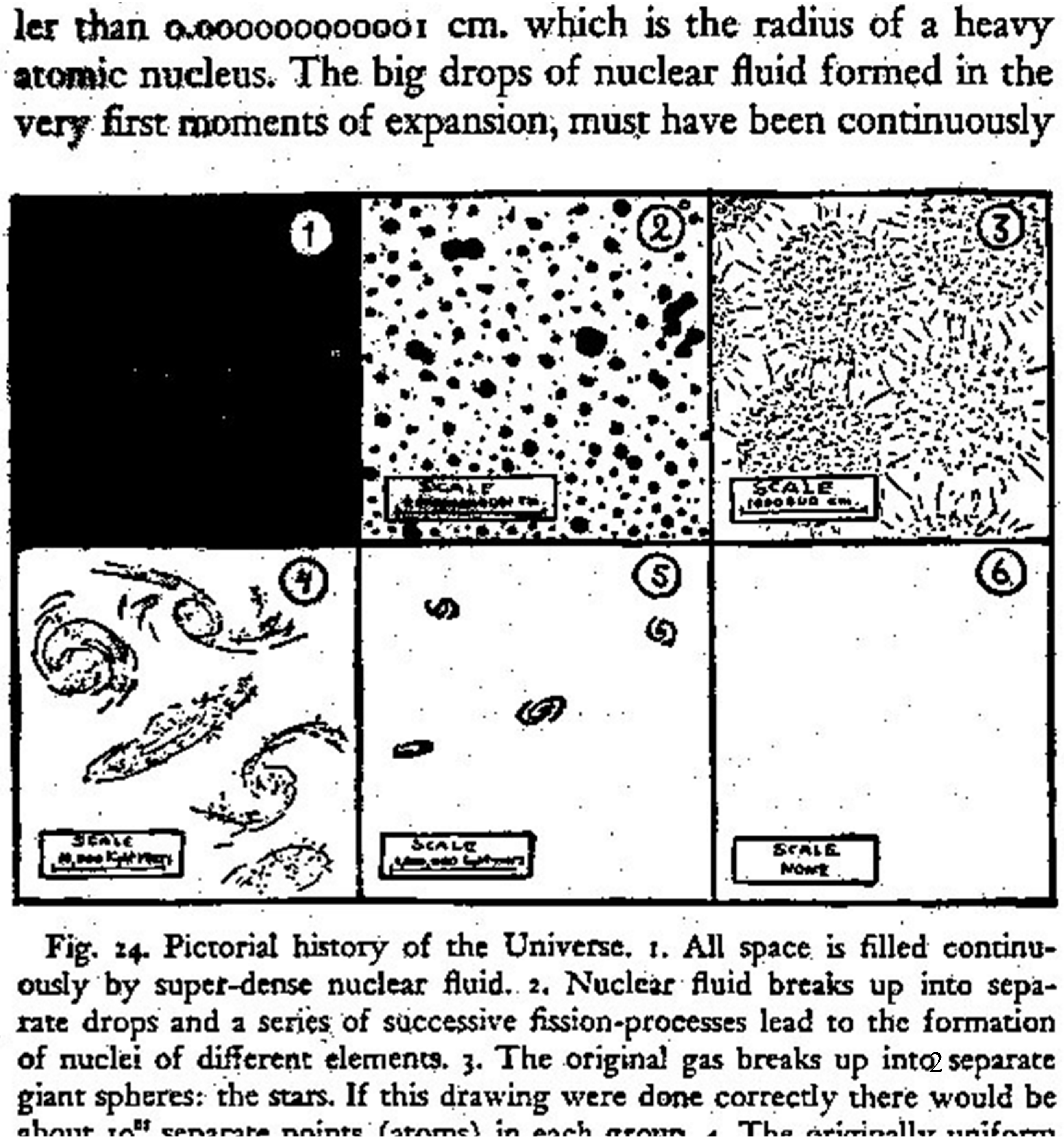
Nuclear Clusters in Astrophysics

Shigeru KUBONO
Center for Nuclear Study (CNS)

1. Nuclear Clusters in Nucleosynthesis
2. Thick target method with RI beams
3. Resonant α scattering
    – elastic and rearrangement
4. Direct α-transfer reactions

Gamow; Big-Bang Model

1947



ler than 0.000000000001 cm. which is the radius of a heavy atomic nucleus. The big drops of nuclear fluid formed in the very first moments of expansion, must have been continuously

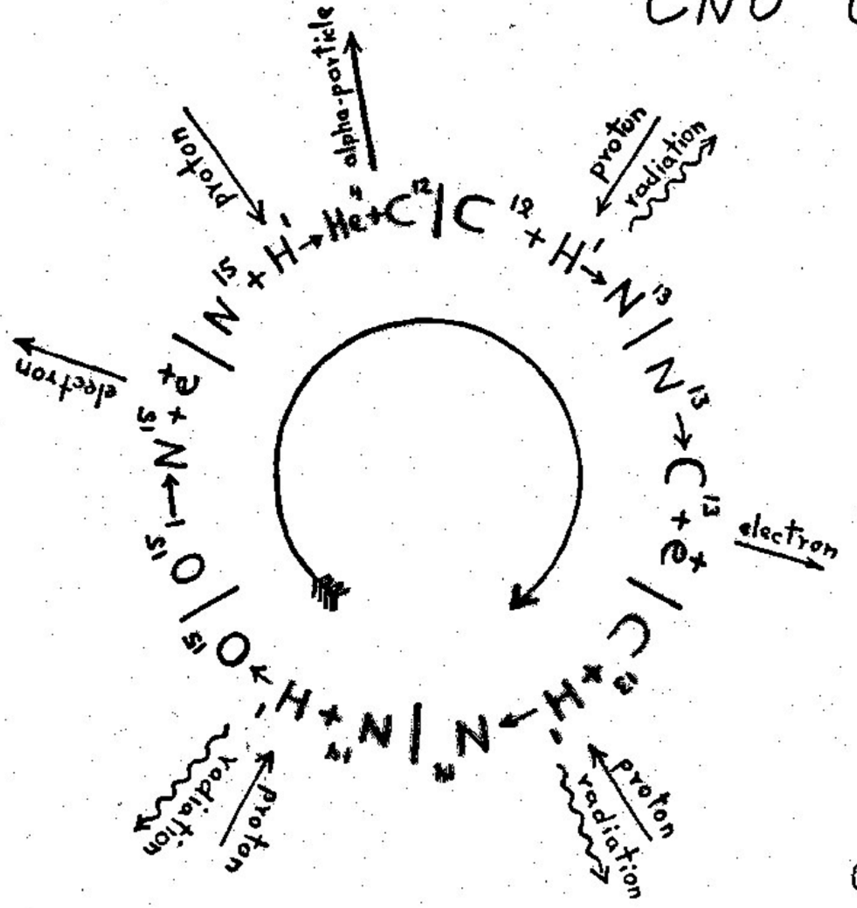
Fig. 24. Pictorial history of the Universe. 1. All space is filled continuously by super-dense nuclear fluid. 2. Nuclear fluid breaks up into separate drops and a series of successive fission-processes lead to the formation of nuclei of different elements. 3. The original gas breaks up into separate giant spheres: the stars. If this drawing were done correctly there would be about $10^{[illegible]}$ separate points (atoms) in each group. 4. The originally uniform

Gamow; CNO-Cycle

HOW THE STARS USE ATOMIC ENERGY 73

with a carbon-nucleus, we can just as well start it with a nucleus of nitrogen, or for that matter with any stable nucleus participating in the cycle. Since, in the final count,

CNO Cycle



Gamov (47)

Fig. 21. "Stellar reaction." Carbon-nitrogen-cycle according to Bethe and Weizsäcker.

the stellar reaction reduces to the transformation of hydrogen into helium, the catalyzing nuclei of carbon and nitrogen

Gamow’s Nuclear Cluster Model

oth

we

ium. Thus in this case the two fragments take respectively 59

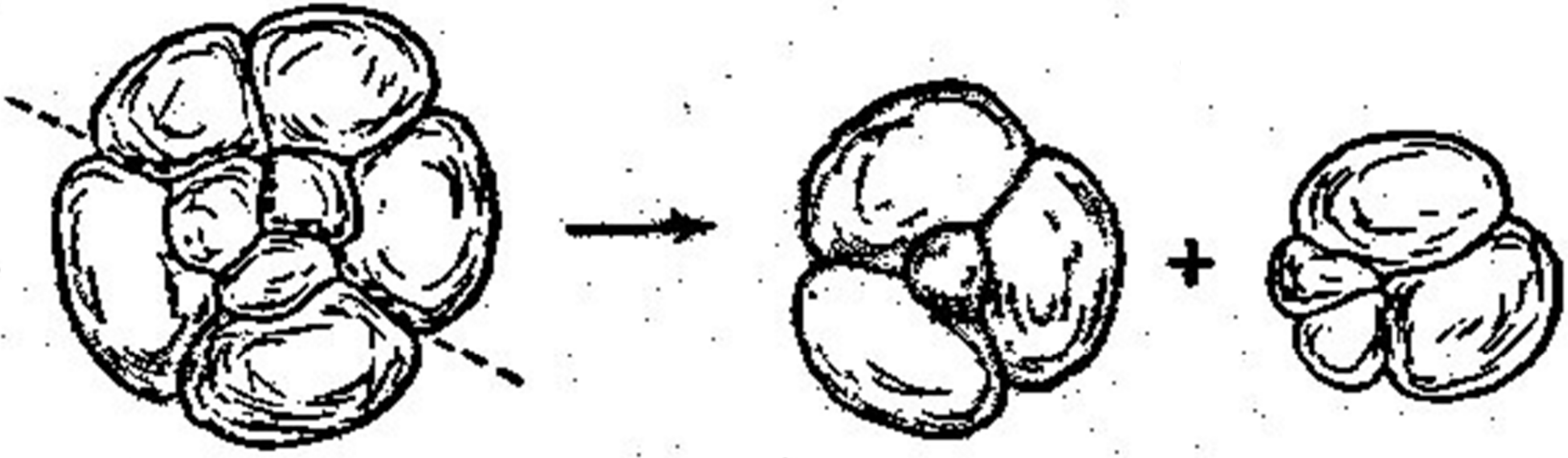
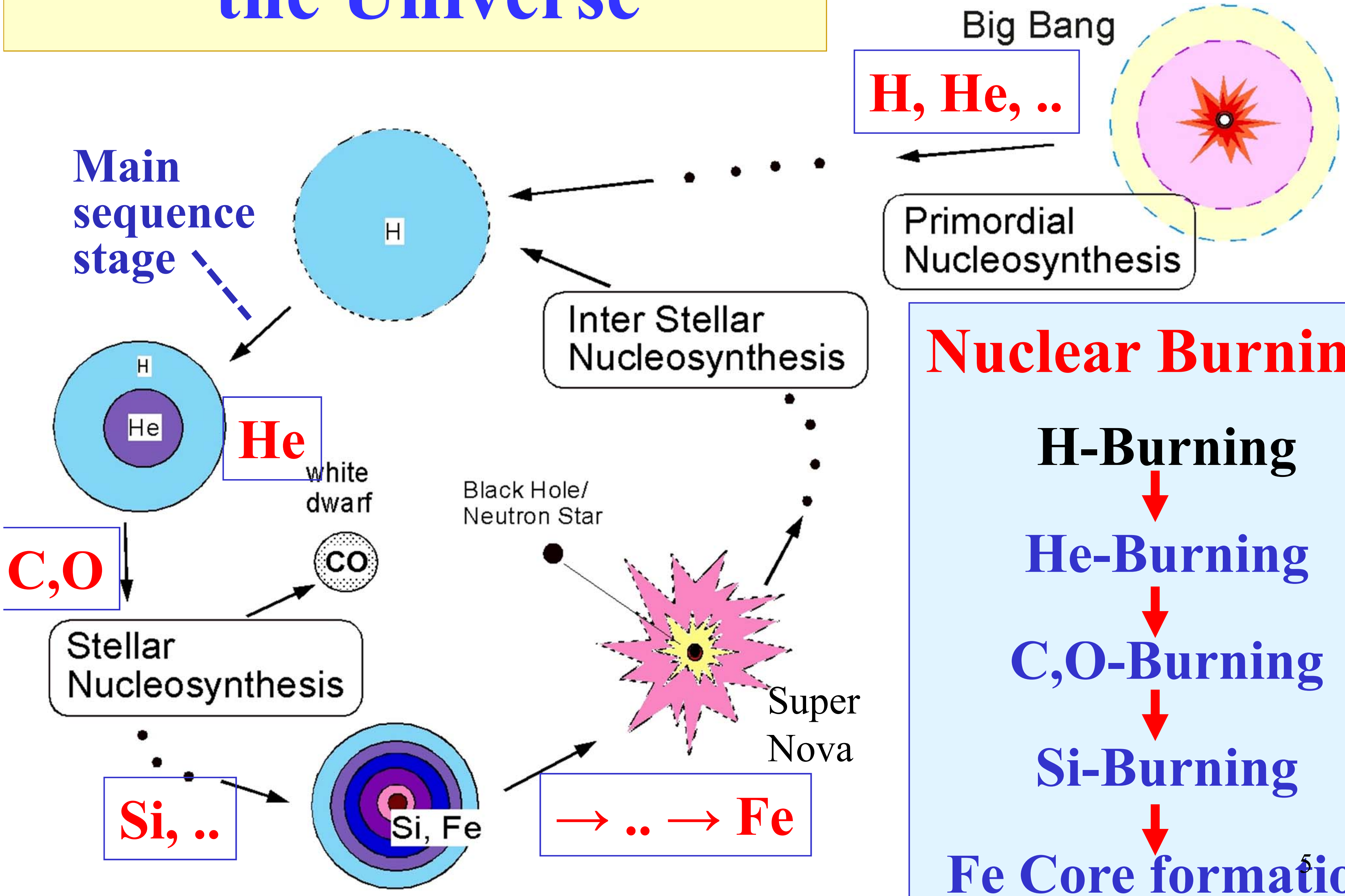


