Nuclear Astrophysics with low-energy RI beams

Lecture by

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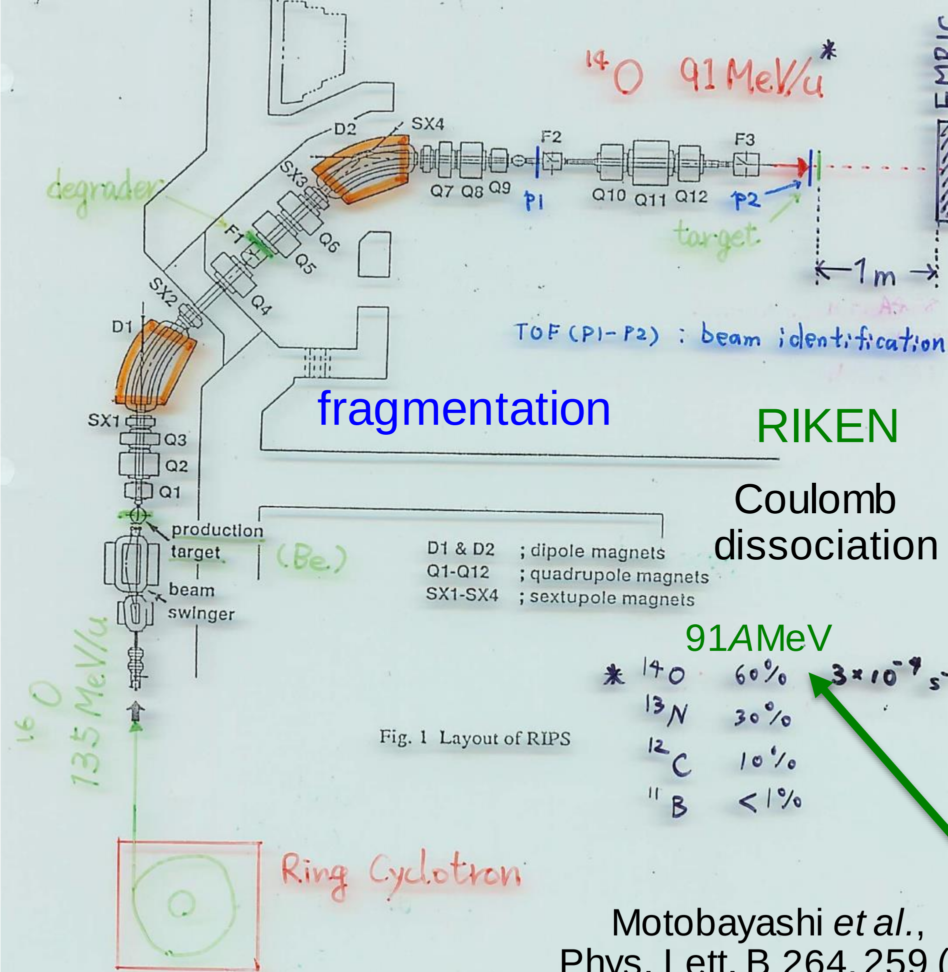
Lecture #2

- How to perform RI beam experiments for astrophysical reactions?

- One method: thick target method in inverse kinematics
  - ◆Principle
  - ◆Application ^{7}Be+α, ^{25}Al+p, ^{10}Be+α

Louvain la Neuve

$^{13}N + ^{1}H \rightarrow ^{14}O + \gamma$



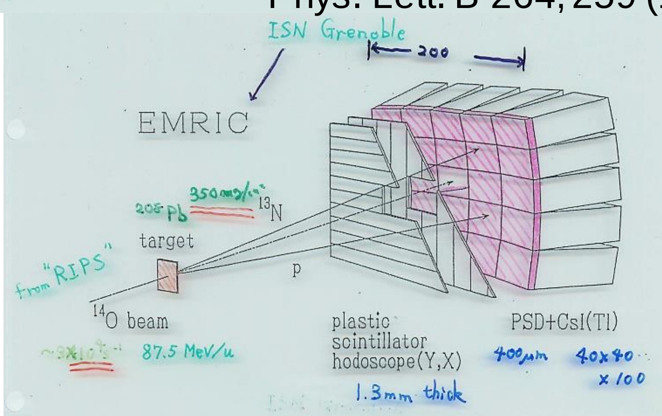
fragmentation

RIKEN

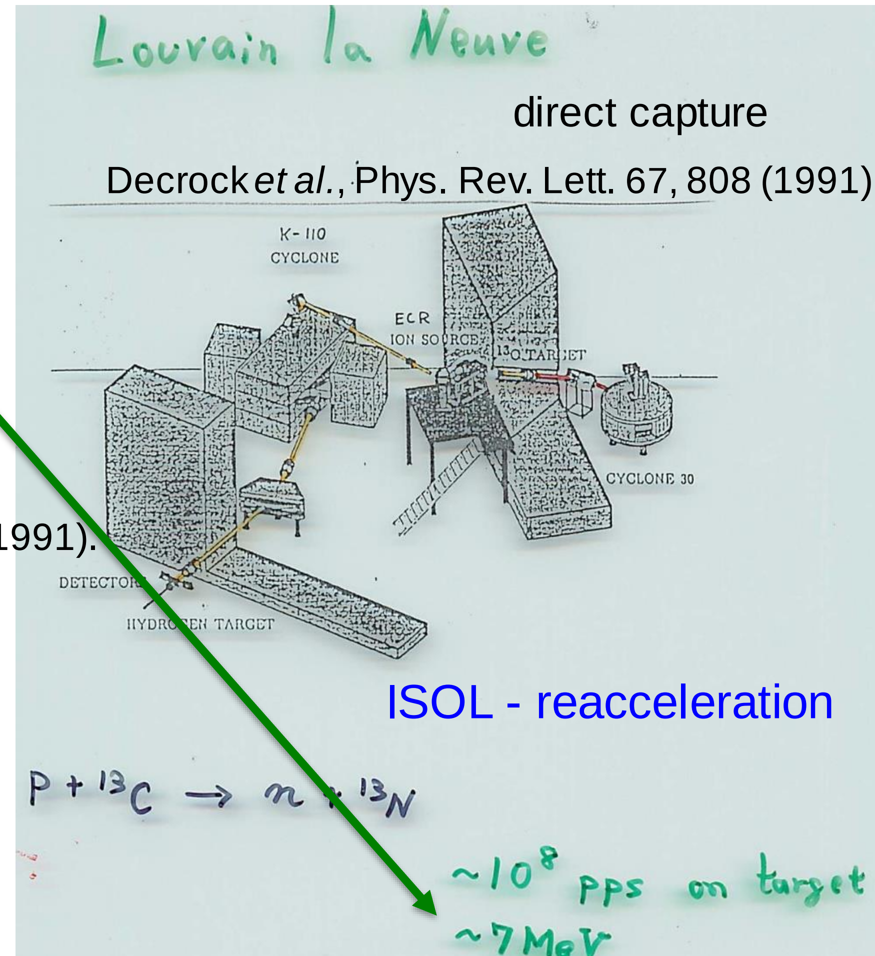
Coulomb dissociation

91*A*MeV

Motobayashi *et al.*,
Phys. Lett. B 264, 259 (1991).



RIKEN
$^{14}O + Pb \rightarrow$
$^{13}N + p + Pb$



direct capture

Decrock *et al.*, Phys. Rev. Lett. 67, 808 (1991)

ISOL - reacceleration

Direct measurement of astrophysical (capture) reactions with unstable nuclei…

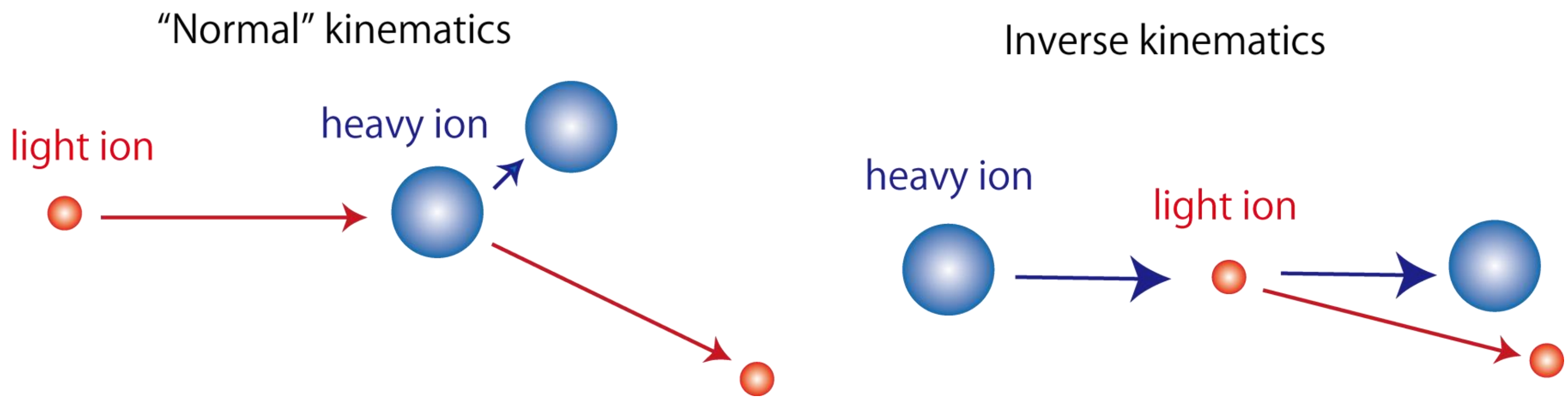
- Works for at least relatively intense RI beams, such as (^{13}N, ^{7}Be).

- But still not easy for others, such as $^{15}O(\alpha, \gamma)$, because of the low RI beam intensity/reaction cross section.

Then, what can we do?

1. Use "indirect" methods (Coulomb dissociation, ANC, Trojan Horse Method, …)
2. Use TTIK (Thick target in inverse kinematics, I will discuss on this)
   - Direct measurement with a thicker target ⇒More efficient measurement.
   - Resonant scattering⇒High cross section (~100 mb/sr), to study resonances.

Inverse kinematics



Features of (ideal) inverse kinematics:

Heavy ion as the beam…keep going forward.

Light ion as the target…tend to be scattered to forward angle (compared to the normal kinematics).

1. Inverse kinematics at RI-beam production…The produced RI is already like a beam (cf. ISOL).

2. Inverse kinematics at scattering/reaction measurement…discussed later.

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

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 $^{15}N + \alpha$.

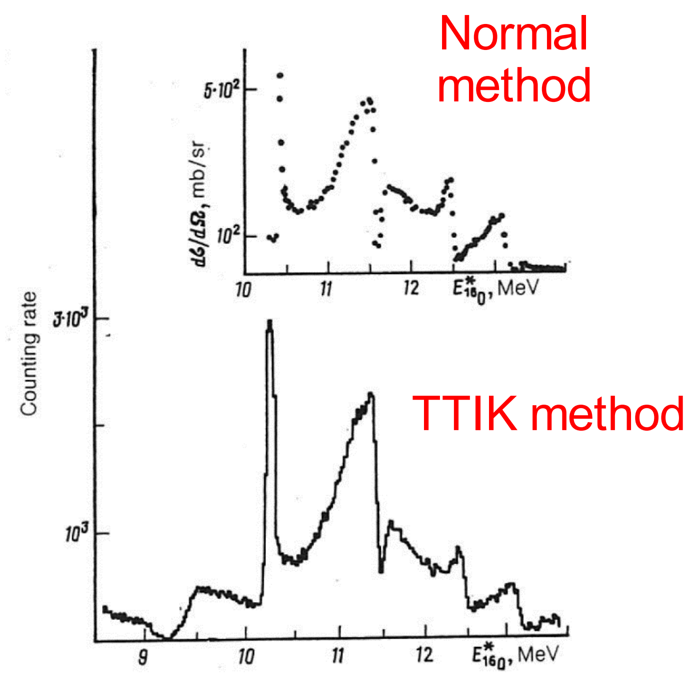
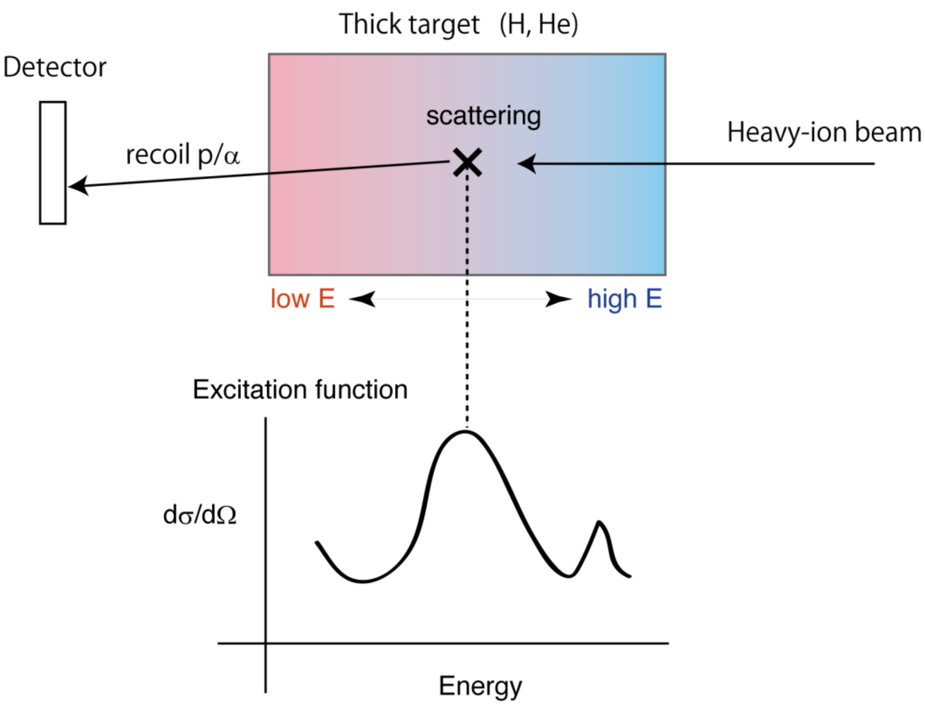


FIG. 1. Spectrum of α particles obtained in interaction of ^{12}C ions with initial energy 28 MeV with helium. The detection angle is 0°. In the insert we have given the excitation function for elastic scattering of α particles by carbon from Ref. 4. The detection angle is 158.8°.

