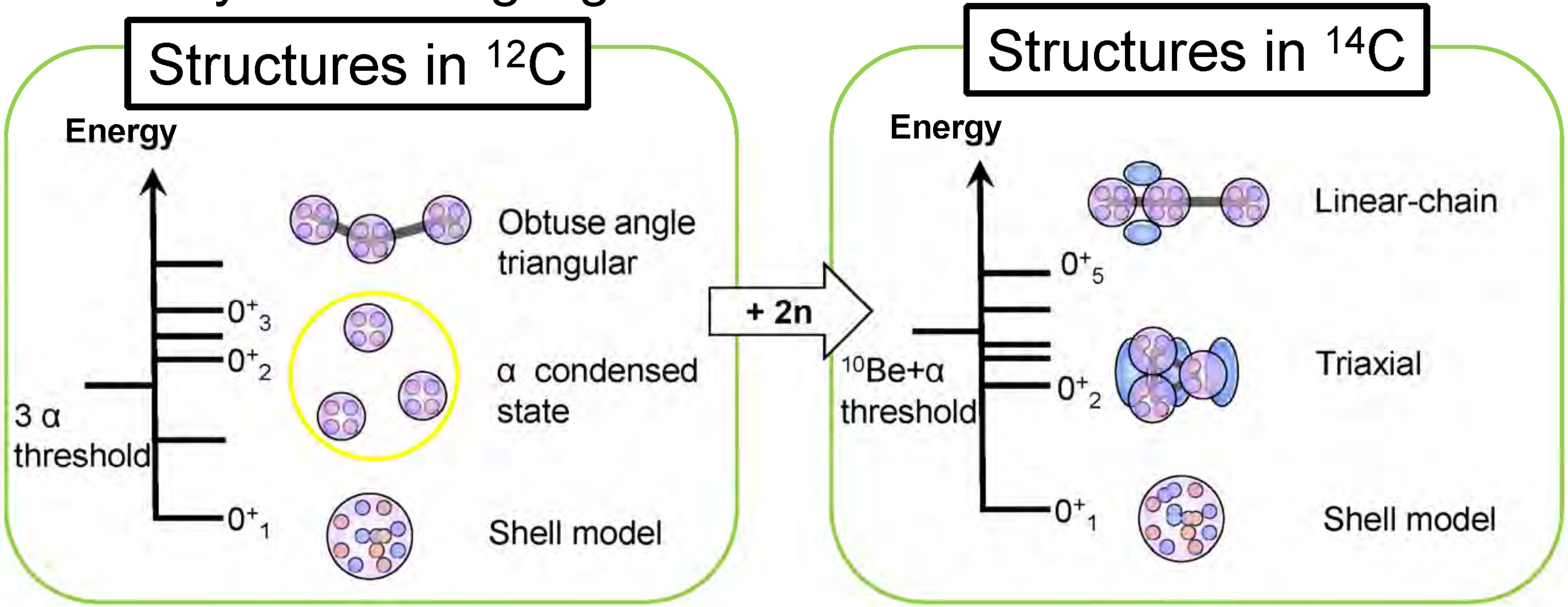
Phase transition and ^{12}C-^{14}C

- Solid, Liquid, Gas structure [Itagaki et al.]

shell model…liquid

crystallic…solid

weakly interacting…gas

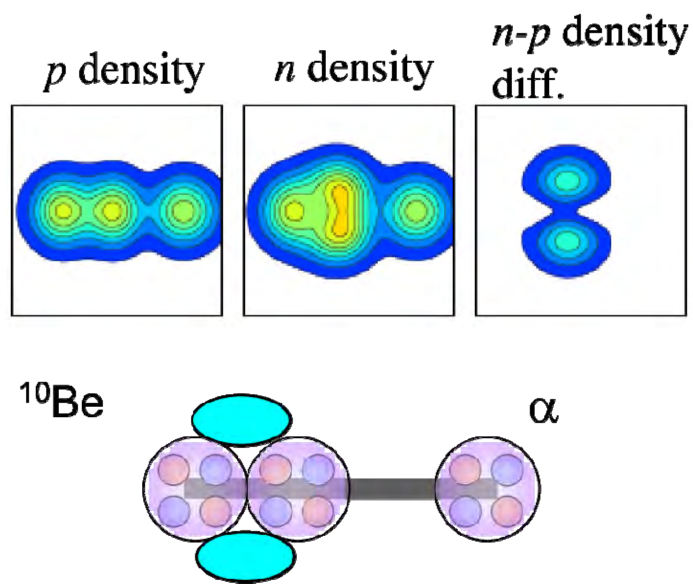


^{10}Be+α

- Linear-chain cluster levels in ^{14}C were predicted in Suhara & En'yo calculation.
- Asymmetric, ^{10}Be+α configuration …likely to be observed with ^{10}Be+α 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.

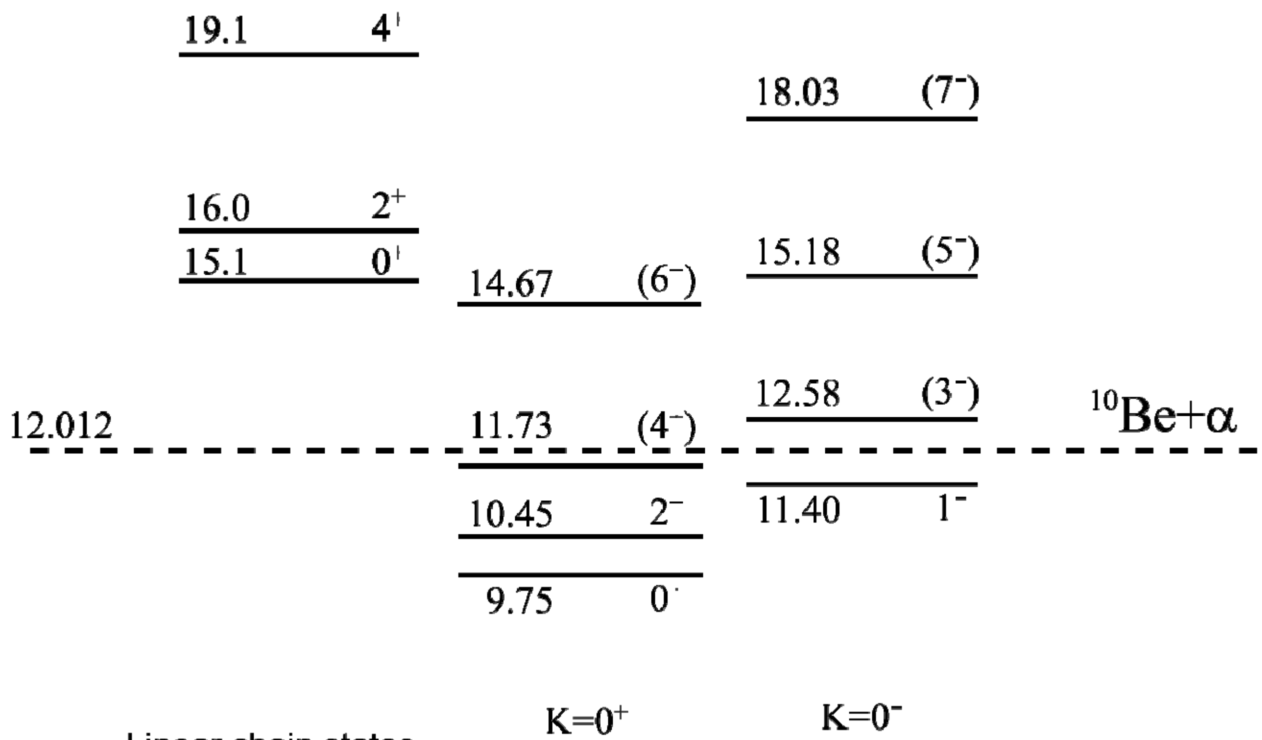
Suhara-san introduced this to me in 2011. I thought, this configuration is very suitable for the α-resonant scattering.