Fig. 31. Why a nucleus containing several subgroups of particles does not necessarily break up into two equal parts. Of course, this figure gives only a suggestion of the actual situation in the nucleus. In fact, different subgroups in the nuclei are not separated, but penetrate through each other like members of different political parties in a country.

and 41 percent of the original mass, with the possible additional variations caused by the circumstances of collision with

Evolution of the Universe



Nuclear Burning

H-Burning

↓

He-Burning

↓

C,O-Burning

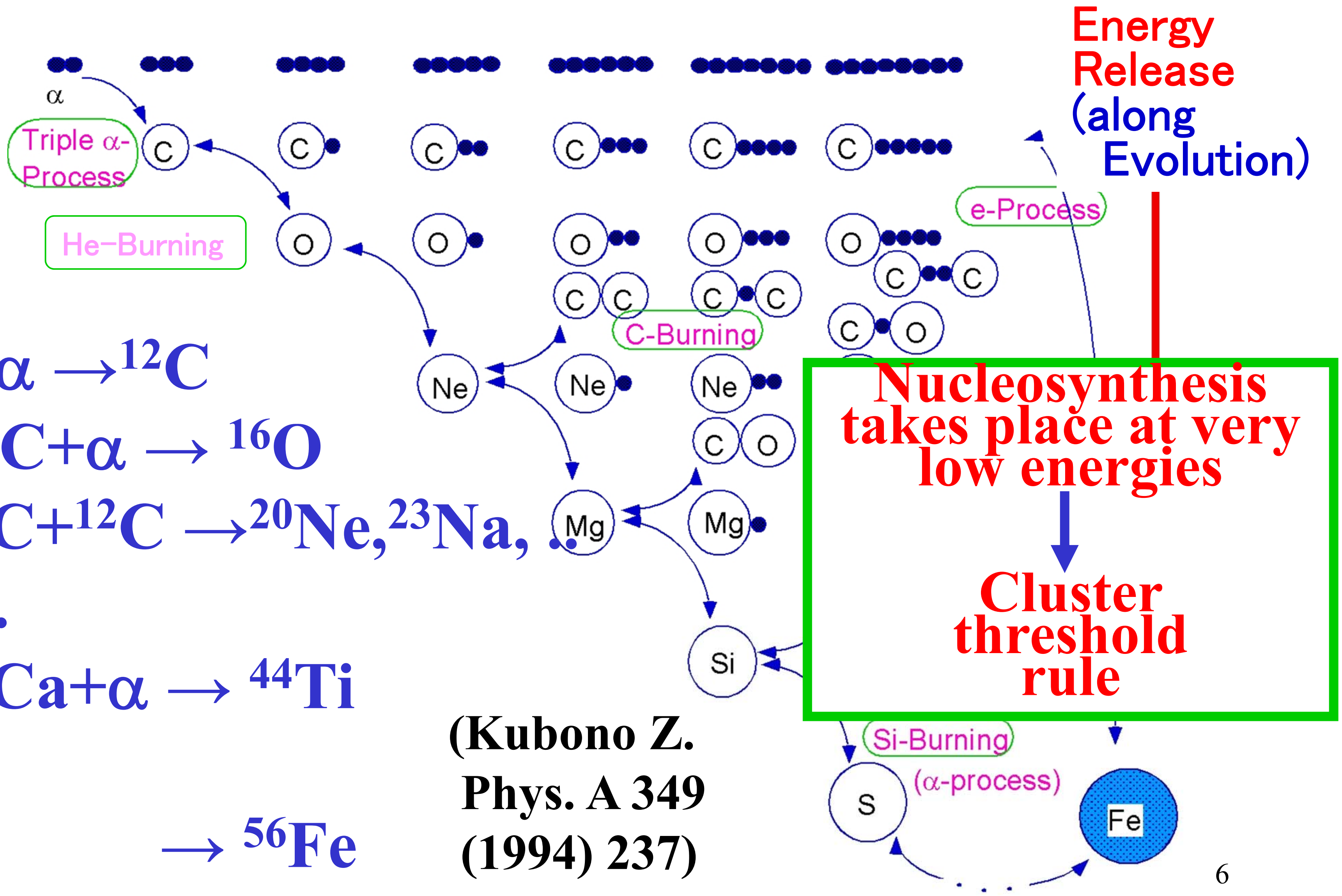
↓

Si-Burning

↓

Fe Core formation

Cluster Nucleosynthesis Diagram (CND)



Energy Release (along Evolution)

Nucleosynthesis takes place at very low energies

↓

Cluster threshold rule

- $3\alpha \rightarrow {}^{12}C$
- ${}^{12}C+\alpha \rightarrow {}^{16}O$
- ${}^{12}C+{}^{12}C \rightarrow {}^{20}Ne, {}^{23}Na$, ..

…..

- ${}^{40}Ca+\alpha \rightarrow {}^{44}Ti$

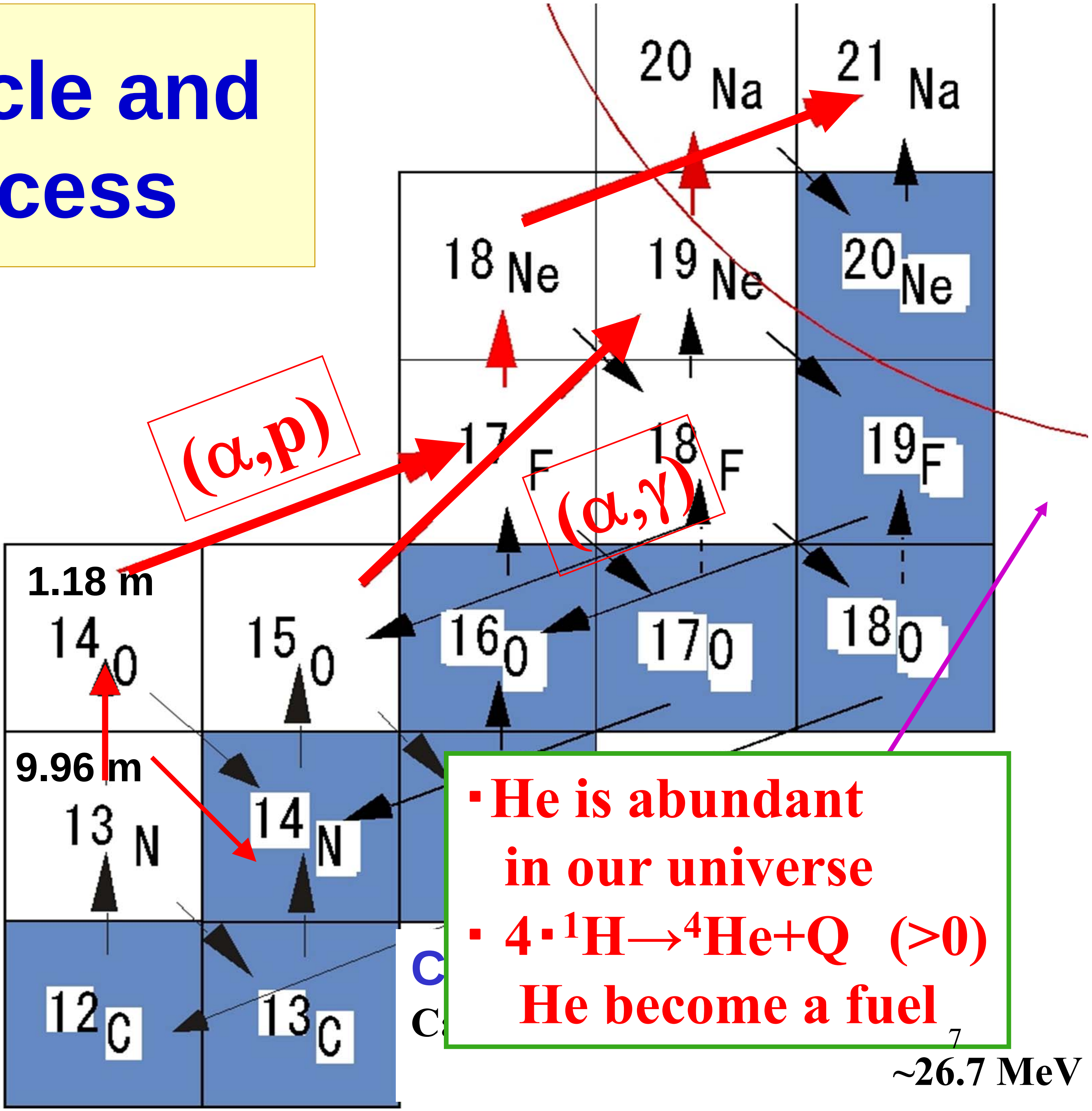
….

$\rightarrow {}^{56}Fe$

(Kubono Z. Phys. A 349 (1994) 237)

CNO Cycle and rp-process

Hot-CNO Cycle



- He is abundant in our universe
- $4 \cdot {}^1H \rightarrow {}^4He + Q \quad (>0)$ He become a fuel

~26.7 MeV

Two Methods for cluster states in unstable nuclei

[1] Cluster resonant scattering with RI beams

- Thick target method with inverse kinematics

[2] Cluster transfer reactions

- Direct transfer reactions

Thick target method with RI beams

Direct Method with RI Beams

RIB intensities		reaction type
10^4 pps	→	Resonant scattering w/thick target method eg. ^{22}Mg+p
10^6 pps	→	Rearrangement reactions eg. (α,p), (α,n), (d,p), . . .
10^8 pps	→	(p,γ), (α,γ), . . .

Total system development;

1. Ion source
- SuperECR

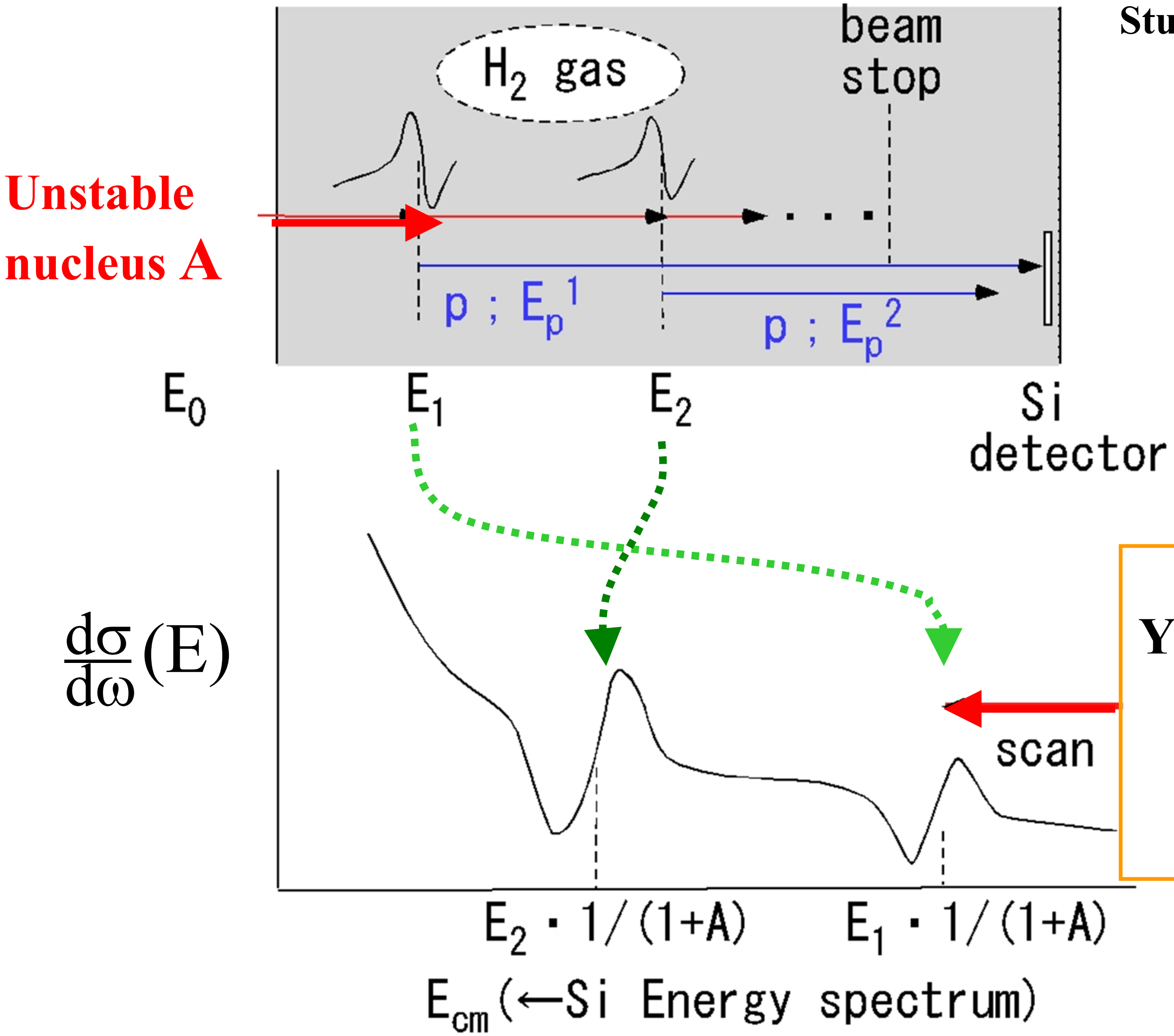
2. Accelerator
- Modify central region

3. Beam transport

4. Production target

5. Separator - Multipole element

Thick target method for resonant scattering; A+p



For a case of proton resonance
Study of p + A(=unsyable nucleus);

$$* \ E_p{}^1 = 4 \cdot A/(1+A)^2$$

- **Originally proposed by K.P.Artemov,et al., Sov.J.Nucl.Phys.52 (1990)408**

$$\mathbf{Y(E) = I(E)\int_{E-\Delta E/2}^{E+\Delta E/2} \frac{\sigma(E_i)}{\varepsilon(E_i)} dE_i}$$