The thick-target method in inverse kinematics

Measurement of resonance scattering

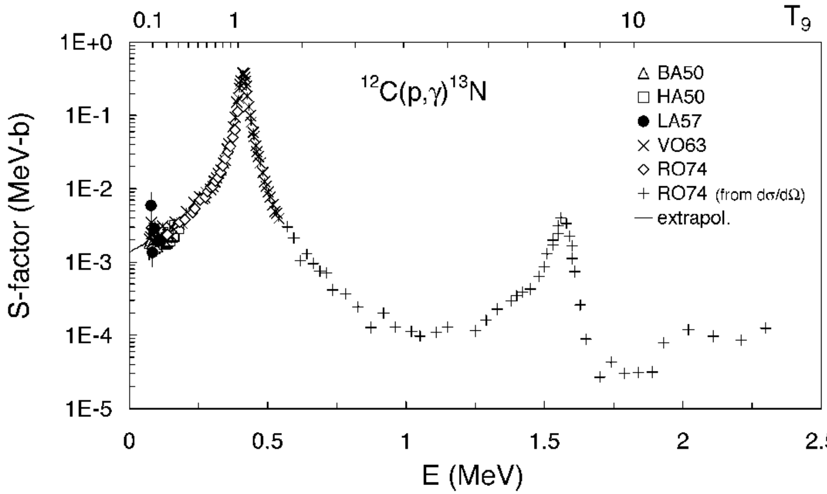


- Measurement is possible for short-lived RI which cannot be used as the target.
- $E_{cm}=E_{beam}*A_t/(A_p+A_t) \ll E_{beam}$

  Measurement can be at low energy with high resolution.
- Simultaneous measurement for a certain energy range.(No need to change beam energy.)
- The beam can be stopped in the target…measurement at $\theta_{cm}=180^{o}$ is possible.

Resonant reaction

- Sometimes the reaction is dominated by resonant reactions.
- We only need to know resonance parameters (E, Γ, J^{π}) and apply the resonant reaction formula:



$$\sigma(E) = \pi \bar{\lambda}^2 \frac{2J+1}{(2J_1+1)(2J_2+1)}(1+\delta_{12})\frac{\Gamma_a \Gamma_b}{(E-E_0)^2+(\Gamma/2)^2}$$

$$\sigma(E=E_0) \propto \frac{\Gamma_a \Gamma_b}{\Gamma^2}(\text{max.c.s.}),\ \int_0^{\infty}\sigma(E)dE \propto \frac{\Gamma_a \Gamma_b}{\Gamma}(\text{integrated c.s.}).$$

If $\Gamma_a \ll \Gamma_b$, the integrated c.s. $\propto \Gamma_a \Gamma_b/(\Gamma_a+\Gamma_b) \sim \Gamma_a$

($\Gamma_\gamma \ll \Gamma_p$ for low-energy (p,γ) reactions.)

Breit-Wigner formula

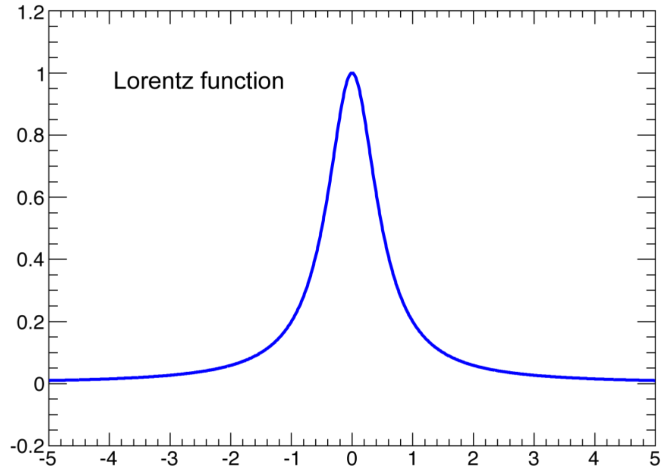
- Atomic Breit-Wigner:

  Lorentz function

$$I(E) \propto \frac{1}{(E-E_0)^2 + (\Gamma/2)^2}$$

E_0 : transition energy

Γ : natural width ($2\pi\Gamma = \tau^{-1}$)



- Breit-Wigner for nuclear resonant reaction:

$$\sigma(E) = \pi\lambda\!\!\!^{-}{}^2 \frac{2J+1}{(2J_1+1)(2J_2+1)}(1+\delta_{12})\frac{\Gamma_a\Gamma_b}{(E-E_0)^2+(\Gamma/2)^2}$$

$\lambda\!\!\!^{-}$: de Broglie wavelength

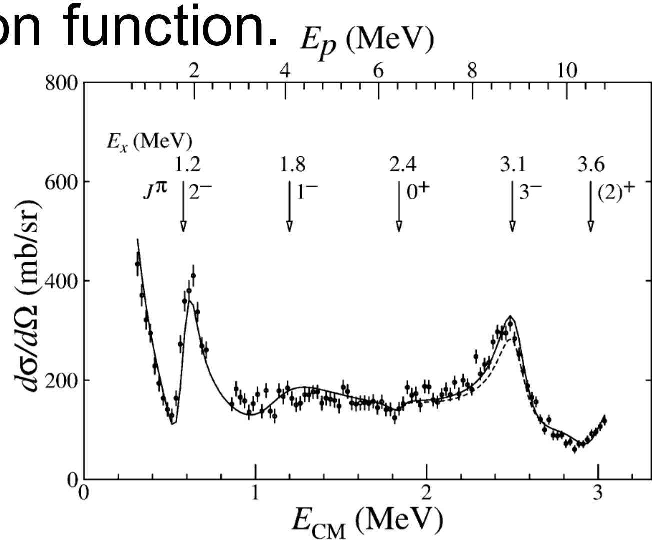
J_1, J_2, J : spins of projectile, target, excited state in the compound nucleus

δ_{12} : 1 for identical particles, 0 otherwise

Γ_a, Γ_b : Widths of entrance and exit channels

Resonant elastic scattering

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

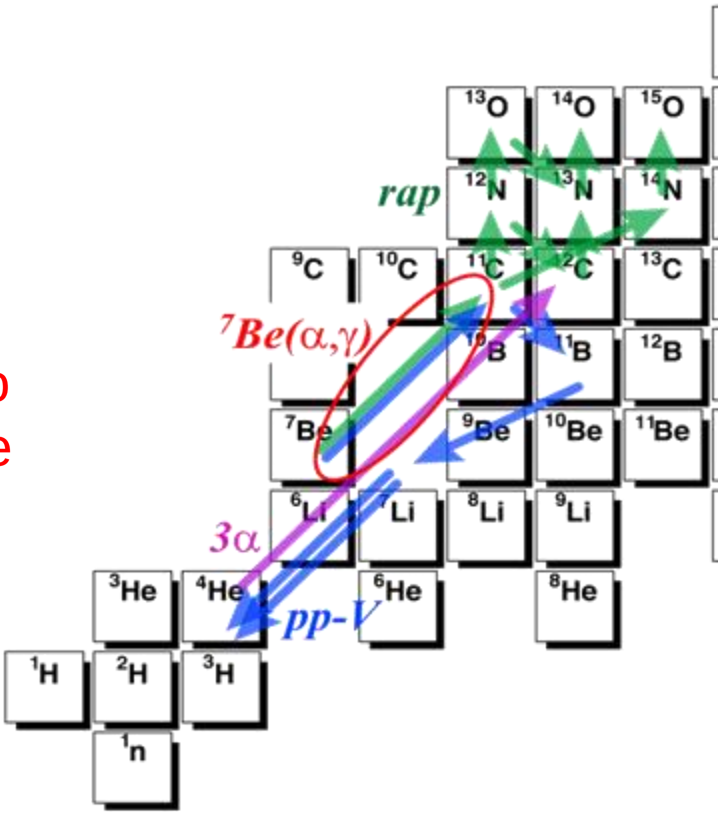


T. Teranishi et al. / Physics Letters B 556 (2003) 27–32

^{7}Li+α/ ^{7}Be+α study

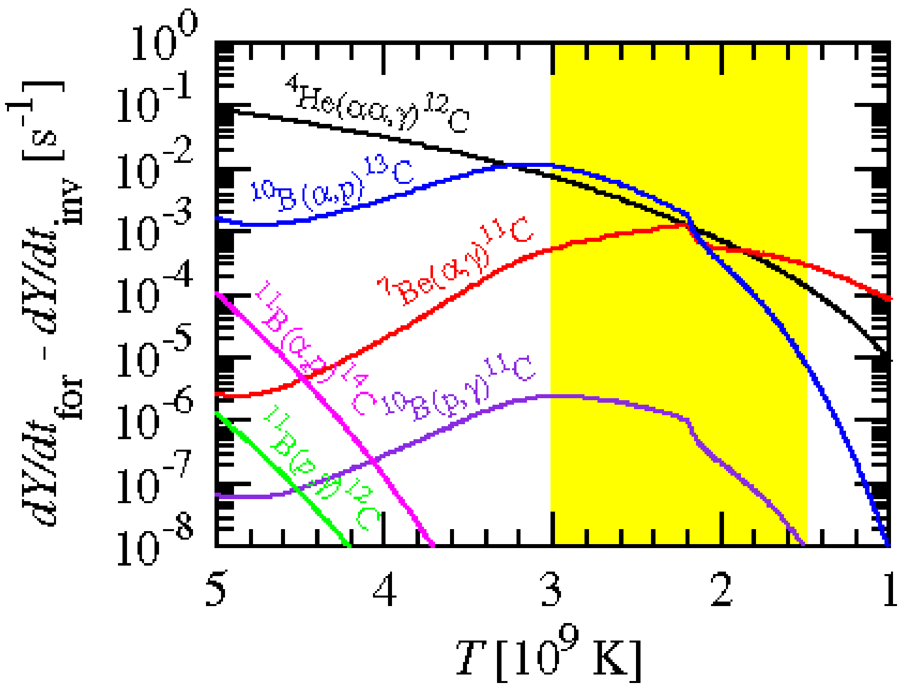
- $^7Li(\alpha,\gamma)^{11}B$ …important at high-T, as a production reaction of ^{11}B (the ν-process in core-collapse supernovae).
- $^7Be(\alpha,\gamma)^{11}B$ … one of the reaction in hot *p-p* chain, relevant at high-T.

- α-cluster structure in ^{11}B/^{11}C :
  - 2α+*t* / 2α+^{3}He cluster states are known to exist (similar to the dilute cluster structure in ^{12}C.)
  - Several "bands" which have α-cluster structure could be formed. We can study the band and cluster structure more in detail.



$^{7}Be(\alpha,\gamma)$ in supernovae

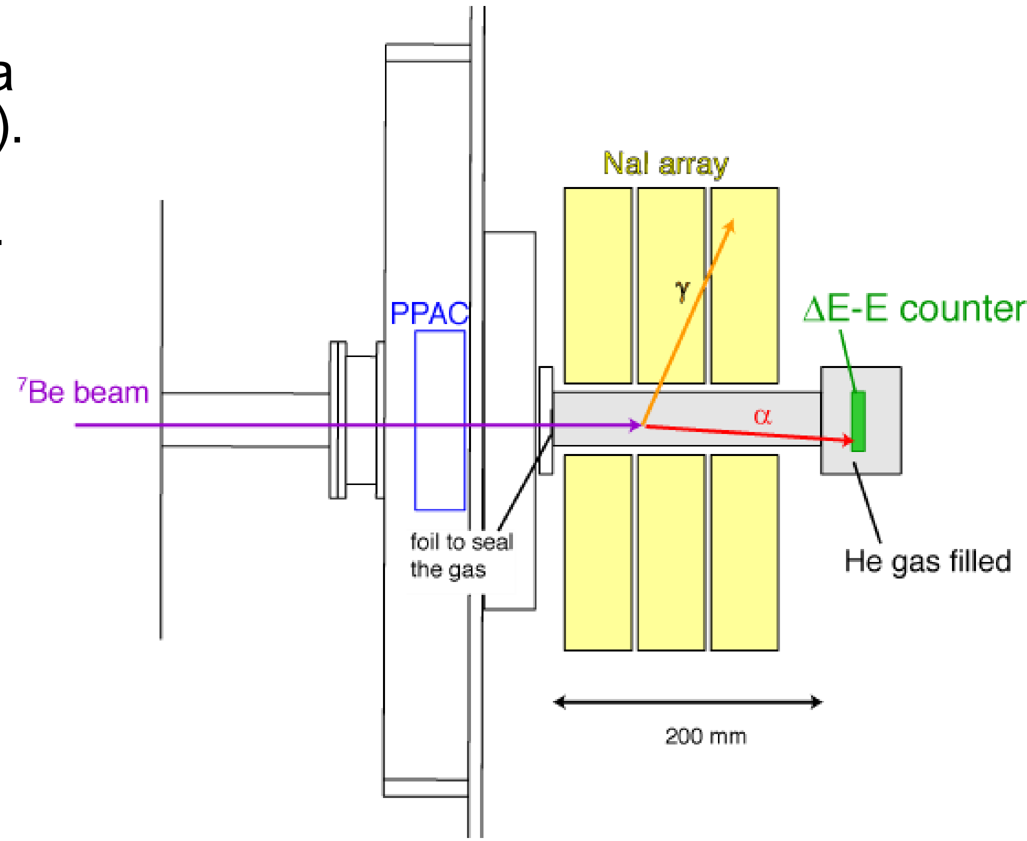
νp-process calculation (T_9>1) shows considerable contribution by $^{10}B(\alpha,p)^{13}C$ and $^{7}Be(\alpha,\gamma)^{11}C$ as much as the triple-alpha process.



