α共鳴散乱による
クラスター状態探索
Searching cluster states with α resonant scattering

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Outline

- (α) cluster states:

My understanding: "nuclear states in which a specific set of nucleons (e.g. α particle) behaves as if it were a single particle."

Another formal expression: "Spatially localized substructure composed of strongly correlated nucleons"

History/Example: Hoyle state (7.367-MeV level in ^{12}C), in relation with nuclear astrophysics

Method: α-resonant scattering with thick-target method in inverse kinematics (TTIK). (Also a little discussion on transfer reaction.)

Experiments:

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

$^{7}Be+\alpha$ (^{11}C), mirror of ^{11}B, Supernovae nucleosynthesis

$^{10}Be+\alpha$ (^{14}C), Linear-chain structure nucleosynthesis

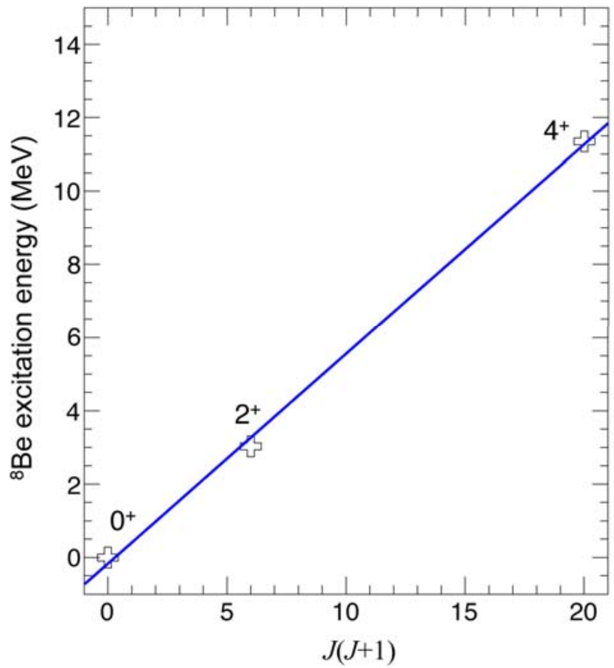
$^{15}O+\alpha$ (^{19}Ne), corresponding to ^{20}Ne cluster levels

Few words for the current situation and future

Early evidences of cluster structure

- High binding energy of ^{4}He, ^{12}C, ^{16}O, …

- ^{8}Be
  - ✓ Strong 2α decay with a short lifetime
  - ✓ 0 MeV (0+), 3.03 MeV (2+), 11.35 MeV(4+) levels…rotational band with Large momentum inertia.



- ^{12}C: Hoyle state (demanded by astrophysics)…discussed in 1950s.

  Difficult to form with ordinary reactions.

Stability gaps, A=5,8

- The earliest stage of the nucleosynthesis (p-p I chain)…adding nucleon one by one.

Does not work for gaps

at A=5 and A=8.

- How about

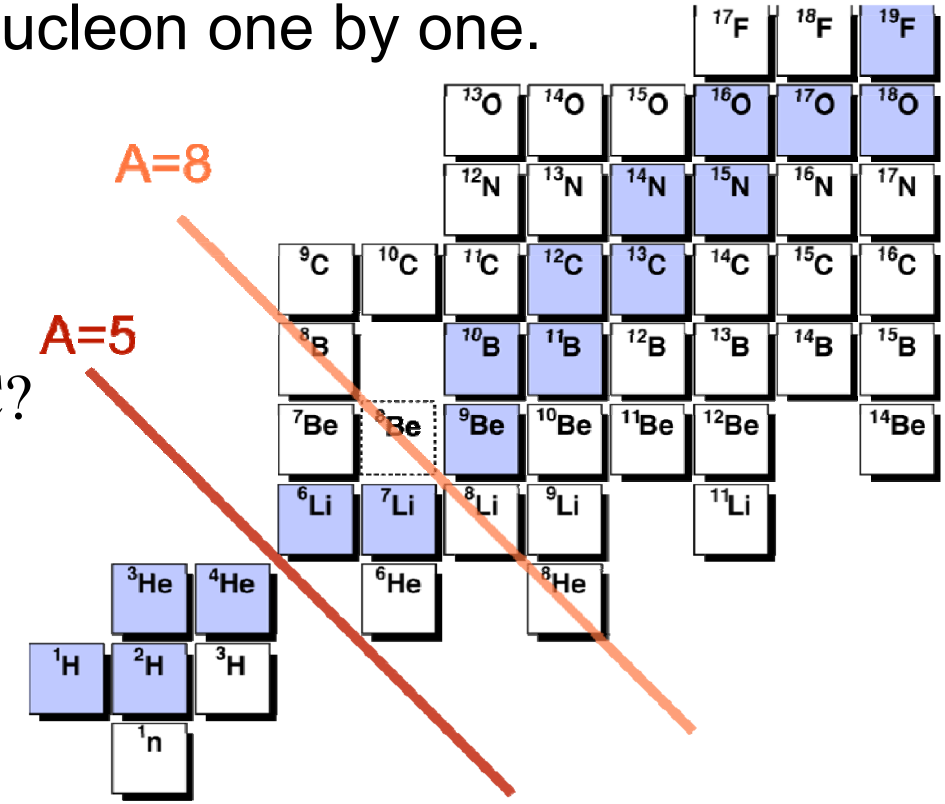
$^{3}He(\alpha,\gamma)^{7}Be(p,\gamma)^{8}B(\alpha, p)^{11}C$?

possible! (hot p-p chain)

but only at high T.

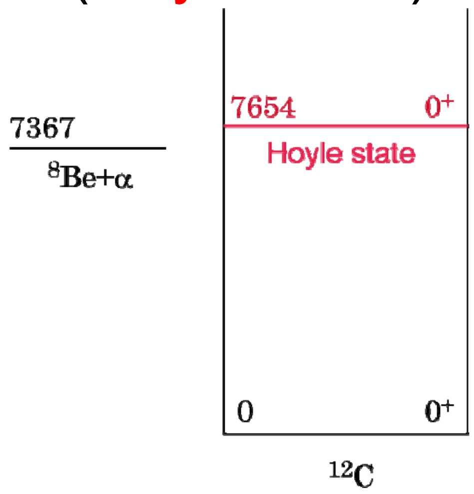
- A major process:

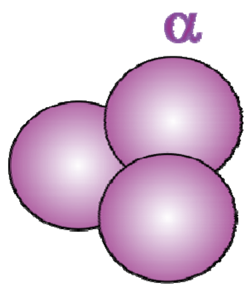
triple-α process



Triple α process

- While the ^{8}Be is formed by two α particles for a short time (τ=6.7 x 10^{-17} s), ^{12}C can be created via ^{8}Be(α,γ).
- $\alpha+\alpha \Leftrightarrow {}^{8}$Be   N(^{8}Be)/N(^{4}He)=5 x 10^{-10}.
- F. Hoyle noticed (non-resonant) production rate of ^{12}C is not sufficient to explain its abundance (1953). He predicted a resonance state around ^{8}Be+α threshold (=7.367 MeV), $J^{\pi}=0^{+}$ (Hoyle state).
- Hoyle state:
  - ✓ Actually found at 7.65 MeV by a later experiment.
  - ✓ Known to have an α-cluster structure.





Hoyle state experimental observation

- Typical experiment: transfer with a light-ion beam
  - ✓ $^{14}N(d,\alpha)^{12}C$
  - ✓ $^{11}B(d,n)^{12}C$

  Hoyle state was not observed.
- Fowler @ Caltech (1957)

  ^{12}B ($\tau_{1/2}$=20ms) α-decay (fig):

  Hoyle state was observed!

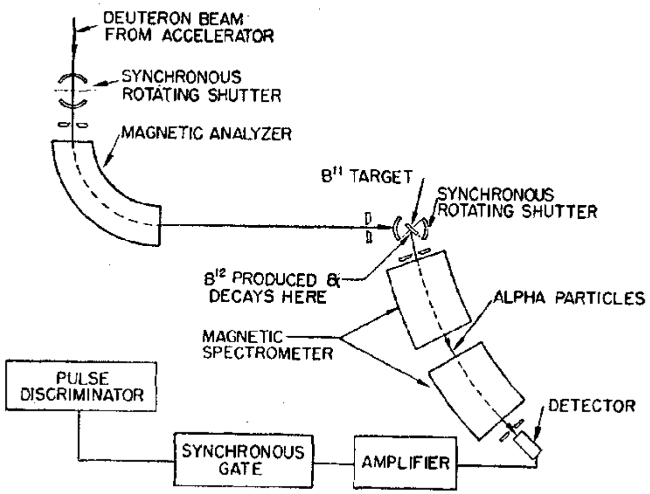


FIG. 2. Schematic diagram of apparatus. The B^{12} is produced by deuteron bombardment of a B^{11} target; alpha particles emerging from the target are focused by a magnetic spectrometer. Synchronous shutters permit alternate bombardment and detection.

- What was the difficulty?

  The probability of excitation much depends on the level and reaction (spectroscopic factor). A proper reaction was necessary.

  The failed reaction above: *^{11}B (J^{π}=3/2-) with p(1/2+) transfer can make an α-cluster-like 0+ state?* ^{11}B can be decomposed into α+^{7}Li(3/2-) and then ^{7}Li and p could couple with l=1, cancelling each angular momentum…not very likely?

α-probe reactions

Based on the historical discovery of Hoyle state, what would be the efficient way of studying α-cluster levels?

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

1. X(α,γ) reaction…low-cross section
2. α-transfer reaction X(^{6}Li,*d*)X+α.
3. X(α, α)X resonant elastic scattering. States of X+α compound nucleus is observed as resonances.

- Unique studies can be performed with RI beams

How are the cluster states in “non 4n-nuclei”??

Recent research: non 4n-nuclei

- For a long time, the alpha-cluster structure was studied mainly for 4n-nuclei (^{8}Be, ^{12}C, ^{16}O, …).
  - ✓ They can be described only with alpha particles.

  Theory can be simple, providing the most sensitive test of cluster feature.
  - ✓ They are stable nuclei in low-mass region (up to A~40)

  No need of RI beams, thus easy to make experiments.

- Development of theory, computing, and experimental technology (RI beam)…Now we can go into non 4n-nuclei, to obtain a more universal cluster theory.