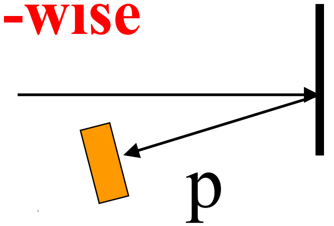
I(E) : Number of beam particles

ε(E) : Stopping cross sections

^{12}C+p Resonances

^{12}C(p,p) Excitation functions

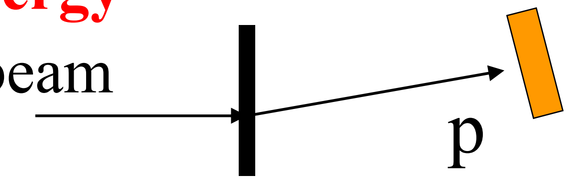
Thick target method ; ^{1}H(^{12}C,p)



Change Ei step-wise

^{12}C target

p

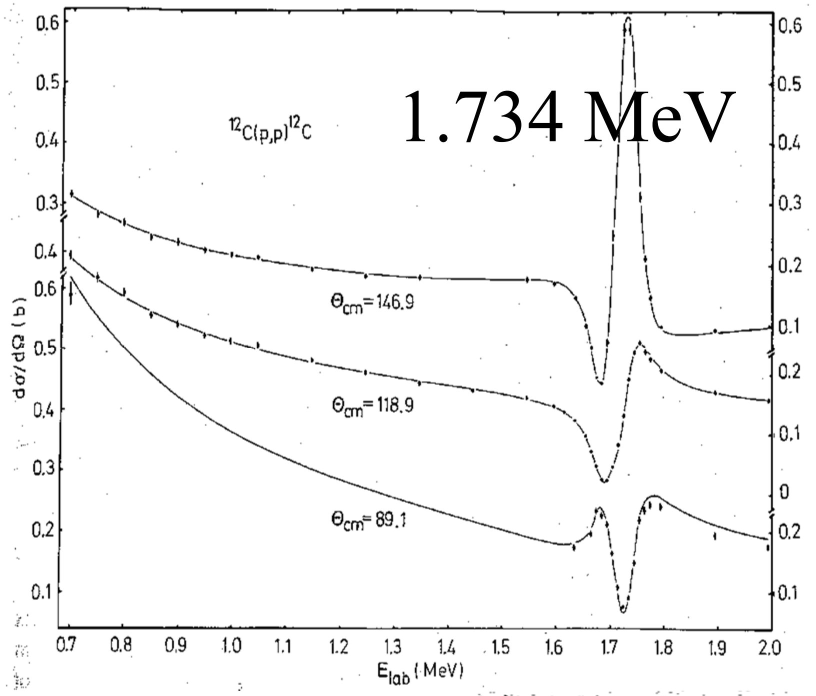


Fixed energy

^{1}H target

^{12}C beam

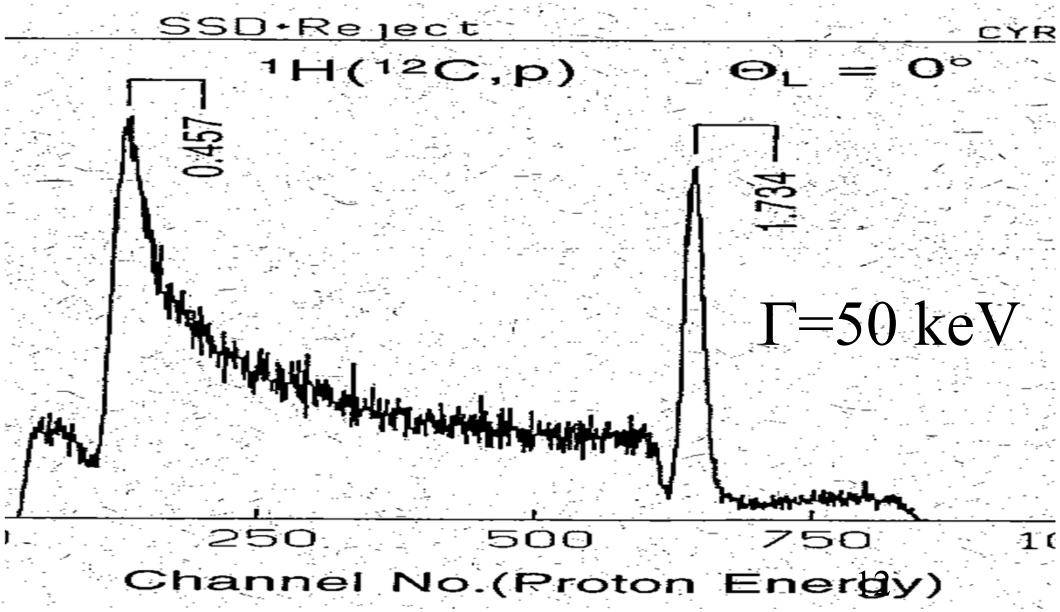
p



1.734 MeV

(Z. Phys. A, 83)

$\Theta_L = 0^o$



Γ=50 keV

Resonance Parameters

The reaction rate can be written as follows;

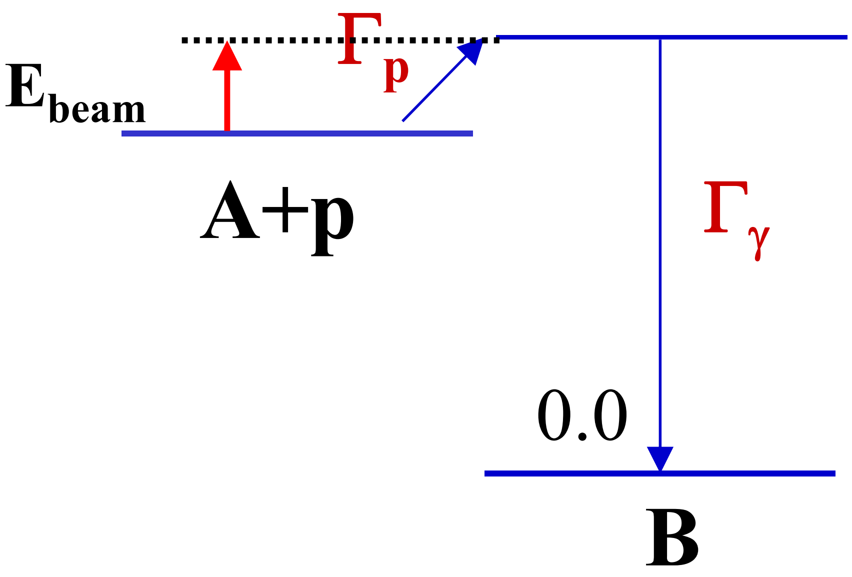
$$<\sigma\upsilon>=(\frac{2\pi}{\mu kT})^{3/2}\hbar^2\omega\gamma \quad e^{-\frac{E_r}{kT}} \quad .$$

Here, the **resonance strength** $\omega\gamma$ is defined by

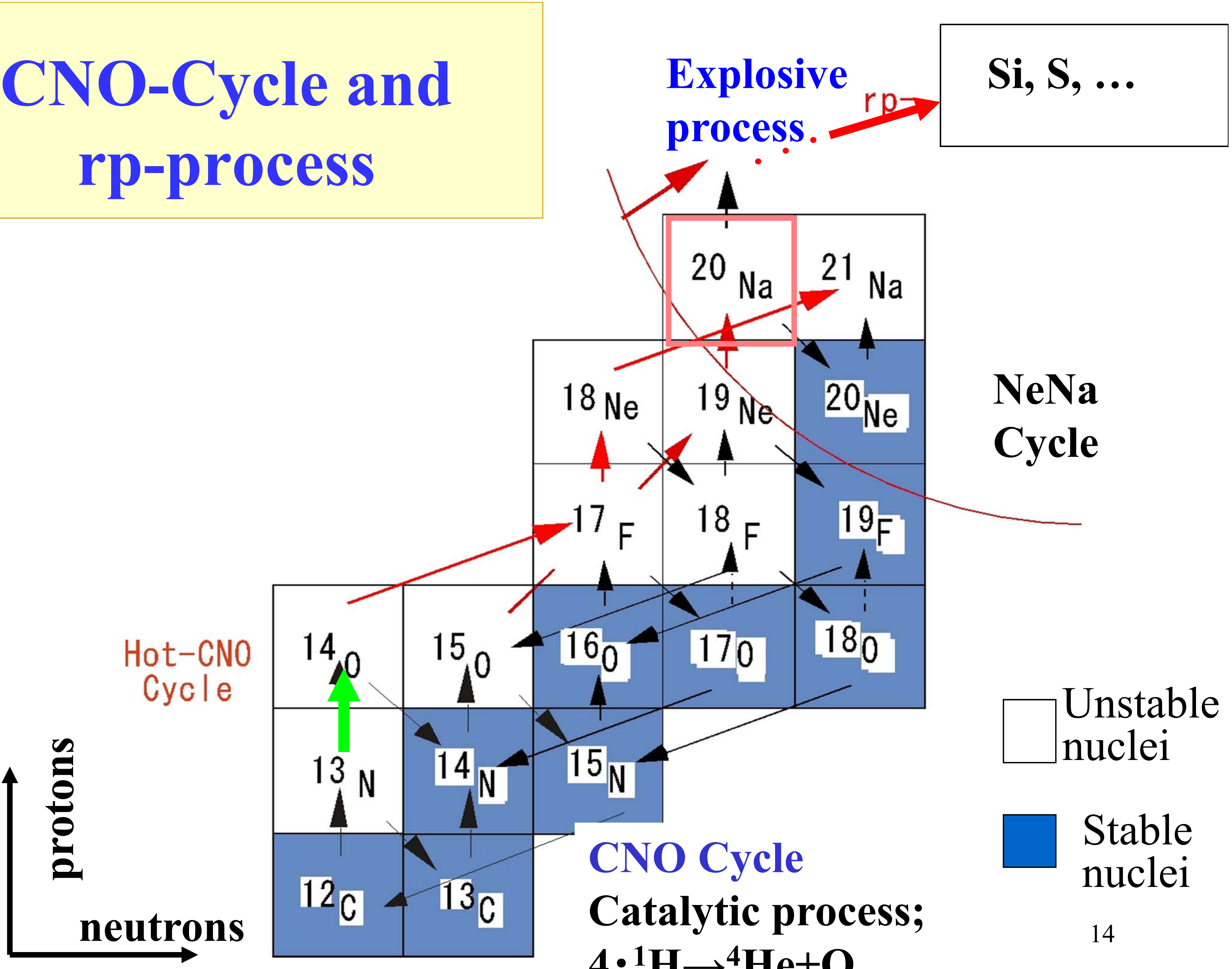
$$\omega\gamma = \frac{(2J_r+1)}{(2J_p+1)(2J_A+1)}\frac{\Gamma_p\Gamma_\gamma}{\Gamma_{tot}} \quad .$$