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

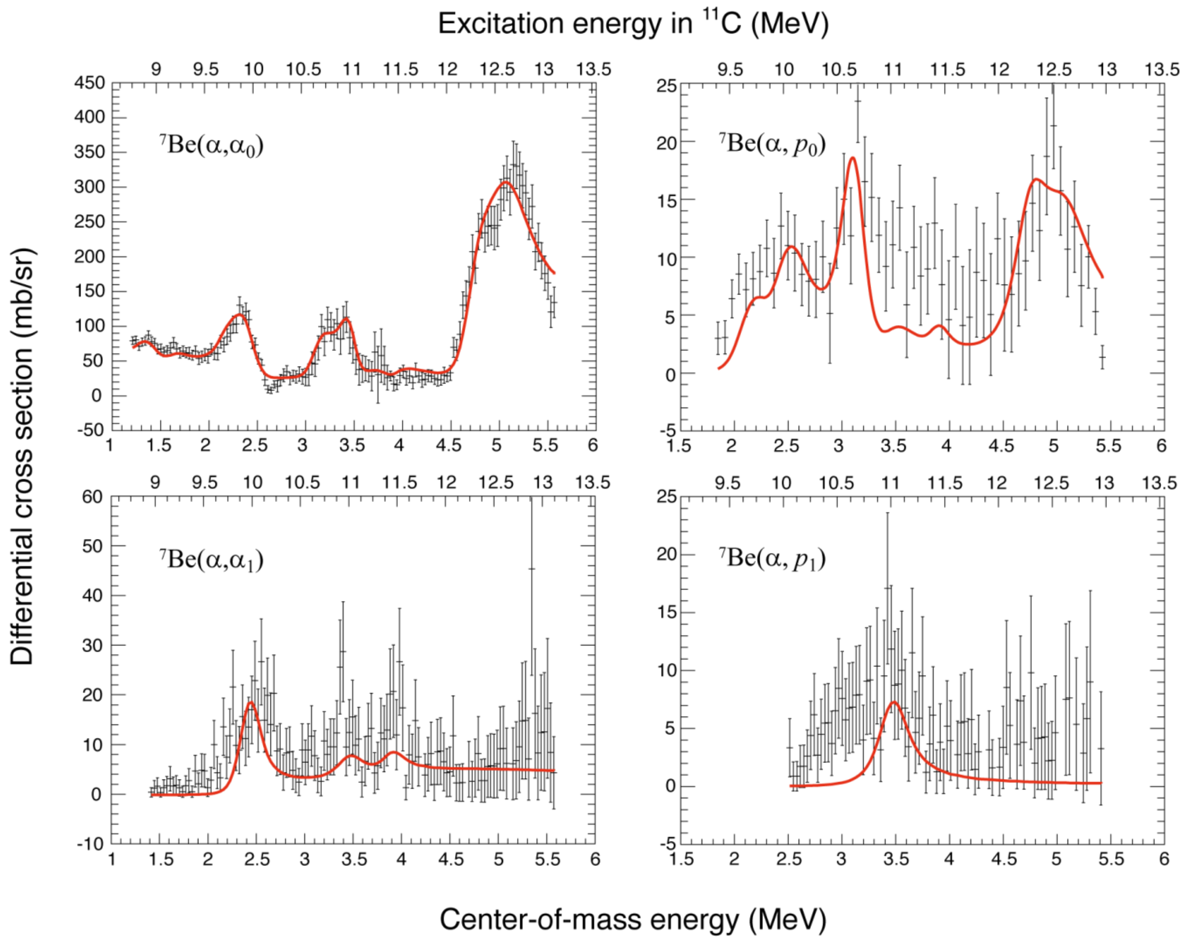
Setup for ^{7}Li/^{7}Be+α

- 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}Be+α Excitation functions

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



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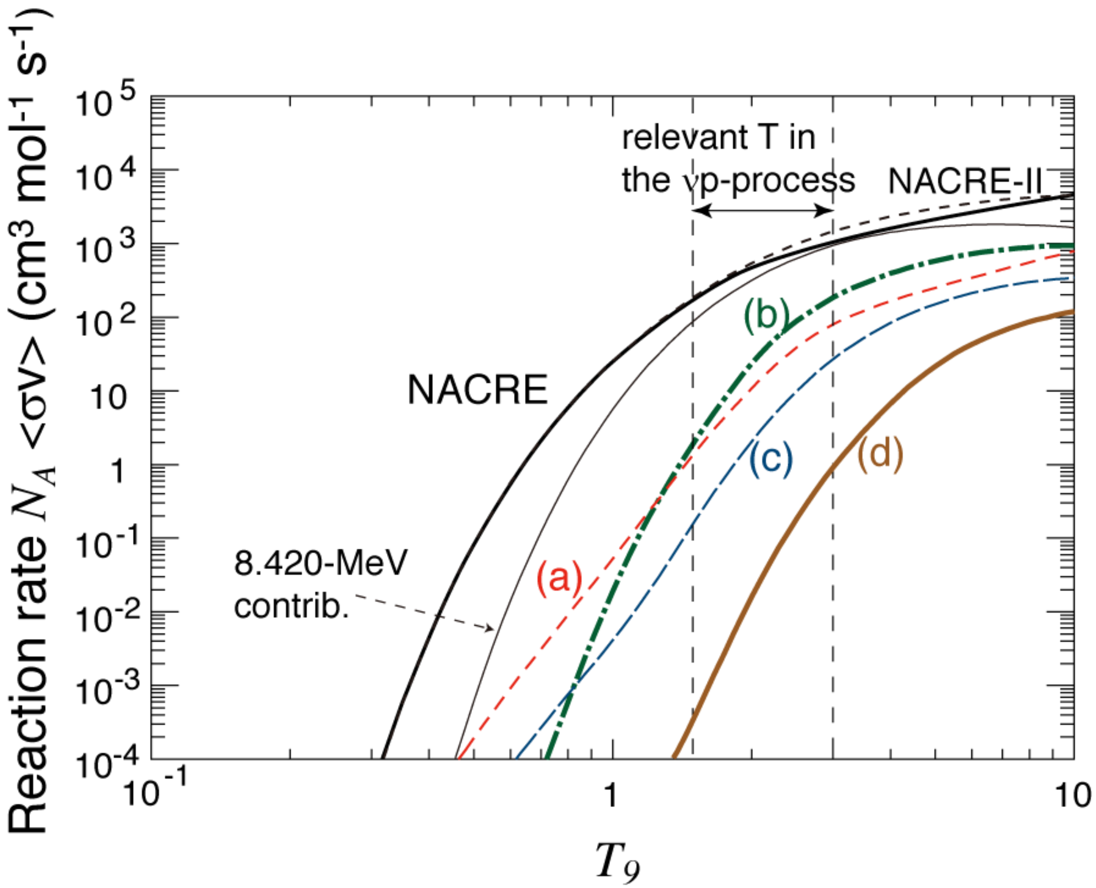
Resonant contribution to $^7Be(\alpha,\gamma)$

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



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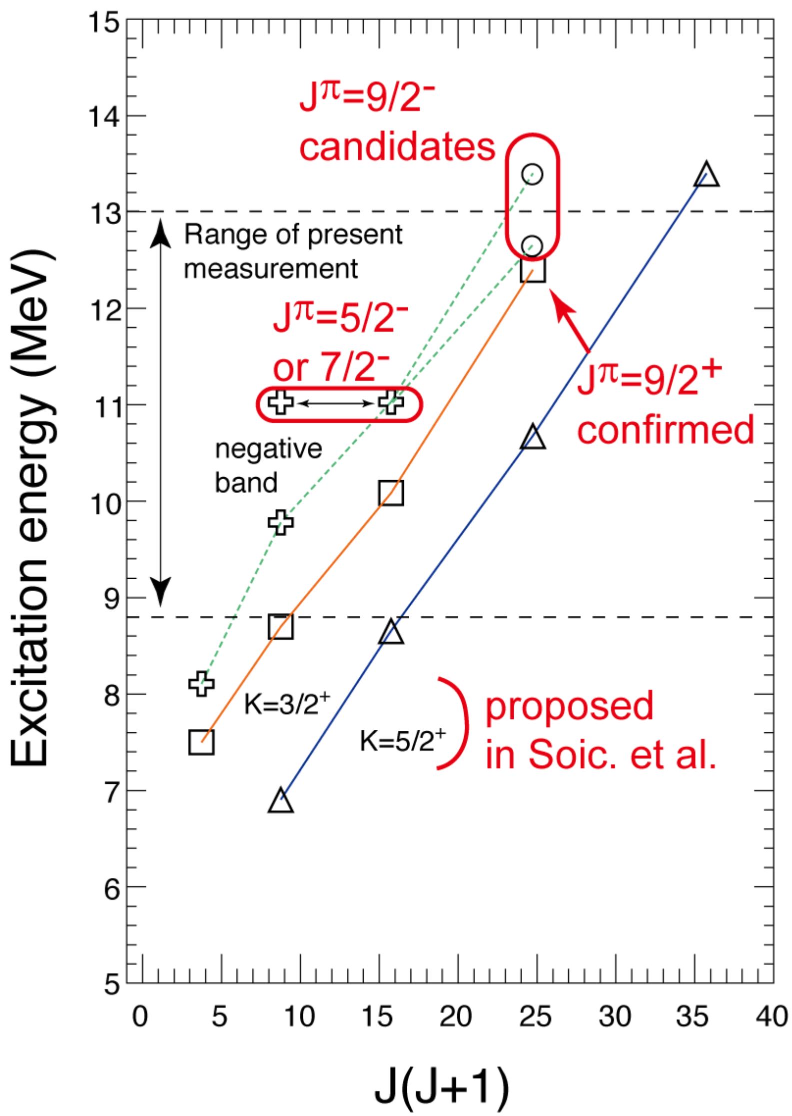
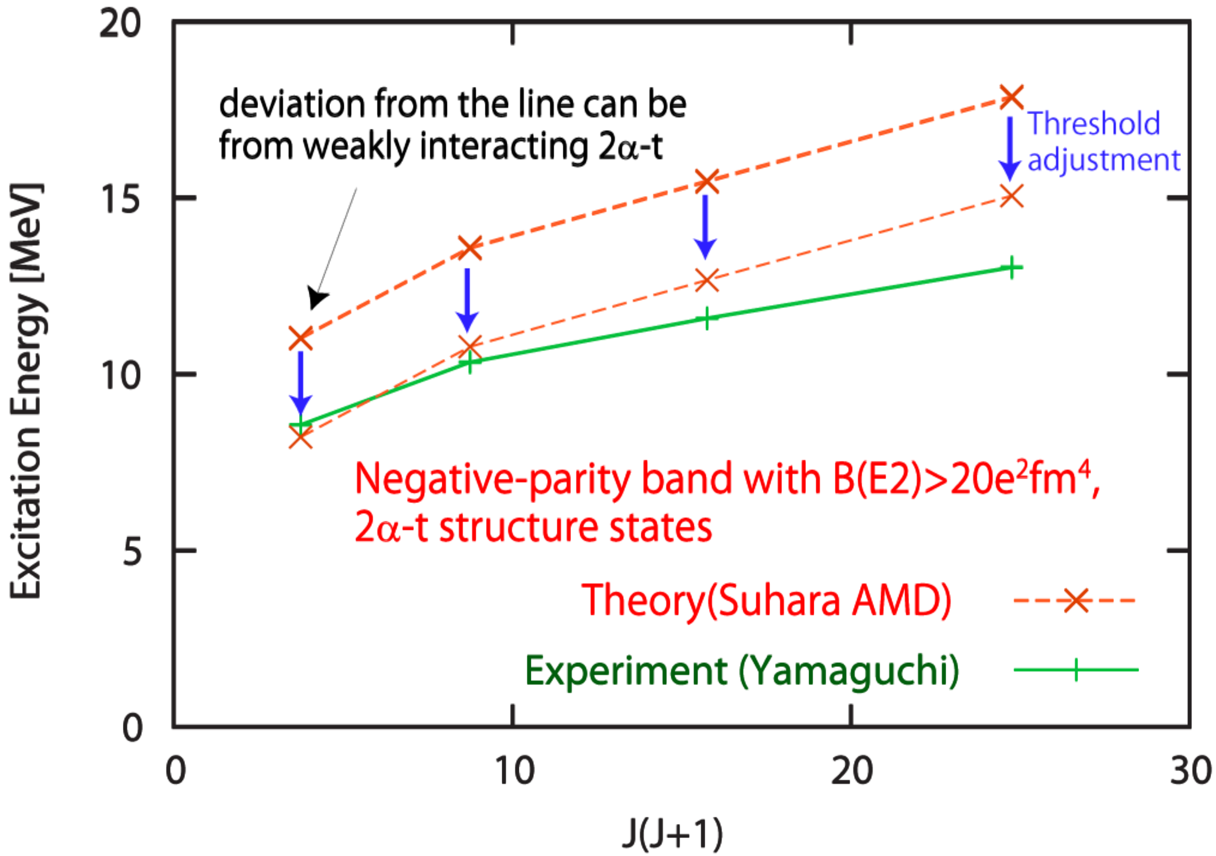
(Rotational) bands in ^{11}C

- 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.



The mirror: Interpretation of the negative-parity band ^{7}Li+α=^{11}B

Suhara & En'yo PRC (2012)



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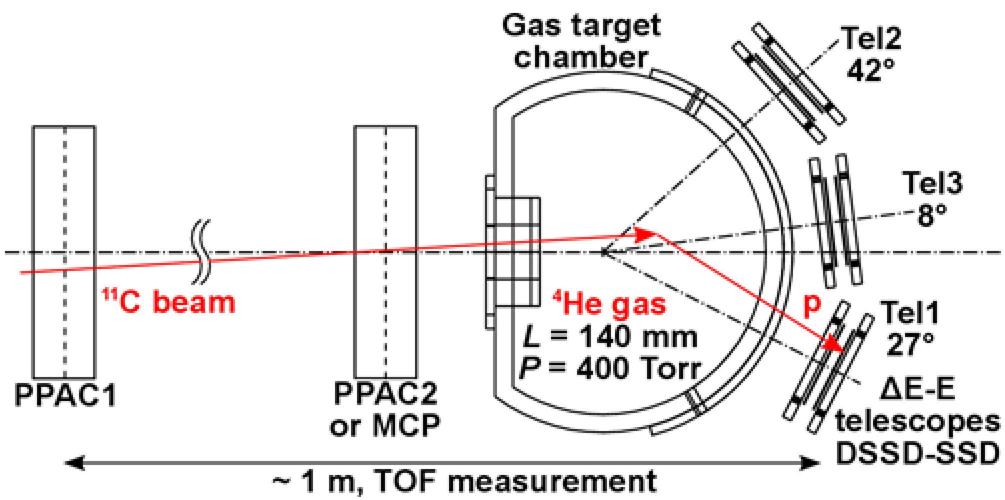
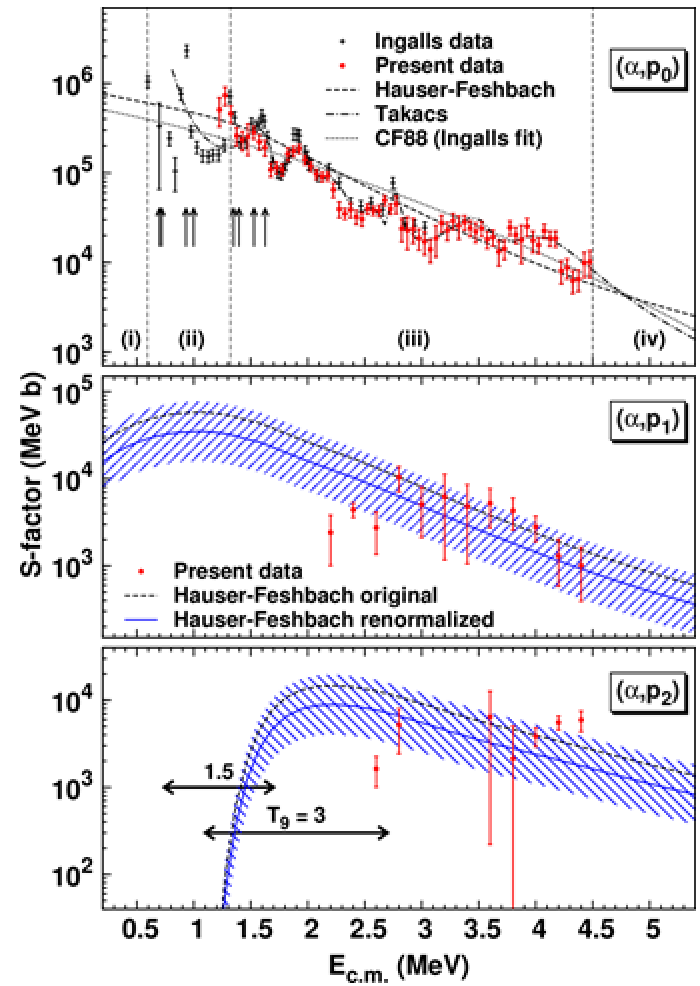
Direct measurement of (α, p) reactions

- $^{11}C(\alpha,p)^{14}N$@CRIB [S. Hayakawa et al., PRC **93**, 065802, (2016)]

An important alpha-induced reaction as a bypass of the 3α process in explosive hydrogen-burning processes.