Suhara & En'yo, PRC 2010 and 2011:



Cluster bands

- Predicted energy…few MeV above the $^{10}Be+\alpha$ threshold

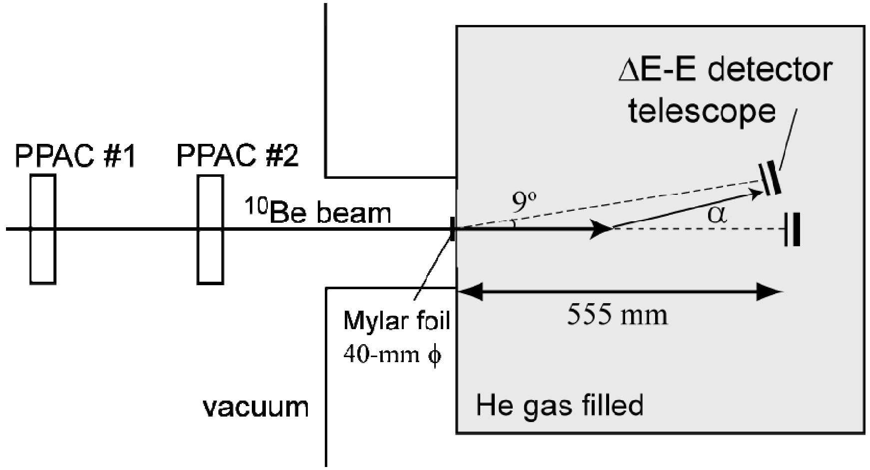


Linear chain states in the calculation by Suhara&En'yo (2010)

Prolate rotational bands in Oertzen et al., (2004)

Experimental setup

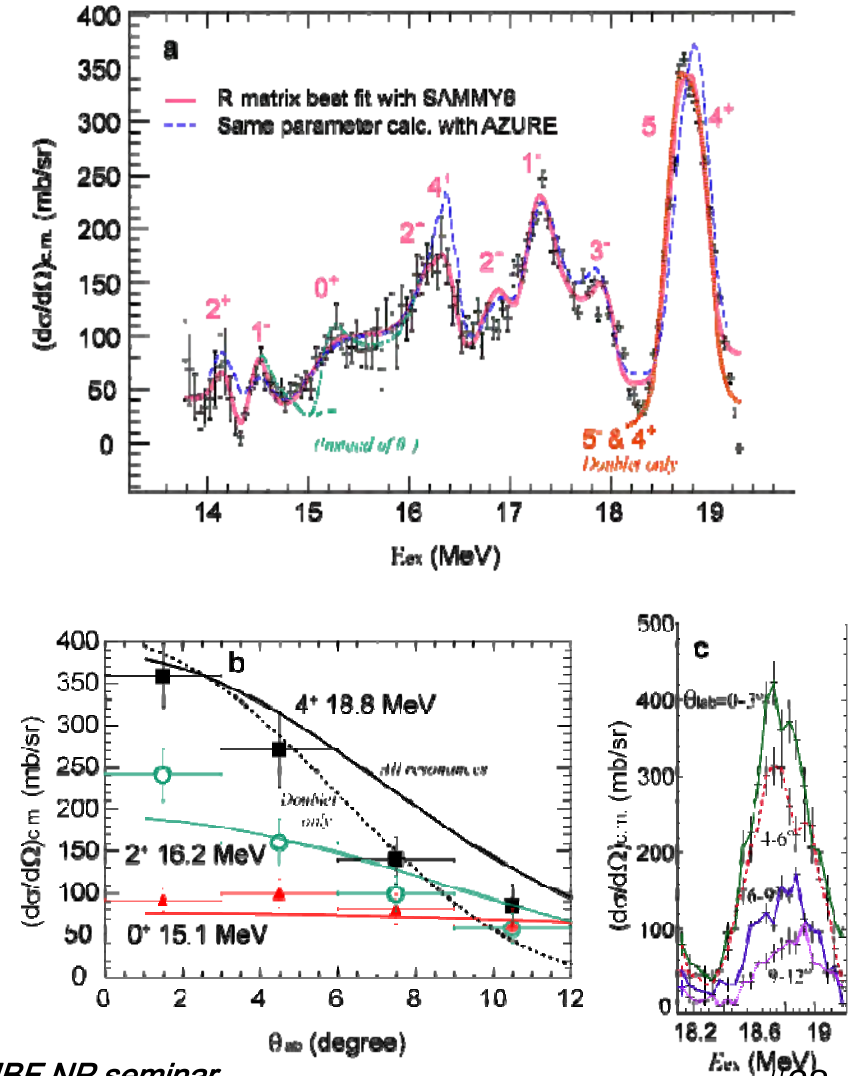
Thick target method in inverse kinematics,
similar to the previous ^{7}Be+α.



- Two PPACs for the beam PI, trajectory, number of particles.
- Two silicon detector telescopes for recoiling α partciles.
- E_{cm} and θ obtained by event-by-event kinematic reconstruction.