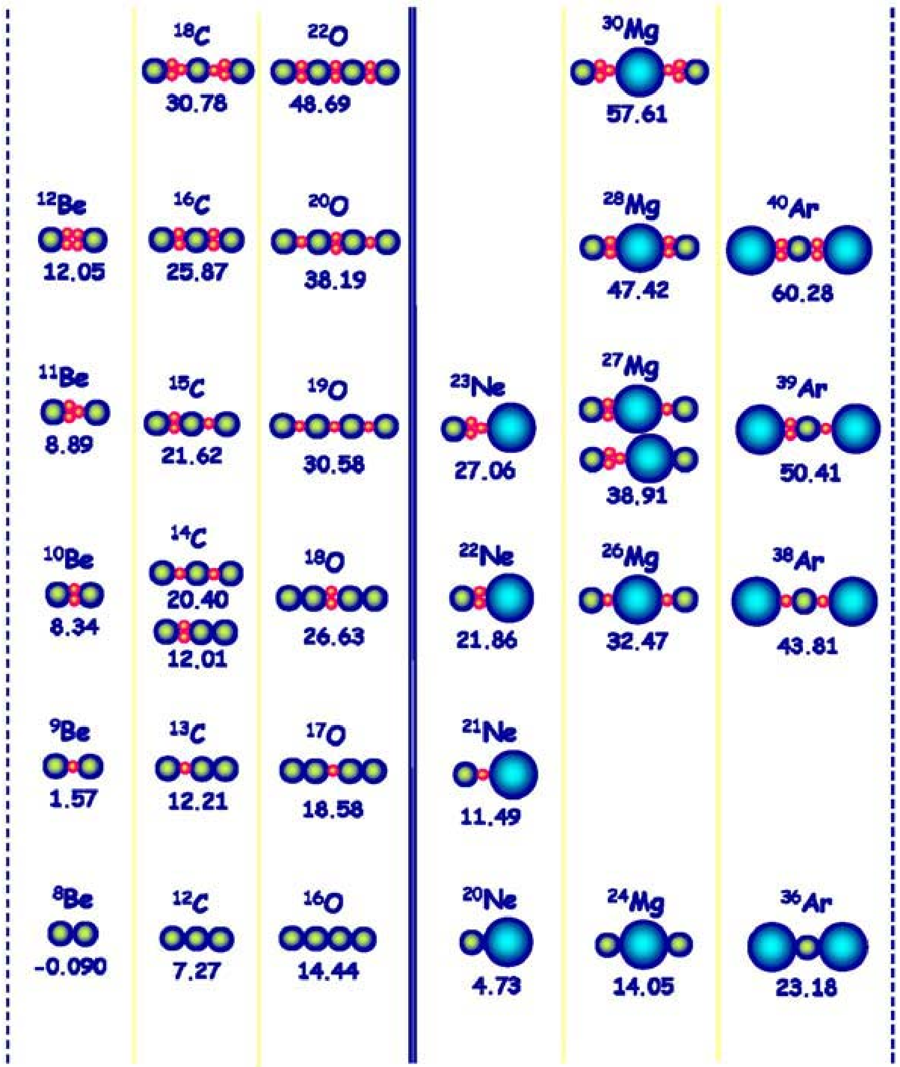
Adding neutrons

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

neutron is the glue between 2α?

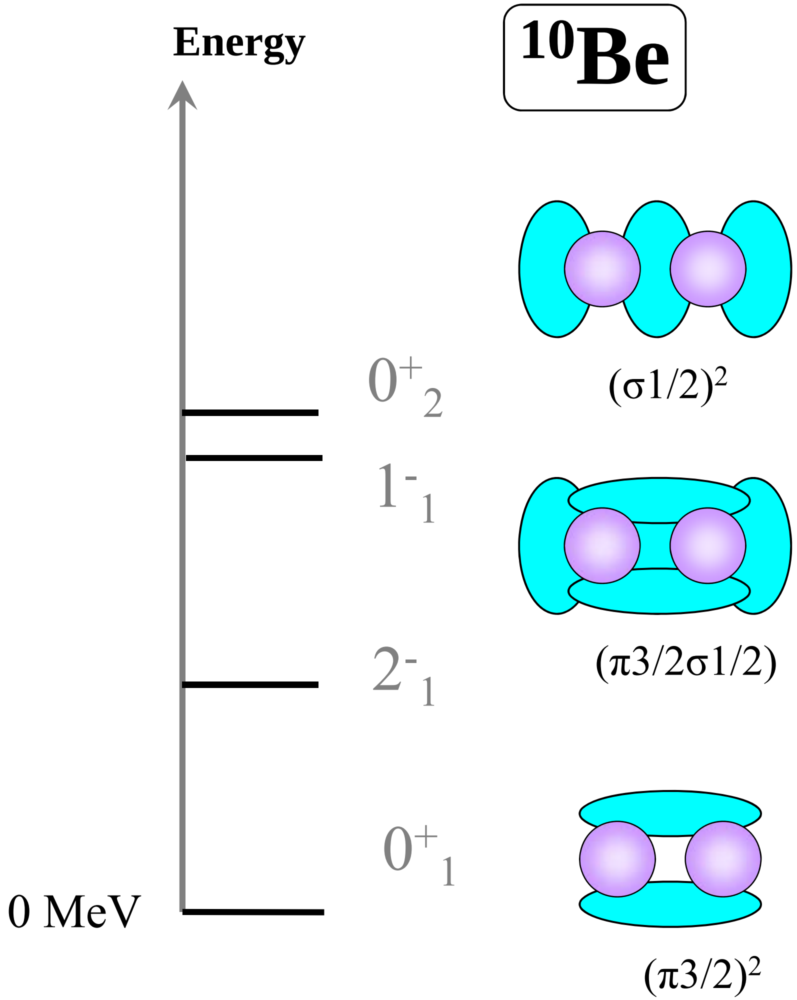
- Cluster structure could be realized in n-rich nuclei…extended Ikeda diagram:

W. von Oertzen et al. / Physics Reports 432 (2006) 43 – 113



^{10}Be

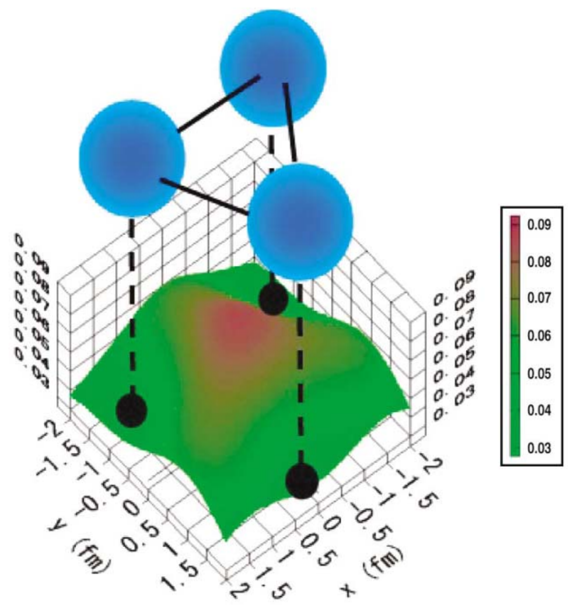
- Z=4, N=6 ⇔ 2α+2n; unstable(half life=1.4 million years)
- Can be described with two α with "valence neutrons" in molecular orbitals (Itagaki, 2005).
  - ✓ σ-orbital
  - ✓ π-orbital

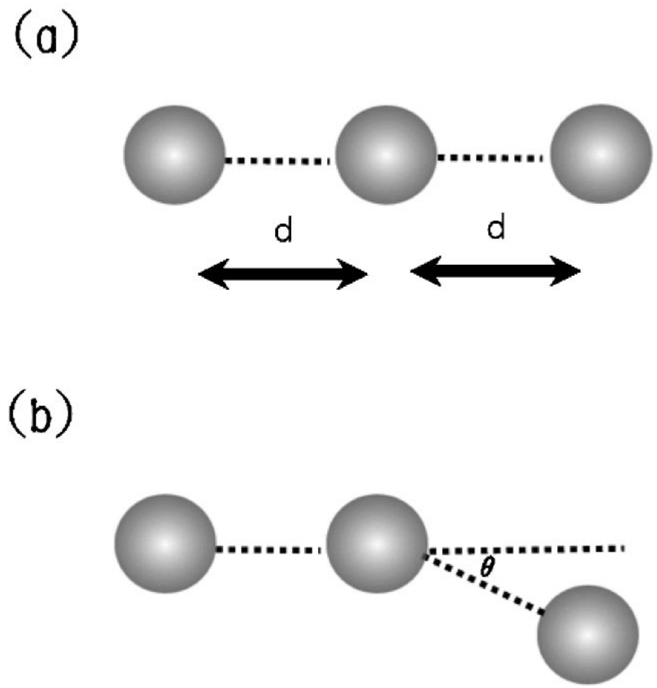


Carbon isotopes

- ^{14}C half-life 5,730±40 years, famous for chronology
- ^{14}C…Itagaki (triangular shape), Oertzen (prolate deformation).
- ^{16}C…stabilized depending on

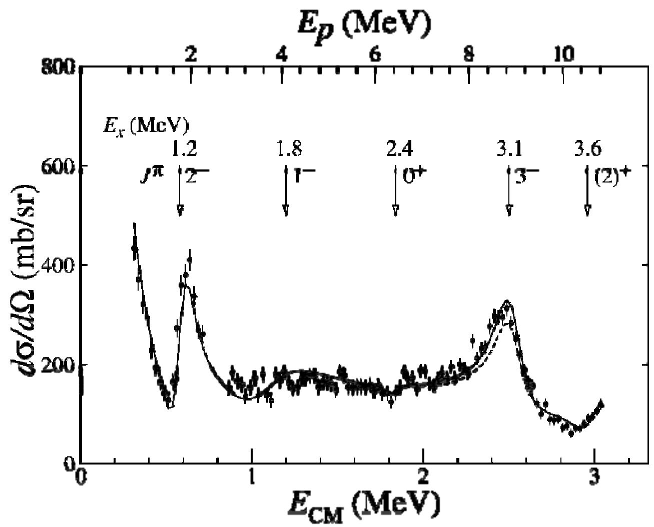
d,theta?





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

The 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 $^{15}N + \alpha$.

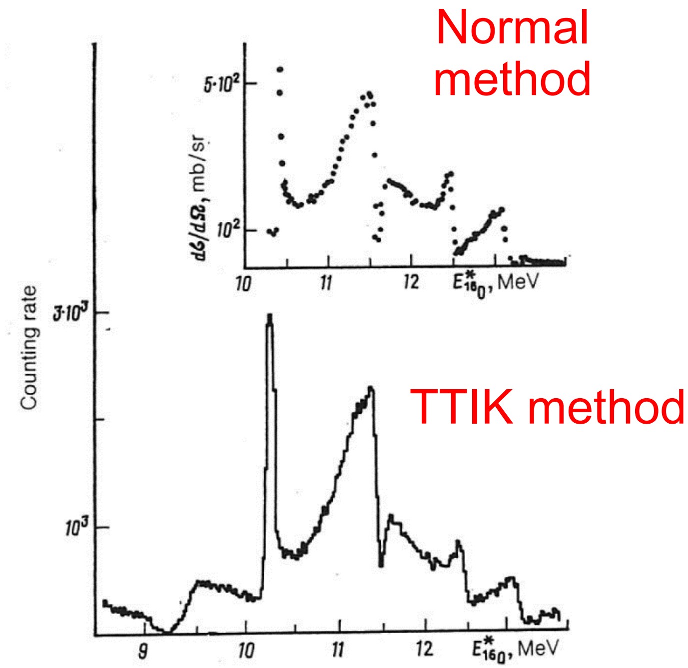
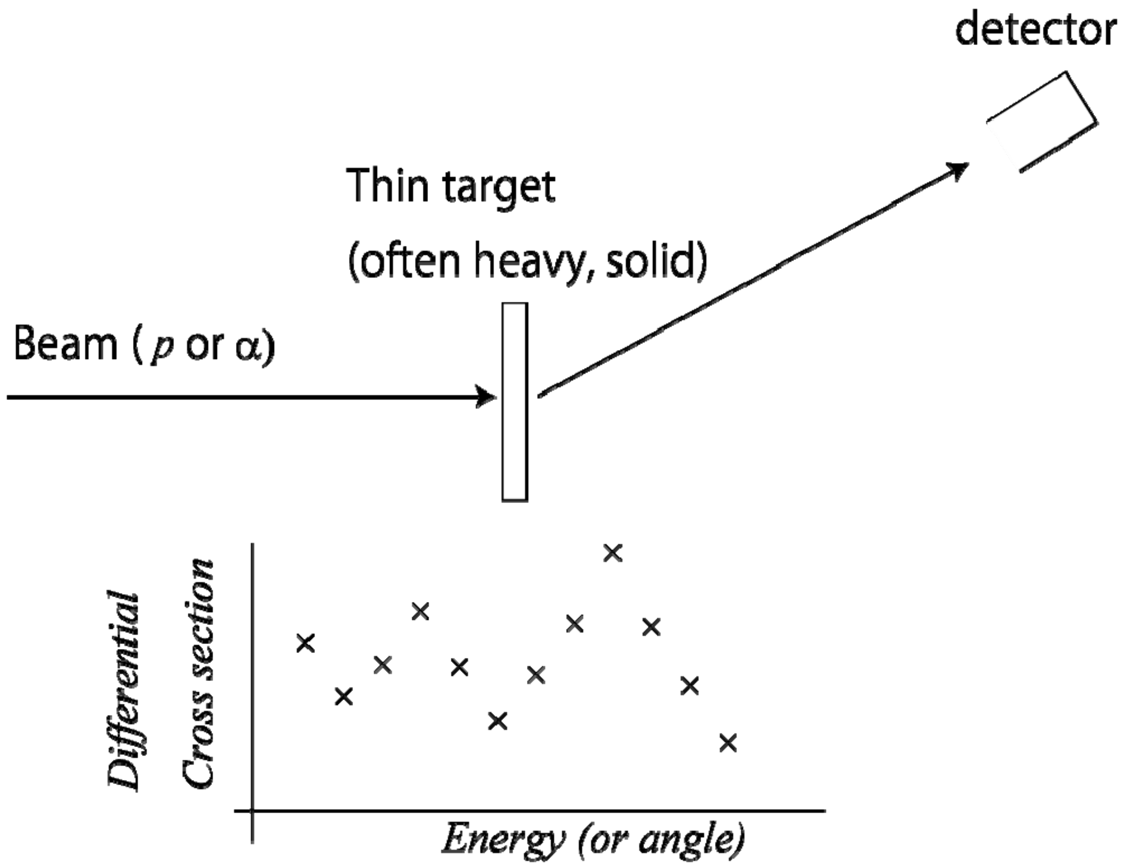