Reactions to excited levels identified by TOF information





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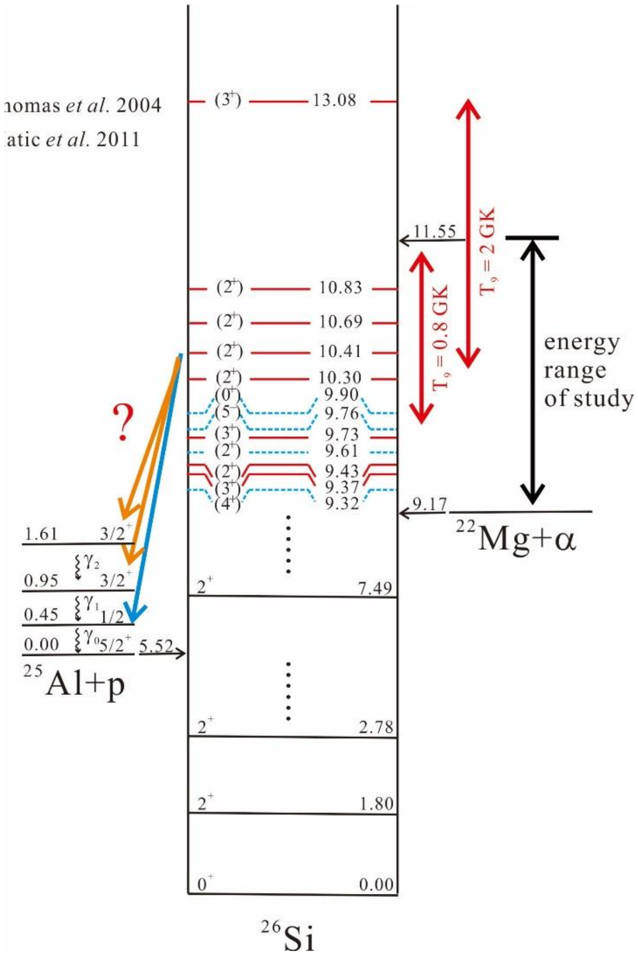
Limitation of the TTIK for astrophysical reaction studies

- Resonant scattering: Very striking experimental method available even with kHz-order RI beams (thanks to the large cross section) and suitable for resonance search, however,…
  - We cannot access the low energy close to the threshold where the Coulomb scattering dominates.
  - Γ_α or Γ_p can be determined (if they are large), but we need another partial width (such as Γ_γ) to determine reaction cross section.
- Direct reaction:
  - Still the yield may not sufficient for capture reactions at low-T, but we can study (α, p) reactions at explosive stellar environments, for example.
- As a common problem, the reaction/scattering channel we observe must be the dominant one. (i.e. we may have backgrounds by reactions producing the same particle, such as inelastic scattering, break up reaction, and fusion evapolation)…this problem can be solved with an active target.

Idea of exit channel scattering

- $^{22}Mg(\alpha,p)^{25}Al$ reaction study by $^{22}Mg+\alpha$ resonant scattering: resonances just above the $^{22}Mg+\alpha$ threshold cannot be accessed, due to the dominance of Coulomb scattering
- $^{22}Mg(\alpha,p)^{25}Al$ reaction study by $^{25}Al+p$ resonant scattering: Coulomb scattering cross section is low enough at the $^{22}Mg+\alpha$ threshold, we can study resonances



Courtesy of Dr. Hu Jun@IMP

Measurement of ^{25}Al+p elastic scattering relevant to the ^{22}Mg(α,p)^{25}Al reaction

Jun Hu, X.D. Tang, S.W. Xu, L.Y. Zhang, S.B Ma, N.T. Zhang, J.J. He, H. Yamaguchi. K. Abe, S. Hayakawa, L. Yang, H. Shimizu, D. Kahl, T. Teranishi, J. Su. H.W. Wang, B. Guo et al.,

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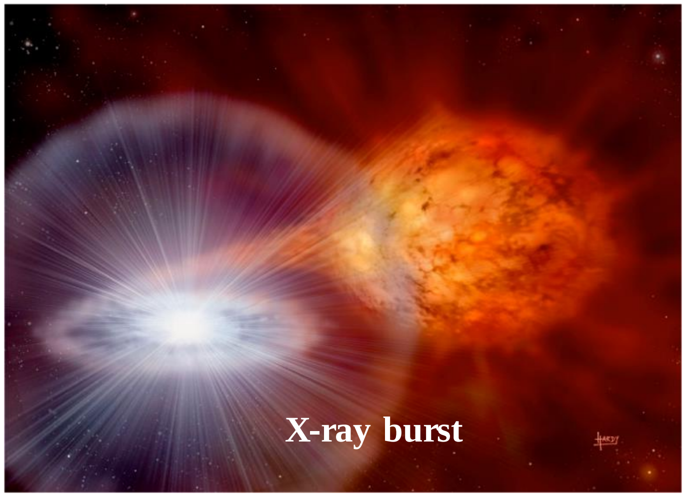
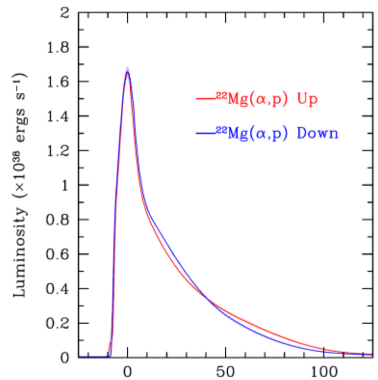
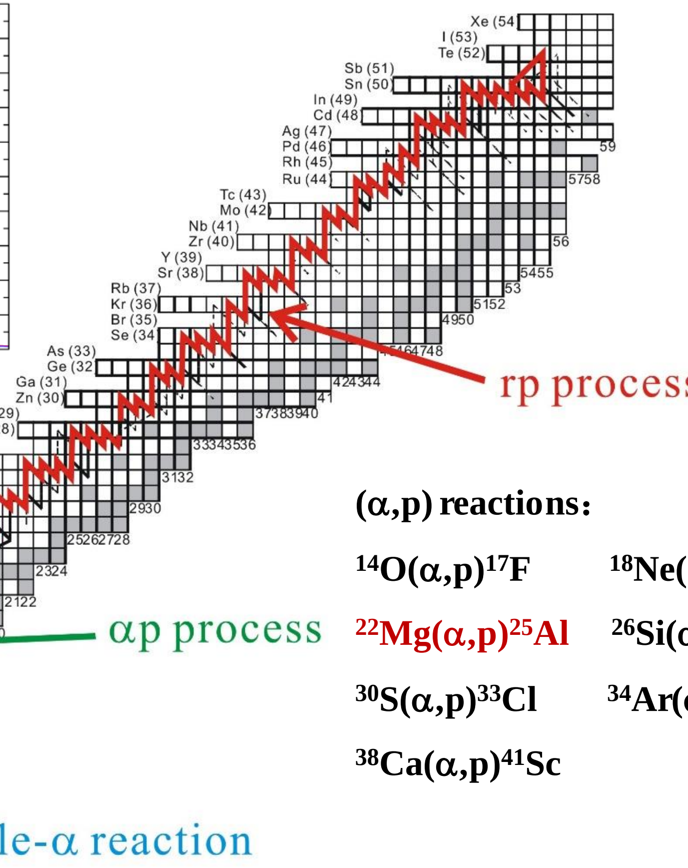
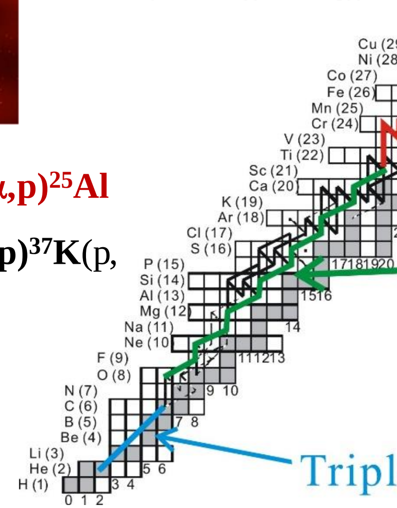
1.1 αp-process in Type I X-ray bursts





^{14}O(α,p)^{17}F(p,γ)^{18}Ne(α,p)^{21}Na(p,γ)^{22}Mg(α,p)^{25}Al(p,γ)^{26}Si(α,p)^{29}P(p,γ)^{30}S(α,p)^{33}Cl(p,γ)^{34}Ar(α,p)^{37}K(p,γ)^{38}Ca(α,p)^{41}Sc

(α,p) reactions:

^{14}O(α,p)^{17}F	^{18}Ne(α,p)^{21}Na
^{22}Mg(α,p)^{25}Al	^{26}Si(α,p)^{29}P
^{30}S(α,p)^{33}Cl	^{34}Ar(α,p)^{37}K
^{38}Ca(α,p)^{41}Sc	

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1.2 Sensitivity study to the light curve of X-ray burst

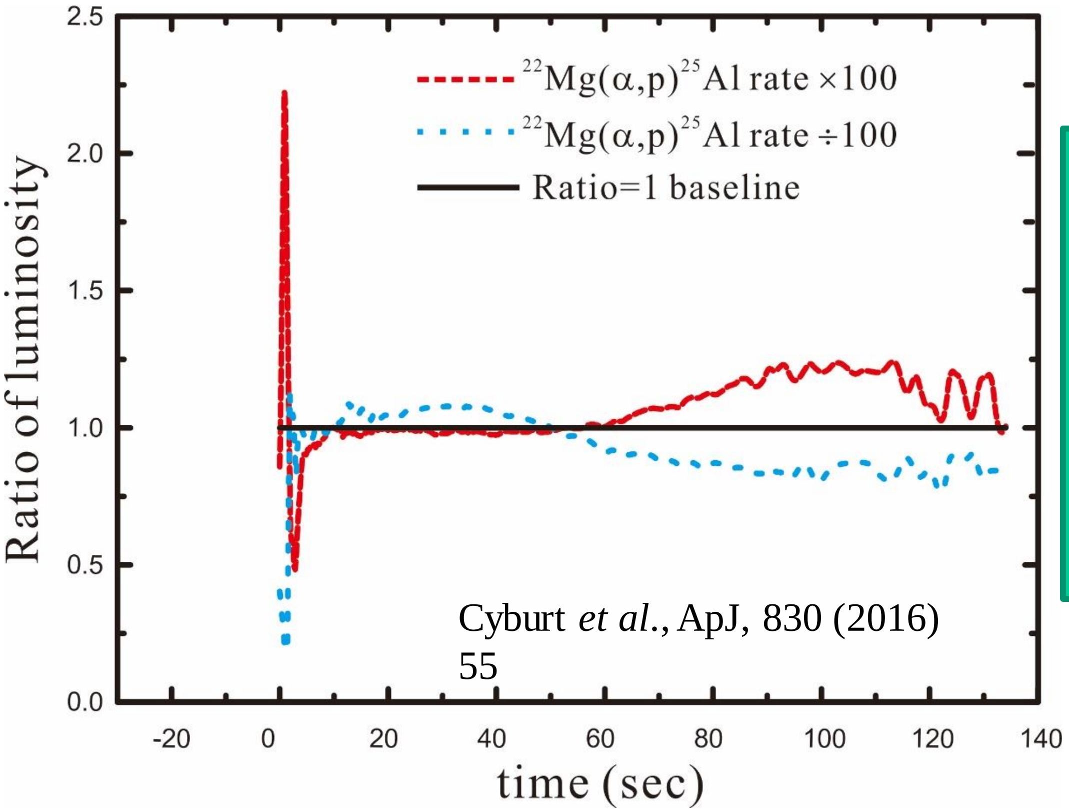
(α, p) reactions that impact the burst light curve in the multi-zone x-ray burst model.

Rank	αp-process reaction	Source of reaction rates adopted by multi-zone model
1.	$^{22}Mg(\alpha,p)^{25}Al$	Non-SMOKER
2.	$^{14}O(\alpha,p)^{17}F$	Hu *et al.* PRC 90 (2014) 025803
3.	$^{18}Ne(\alpha,p)^{21}Na$	He *et al.* PRC 88 (2013) 012801
4.	$^{26}Si(\alpha,p)^{29}P$	Non-SMOKER
5.	$^{30}S(\alpha,p)^{33}Cl$	D. Kahl *et al.* PRC 97 (2018)
6.	$^{34}Ar(\alpha,p)^{37}K$	Non-SMOKER
7.	$^{38}Ca(\alpha,p)^{41}Sc$	Non-SMOKER

Ref: Cyburt *et al.*, ApJ, 830 (2016) 55

$^{22}Mg(\alpha,p)^{25}Al$ could be the most sensitive reaction in the αp-process and may have a prominent impact on the burst light curve.