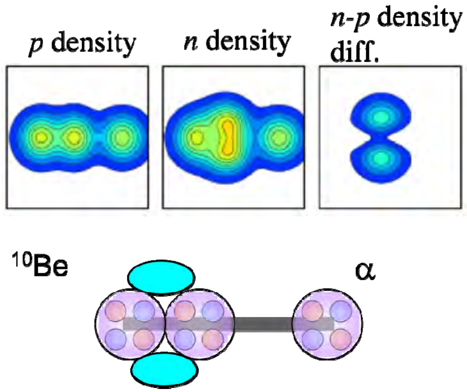
Excitation function

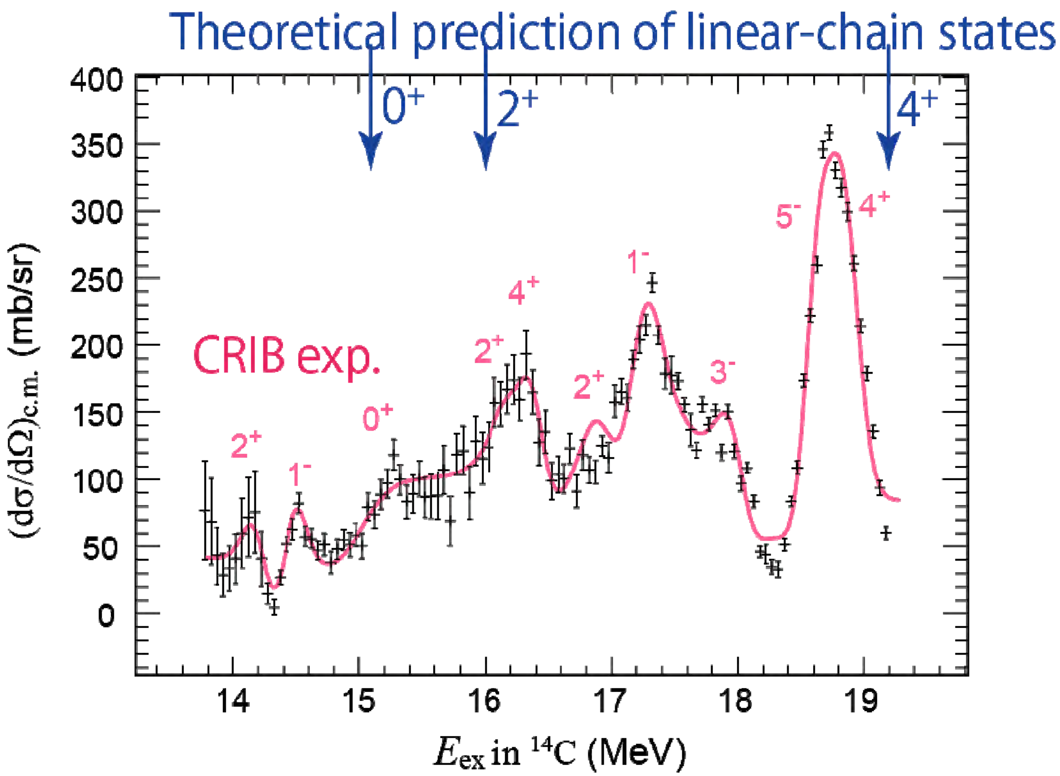
- The excitation function we obtained for 13.8-19.2 MeV exhibits many resonances.
- R-matrix analysis was performed to determine resonance parameters (E, J^{π}, Γ_{α}).



Linear-chain levels

Suhara & En'yo, PRC 2010 and 2011:





Excellent agreement between exp. and theory for the (0+, 2+, 4+) states.

Experiments in other facilities

Results on two other ^{10}Be+α TTIK experiments were published before our publication was made.

- M. Freer et al., Phys. Rev. C (2014)
  Birmingham group+ at ORNL
    - High-intensity ^{10}Be beam, spectrum at very forward angle, no PI
- A. Fritsch et al., Phys. Rev. C (2016)
  MSU group at Notre Dame
    - Low-intensity ^{10}Be beam, Active target, only side angles.

Compare with Birmingham exp.

[Freer et al. (2014)] Nice agreement at least for >15.7 MeV, but their cross section is 4 times higher than us. (Thus they yielded large α widths than us.)

- Cross section normalization by Rutherford c.s. was applied in Freer et al., while our experiment directly yielded absolute c.s.

- Discrepancy in the low-energy part…because of the energy loss calculation?

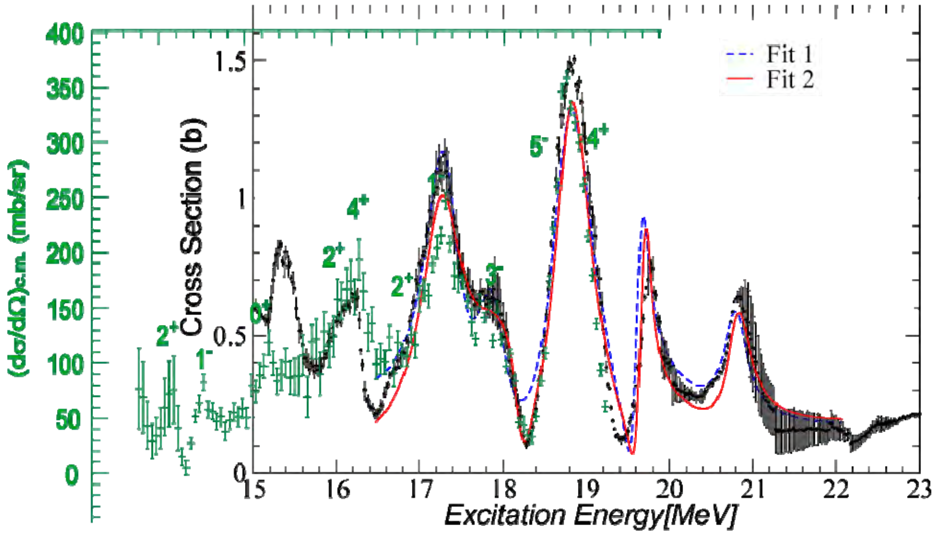


FIG. 11. (Color online) R-matrix fit to the data in the region between E_x = 16.5 and 22 MeV (red-solid and blue-dashed lines). The difference between the two fits is the inclusion of an additional 4^+ state in the calculation shown by the red line. See Table for the parameters of fits 1 and 2.

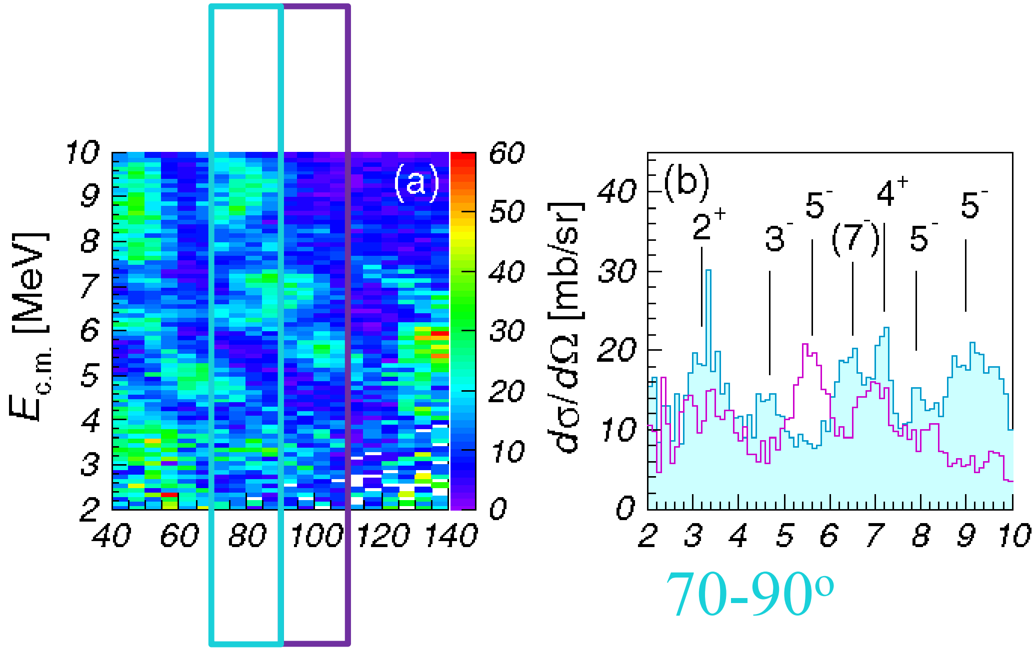
Freer et al. (2014), vs
Our result

Comparison with MSU experiment

- [Fritsch et al. (2016)] Active target experiment covering side angles.