FIG. 1. Spectrum of α particles obtained in interaction of ^{12}C ions with initial energy 28 MeV with helium. The detection angle is 0°. In the insert we have given the excitation function for elastic scattering of α particles by carbon from Ref. 4. The detection angle is 158.8°.

Traditional method (normal kinematics)

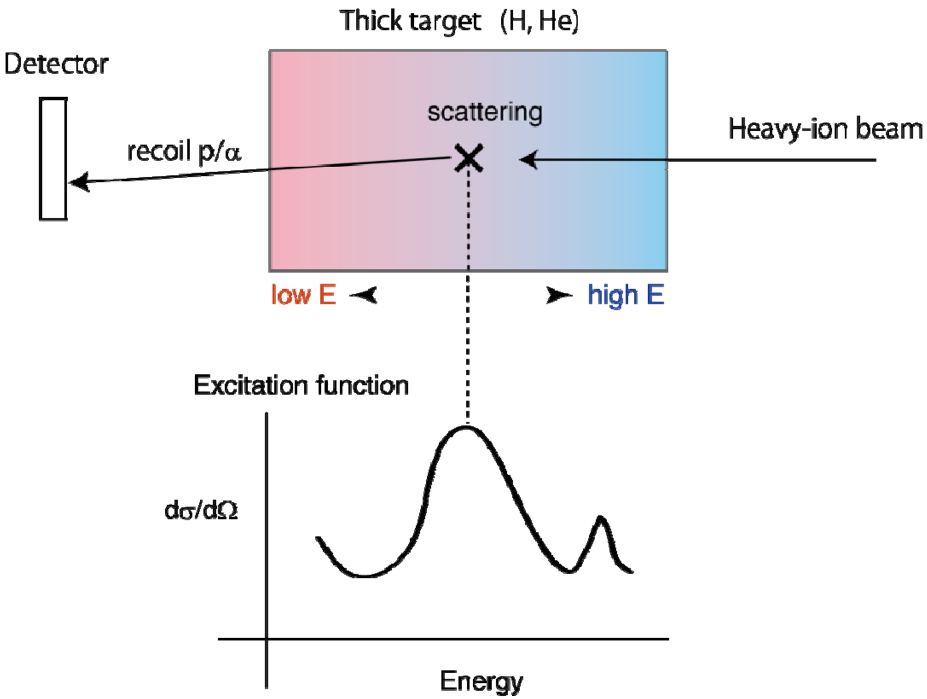


-Beam energy is changed for each data point

to measure excitation function

The thick-target method in inverse kinematics

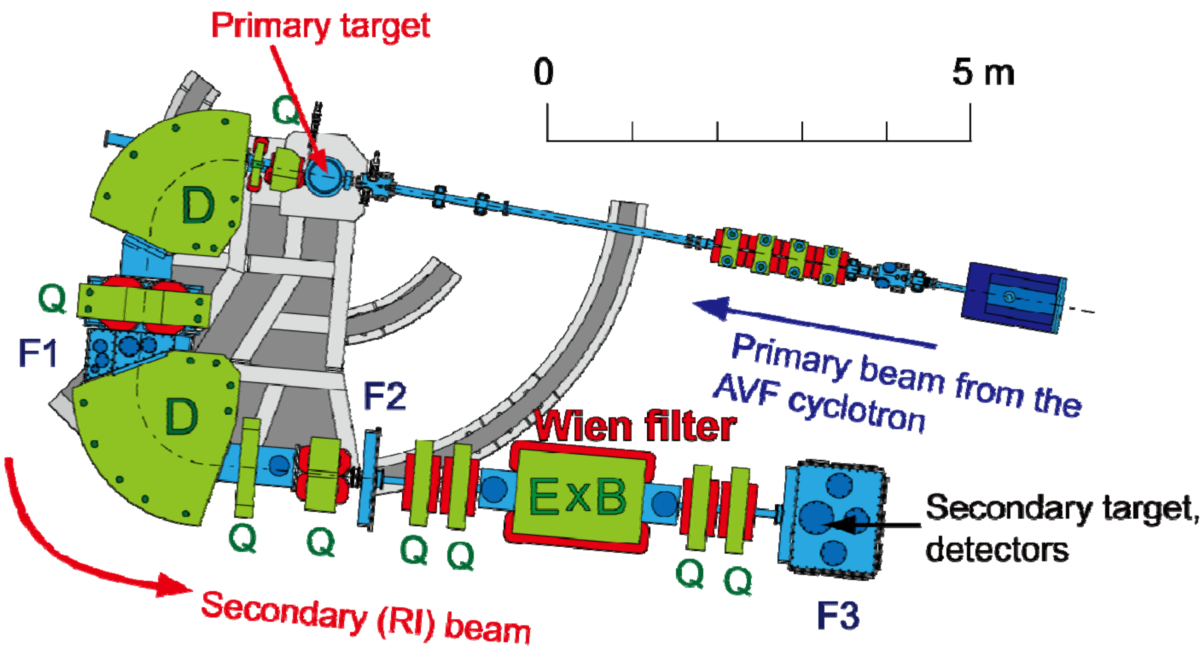
Measurement of resonant scattering



- ✓ 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.

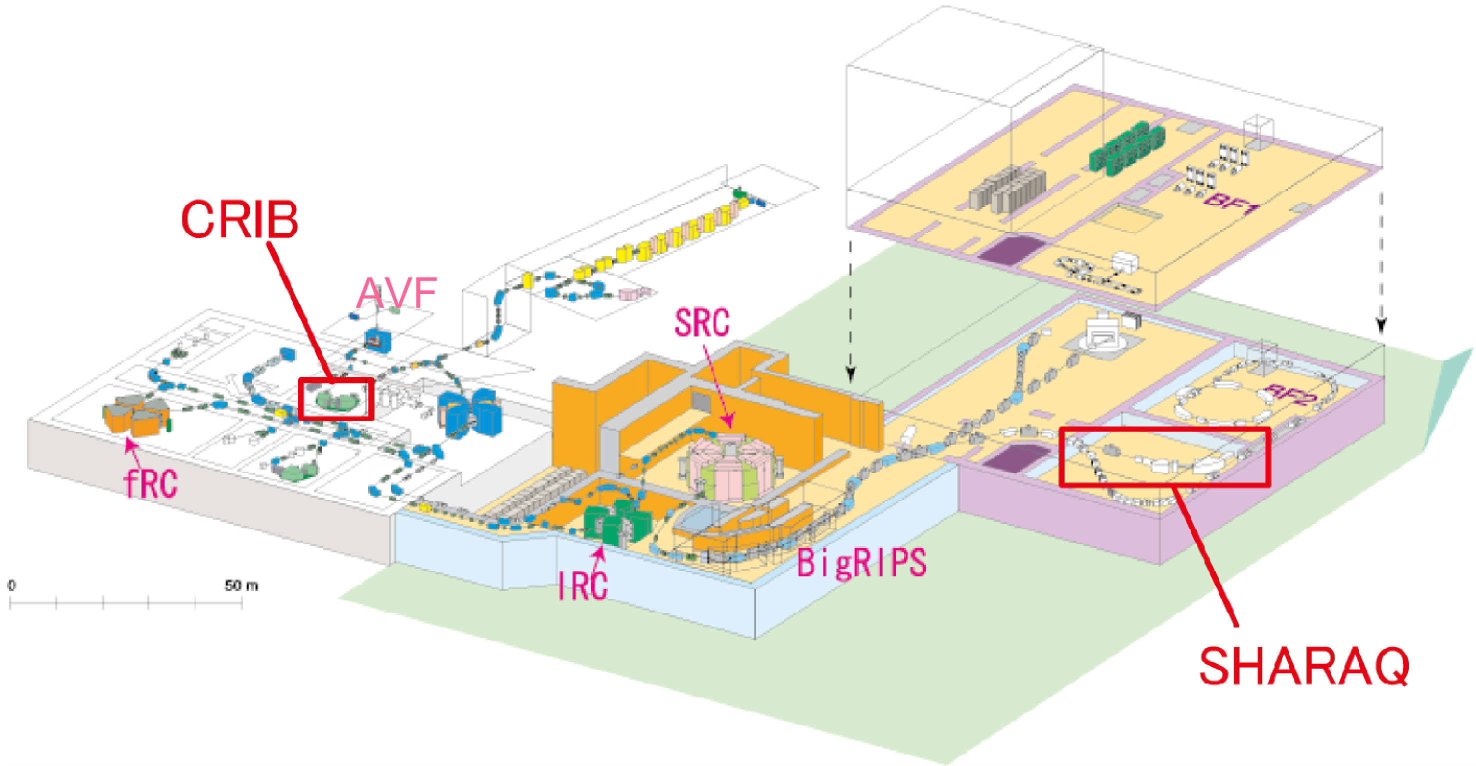
CRIB

- 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.