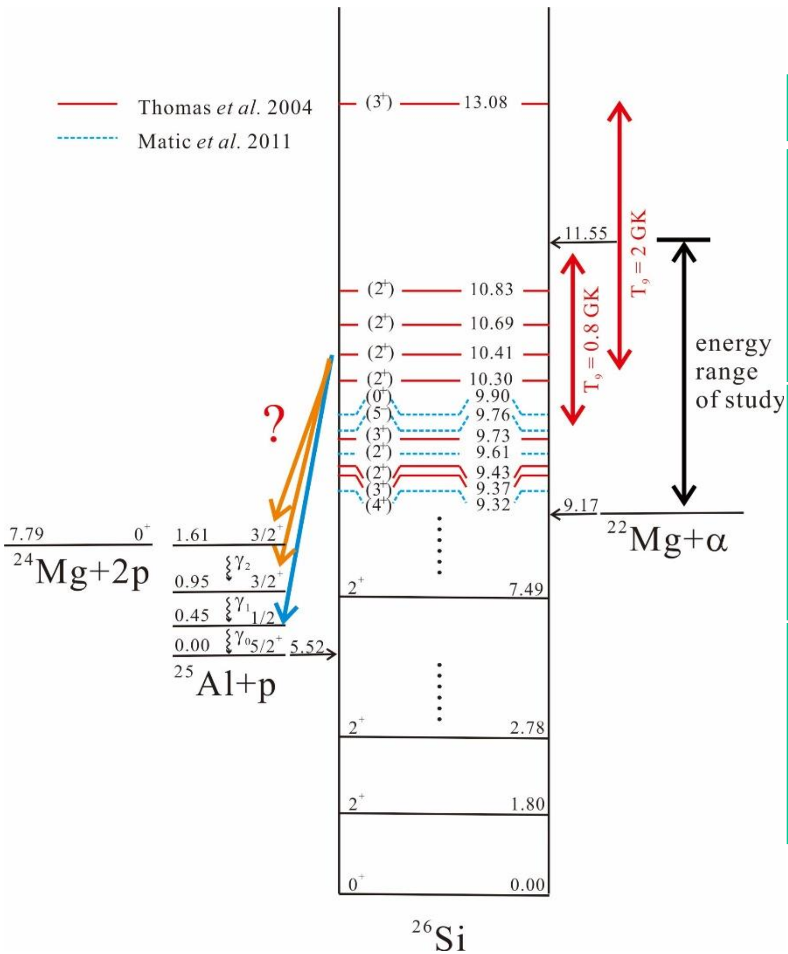
1.3 The effect of $^{22}Mg(\alpha,p)^{25}Al$ on the X-ray burst light curve



The $^{22}Mg(\alpha,p)^{25}Al$ reaction has a sizeable impact on the abundance of ^{22}Na, as well as the isotopic anomalies of $^{20}Ne/^{22}Ne$ ratio found in meteorites.

Change in multi-zone model X-ray burst light curves induced by variation of the $^{22}Mg(\alpha,p)^{25}Al$ reaction up (Up rate $\times 100$) and down (Dn rate $\div 100$)

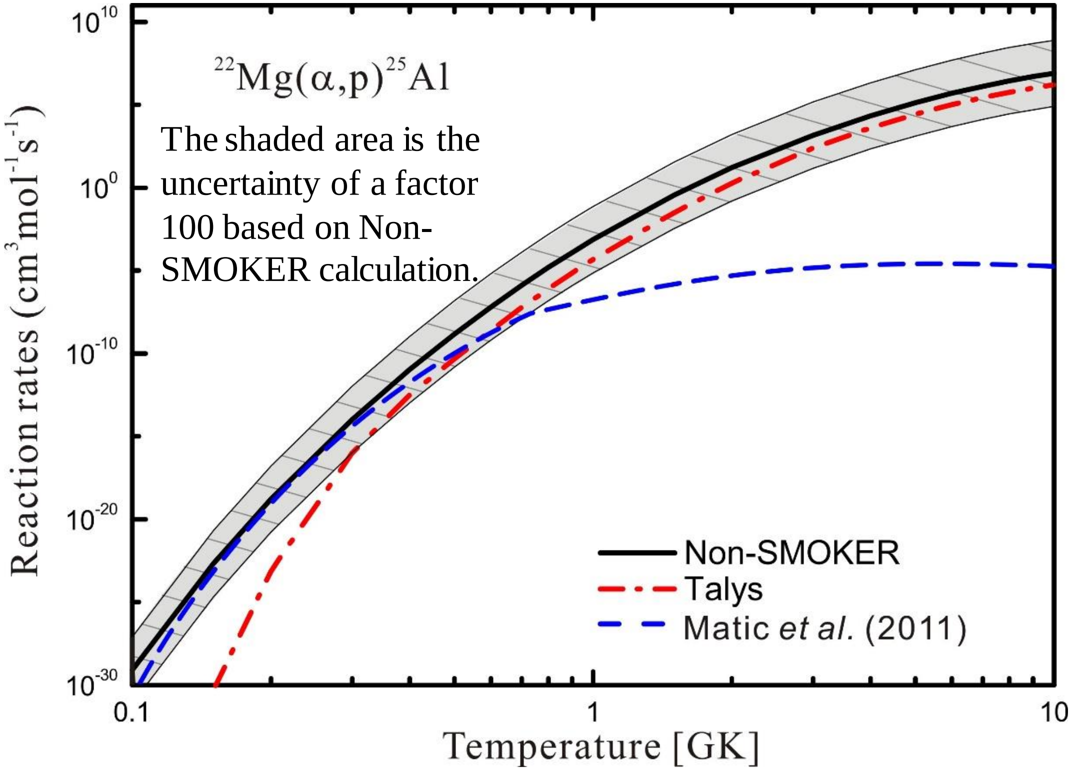
2.2 Status of level properties in ^{26}Si



Experimental technique	E_{res}	J^{π}	Γ_{p0}	$\Gamma_{p'}$	Γ_{α}
β-delayed proton measurement of ^{26}P Thomas et al. 2004	√ Ex>10 MeV	– Shell model calculation	–	–	–
^{28}Si(p,t)^{26}Si Matic et al. 2011	√ Ex<10 MeV	– Analog state assignment	–	–	–
^{25}Al+p scattering measurement above the α threshold of ^{26}Si (will be done)	√ Excitation function measurement	√ R-Matrix fitting	√ ^{25}Al (p, p)^{25}Al	√ ^{25}Al (p, p′)^{25}Al	–

All the previous measurements didn't touch the astrophysical interested energy region.

2.3 Status of $^{22}Mg(\alpha,p)^{25}Al$ astrophysical reaction rate

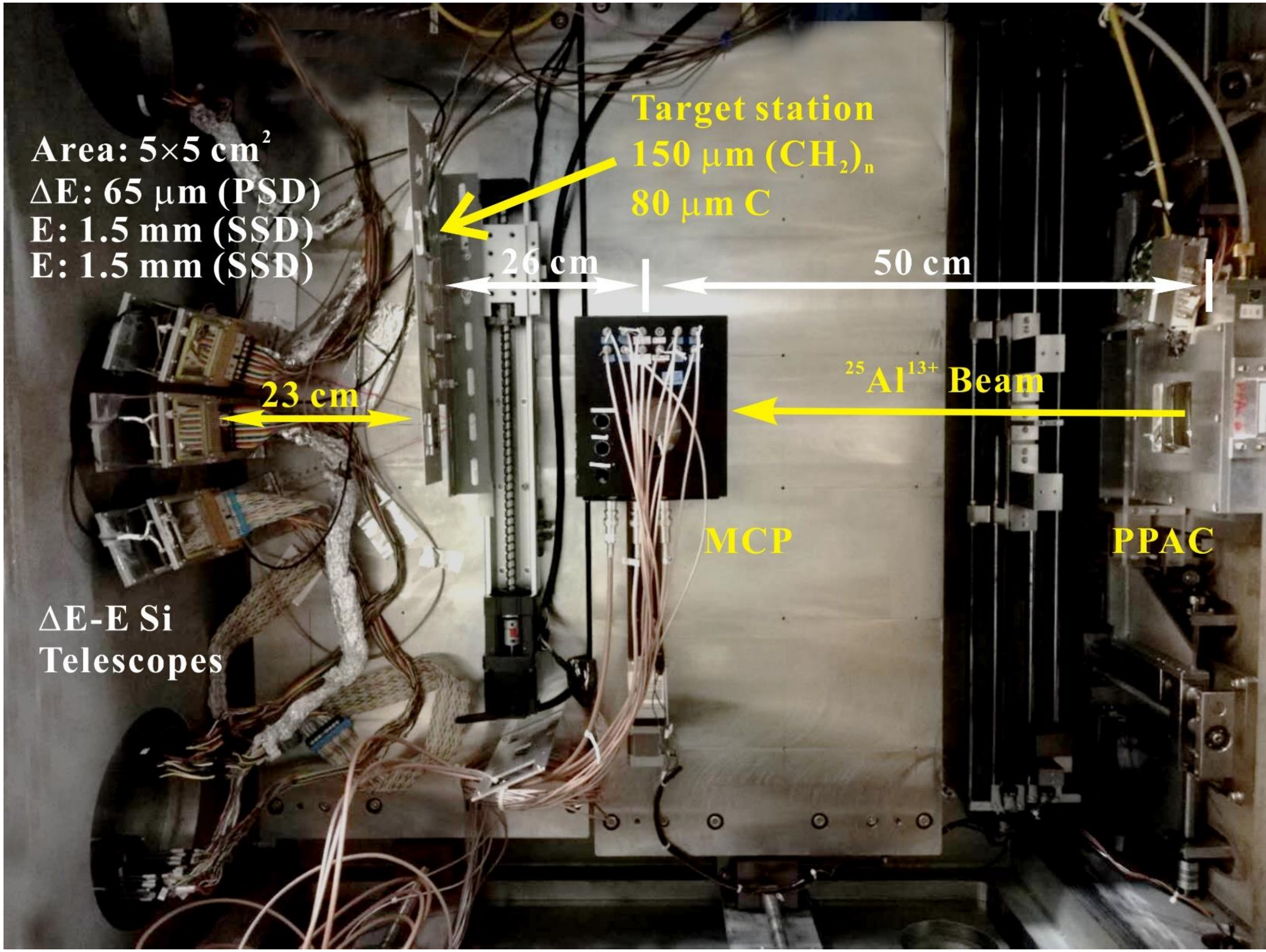


Large difference between the experiment and theoretical calculation.

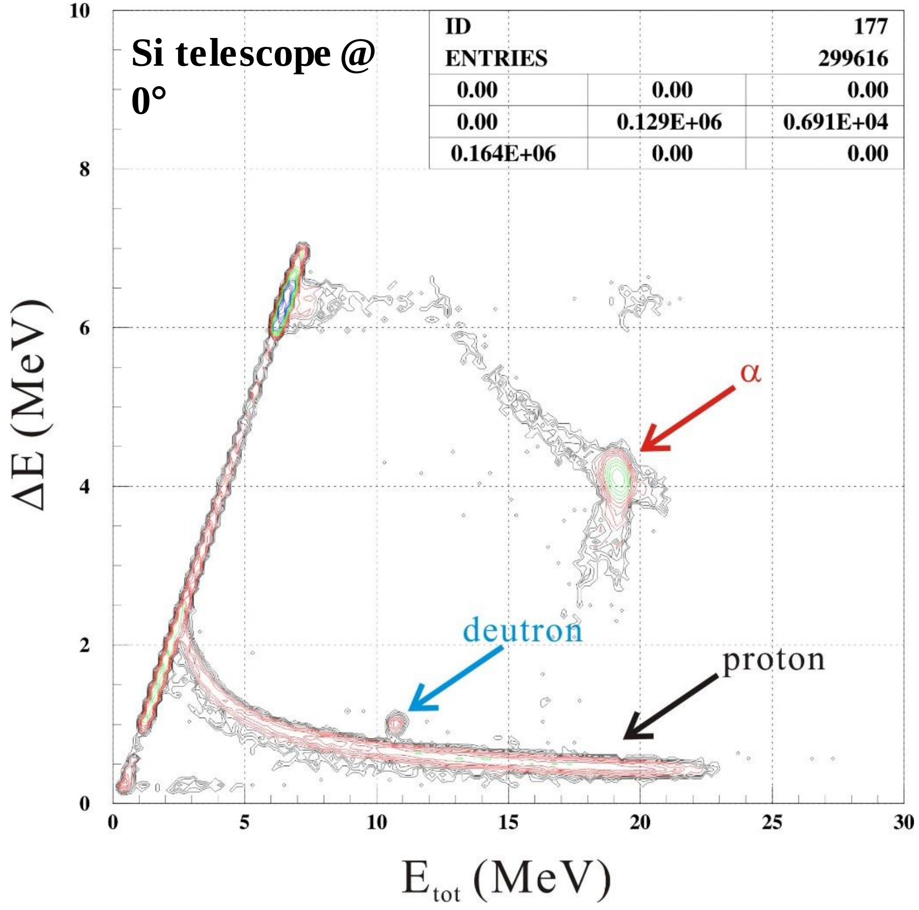
The $^{22}Mg(\alpha,p)^{25}Al$ reaction rate as a function of the temperature for the Hauser-Feshbach predictions TALYS and non-SMOKER