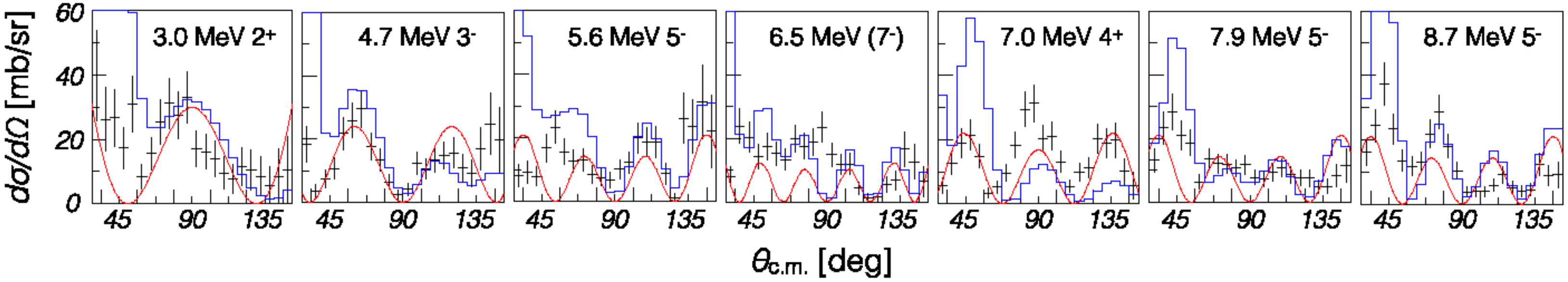
Questionable points in their results:

1. Too low cross section (even lower than Rutherford c.s.), not consistent with broad resonant widths
2. No clear identification for each resonance.
3. Ambiguous spin-parity determination due to simple Legendre function analysis.



70-90°

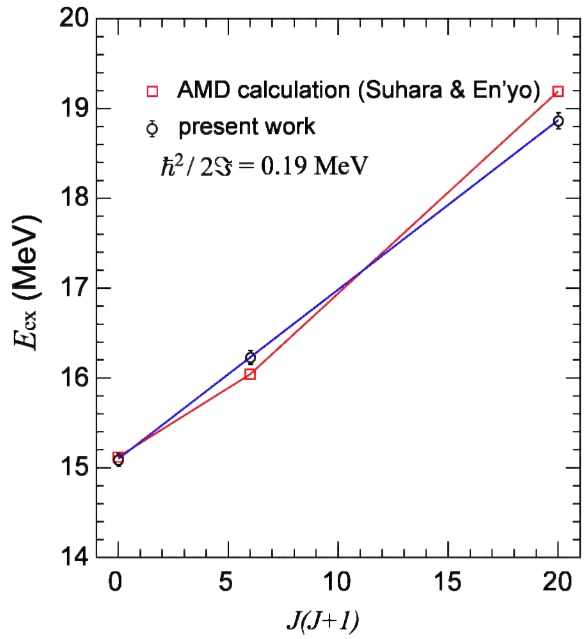
90-110°



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.



Partial width θ_α^2

Experimental θ_α^2 by $\Gamma\alpha/\Gamma\omega$
Theoretical θ_α^2 by overlap of AMD and Brink wavefunctions.

Experimental uncertainties (beyond the error bars):

-Mixing ratio of the (5^-, 4^+) doublet

-Neutron width

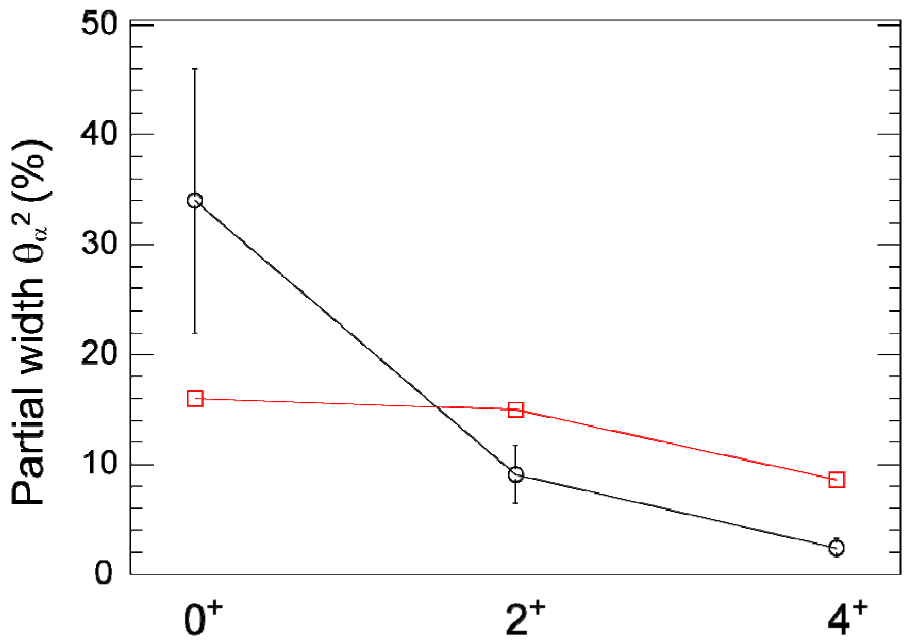
-Additional resonance

Theoretical uncertainties:

-Radial motion of the α particle

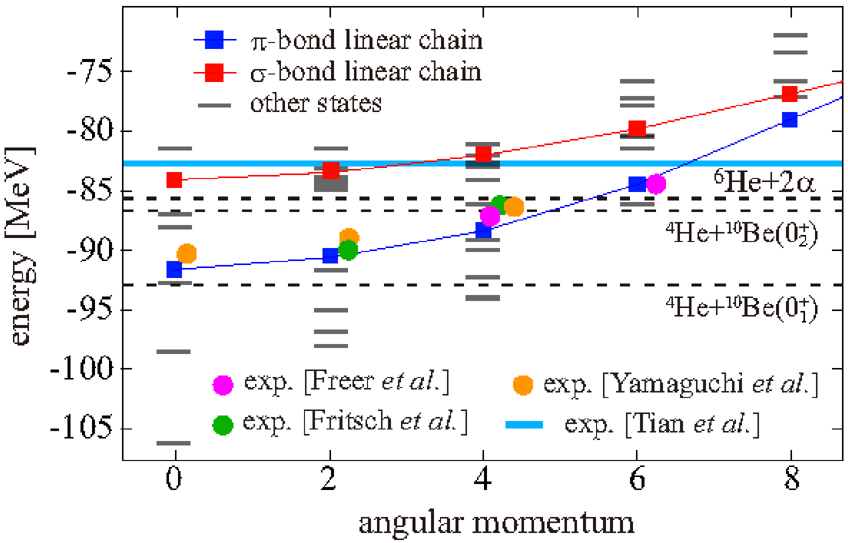
-Rotational motion of the ^{10}Be

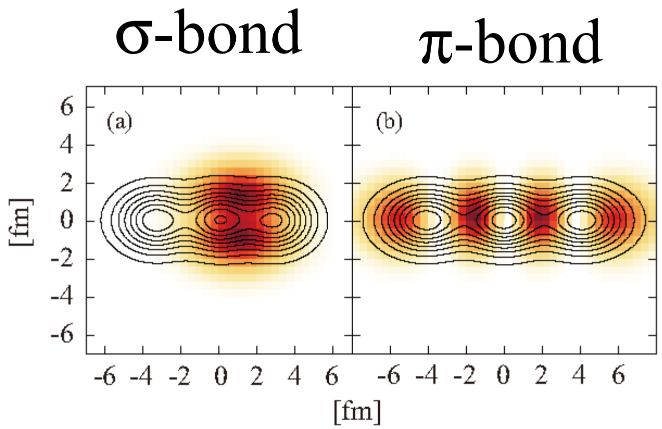
-Fragmentation of the state, coupling with other configurations.