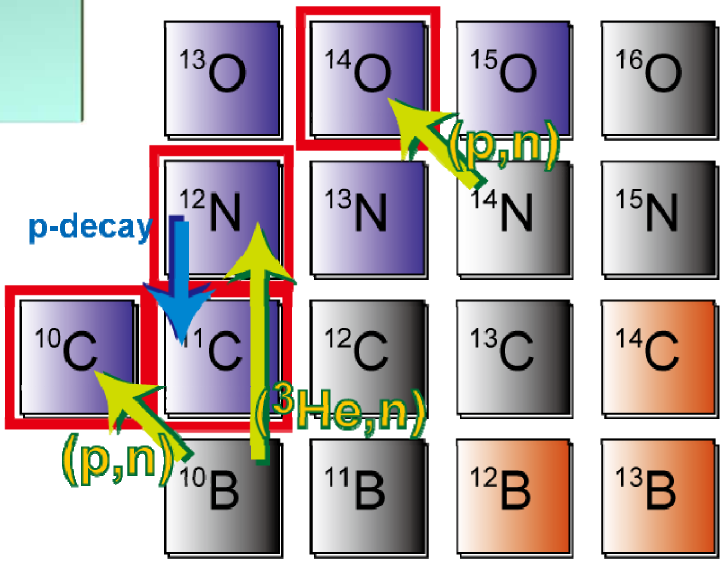
CRIB in RIBF

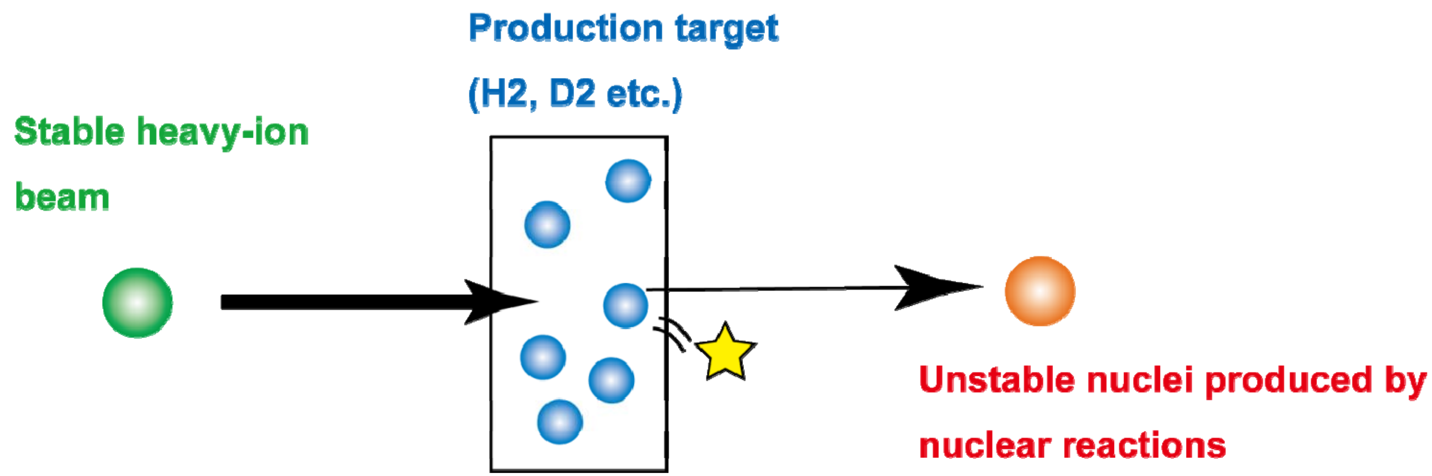
- located at the old part of the RIBF
- Ion source / AVF/ CRIB…development under CNS-RIKEN collaboration (joint venture).



Low-Energy RI beam Production

(p,n), **(d,p)**, **(^{3}He,n): direct reactions** are used in inverse kinematics for the production of the **RI beams**.



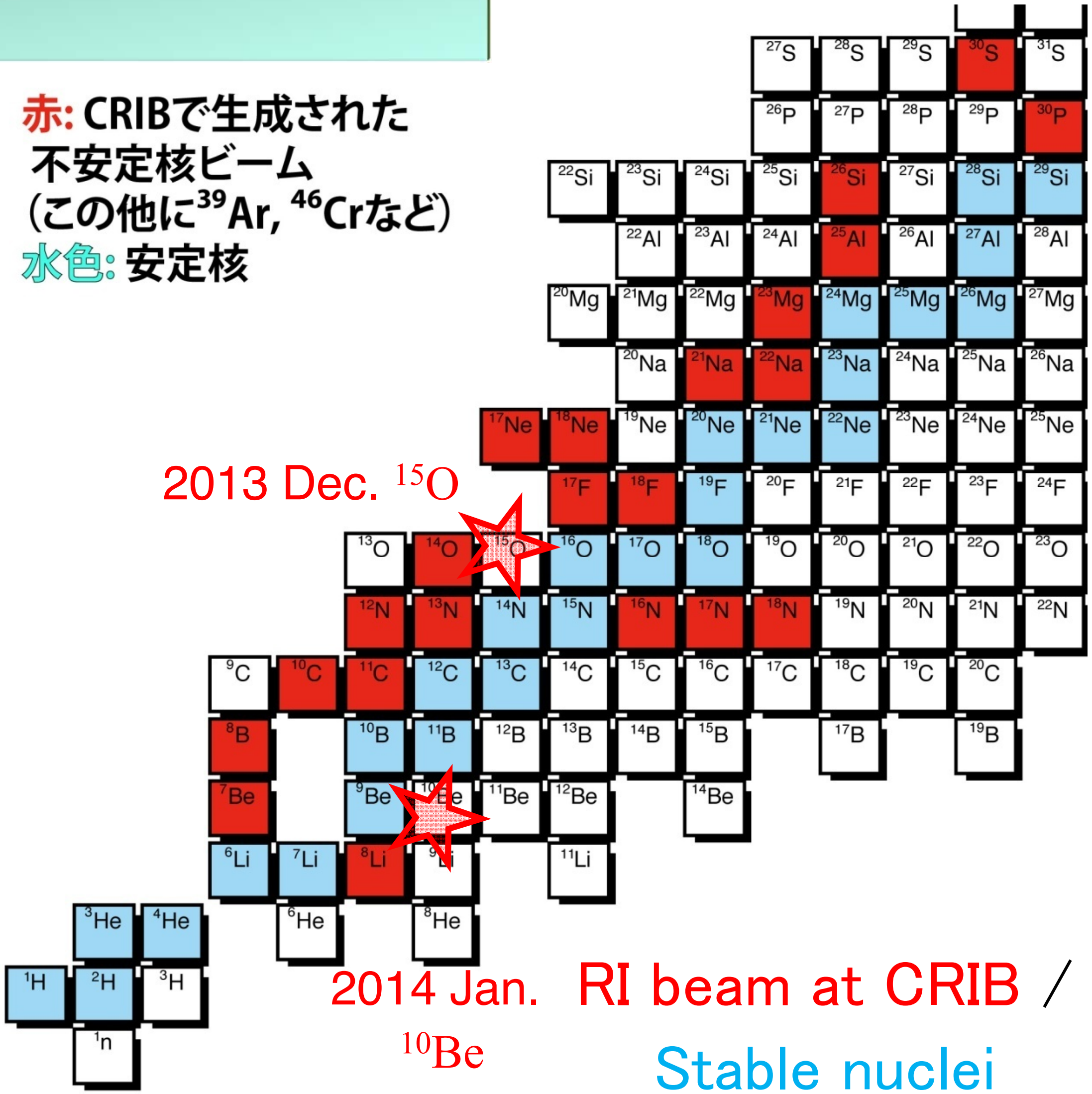


Low-Energy RI beam Productions at CRIB

赤: CRIBで生成された
不安定核ビーム
(この他に^{39}Ar, ^{46}Crなど)
水色: 安定核

Various RI beams have been produced with typical intensities of 10^4-10^6 pps

New beams recently developed:
^{44}Ti, ^{15}O, ^{16}N, ^{10}Be



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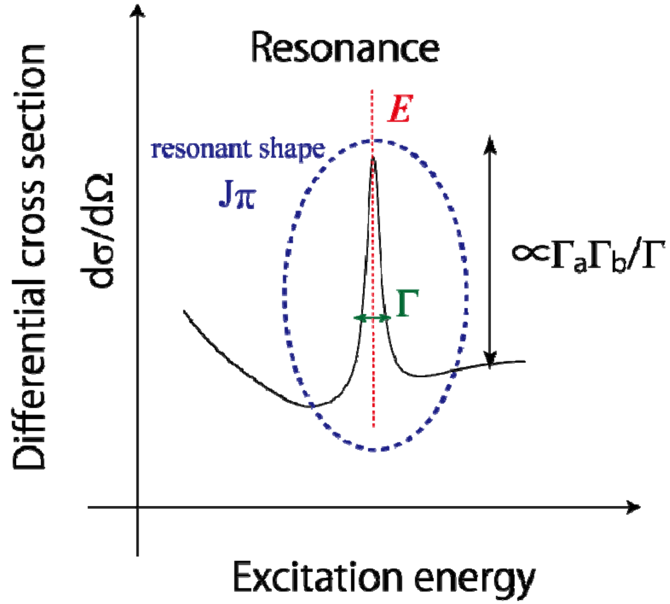
Analysis with R-matrix calculation

- R-matrix theory… developed in '40-'50s [Wigner and Eisenbud(1947), Rane and Thomas(1958)]. Works well for a compound nucleus, direct interaction.
- Treat the system as follows:
  - ✓ At a distance from the center of the system (interaction radius), the system can be separated into two regions.
  - ✓ External region….can be described with Coulomb wave functions
  - ✓ Internal region…Resonances
- Suitable for analysis of excitation function with resonances

⇒ Resonance parameters can be determined.



Importance of α width

Clustering in ^{18}O nucleus

- W. Oertzen, Eur Phys J. 43 (2010) 17:

Negative parity band proposed,

1- 8.04 MeV, 3- 9.7 MeV, 5- 13.6 MeV, 7- 18.63 MeV?

- Florida Gr. [M.L. Avila, et al., arXiv:1406.6734v1] (resonant scattering):

8.04 MeV (1-) reduced width θ^2 is only 0.02.

9.70 MeV (3-) θ^2 =0.04.

9.76 MeV (1-) θ^2 =0.46.

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

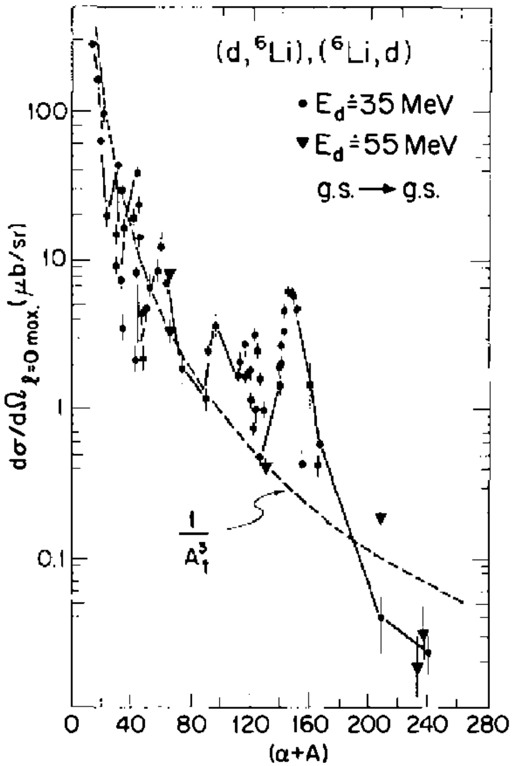
- 4-nucleon transfer reaction with minimum mass.
- Can be a simulation of (α,γ) reaction.
  - ✓ ^{6}Li$\Rightarrow d+\alpha$ …requires 1.47 MeV (reaction Q value becomes lower than (α,γ) .)
- (α,α)…
  - ✓ Simple R-matrix calculation can be applied, direct information on Γ_{α}, large cross section
  -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

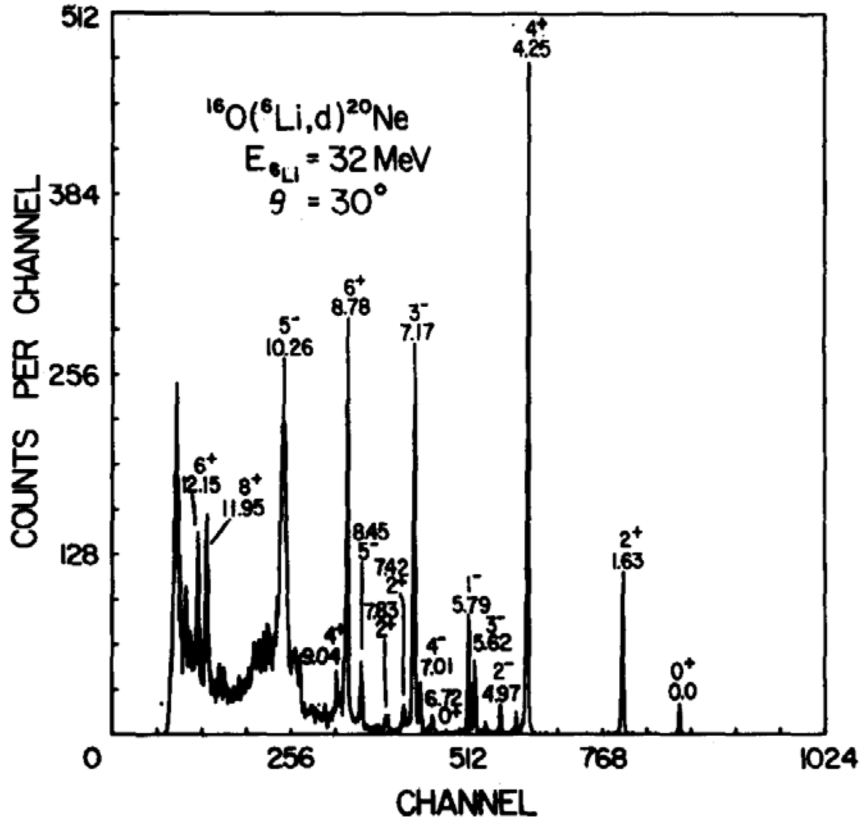
⇔

- (^{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).