Experimental Setup at F3 focal plane

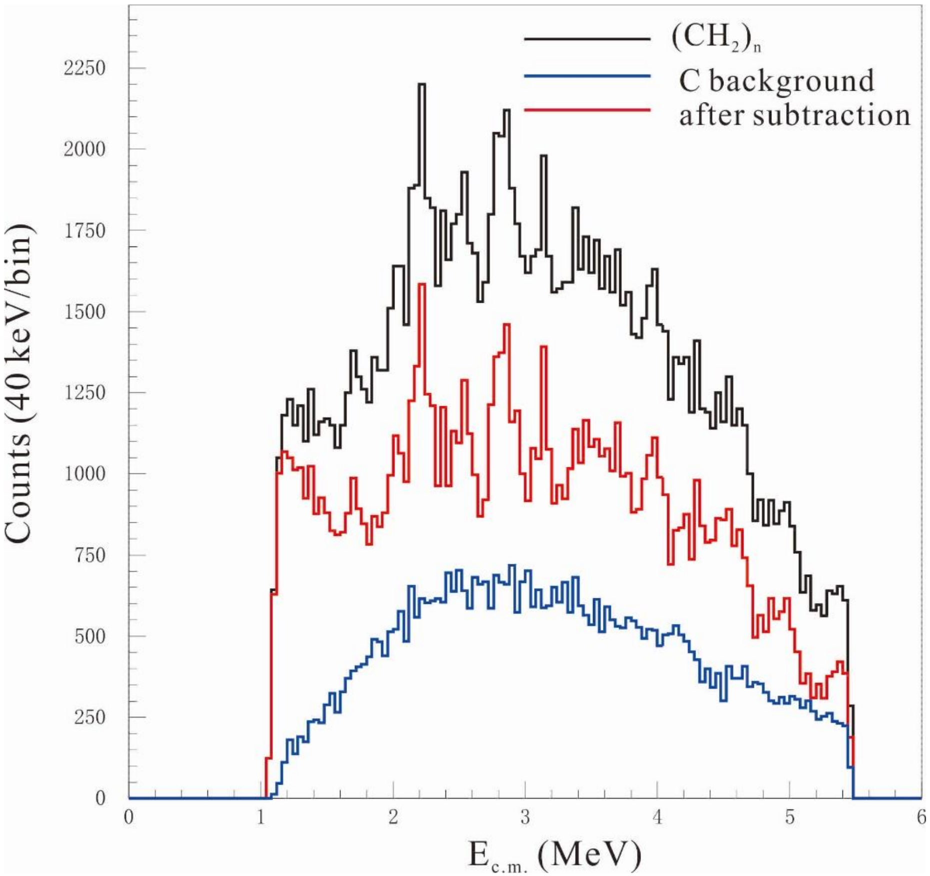
^{25}Al beam:
2 x 10^5 pps, 80% purity



Particle Identification for the Recoiling Particles



$^{1}H(^{25}Al, p)^{25}Al$ Excitation Function @ 0°



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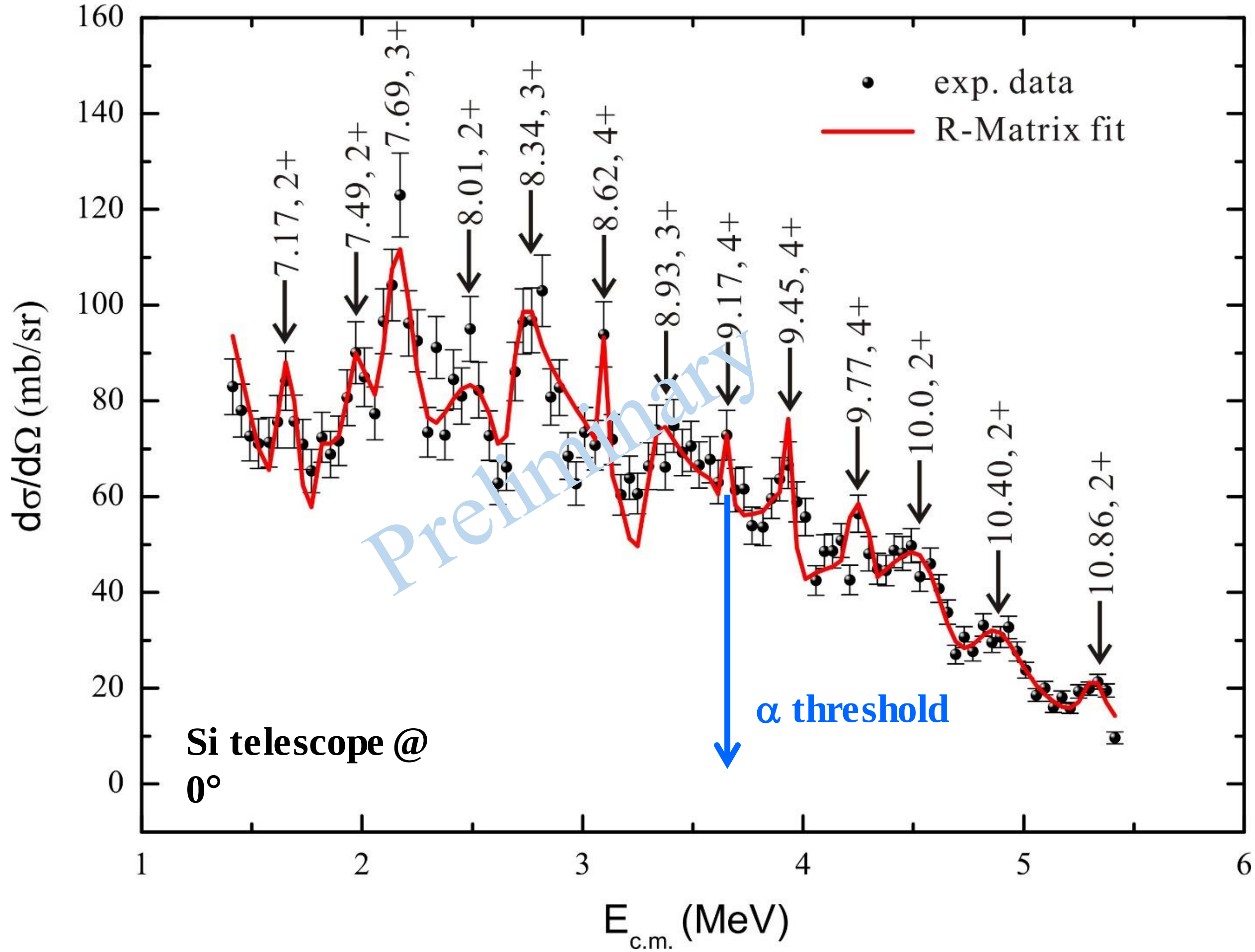
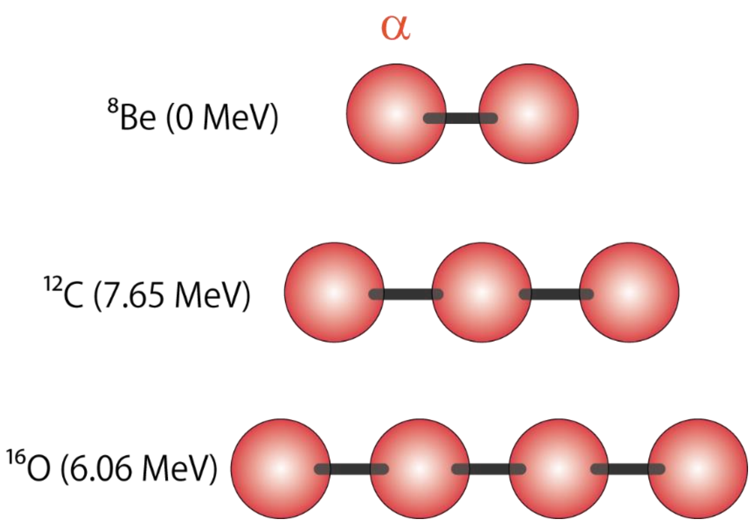
Preliminary R-Matrix Fit Result

1. We observed 13 resonant states in ^{26}Si.
2. The spin parities of 5 states above the α threshold were determined for the first time (in the present tentative analysis).



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.

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).

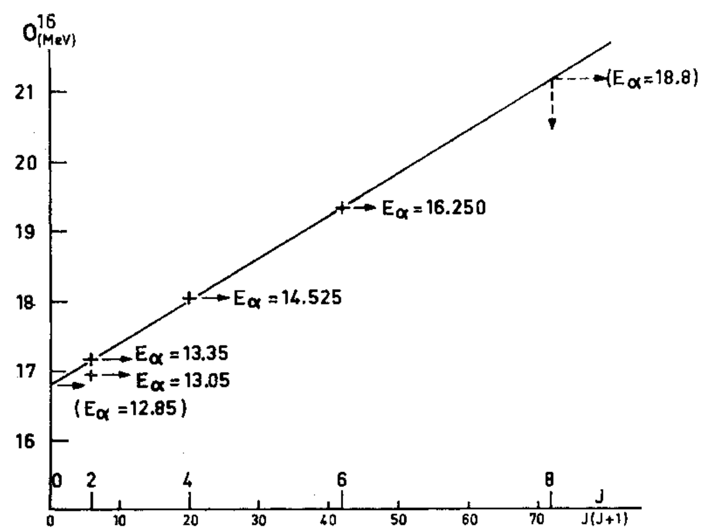


FIG. 14. The energies of the four established resonances on an $J(J+1)$ scale exhibiting a possible rotational-band structure of some of these levels.

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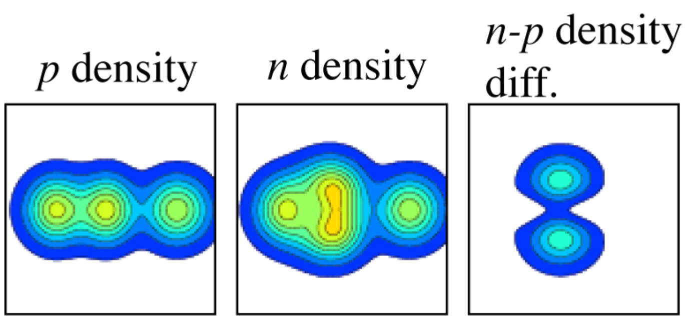
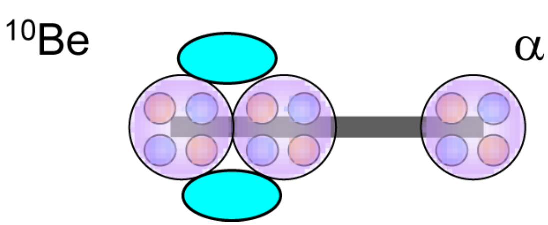
^{10}Be+α

- Linear-chain cluster levels in ^{14}C were predicted in Suhara & En'yo papers.
- Asymmetric, ^{10}Be+α configuration …likely to be observed with ^{10}Be+α alpha-resonant scattering.
- May form a band with J^{π}=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:

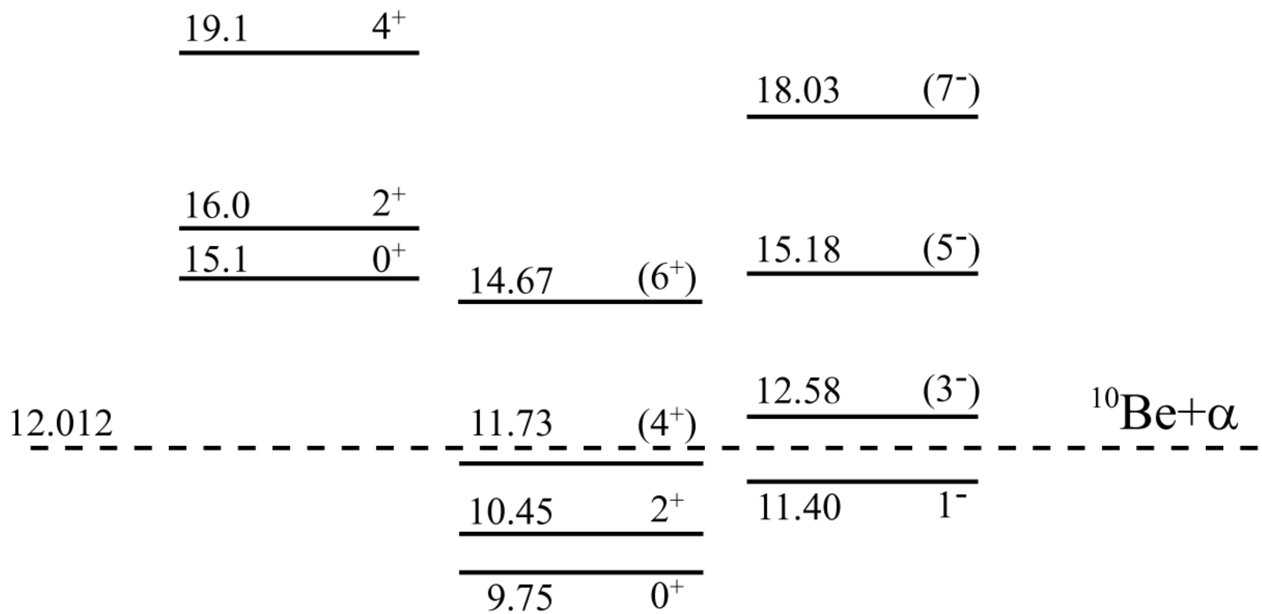




Similar experiments independently conducted by Birmingham group [M. Freer et al., PRC 2014] and MSU group [A. Frisch et al., PRC 2016]

Cluster bands

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

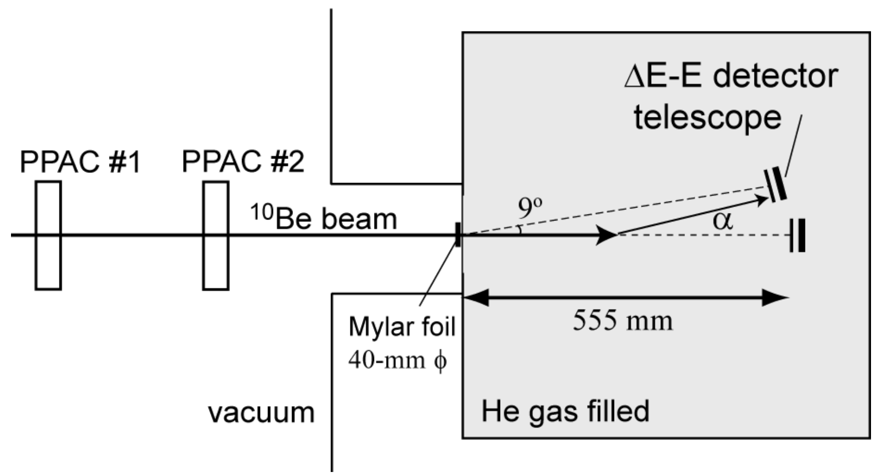


Linear chain states in the calculation by Suhara&En'yo (2010)

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

Experimental setup

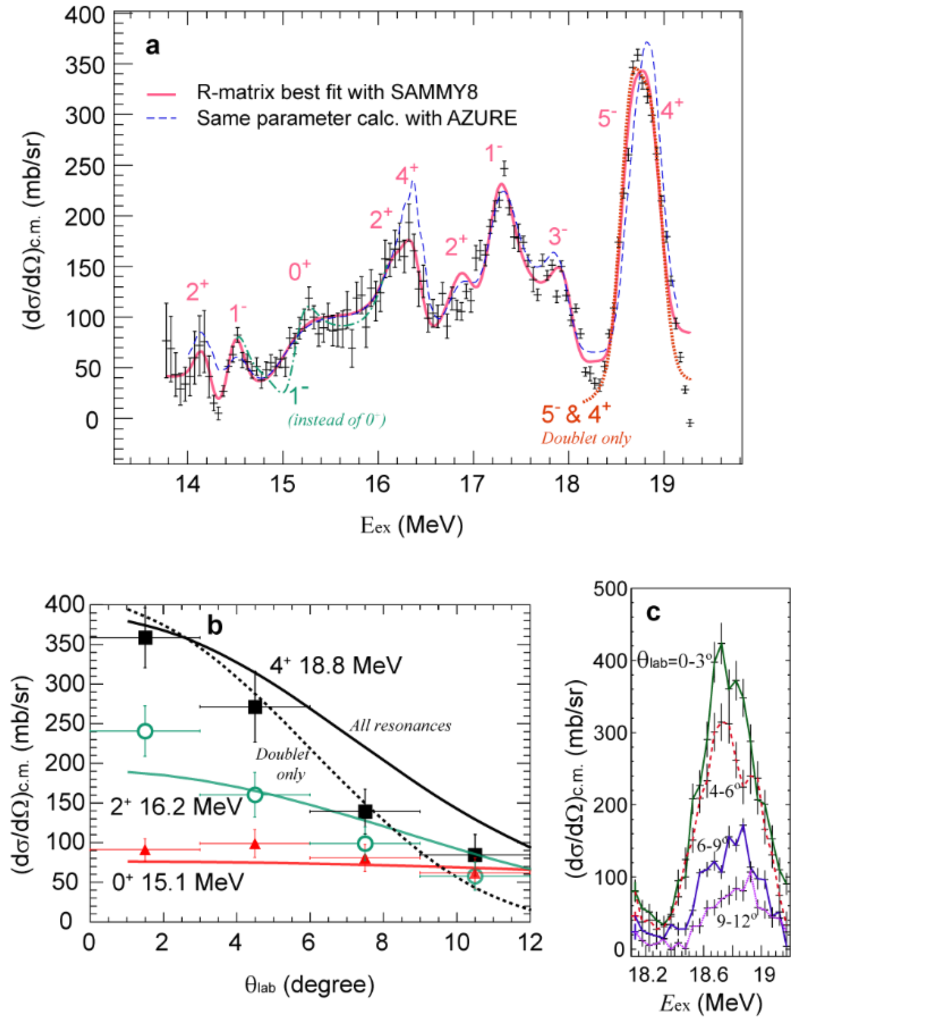
Thick target method in inverse kinematics, similar to the previous $^{7}Be+\alpha$.