Baba and Kimura (2016 & 2017)

PHYSICAL REVIEW C 95, 064318 (2017)





Another AMD calculation,

"σ-bond" linear chain band, consistent with 3 experiments

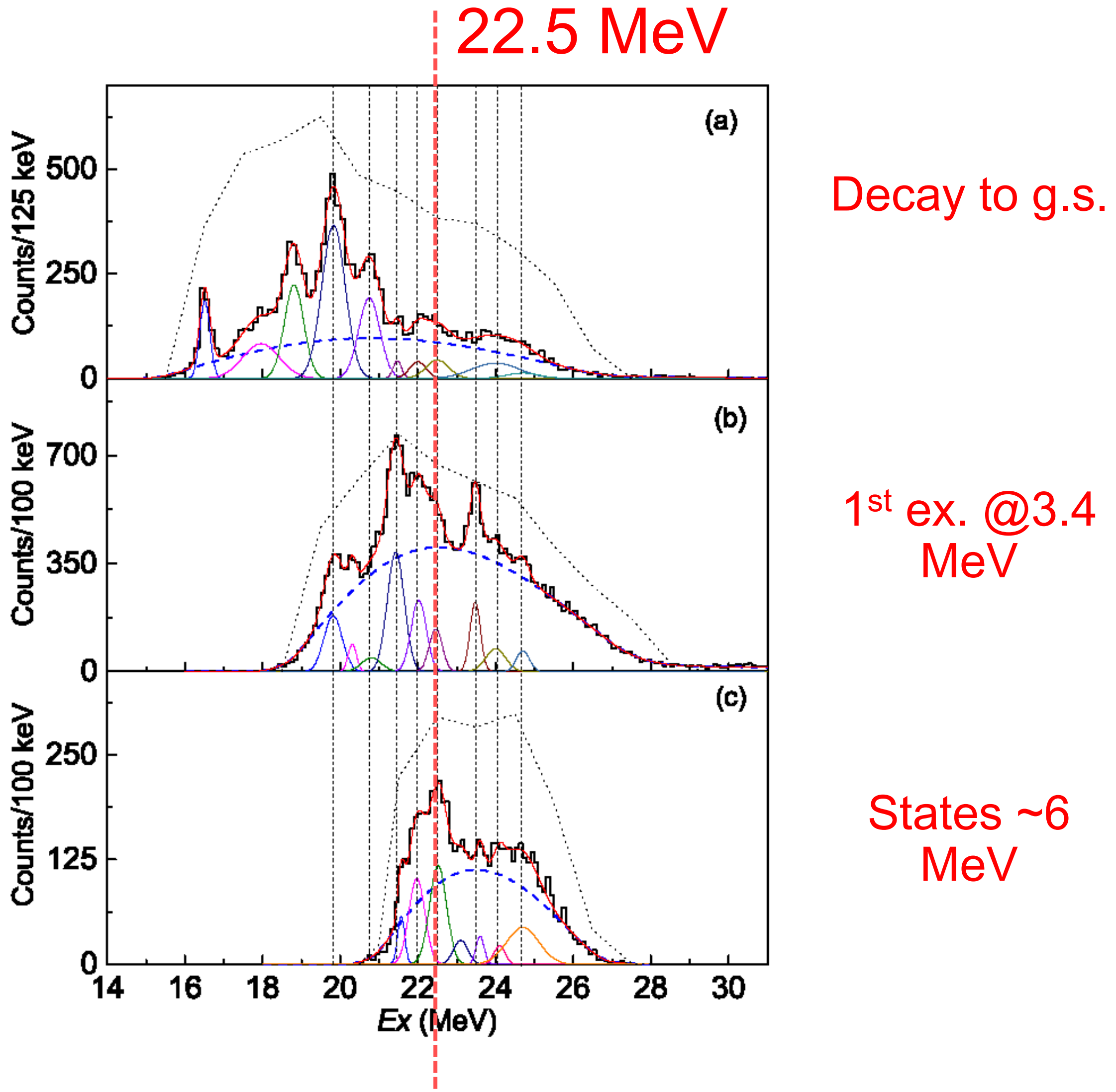
"π-bond" linear chain band at higher energy (studied by Peking Univ. group).

Evidence for σ-bond chain?

J. Li, Y.L. Ye et al., PRC (2017):

Breakup of ^{14}C with ^{9}Be beam.

22.5-MeV resonance… could be the predicted σ-bond chain from the energy (22.2 MeV) and the dominance of the decay to the 6-MeV states.



How certain are the linear-chain states?

- Identification of the 0^+ state…1^- was excluded with 3σ significance, but the error can be systematic.
  - ◆Limited statistics and angular range
  - ◆Background subtraction
  - ◆Inelastic scattering?

- We planned the 4th experiment at INFN-LNS (Catania, Italy):
  - ◆With offline-production ^{10}Be beam
  - ◆Inelastic scattering separation with TOF.

⇒*Performed in Oct., 2018.*

More recent studies at CRIB

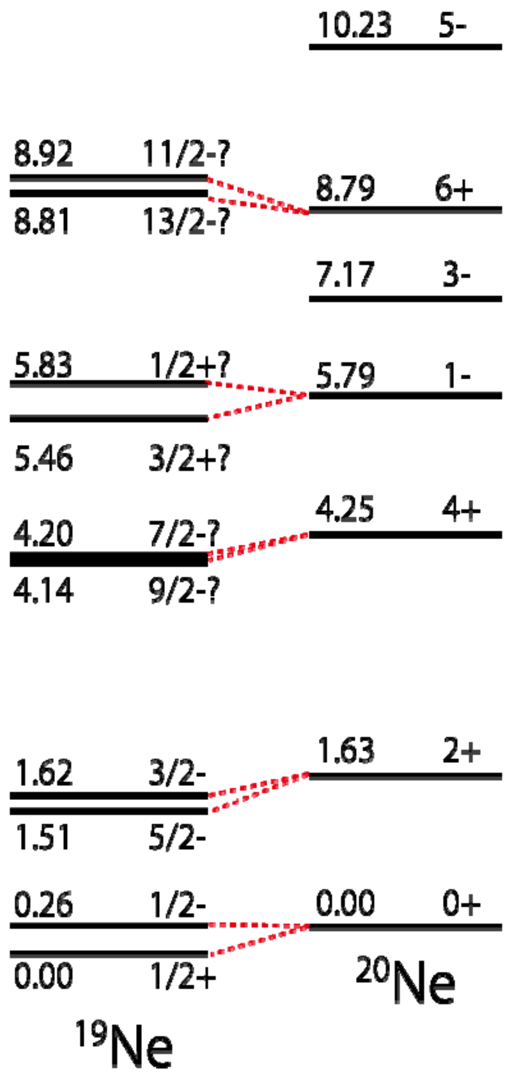
- ^{30}S+α…^{30}S(α, p) rate for X-ray bursts published as D. Kahl et al., Phys. Rev. C (2018).
- ^{15}O+α …Cluster bands, astrophysical ^{18}F(p, α) reaction rate
- ^{18}Ne+α …Missing ^{22}Mg cluster levels
- ^{10}C+α... mirror of ^{10}Be+α, proposal just accepted in the last NP-PAC (M. Sferrazza et al.)