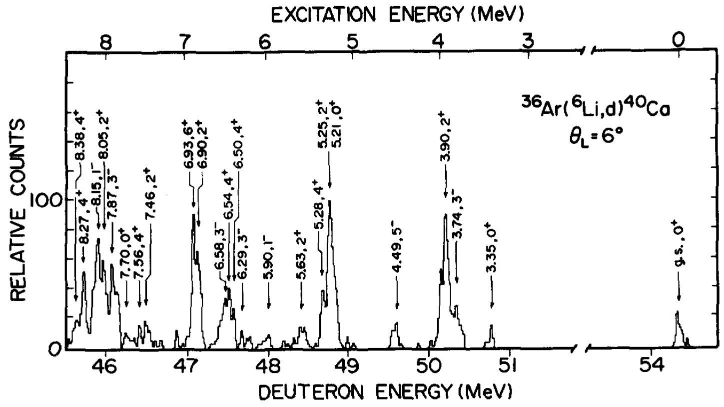
^{16}O(^{6}Li, d) @32MeV
Anantaraman et al. (1979).

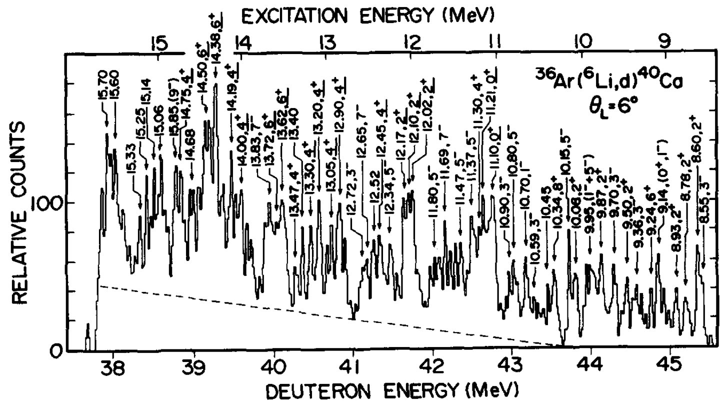
(^{6}Li,*d*), previous studies

- 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.

Still not so easy to perform a similar experiment with RI beam…

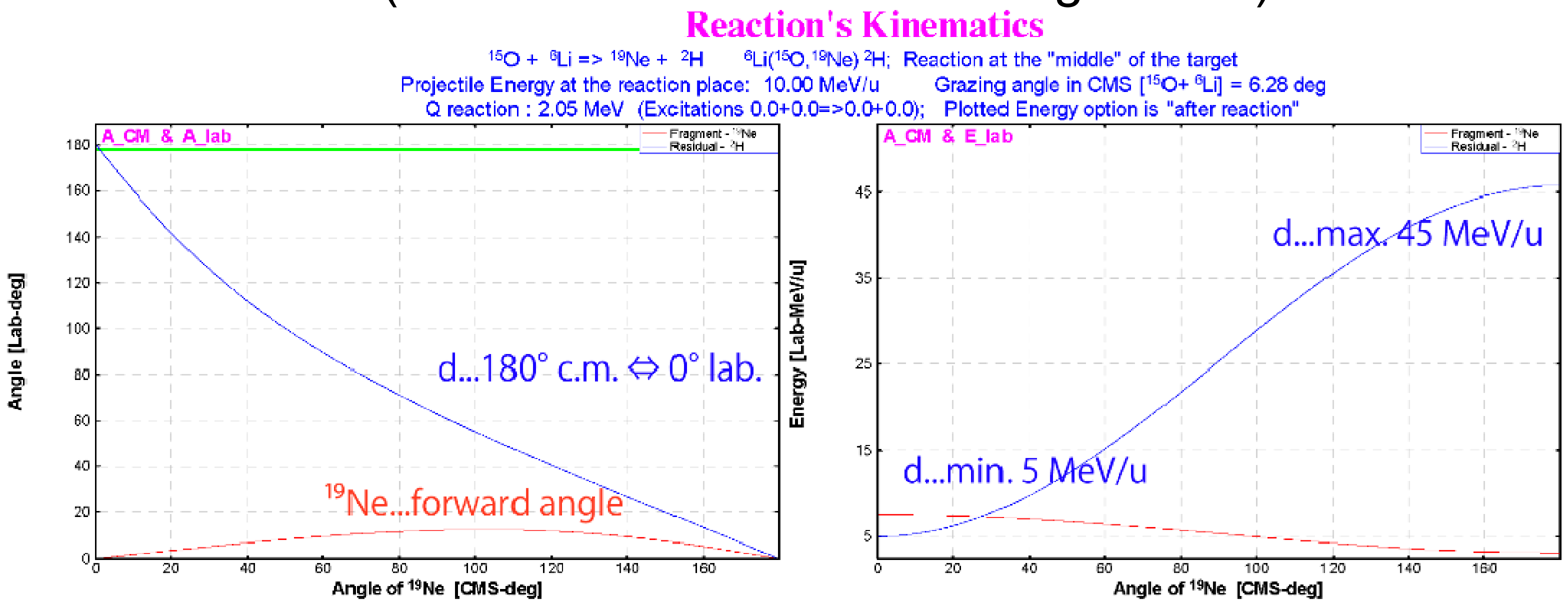
T. Yamaya et al. / Nuclear Physics A573 (1994) 154–172





Energy and kinematics

- Cross section, not strongly dependent on beam energy (though not much data available).
- Kinematics (10 MeV/u ^{15}O beam +^{6}Li target case):



When Ebeam=100MeV/u…min energy of deuteron~50 MeV

[講演後追記: 実際には100MeV/uのビームを使った例は余りなく、
断面積は10MeV/uと比較して1桁～数桁小さくなる可能性があります。]

α-resonant scattering 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

4. ^{15}O+α (^{19}Ne), Comparison with ^{20}Ne cluster, astrophysical ^{18}F(p, α) reaction

7Li+α measurement; interests

- Related to ^{7}Li(α,γ), measured only at resonances:
  - Paul et al., PR 164 (1967) 1332.
  - Hardie et al., PRC, 29 (1984)1199.
- 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 may play important roles in some environments:

✓ ^{11}B/^{7}Li ratio in core-collapse supernovae …the ν-process

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

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

(T. Yoshida et al., PRL2006.)

✓ Boron production in inhomogeneous big-bang nucleosynthesis.

PRL 96, 091101 (2006) PHYSICAL RE

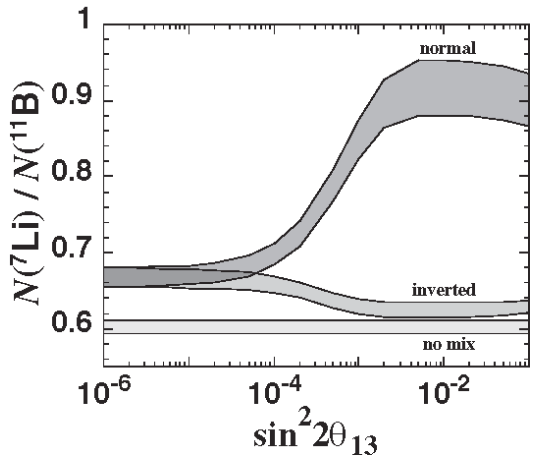
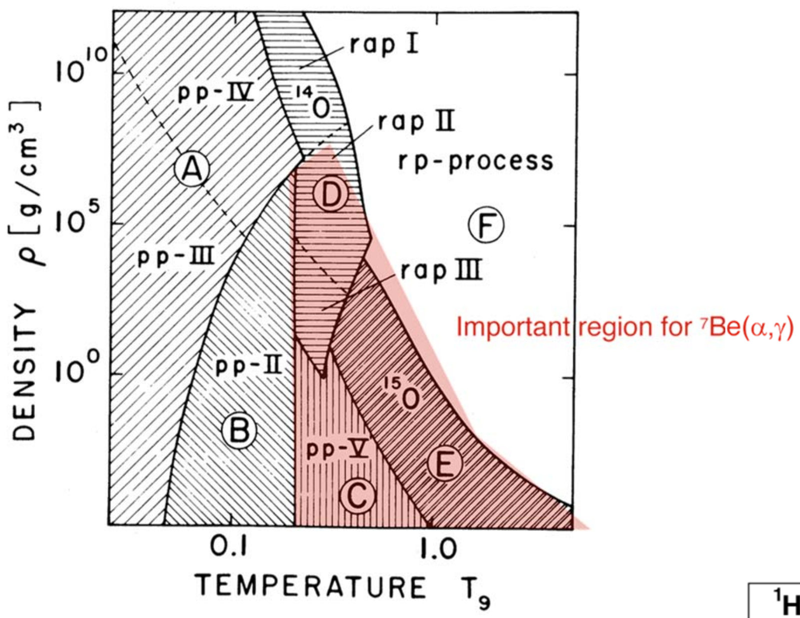