- 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.

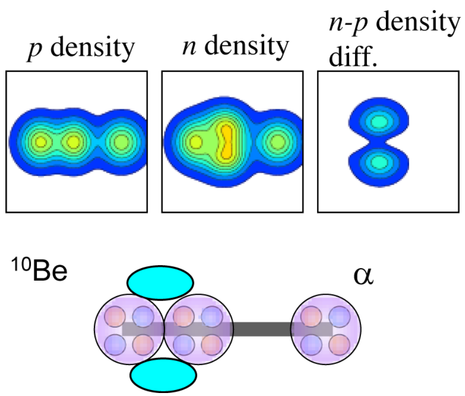
Excitation function

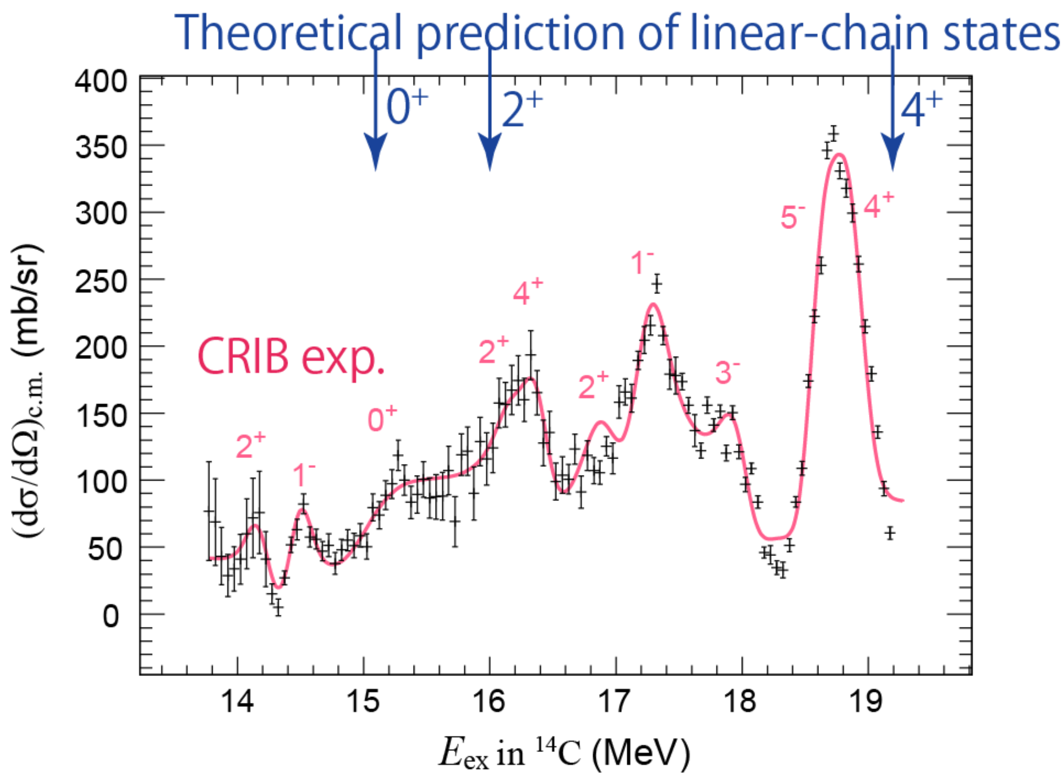
- The excitation function we obtained for 13.8-19.2 MeV exhibits many resonances.
- R-matrix analysis performed, and some of the resonance parameters (E, J^{π}, Γ_{α}) were determined.



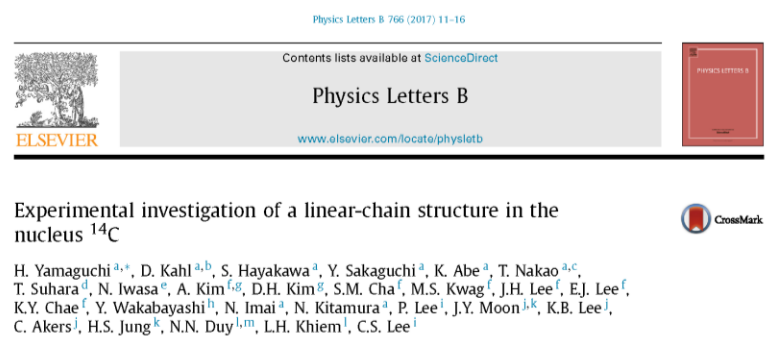
Result of the linear chain search

Suhara & En'yo, PRC 2010 and 2011:





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



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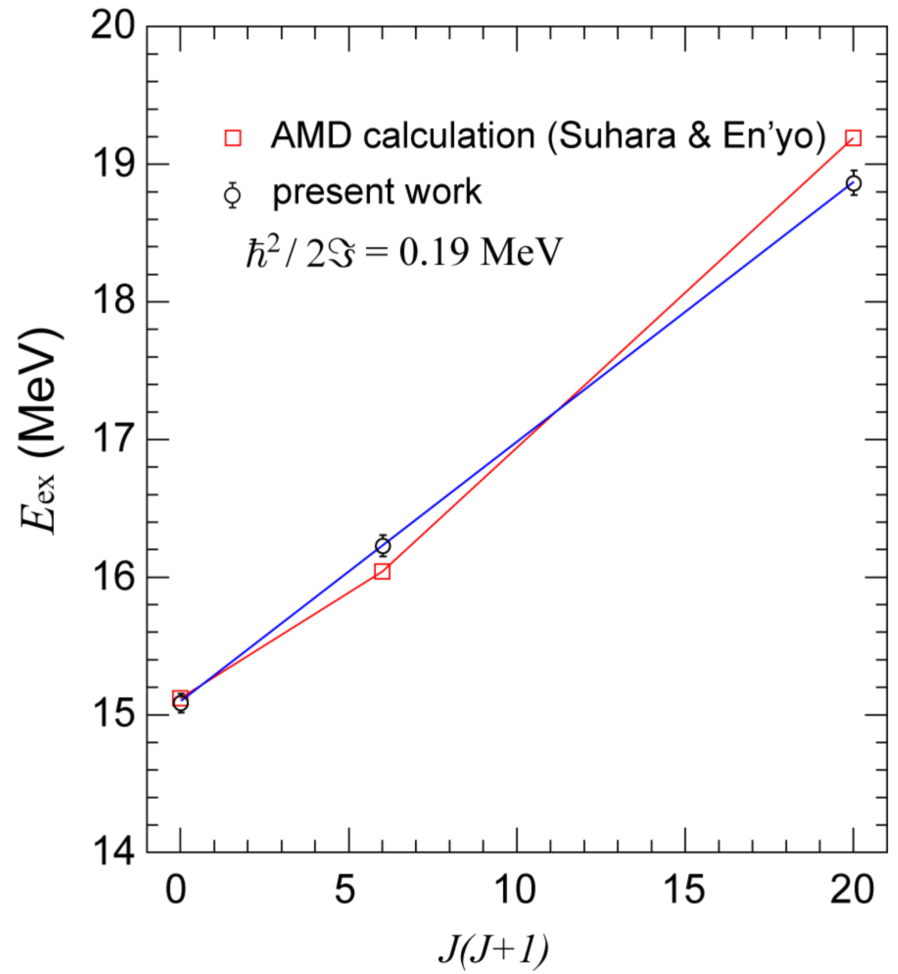
Experimental investigation of a linear-chain structure in the nucleus ^{14}C

H. Yamaguchi [a,*], D. Kahl [a,b], S. Hayakawa [a], Y. Sakaguchi [a], K. Abe [a], T. Nakao [a,c], T. Suhara [d], N. Iwasa [e], A. Kim [f,g], D.H. Kim [g], S.M. Cha [f], M.S. Kwag [f], J.H. Lee [f], E.J. Lee [f], K.Y. Chae [f], Y. Wakabayashi [h], N. Imai [a], N. Kitamura [a], P. Lee [i], J.Y. Moon [j,k], K.B. Lee [j], C. Akers [j], H.S. Jung [k], N.N. Duy [l,m], L.H. Khiem [l], C.S. Lee [i]

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.



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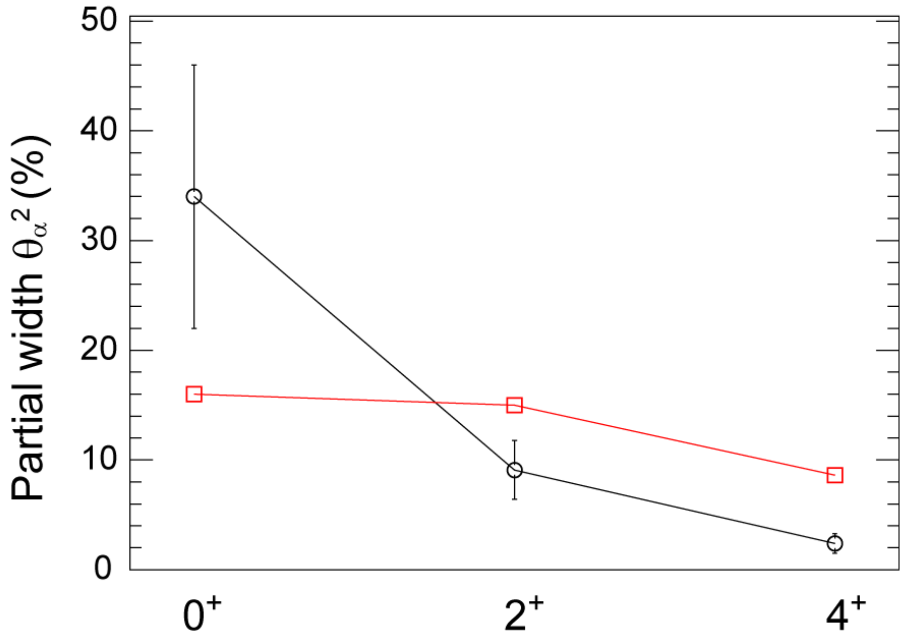
Partial width θ_α^2

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.



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

  Agreement over Ex>16 MeV, in spite of the difference in the absolute c.s.

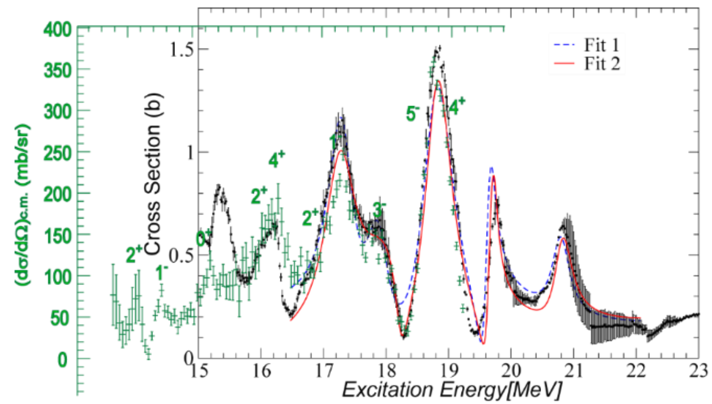
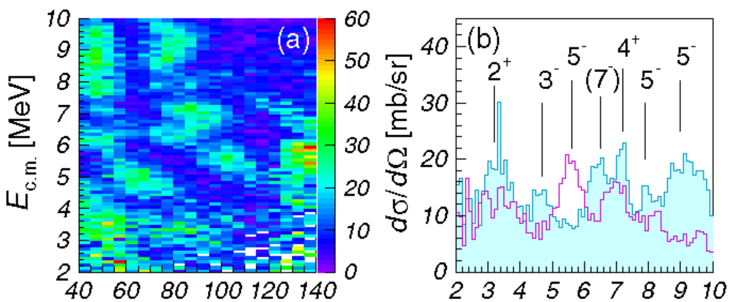


FIG. 11. (Color online) R-matrix fit to the data in the region between E_x = 16.5 and 22 MeV (red-solid and blue-dashed lines). The difference between the two fits is the inclusion of an additional 4^+ state in the calculation shown by the red line. See Table for the parameters of fits 1 and 2.

- A. Fritsch et al., Phys. Rev. C (2016)
  MSU group at Notre Dame
    - Low-intensity ^{10}Be beam, Active target, only side angles.

  Cannot compare directly, but not good agreement?



$E_{cm}=E_x$-12 MeV

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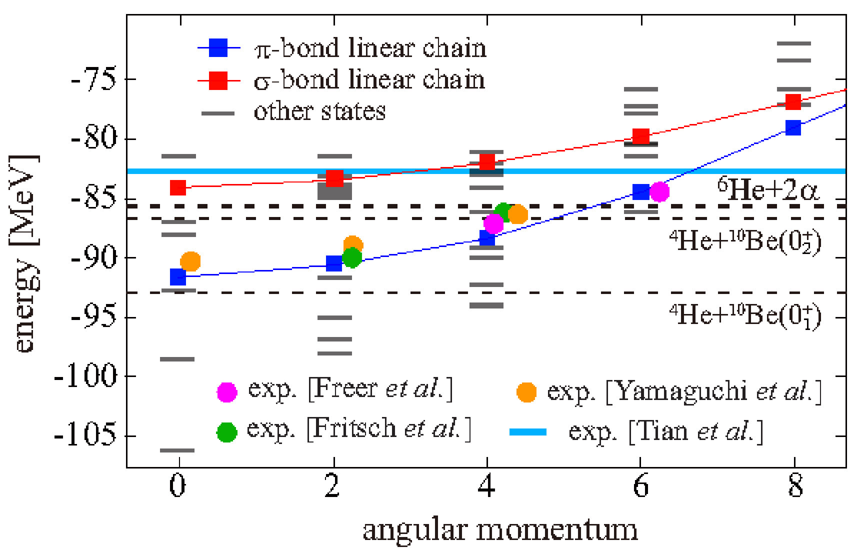
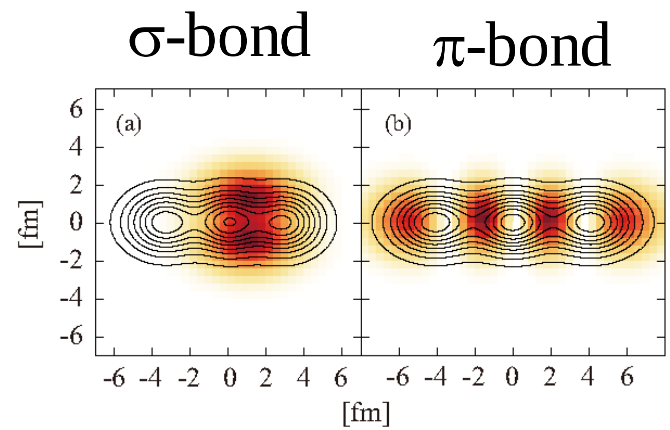
Baba and Kimura (2016 & 2017)

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).