^{15}O+α study

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

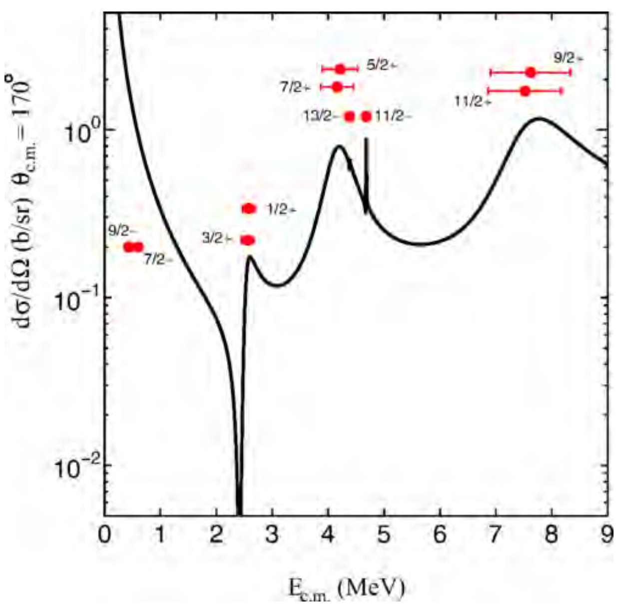
  Nemoto & Bando, PTP (1971).

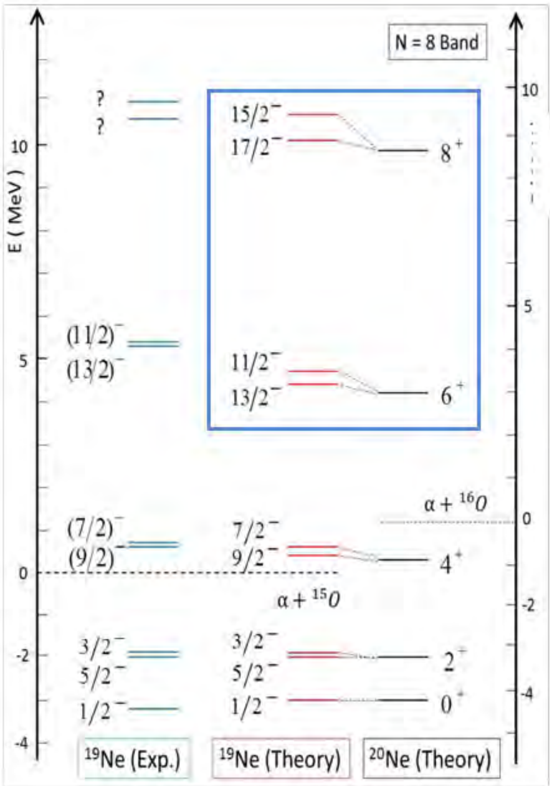
  - ◆Recent calculation by Otani et al. (2014) "ABC" method.
  - ◆Many parameters still unknown.
- ^{15}O+α resonant elastic scattering…these levels can be selectively observed.

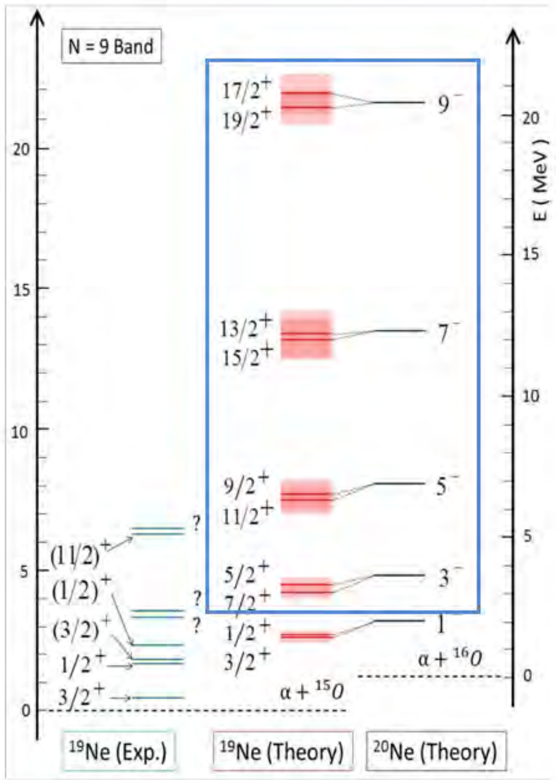


$^{15}O+\alpha$ study

◆Recent calculation by Otani et al. (2014)…Absorbing boundary condition







The importance of ^{19}Ne in nuclear astrophysics

Nucleus	τ	Type of γ-ray radiation	Nova type
^{13}N	862 s	511 keV line continuum (E<511 keV)	CO and ONe
^{18}F	158 m	511 keV line continuum (E<511 keV)	CO and ONe
^{7}Be	77 d	478 keV line	CO
^{22}Na	3.75 y	1275 keV line	ONe
^{26}Al	10^6 y	1809 keV line	ONe

It is known that most of 511keV γ-ray emission by e^+e^- annihilation comes from **β decay** of **^{18}F.**

The lifetime of ^{18}F (158 m) is in good agreement with the time required for the Nova ejecta to be transparent to the γ -ray emission .

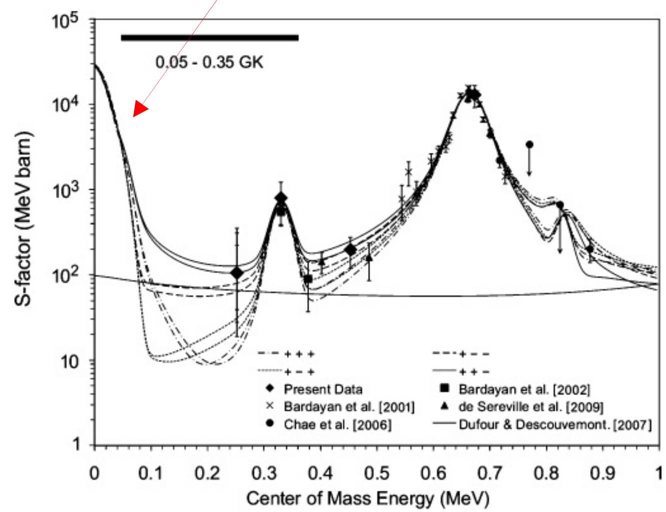
Productive reaction : ^{17}O(p,γ)^{18}F, $^{17}F(p,\gamma)^{18}Ne(e^+\nu_e)^{18}F$