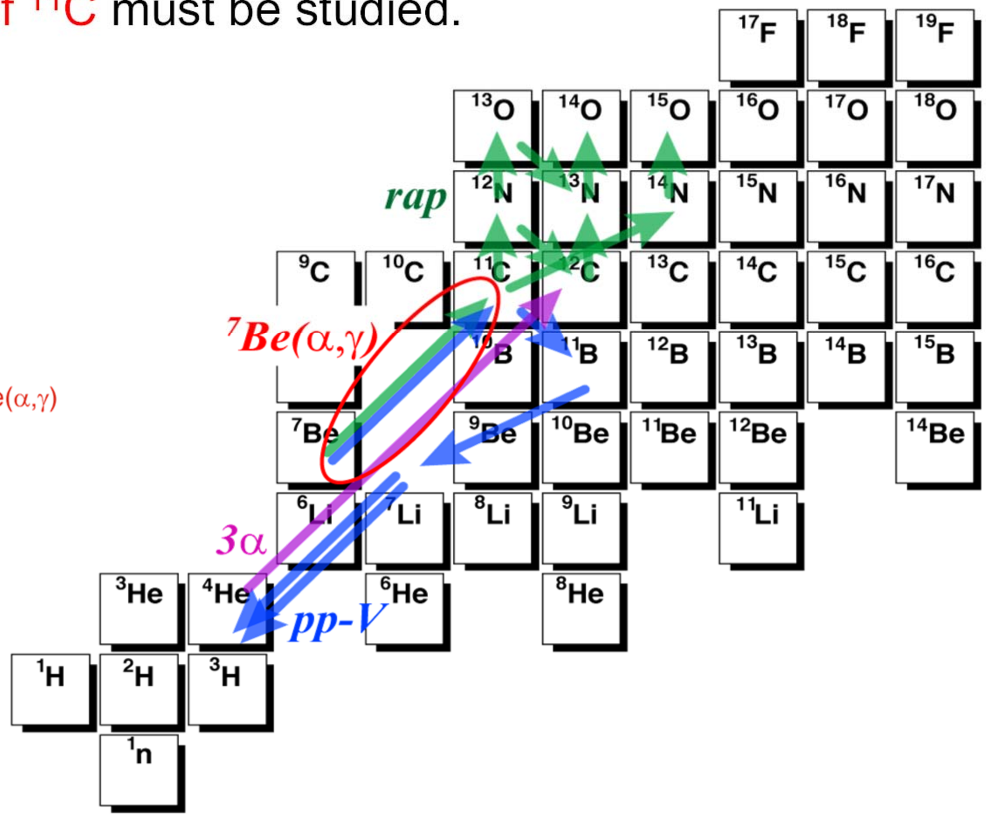
FIG. 3. The number ratio of ^{7}Li/^{11}B with the relation of $\sin^2 2\theta_{13}$. The shaded ranges include the uncertainties of neutrino energy spectra deduced from the calculations using three sets of neutrino temperatures and total neutrino energies (see text).

$^{7}Be(\alpha,\gamma)$ reaction and hot *p-p* chain

- $^{7}Be(\alpha,\gamma)^{11}C$ …reaction in hot *p-p* chain ($4p \Rightarrow {}^{4}He$ + energy)
  Important at high temperature (Wiesher *et al.*,1986)
- Supermassive objects, pop-III stars (Fuller *et al.*, Mitalas), Novae (Hernanz *et al.*), Big-bang nucleosynthesis (Andouze and Reeves),…
- Reaction rate … resonances of ^{11}C must be studied.

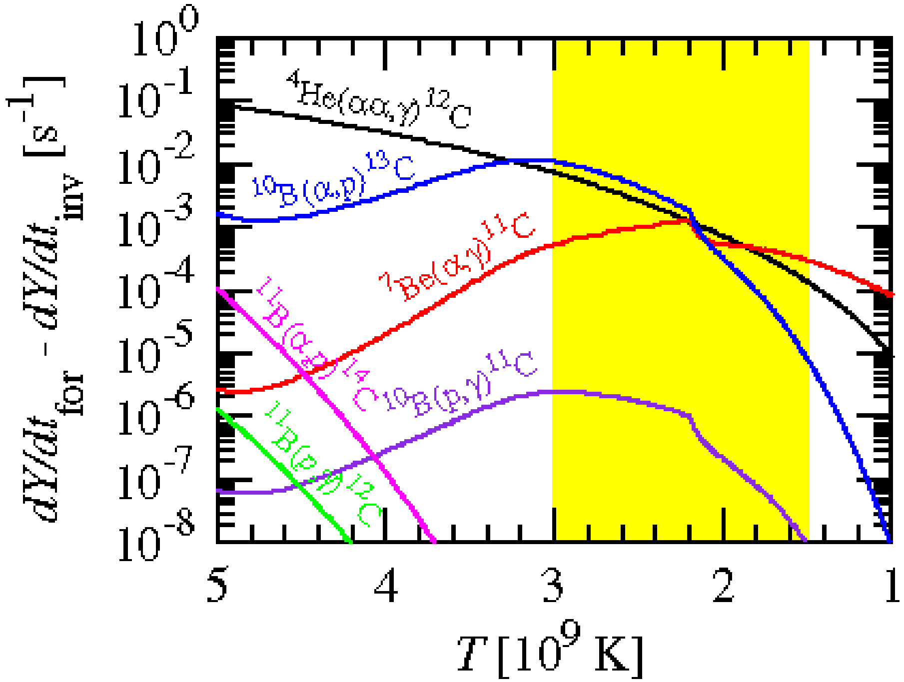


Wiesher *et al.*(1986)



^{7}Be(α,γ) in supernovae

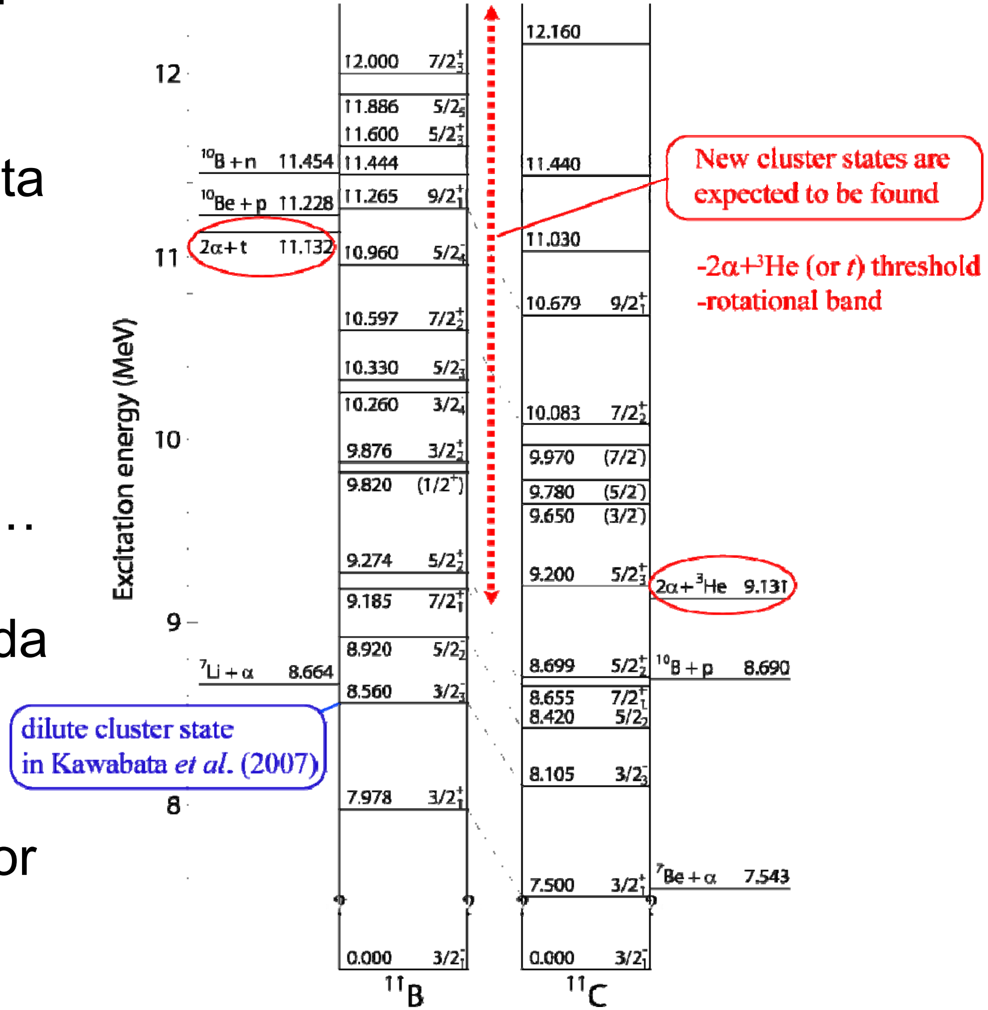
νp-process calculation (T_9>1) shows considerable contribution by ^{10}B(α,p)^{13}C and ^{7}Be(α,γ)^{11}C as much as the triple-alpha process.



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

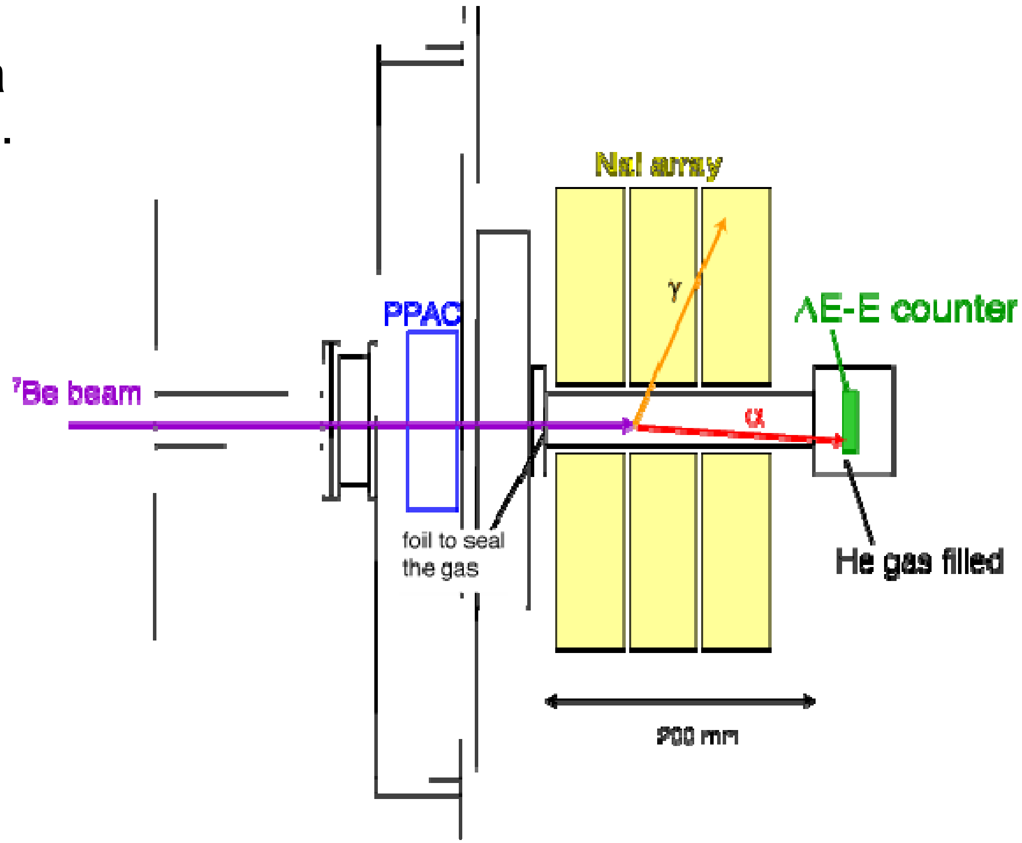
Exotic cluster structure

- $2\alpha+t$ / $2\alpha+{}^3$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 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