Resonant elastic scattering is sensitive single particle nature

A(p,γ)B



CNO-Cycle and rp-process



Explosive process

Si, S, …

NeNa Cycle

protons

neutrons

CNO Cycle

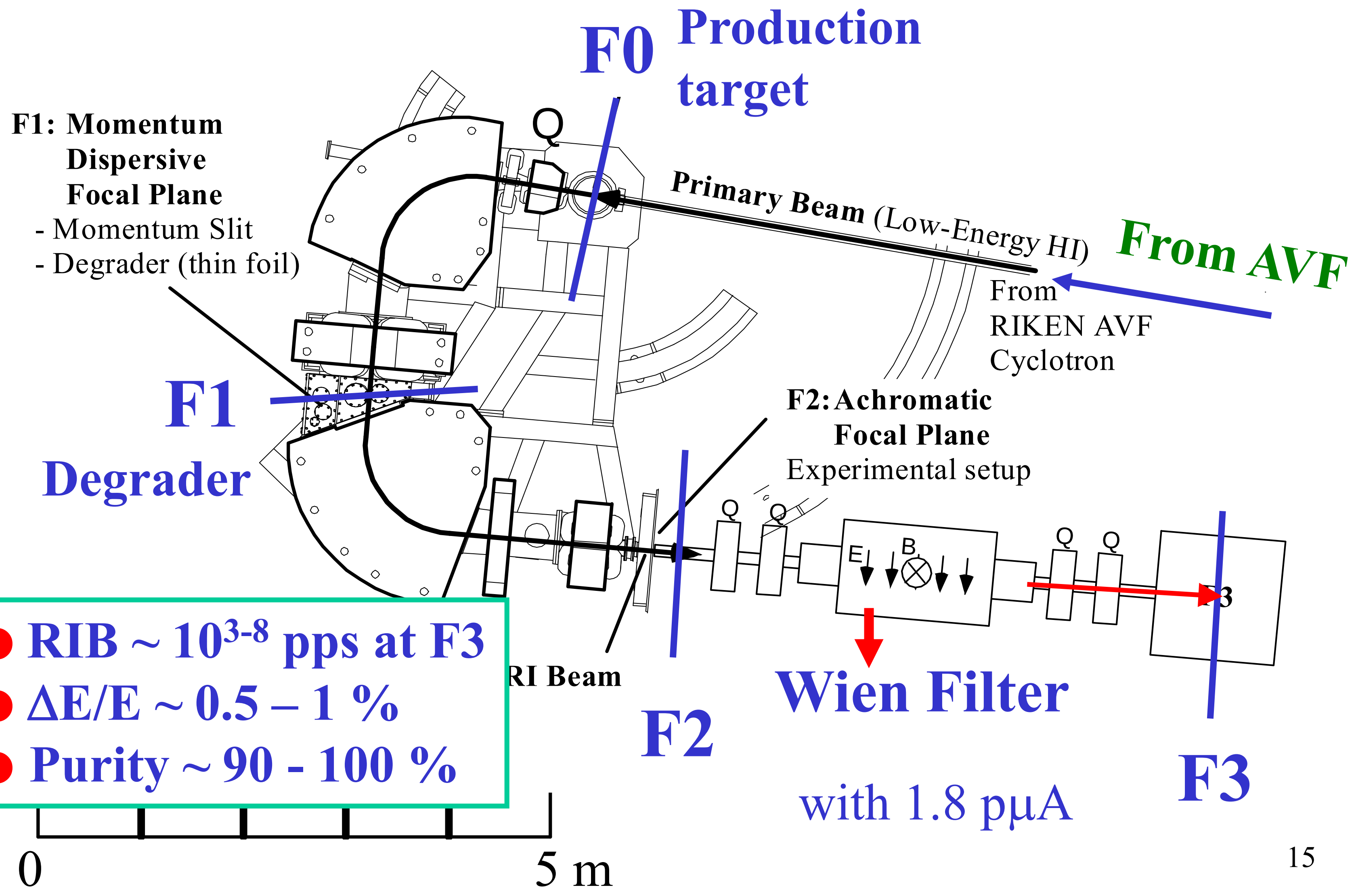
Catalytic process;

$4 \cdot {}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + Q$

☐ Unstable nuclei

■ Stable nuclei

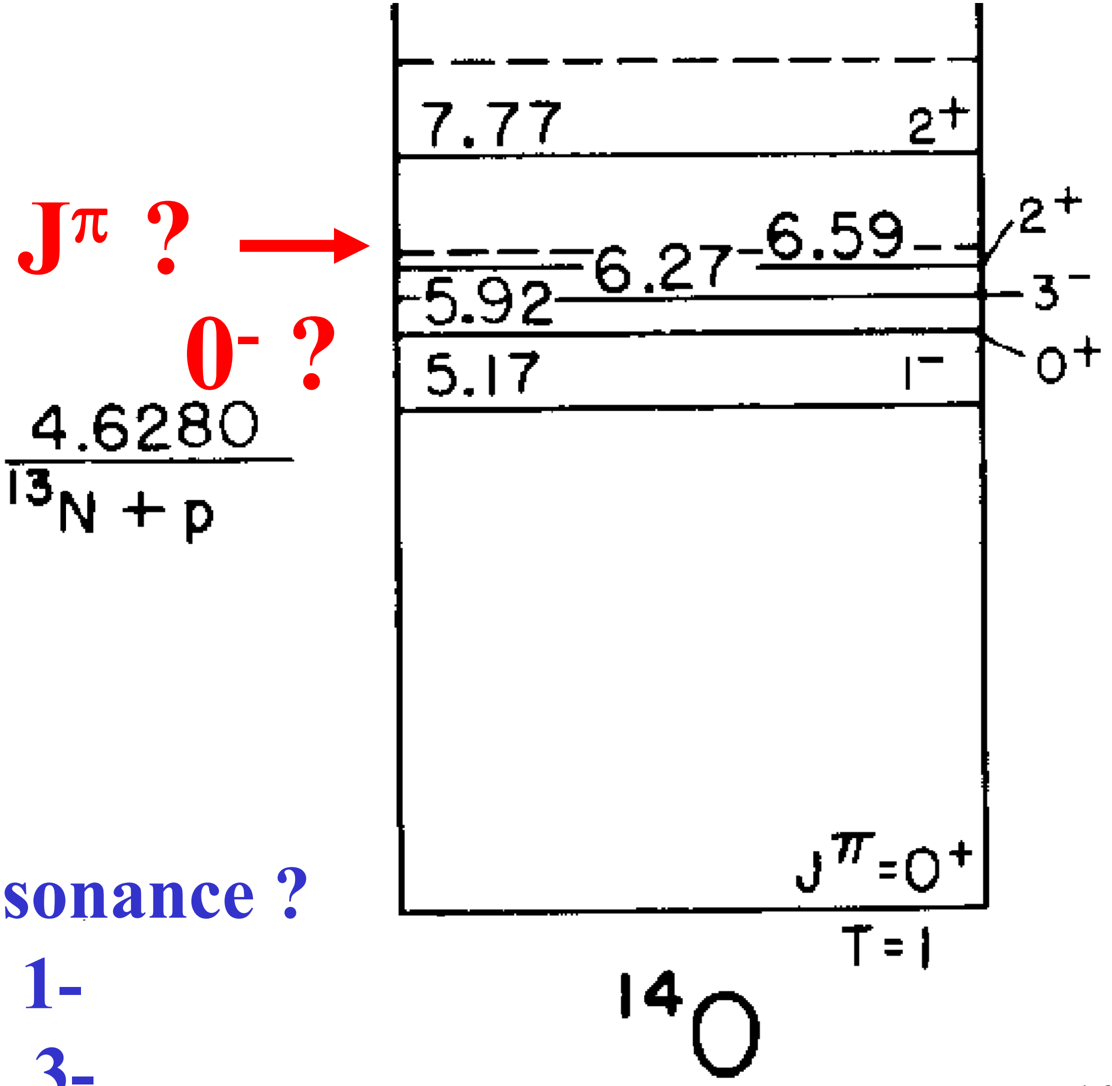
CRIB; Low-Energy In-Flight RI Beam Separator at CNS



- ● RIB ~ $10^{3\text{-}8}$ pps at F3
- ● ΔE/E ~ 0.5 – 1 %
- ● Purity ~ 90 - 100 %

^{13}N+p experiment (^{14}O resonances)

- Search for unknown resonances
  - Astrophysical $^{13}N(p,\gamma)^{14}O$ reaction rates
- Spectroscopic factors for single-particle proton orbitals


J^{π} ?

0^- ?

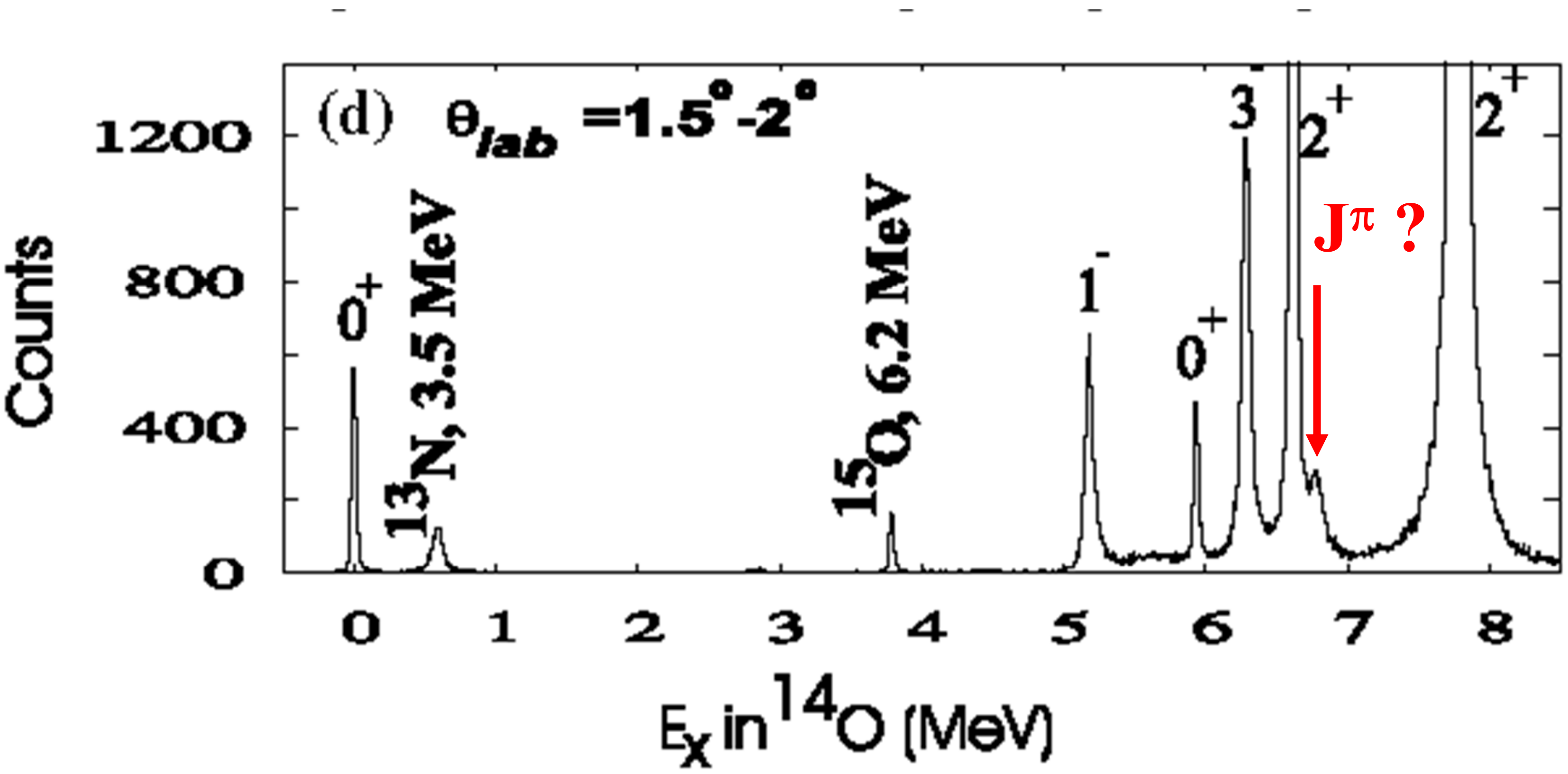
single particle resonance ?

(p1/2・s1/2) J=0-, 1-

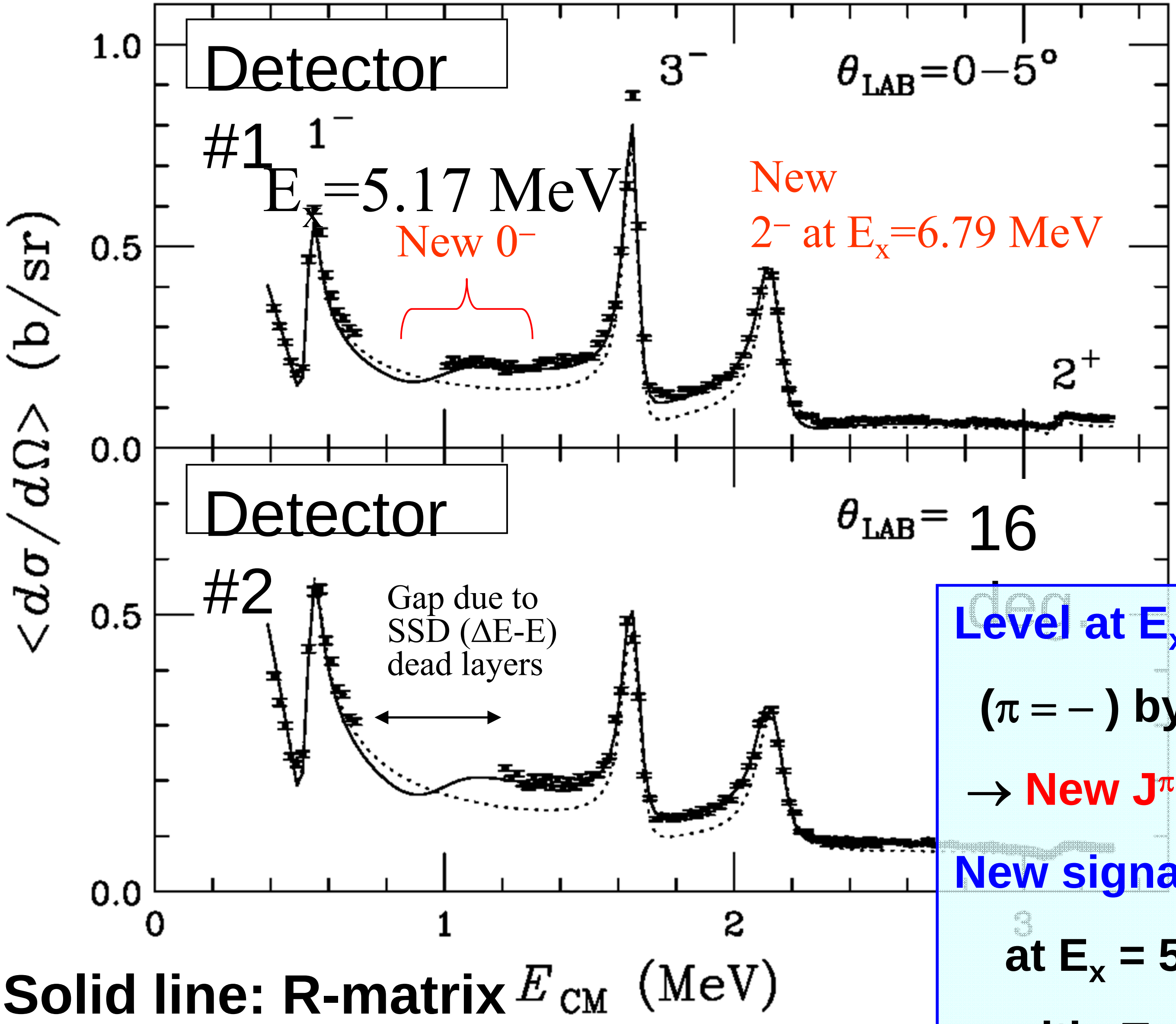
(p1/2・d5/2) J=2-, 3-

$^{14}N(^3He,t)^{14}O$ E_L=420 MeV

(RCNP / Negret 05)