Destructive reaction : ^{18}F(p,α)^{15}O, ^{18}F(p,γ)^{19}Ne

$^{15}O+\alpha$; astrophysics

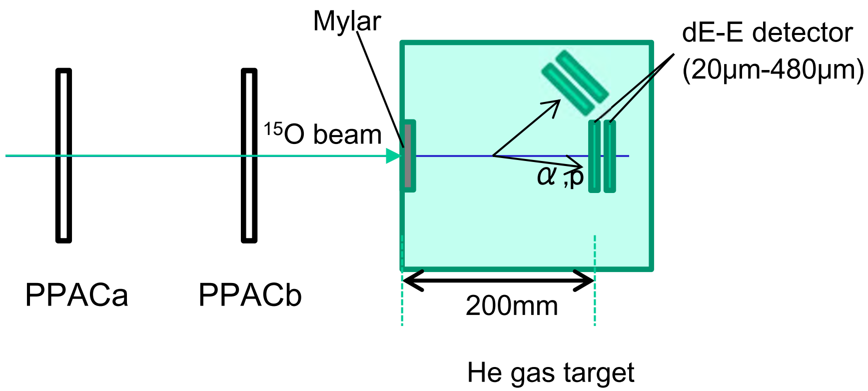
- $^{18}F(p,\alpha)^{15}O$ reaction…important in novae as a destruction process of ^{18}F.

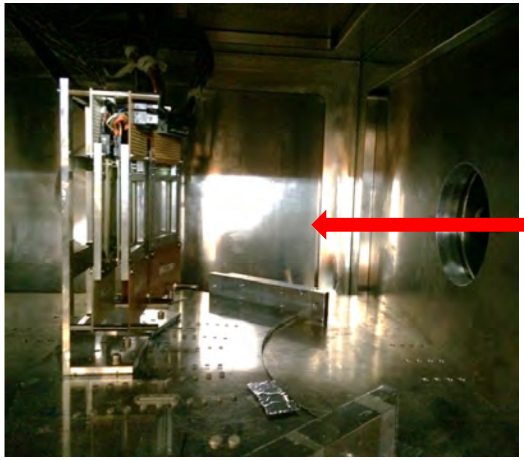
- Resonance at 6.42 MeV…relevant resonance, but the spin-parity has not determined uniquely yet.



Study from exit channel $^{15}O+\alpha$ to determine J^{π}.

Detector and target setup: thick target method

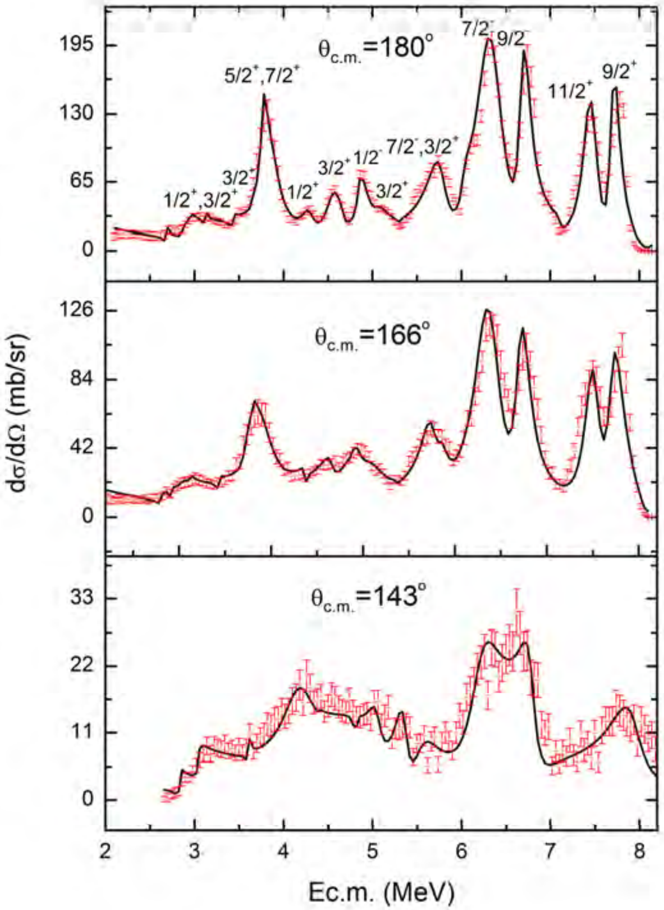




Primary beam : $^{15}N^{7+}$, 7.0 MeV/u, 600npA
Primary target : H_2 gas, 90k, 540torr, 80mm
Secondary beam: $^{15}O^{8+}$, 2.4MeV/u, 6×10^5 pps
Secondary target : He gas, 600 torr, 300K, 200mm
Background measurement : Ar gas, 115 torr
Beam energy after the entrance window: 36 MeV

Ex = 3.5 ~ 11.5 MeV in ^{19}Ne was scanned.

R-matrix fitting



- R-matrix calculation was performed at three angles
  - for obtaining the resonant parameters. (SAMMY8)
- Many J^{π} combinations referred from theoretical values an
  - previous experimental ones were applied.
- Finally, J^{π} which has the least χ^2 was assigned.

E_x(MeV)	J^{π}	Γ_{α}(keV)	$\Theta_{\alpha}{}^2$
6.23	$\frac{3}{2}^+$	19.7± 6.8	0.069
6.49	$\frac{1}{2}^+$	15.2± 8.5	0.018
6.87	$\frac{3}{2}^-$	334± 39	0.464
6.93	$\frac{3}{2}^+$	8.8± 2.0	0.013
7.21	$\frac{7}{2}^+$	49.2± 4.2	0.207
7.40	$\frac{5}{2}^+$	45.1± 7.8	0.145
7.78	$\frac{1}{2}^+$	166.4± 24.4	0.127
8.04	$\frac{3}{2}^+$	213±11	0.143
8.22	$\frac{1}{2}^-$	263±20	0.142
8.38	$\frac{3}{2}^+$	133±15	0.077
8.59	$\frac{1}{2}^-$	38±8	0.018
9.48	$\frac{3}{2}^+$	120±12	0.053
9.68	$\frac{7}{2}^-$	136±5	0.148
10.41	$\frac{9}{2}^-$	560±13	0.424
10.52	$\frac{7}{2}^-$	445±20	0.323
11.49	$\frac{11}{2}$	315±10	0.277
11.58	$\frac{9}{2}^+$	202±7	0.175