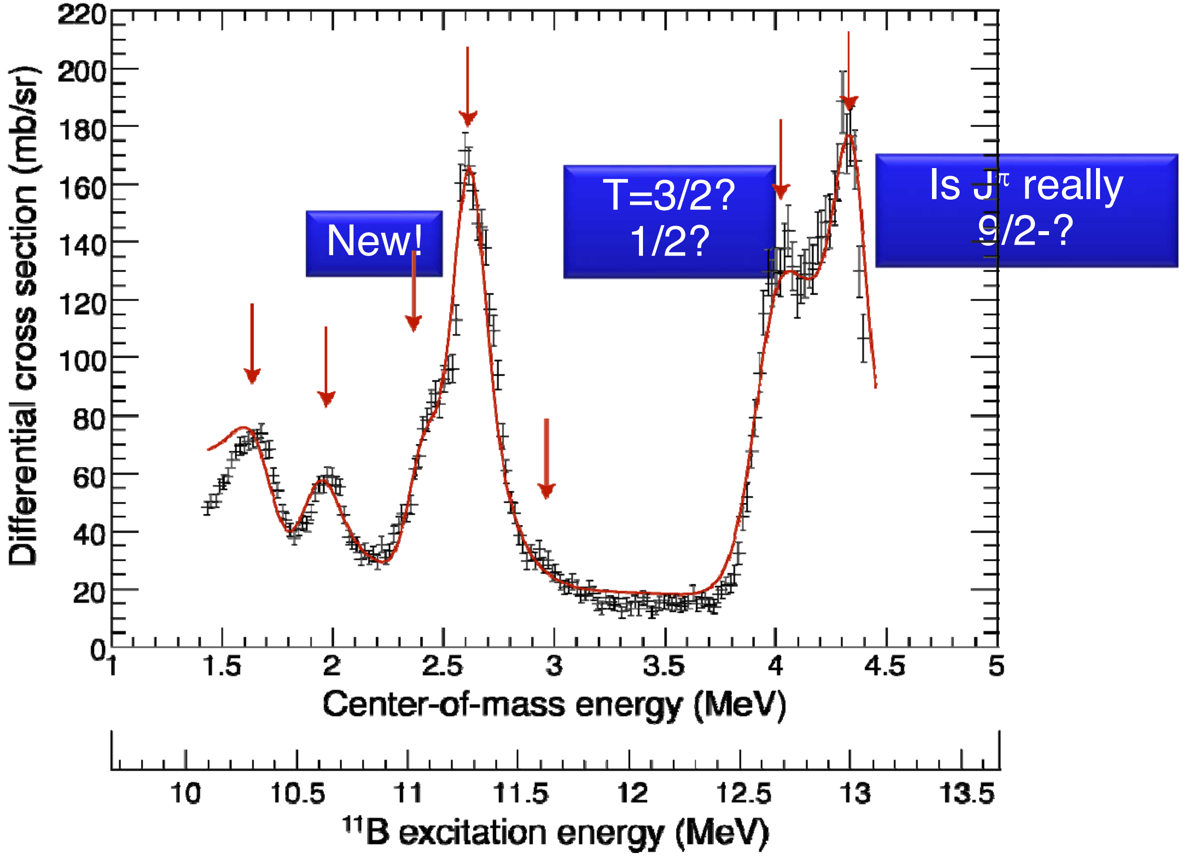
Setup for ^{7}Li/^{7}Be+α

- 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).*



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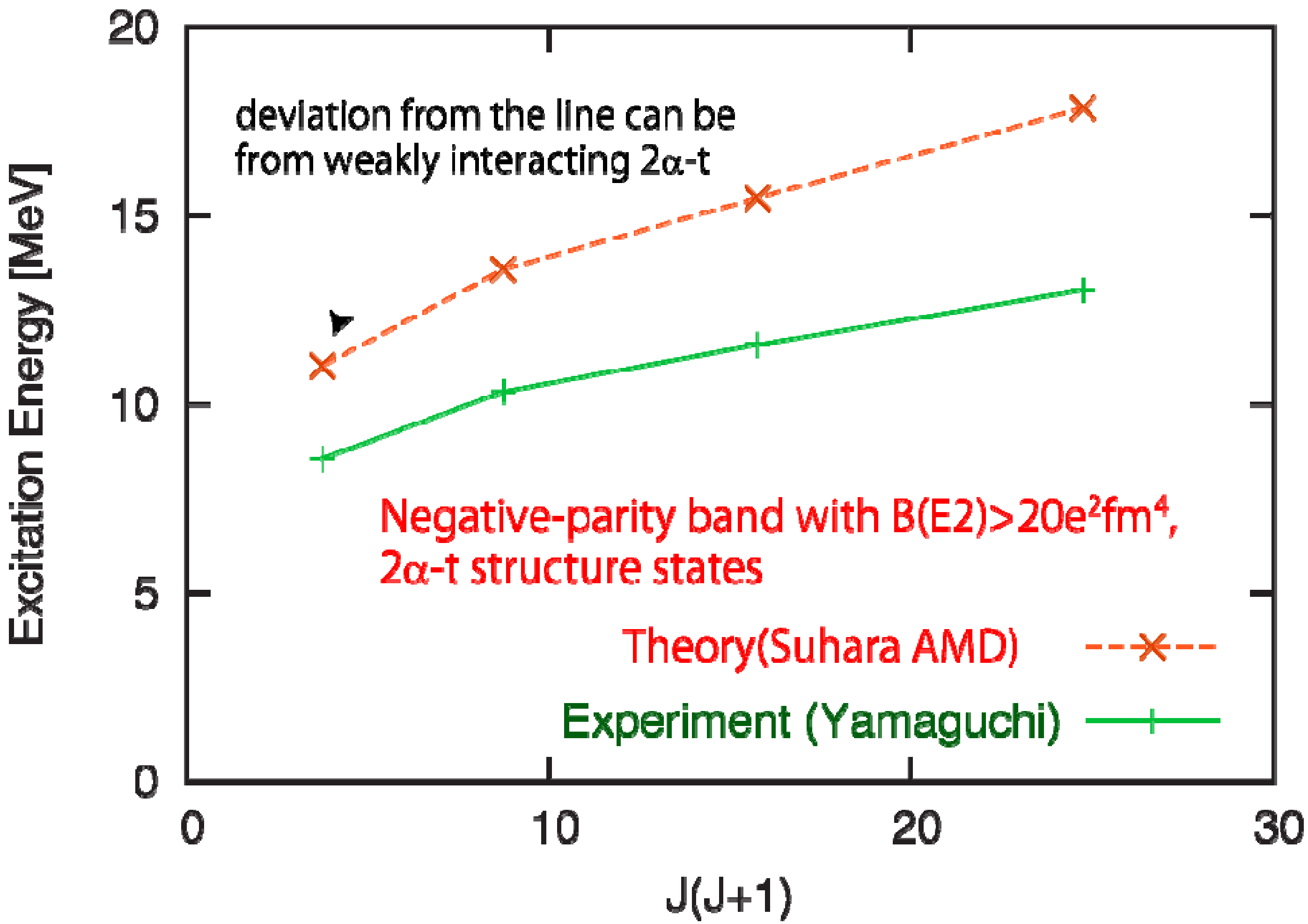
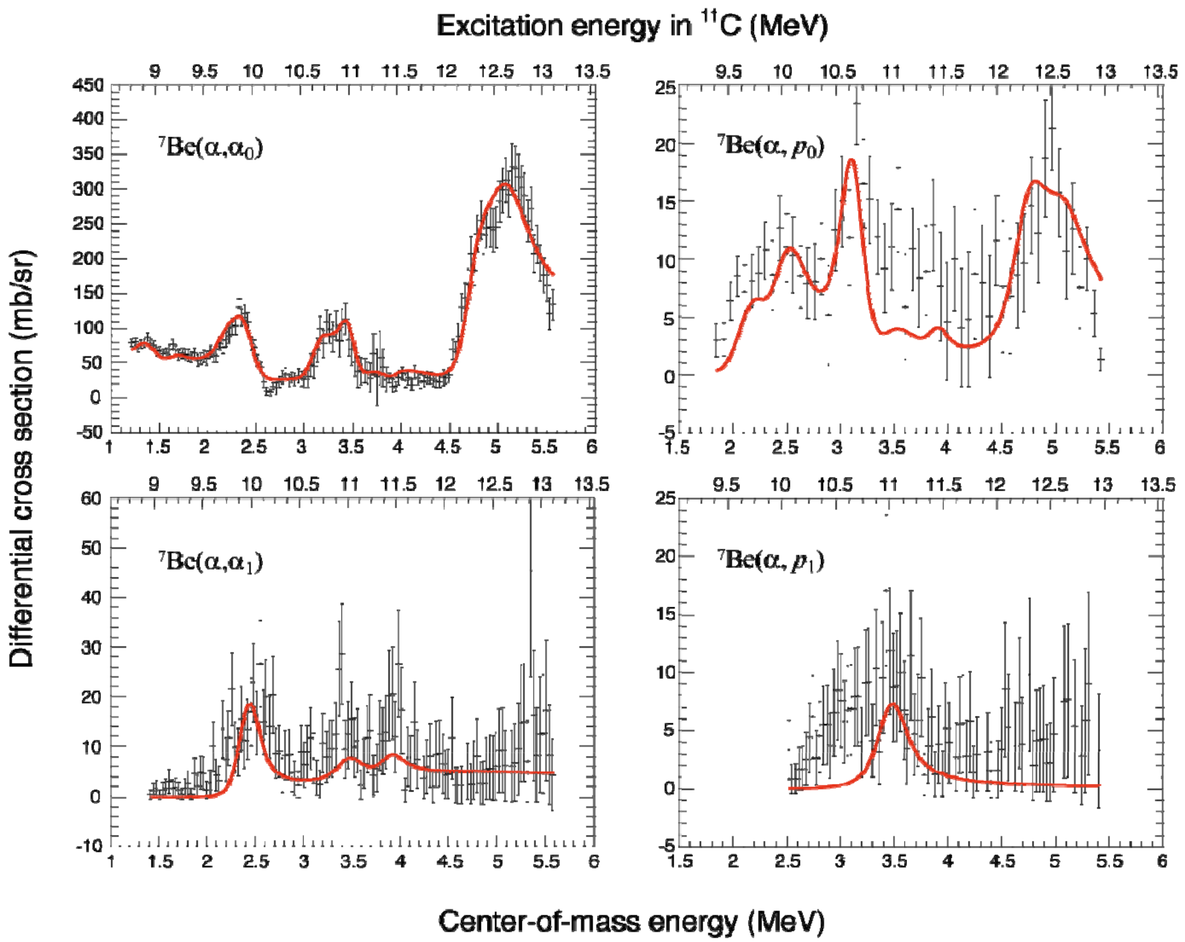
Interpretation of the new negative-parity band

Suhara & En'yo PRC (2012)



$^{7}Be+\alpha$ Excitation functions

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



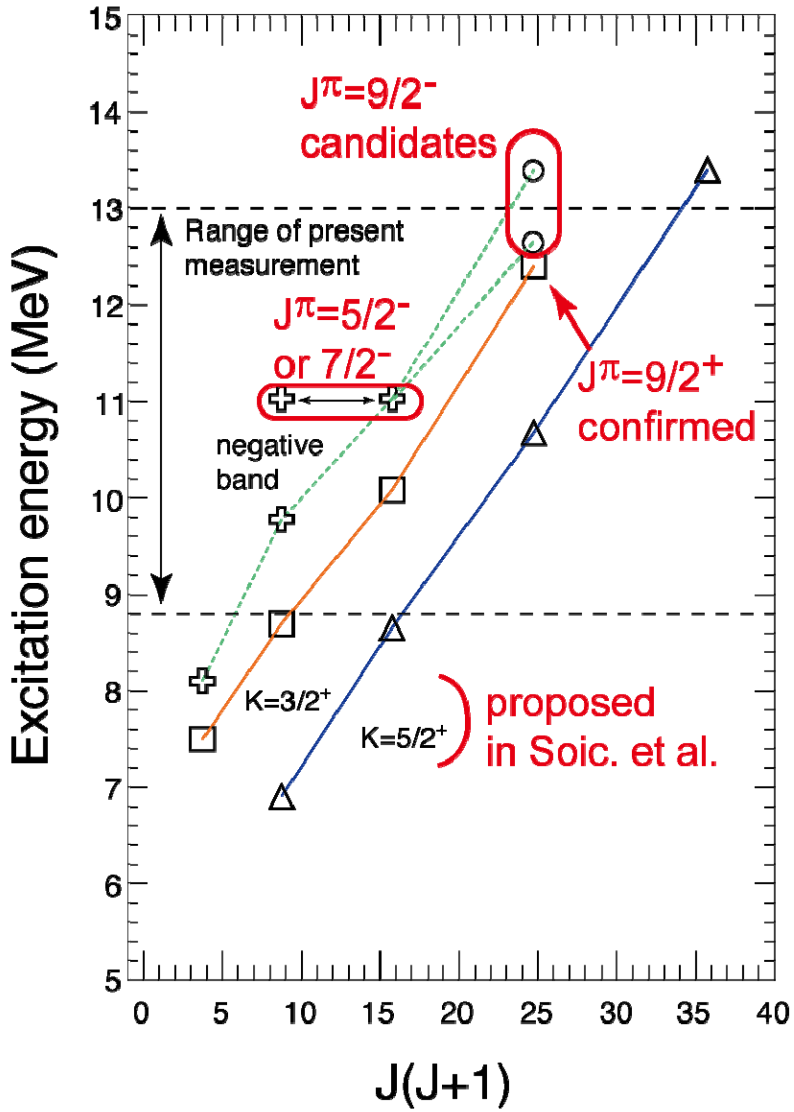
^{7}Be+α; level parameters

TABLE I. Best-fit resonance parameters of ^{11}B determined by the present work. The E_{ex} and J^π values shown in italic letters were fixed to those in [36,38], and the others are proposed in the present work. See text for other possible J^π assignments.