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.

The "CHAIN" experiment at INFN-LNS (Catania, Italy)

^{10}Be+α with more intense beam, higher energy and angular resolution: ~2 weeks beamtime.

Investigation of α-chain structures in ^{14}C.

H. Yamaguchi [1], A. Di Pietro[2], R. Dressler[3], J. P. Fernández-García[4], P. Figuera[2], S. Hayakawa[1], S. Heinitz[3], D. Lattuada[5], M. Lattuada[2,6], E. Maugeri[3], M. Milin[7], H. Shimizu[1], A. C. Shotter[8], D. Shumann[3], N. Soic[9], D. Torresi[2], L. Yang[1] M. Zadro[9],

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[2] *INFN, Laboratori Nazionali del Sud, Catania, Italy*

[4] *Paul Scherrer Institute, Villigen, Switzerland*

[3] *Departamento FAMN, Universidad de Sevilla, Sevilla, Spain.*

[5] *Extreme Light Infrastructure - Nuclear Physics (ELI-NP),IFIN-HH, Magurele, Romania*

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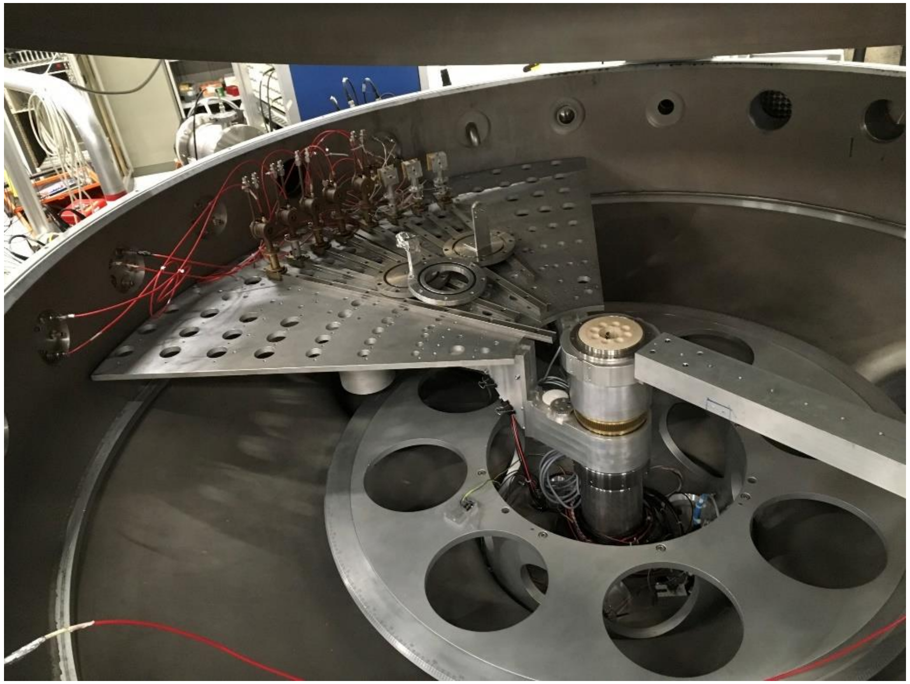
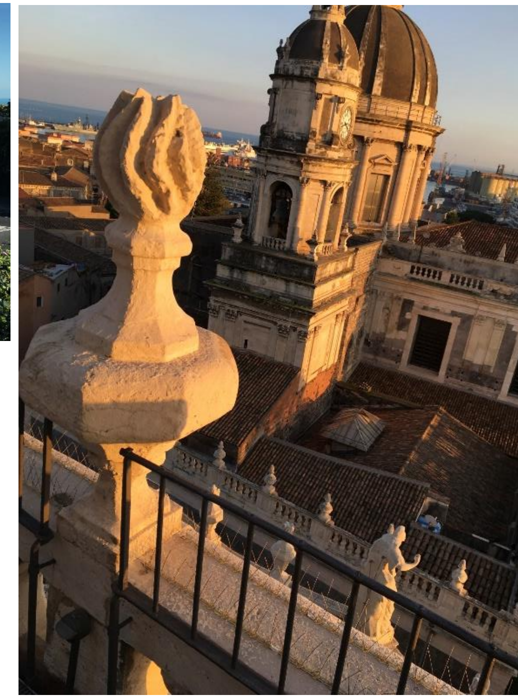
Abstract

We propose to measure the excitation function for the elastic scattering process ^{10}Be+^{4}He, in order to shed some light upon the existence of linear-chain cluster states in the n-rich ^{14}C nucleus. These states are expected to have a configuration in which ^{10}Be and α are spatially separated, and thus they can be observed by the ^{10}Be+α resonant elastic scattering. In order

Experiment at Catania, Oct. 2018

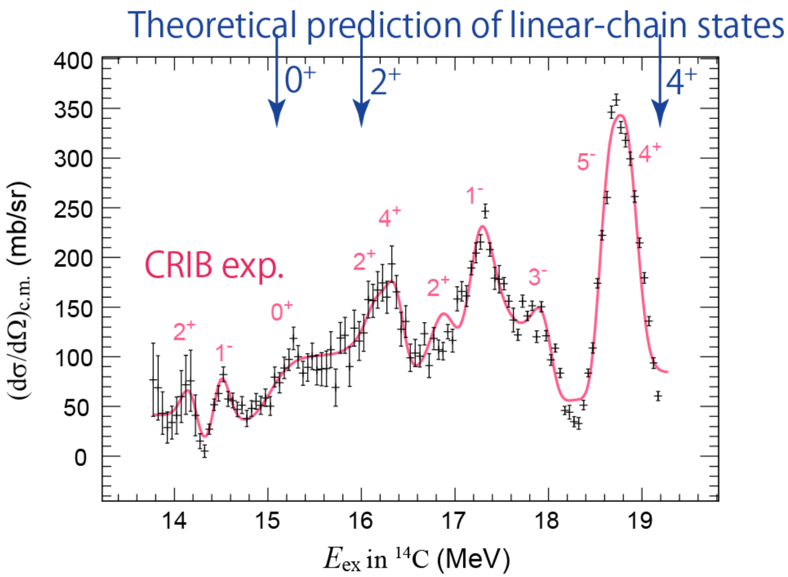




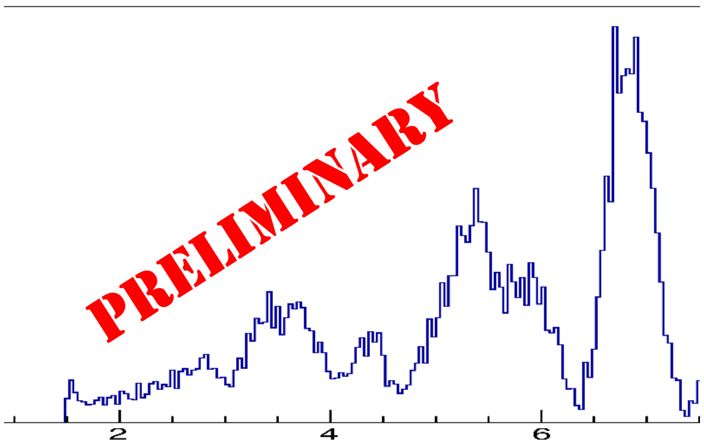
Result (very preliminary)

CRIB vs LNS(Tandem)

Including 0-8 deg events



@5 deg, No normalization for the effective target thickness/absolute cross section yet



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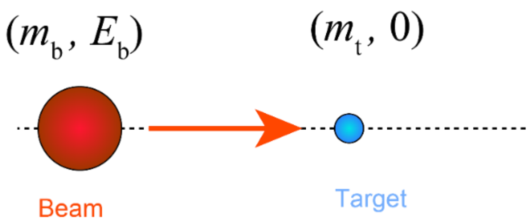
Summary of Lecture #2

- Resonant scattering with TTIK…very striking method to study nuclear resonances, suitable even for low-intensity RI beams.
- Physics cases:
  - ◆ ^{7}Be+α … for ^{7}Be(α,γ) reaction in core-collapse supernovae
  - ◆ ^{25}Al+p…for ^{22}Mg(α,p) reaction, relevant in X-ray bursts
  - ◆ ^{10}Be+α… special linear-chain cluster state

Homework (In-flight RI beam)

[1] A ^{7}Be beam is created by the in-flight method, using a ^{7}Li beam (mass: M_b) at an energy of E_b and a hydrogen (Mass M_t) target. How much is the maximum angle deviation of the produced ^{7}Be particle from the original ^{7}Li beam trajectory?



For simplicity, you can assume

-The maximum angle deviation occurs when $\theta_{\text{c.m.}}$ is close to $90°$.

-Q-value in the production reaction (p,n) is negligible. (^{7}Li/^{7}Be masses are the same.)

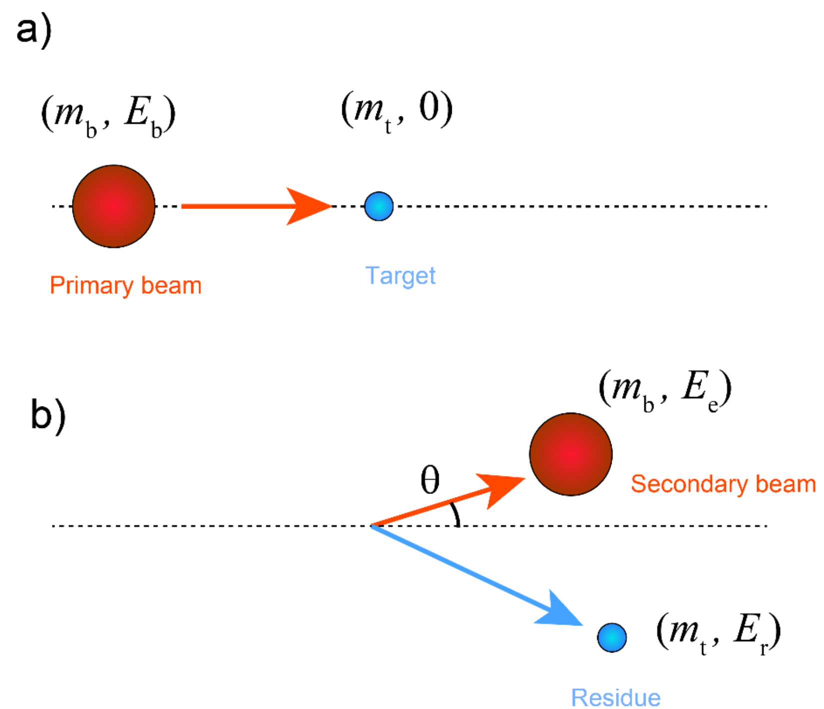
-The energy loss in the target is ignorable.

Hint) You can use the formula, $\cos\theta_{\text{lab}} = \dfrac{x+\cos\theta_{\text{c.m.}}}{\sqrt{1+x^2+2x\cos\theta_{\text{c.m}}}^{2}}, \; x = \dfrac{M_b}{M_t}$

Homework

[2] When the ^{7}Li beam energy is E_b = 10MeV/u (~70 MeV) and ^{7}Be produced with the angle $\theta_{lab} < 3°$ is accepted, how much is the energy spread $\Delta E_e/E_e$? Here we define ΔE_e as the energy difference of the ^{7}Be beam particle at $0°$ and $3°$.

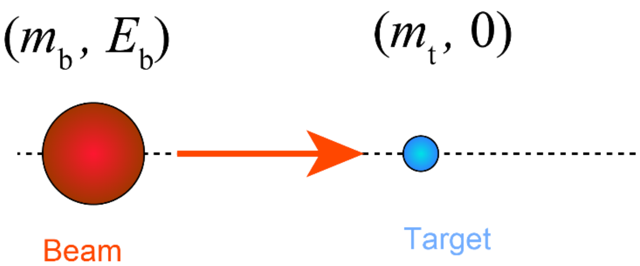
Hint) Consider energy -momentum conservation.



Homework (TTIK)

[1] Suppose we make a scattering experiment by irradiating a beam (kinetic energy E_b, mass M_b) onto a target (Mass M_t). Show that the center-of-mass energy $E_{c.m.}$ (energy of the system in the center-of-mass frame) at the scattering is given by the following formula for non-relativistic energy:

$$E_{c.m.} = \frac{M_t}{(M_b + M_t)} E_b$$



Hint) In c.m. frame, the sum of the momentum vectors will be zero.

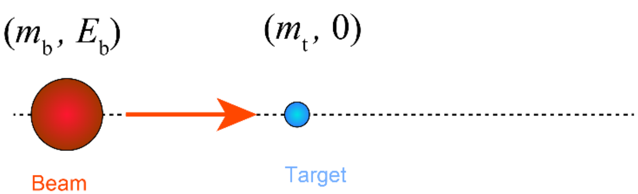
Note) This result implies that the $E_{c.m.}$ resolution can be better than the uncertainty of the beam energy in the inverse kinematics condition, $M_b > M_t$.

Homework

[2] In the resonant scattering experiments in inverse kinematics, we measure the energy and the angle of the recoiling ion, E_r and θ. First we consider a thin-target case, where the energy loss in the target is negligible.

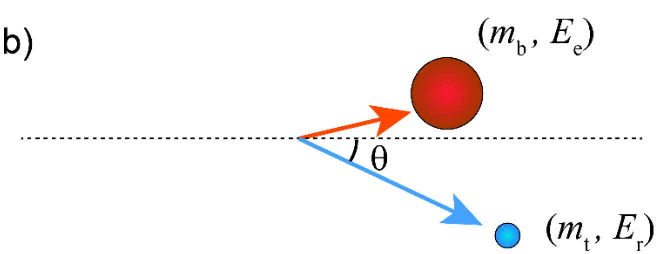
Assuming the particle masses and the beam energy E_b are known, how do you obtain the $E_{c.m.}$ of the scattering events from the measured quantities?

a)



a) Before scattering

b)



b) After scattering

Homework

[3] How the formula can be modified when we use a thick-target in which the beam energy is significantly degraded. (Can we still obtain $E_{\mathrm{c.m.}}$ from the measured E_{r} and θ?)

[4] What are the advantages and disadvantages of the TTIK (thick-target in inverse kinematics) method, as compared to the traditional, normal kinematics method?