^{18}Ne+α

- *Goldberg et al. (2004)*

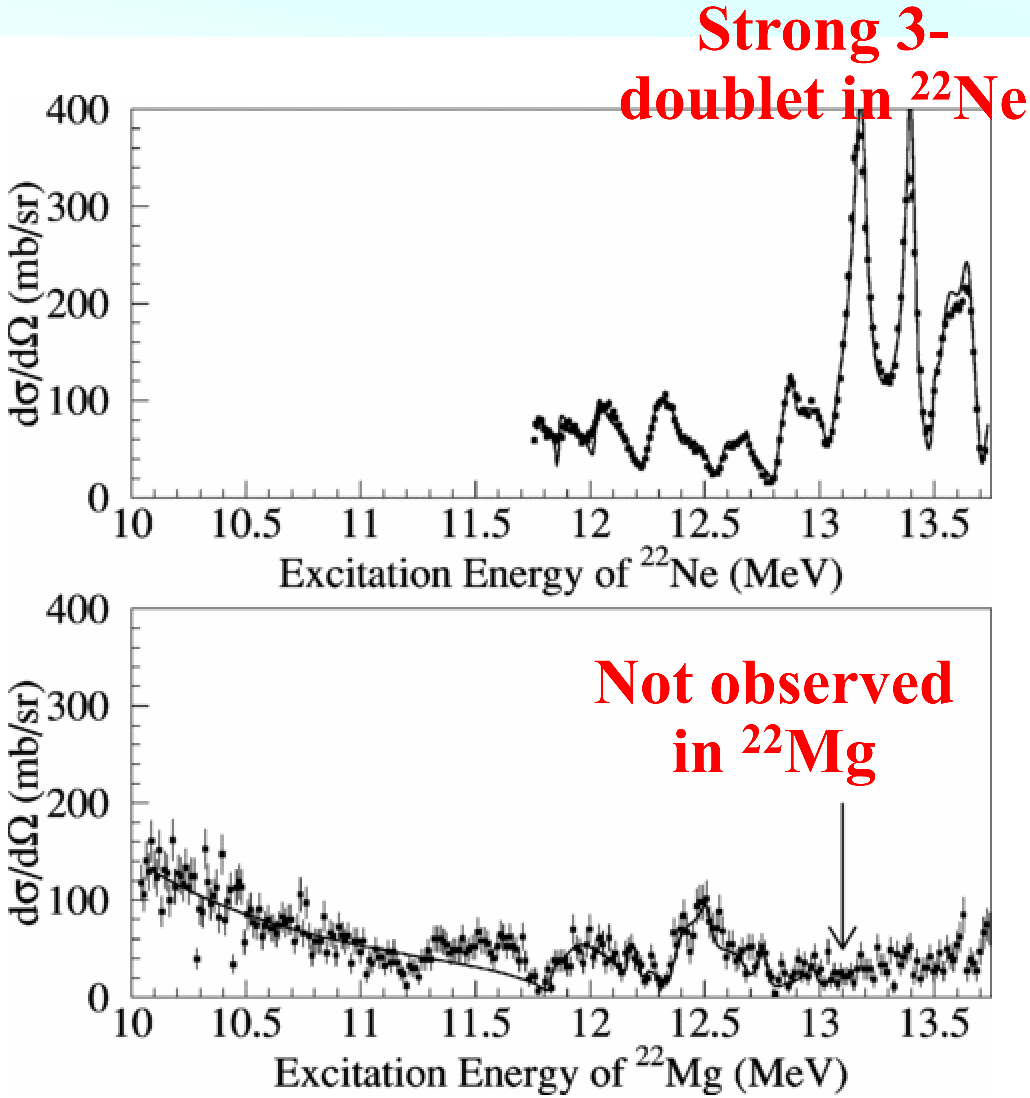
Resonant scattering of ^{18}O+α/^{18}Ne+α

⇒Inconsistency between mirror levels in ^{22}Ne/^{22}Mg

- Theory: *Descouvemont (1998), Kimura (2007)…* for ^{22}Ne levels.

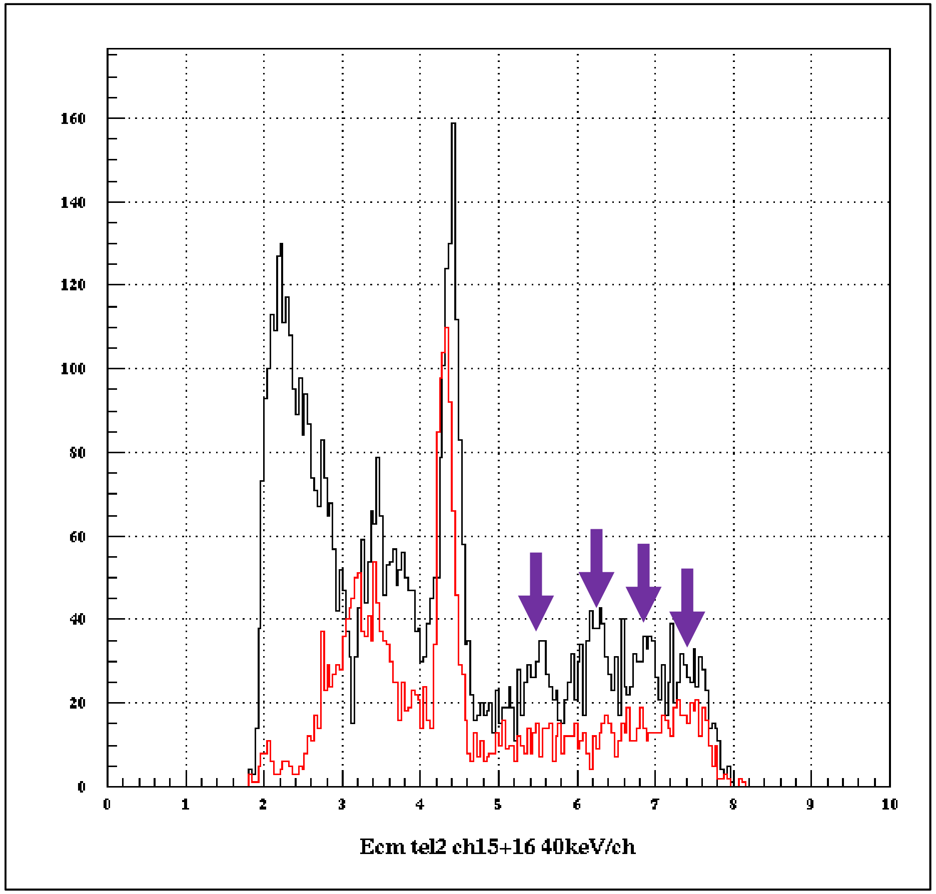
The levels are shifted or quenched by stronger Coulomb interaction?

New measurement at CRIB, covering wider energy range (up to Ex=20 MeV).



18Ne+a; preliminary result

^{18}Ne(α,α) : Yield vs $E_{c.m.}$ (=E_{ex} - 8.14 MeV)



- Background alpha…

contamination in the secondary

beam, peaked at 4.3 MeV.

Summary

- CRIB is a low-energy RI beam facility operated by CNS, University of Tokyo, providing RI beams of good intensity and purity.
  - CRIB is good at producing RI beams of low-mass (A<40) and near the stability line.
  - Alpha resonant elastic scattering …a striking method to study alpha cluster structure.
- ^{7}Li+α,^{7}Be+α…strong resonances were observed. We studied astrophysical reactions and alpha-cluster structures, proposing negative parity bands.
- ^{10}Be+α... A rotational band was observed, completely consistent with the prediction of the linear-chain cluster states by Suhara-En'yo AMD calculation.
- Newer studies: ^{15}O+α, ^{18}Ne+α, and more.
- We welcome **theoretical suggestions** and **experimental collaborators** with new ideas!