^{13}N+p result (^{14}O resonances)



Solid line: R-matrix

Energy resolution ~20 keV (FWHM)

Level at E_x = 6.79 MeV

($\pi = -$) by ^{14}N(^{3}He,t) reaction

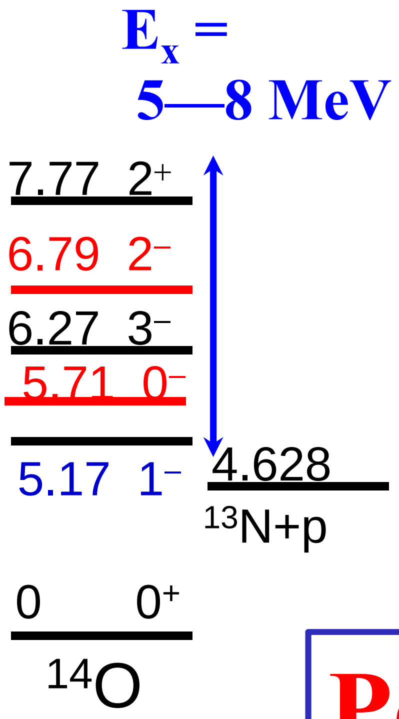
→ New J^π assignment $J^\pi = 2^-$

New signature of 0^- level

at E_x = 5.71(2) MeV

with Γ = 400(100) keV

Summary of ^{13}N+p



J^π	l_j	Γ_{exp} (keV)	$\Gamma_{s.p.}$ (keV)
1^-	$s_{1/2}$	42(3)	45
0^-	$s_{1/2}$	400(100)	550
3^-	$d_{5/2}$	42(3)	53
2^-	$d_{5/2}$	96(4)	130

Powerful to study single particle configuration

- The first experi… el in ^{14}O.
- $J^\pi = 2^-$ has bee… .8 MeV level.
- The Γ of 1^-, 0^-, 3^- & … particle values (Γs.p.).

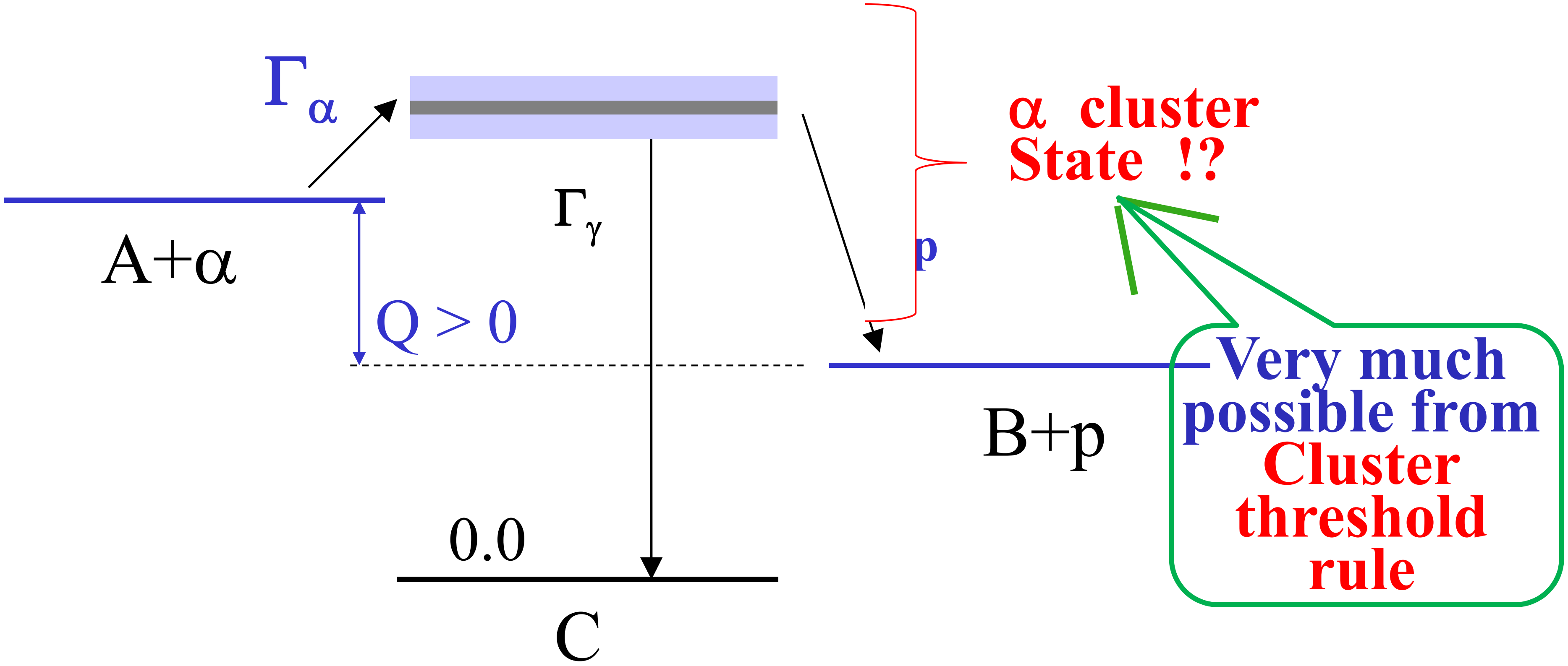
$\Gamma_{s.p.}$ values were estimated using phase shifts in a Woods-Saxon potential model.

1^- & 0^- levels: ^{13}N+p ($2s_{1/2}$) resonance
3^- & 2^- levels: ^{13}N+p ($1d_{5/2}$) resonance

Resonant α-scattering

- ^{21}Na(α, p) reaction -

Basic flow of A(α, p) reactions



α cluster State !?

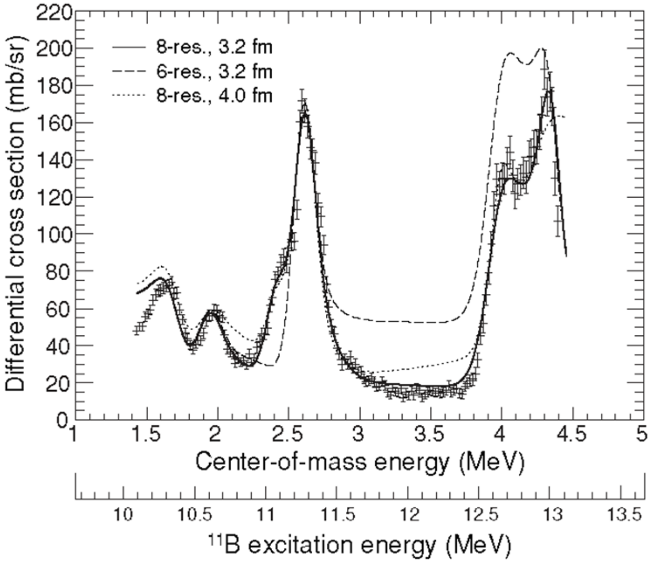
Very much possible from Cluster threshold rule

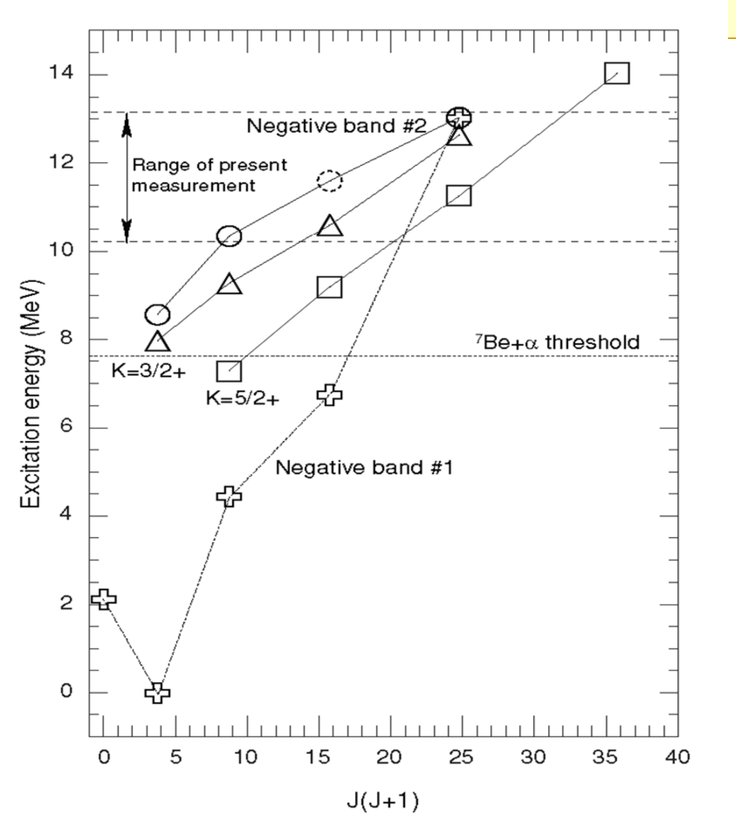
Reaction rate $\propto \omega\gamma = \frac{(2J_r+1)}{(2J_\alpha+1)(2J_A+1)} \frac{\Gamma_\alpha \Gamma_p}{\Gamma_{tot}}$.

$\propto \Gamma_\alpha$ **(if $\Gamma_p >> \Gamma_\alpha$)**

A resonant scattering of $\alpha + {}^7$Li

(Yamaguchi, PRC83)





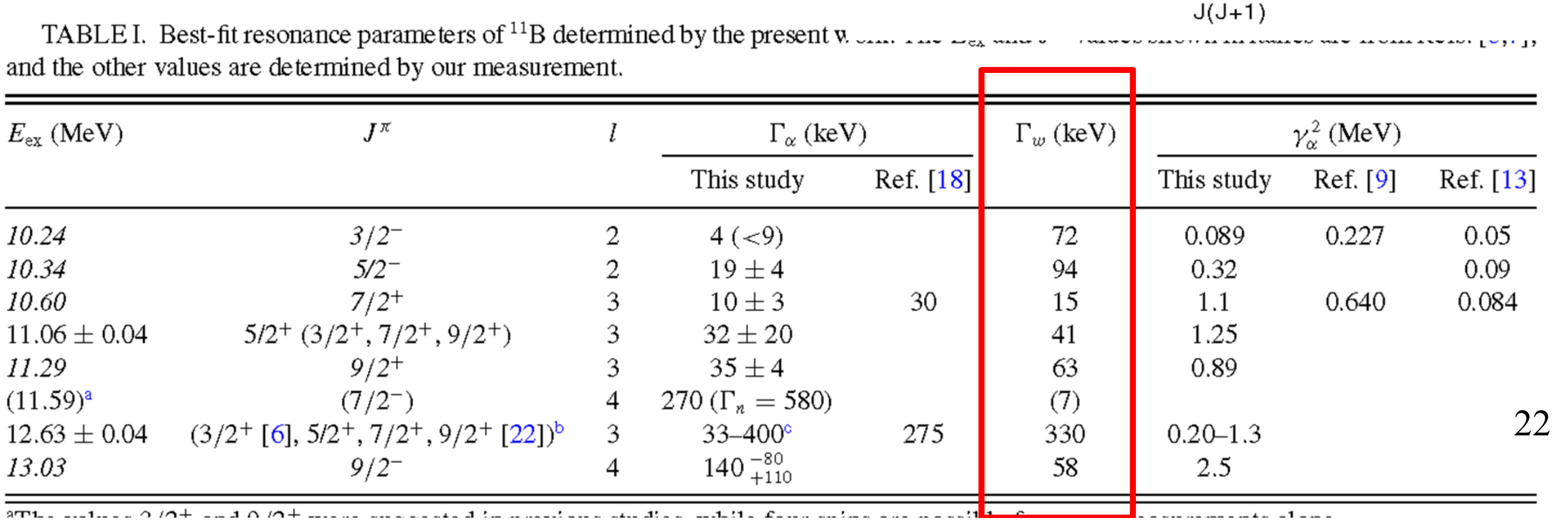


TABLE I. Best-fit resonance parameters of ^{11}B determined by the present w
and the other values are determined by our measurement.