E_{ex} (MeV)	J^π	$l_{\alpha 0}$	$\Gamma_{\alpha 0}$ (KeV)	Γ_{p0} (KeV)	$\Gamma_{\alpha 1}$ (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

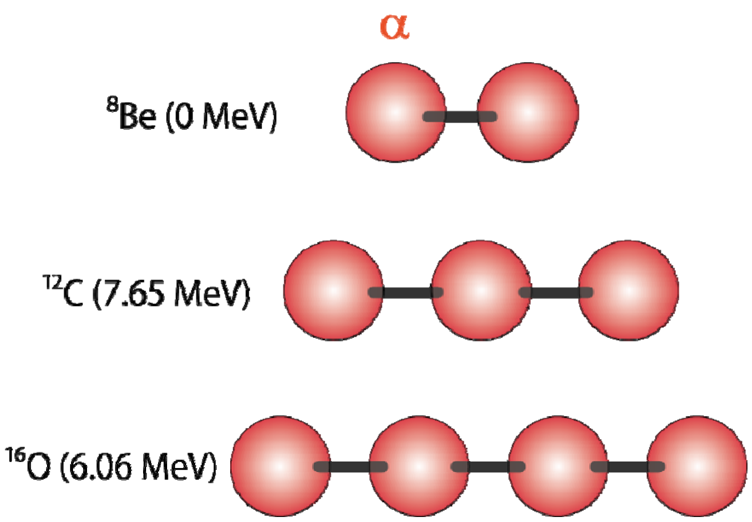
(Rotational) bands in ^{11}C

- 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.



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.

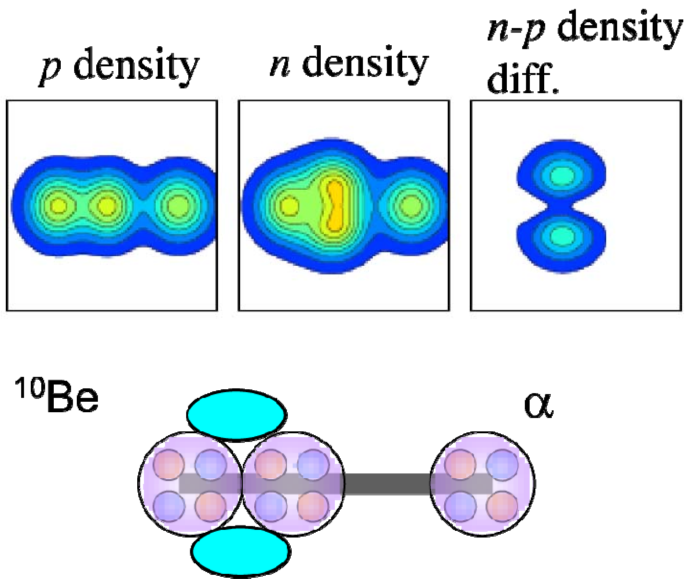


- It was shown in later studies that the Hoyle state is NOT a linear-chain state.

^{10}Be+α

- Linear-chain cluster levels in ^{14}C were predicted in Suhara & En'yo (2010,2011).
- 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.

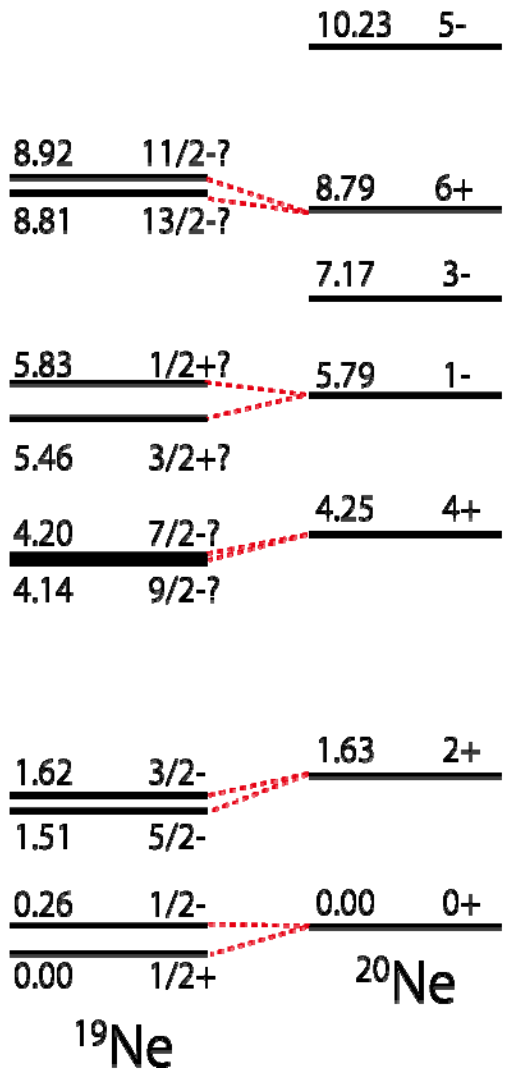
Suhara & En'yo, PRC 2010 and 2011:



^{15}O+α study

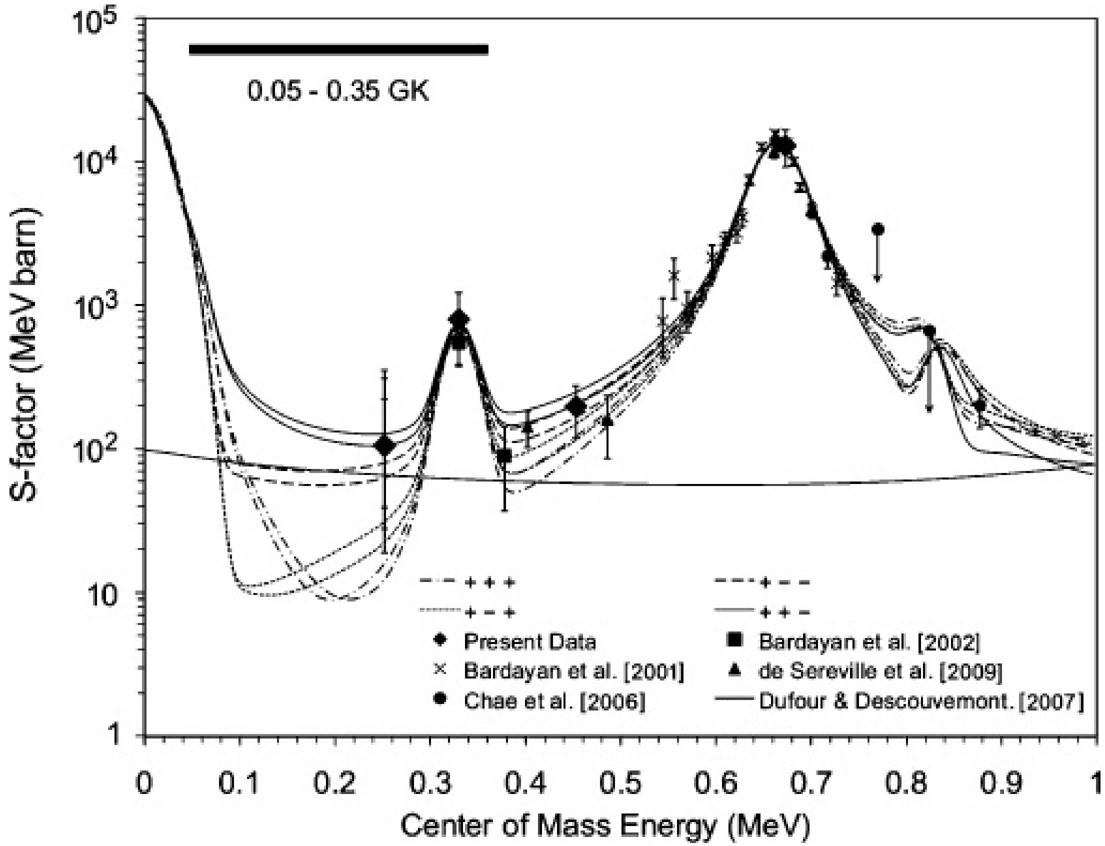
- Rotational band in ^{20}Ne
  - ✓ positive ($0^+, 2^+, \ldots$)& negative($1^-, 3^-, \ldots$)
  - ✓ Corresponding states in doublets expected in ^{19}Ne, which should also have α-cluster feature.

  Nemoto & Bando, PTP (1971).
  - ✓ Many parameters still unknown.
- ^{15}O+α resonant elastic scattering…these levels can be selectively observed.
- However, see Ito-san's discussion



$^{18}F(p,a)$ reaction

- $^{18}F(p, \alpha)$… an important reaction in novae, production of positrons, of which annihilations observed as 511-keV gamma rays.
- ^{19}Ne resonances make relevant contributions.



Future prospects at RIBF

Alpha resonant scattering…main issue is the beam energy.

- CRIB…very suitable machine (<10 MeV/u).
- RIPS…proton resonant scattering exp. by N. Imai et al.,

Isobaric analog resonances of the *N* = 21 nucleus 35Si [*Phys. Rev. C, 085 034313 (2012)*]… 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 >>100MeV/u is not favored). Beam intensity is another key issue.

More are involved in resonant scattering

Previously (~10 years ago) not many groups are working on this method: Russia (Goldberg), Florida(Rogachev), CNS-CRIB, and few others. Mostly with stable beams.

More competitive situation:

Birmingham (Charissa collaboration),

Texas A&M (where Rogachev is now),

MSU with Notre Dame,

INFN, Catania and Padova (Italy).

…CRIB still has an advantage in the beam intensity and energy, but efforts must be spent to perform really unique experiments!

Summary

- Alpha resonant scattering is a striking method for the

α-cluster structure study.

  - ✓ Go together well with Thick Target with Inverse Kinematics, when RI beam is used.

- Studies 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. ^{15}O+α (^{19}Ne), Comparison with ^{20}Ne cluster, astrophysical ^{18}F(p, α) reaction

Many more unexplored nuclei. New ideas based on theoretical investigation are welcomed!

- α–transfer…another method to study α-clusters, which could be extensively used in the future.