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		

Early Stage of rp-Process

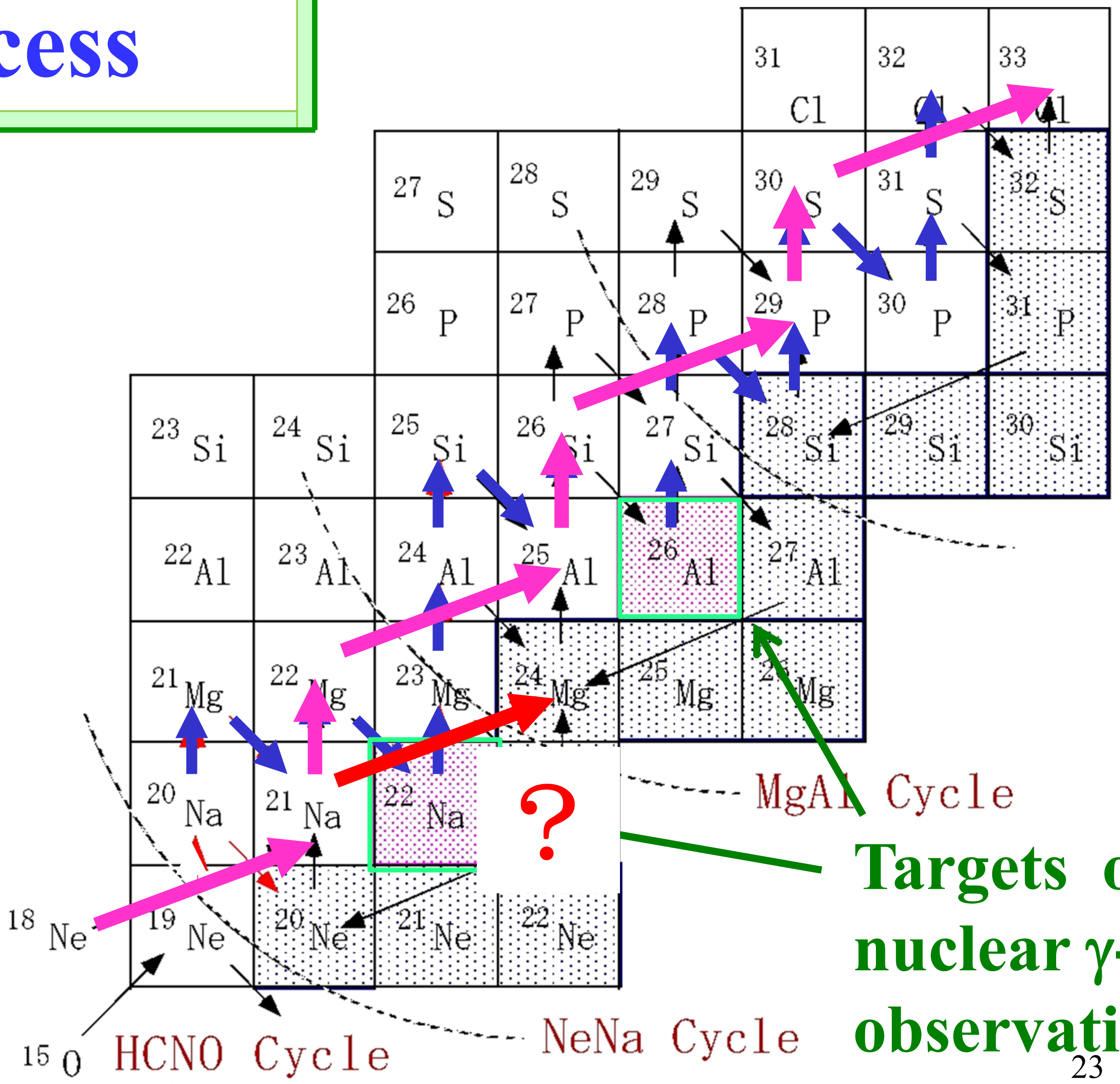
Cycle;
4H→^{4}He+Q

↓

rp-process

↓

→
αp-process



Targets of nuclear γ-ray observation

Scientific Motivation

❑ Gamma ray observation of ^{22}Na

^{22}Na ($t_{1/2}$=2.6 yr) is one of the target nuclei of gamma-ray observation

- Try to observe this gamma rays (1.275 MeV)
to learn nucleosynthesis in novae and other explosive phenomena

❑ Ne-E problem in presolar grains

Origin of isotopic anomaly; high enrichment of ^{22}Ne in meteorites

In the Orgueuil meteorite, $^{22}\mathrm{Ne}/^{20}\mathrm{Ne} > 0.67$

(terrestrial abundance: $^{22}\mathrm{Ne}/^{20}\mathrm{Ne} \approx 0.10$)

❑ Study the αp-process

Very few (α,p) reactions were investigated directly. Need experimental study.

Beam production

^{21}Na beam

Energy:

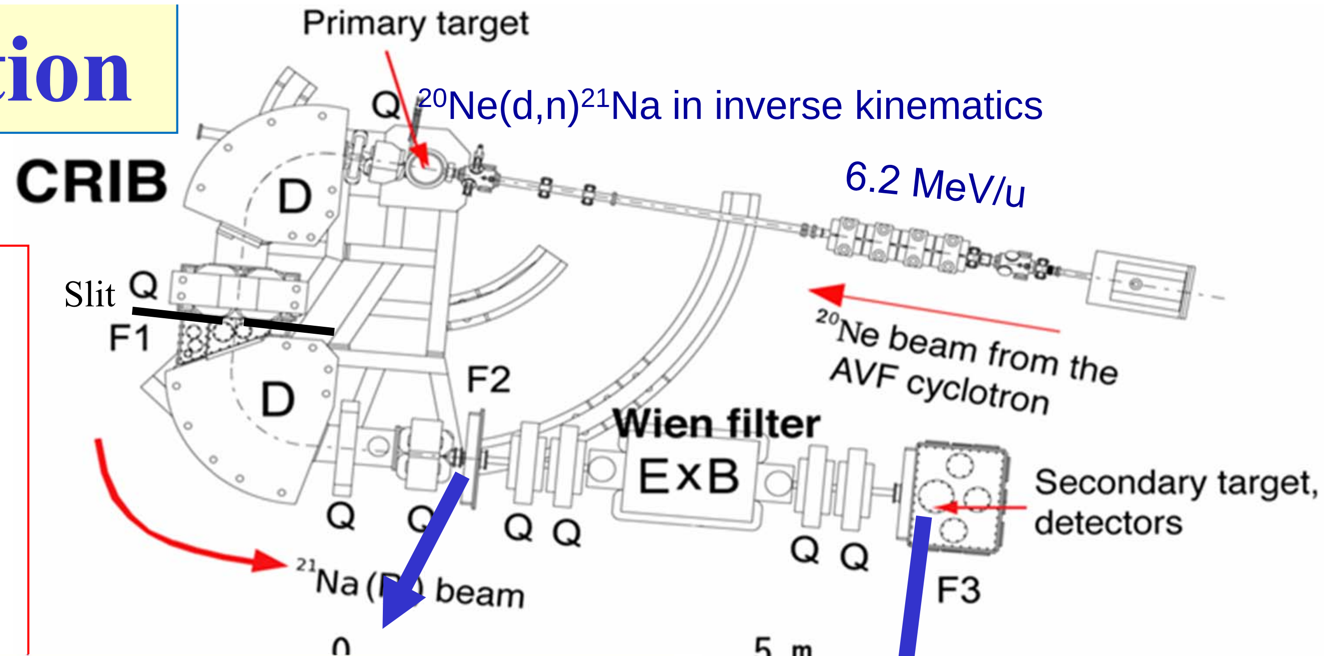
39.5 ± 0.9 MeV

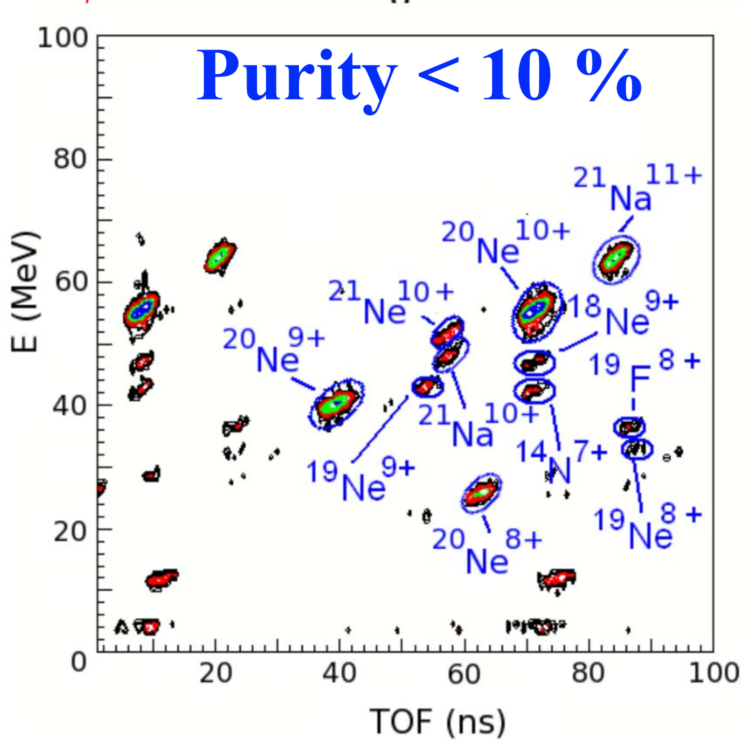
Purity:

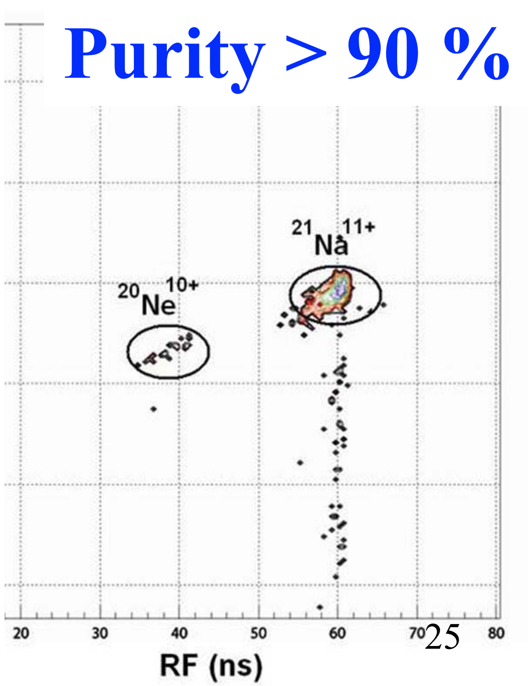
83 – 95 %

Intensity:

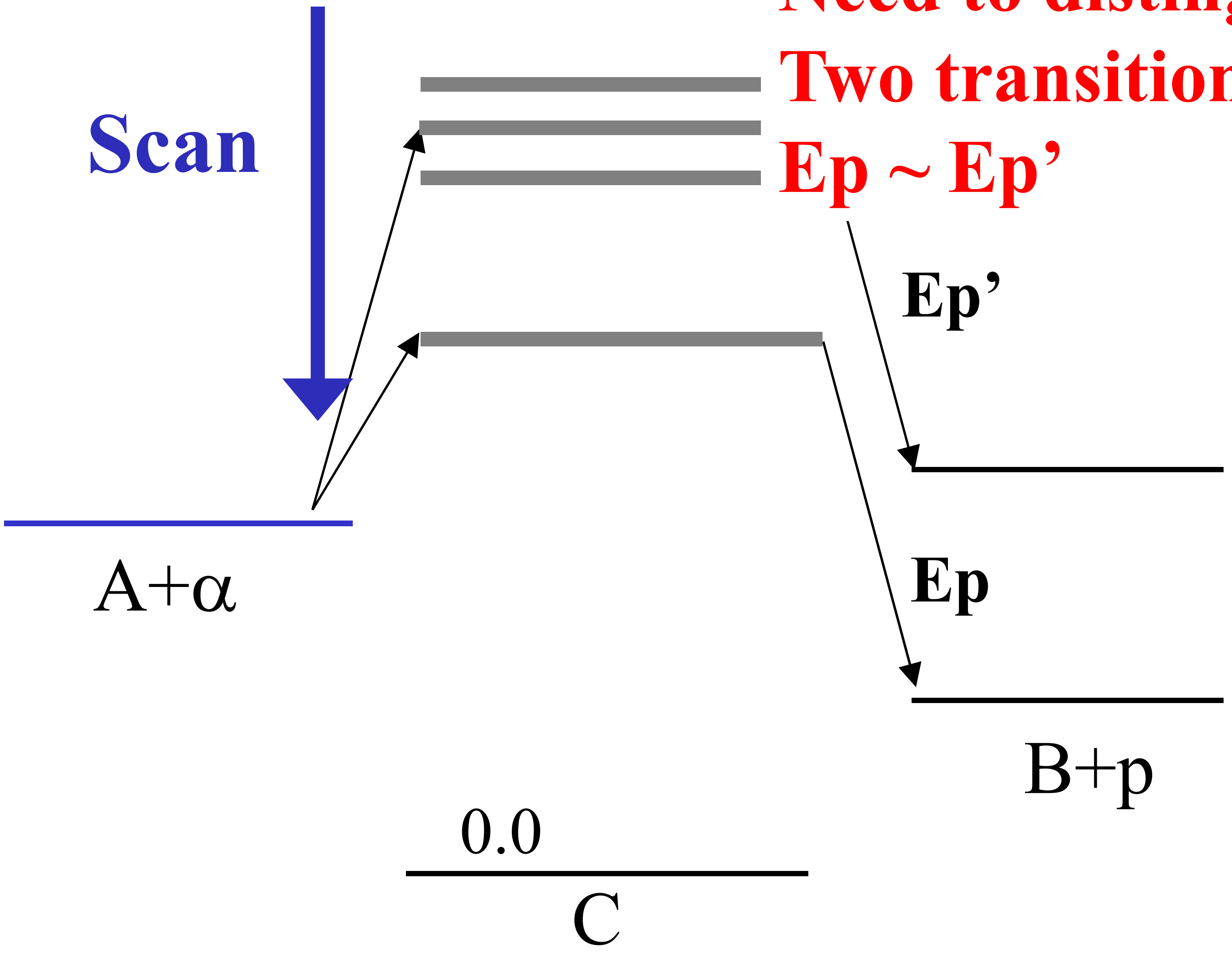
~ 5×10^{5} pps







Problem with the thick target method



Need to distinguish
Two transitions !
Ep ~ Ep'

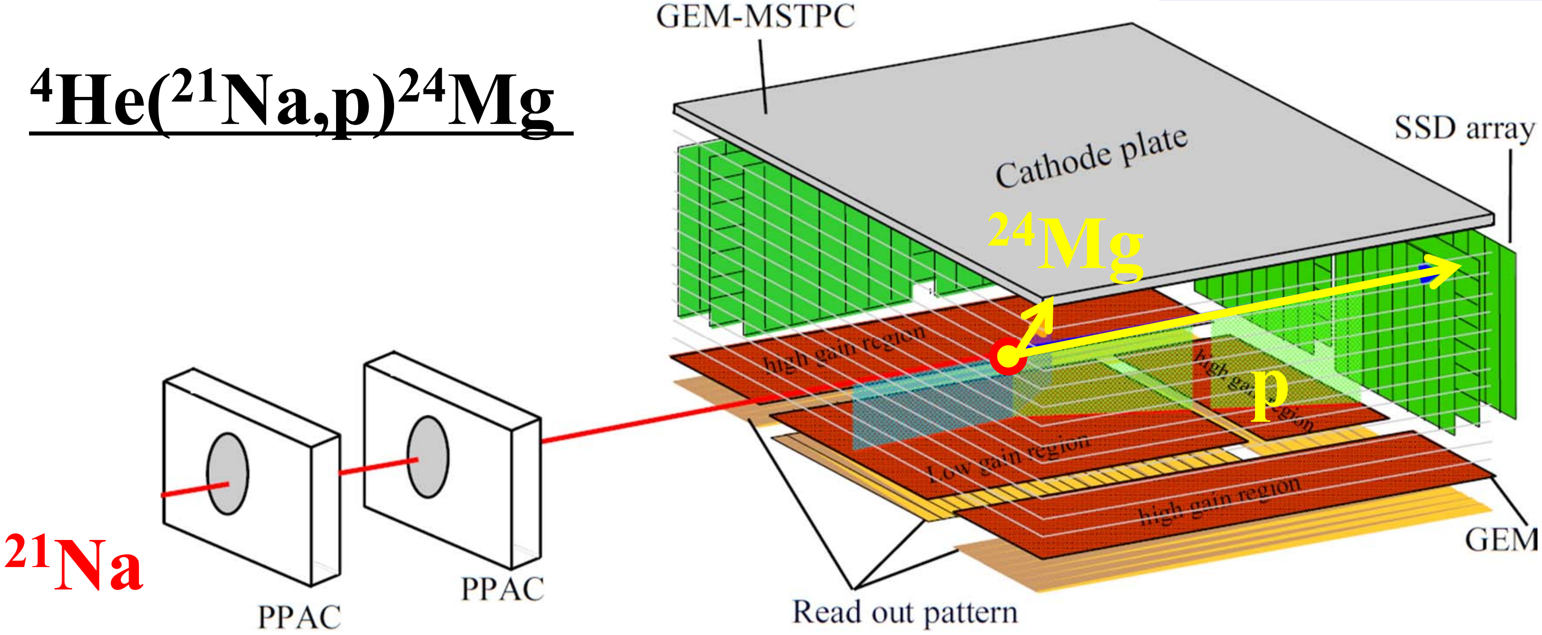
Extensive Active Target ; GEM-MSTPC Target/Detector System

Hashimoto

- **High rate operation of tracking both the beam and the reaction particles with a rate of 5×10^5 pps**
- **Measure a full set of data (x,y,z,ΔE,E,t)**

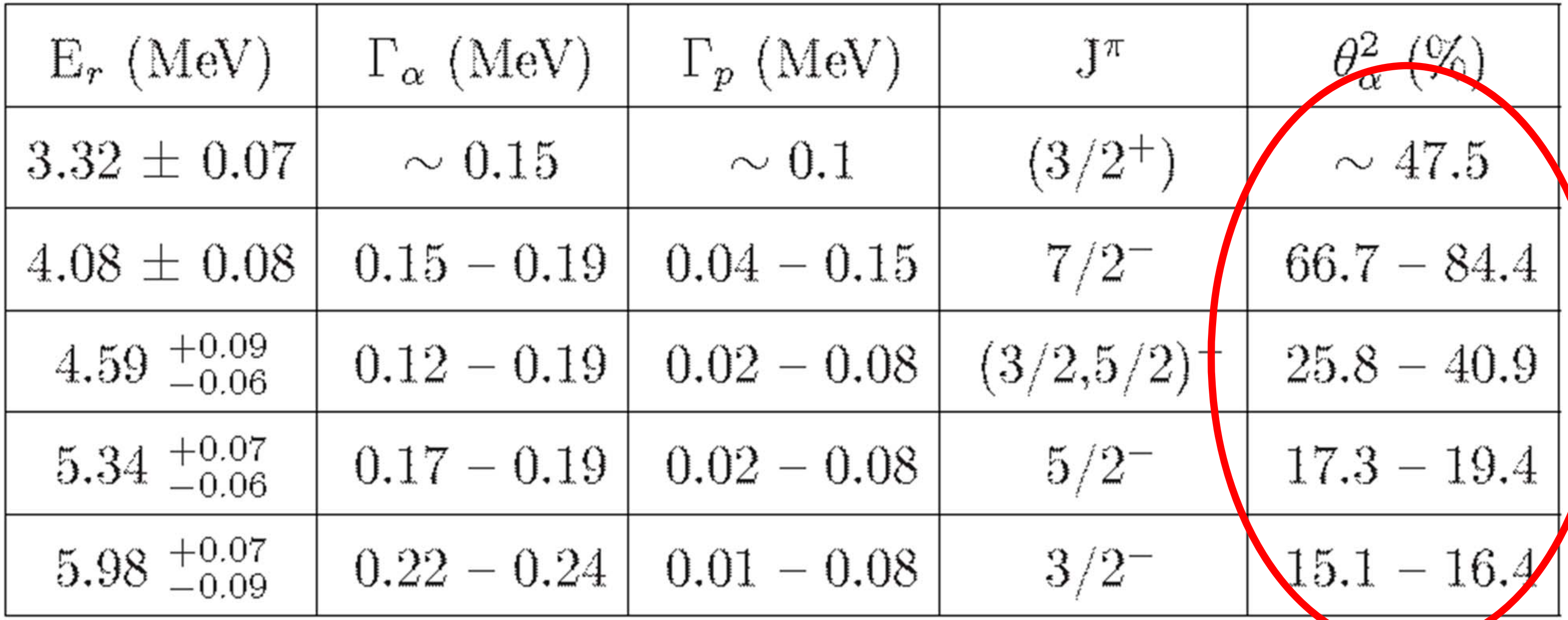
Identify the reaction position ⇒ Er

<u>$^4He(^{21}Na,p)^{24}Mg$</u>



R-matrix analysis on ^{21}Na(α,α)

α reduced width

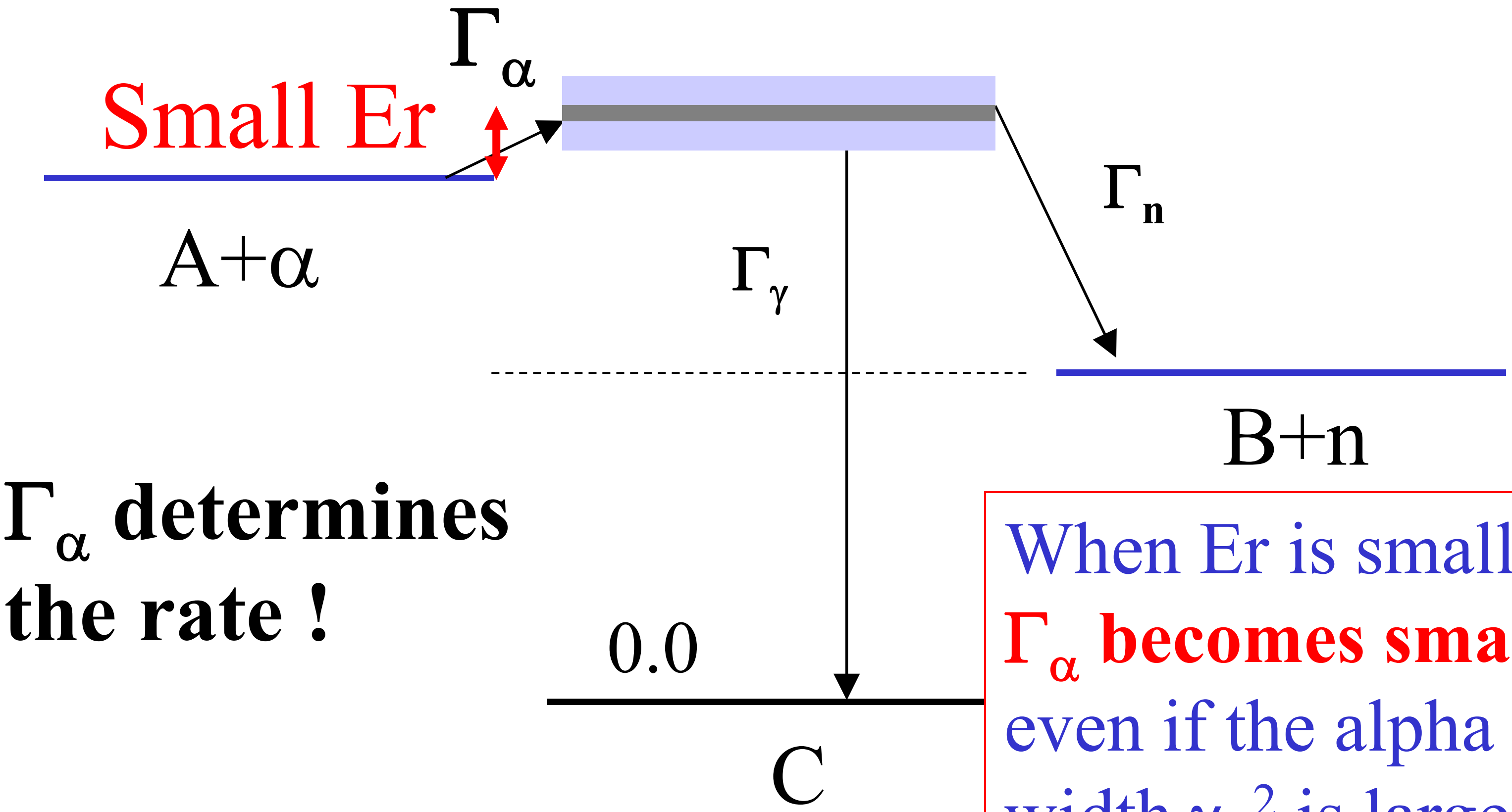


E_r (MeV)	Γ_α (MeV)	Γ_p (MeV)	J^π	θ_α^2 (%)
3.32 ± 0.07	~ 0.15	~ 0.1	$(3/2^+)$	~ 47.5
4.08 ± 0.08	$0.15 - 0.19$	$0.04 - 0.15$	$7/2^-$	$66.7 - 84.4$
$4.59\ ^{+0.09}_{-0.06}$	$0.12 - 0.19$	$0.02 - 0.08$	$(3/2,5/2)^-$	$25.8 - 40.9$
$5.34\ ^{+0.07}_{-0.06}$	$0.17 - 0.19$	$0.02 - 0.08$	$5/2^-$	$17.3 - 19.4$
$5.98\ ^{+0.07}_{-0.09}$	$0.22 - 0.24$	$0.01 - 0.08$	$3/2^-$	$15.1 - 16.4$

α-cluster resonances !

Direct α-transfer reactions

(α,p), (α,n) reactions at low energies



Γ_α determines the rate !

When Er is small,
Γ_α becomes smaller
even if the alpha reduced width γ_α^2 is large.

Direct α-transfer reaction

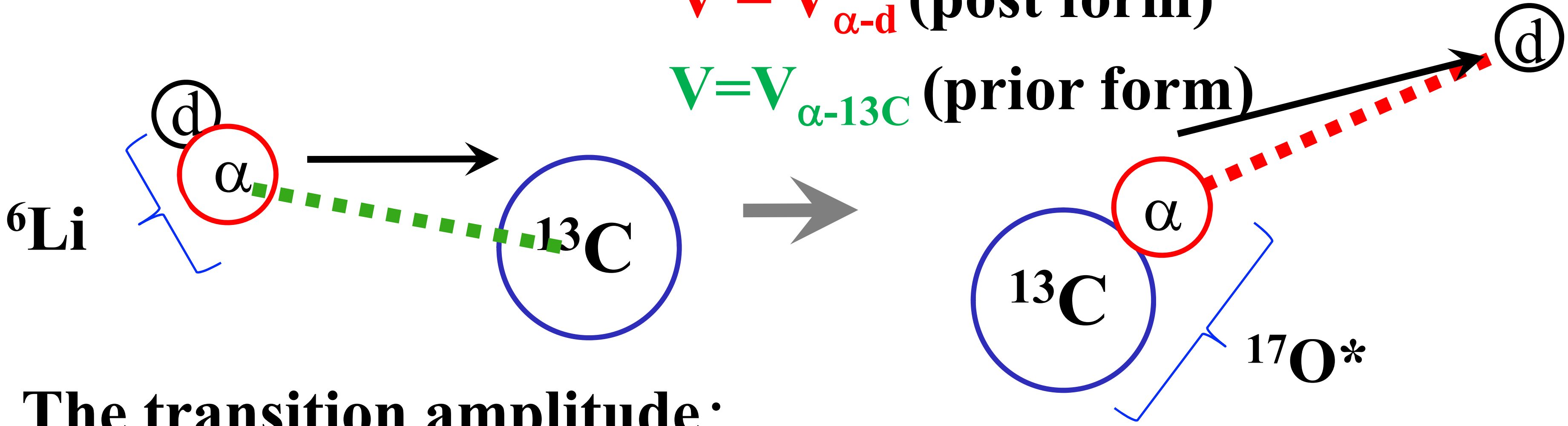
Direct α-Transfer Reaction

$^{13}C(^6Li,d)^{17}O$

Reaction interaction;

$V = V_{\alpha\text{-}d}$ (post form)

$V = V_{\alpha\text{-}13C}$ (prior form)



The transition amplitude;

$$T = \int \chi^*_{d\,^{17}O}(k_d, r) \underbrace{< \varphi_d \varphi_{^{17}O} | V | \varphi_{^6Li}\varphi_{^{13}C} > |}_{\text{Reaction form factor}} \chi_{^{13}C\,^6Li}(k_{^6Li}, r) dr$$

$$\approx \tilde{V}_{\alpha-d} < \varphi_{^{17}O} | \varphi_{^{13}C}\varphi_\alpha >$$

Direct reaction provides structure information when one-step

Direct Reaction Theory ; Distorted Wave Born Approximation (DWBA)

A + a → B + b + Q (e.g. $^{12}C(^{3}He,d)^{13}N^{*}$)

$$\frac{d\sigma}{d\omega}^{DWBA} = \frac{M_{aA} M_{bB}}{(2\pi\hbar^{2})^{2}} \frac{k_b}{k_a} |T|^{2}$$

The transition amplitude T (散乱振幅) is

$$T = \int \chi^{*}_{bB}(k_b, r) < \varphi_b \varphi_B | V | \varphi_a \varphi_A > \chi_{aA}(k_a, r) dr$$

distorted wave
of the exit channel

↑
reaction
interaction

distorted wave （歪曲波）
of the incident channel

The Form factor can be written as

$$< \varphi_b \varphi_B | V | \varphi_a \varphi_A > = < d\, ^{13}N^{*} | V_{dp} | ^{3}He\, ^{12}C > = V_{dp}(r_{dp}) < \phi_{p12C} | \phi_{13C^{*}} >$$

Thus

$$\frac{d\sigma}{d\omega}^{Exp} = S_{p(3He)} \boxed{S_{p(13N^{*})}} \frac{d\sigma}{d\omega}^{DWBA}$$

Spectroscopic factor
(分光学因子)

α-Reduced Width and the α-Spectroscopic Factor

(Indirect method)

$$Breit-Wigner \quad one \quad level \quad formula \qquad :$$

$$\sigma(E)=\pi\frac{\hbar^2}{2\mu E}\frac{2J+1}{(2S_1+1)(2S_2+1)}\frac{\Gamma_\alpha\Gamma_n}{(E-E_R)^2+(\Gamma/2)^2}$$

$$\Gamma_\alpha=2\frac{k_\alpha R}{|F_\ell(k_\alpha R)|^2+|G_\ell(k_\alpha R)|^2}\gamma_\alpha^2$$

;α-width

; (observed)

$$R=r_0(A_1^{1/3}+A_2^{1/3})$$

$$\boxed{\gamma_\alpha^2=\frac{3\hbar^2}{2\mu R^2}S_\alpha}$$

; α-reduced width

α-transfer reactions

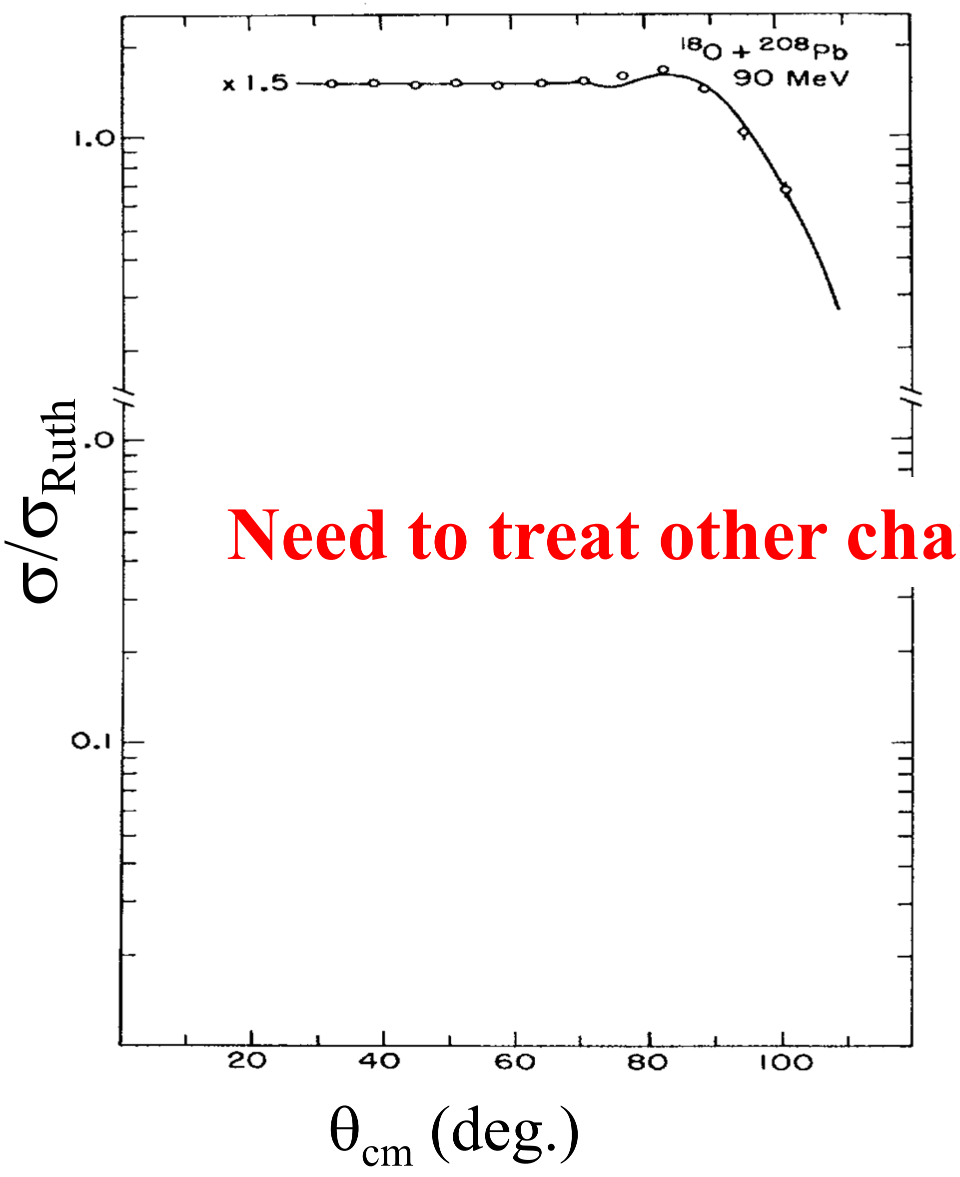
$$S_\alpha=\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{EXP}}\Big/\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{DWBA}}$$

; Spectroscopic factor

Application of Direct Transfer Reactions

1. **Reaction mechanism**
   - **Direct process ?**
   - Coupling to other channels
   - Multi-step processes
   - Compound nucleus formation
2. **Optical potentials**
3. **Bound states** (Interaction)
   - Interaction- separation energy method
   - Bound state wave functions

Elastic Scattering of ^{18}O on ^{184}W and ^{208}Pb

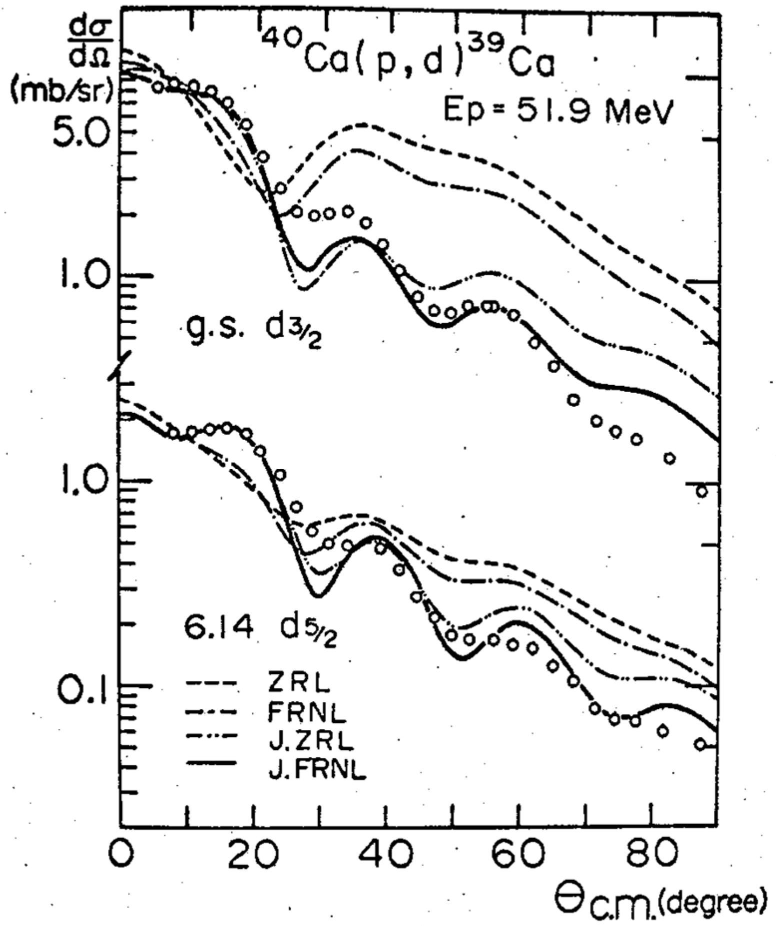


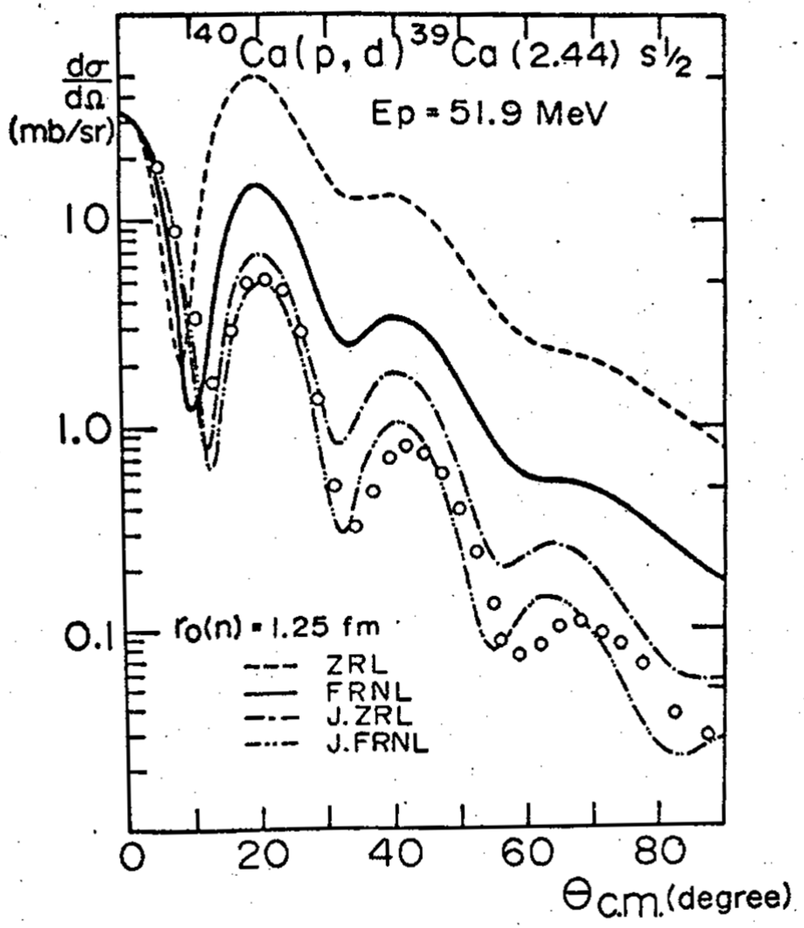
Need to treat other channels explicitly !

(Thorn, PRL38 ('77)384)

L=0 and 2 transitions of $^{40}Ca(p,d)^{39}Ca$

Ep = 51.9 MeV



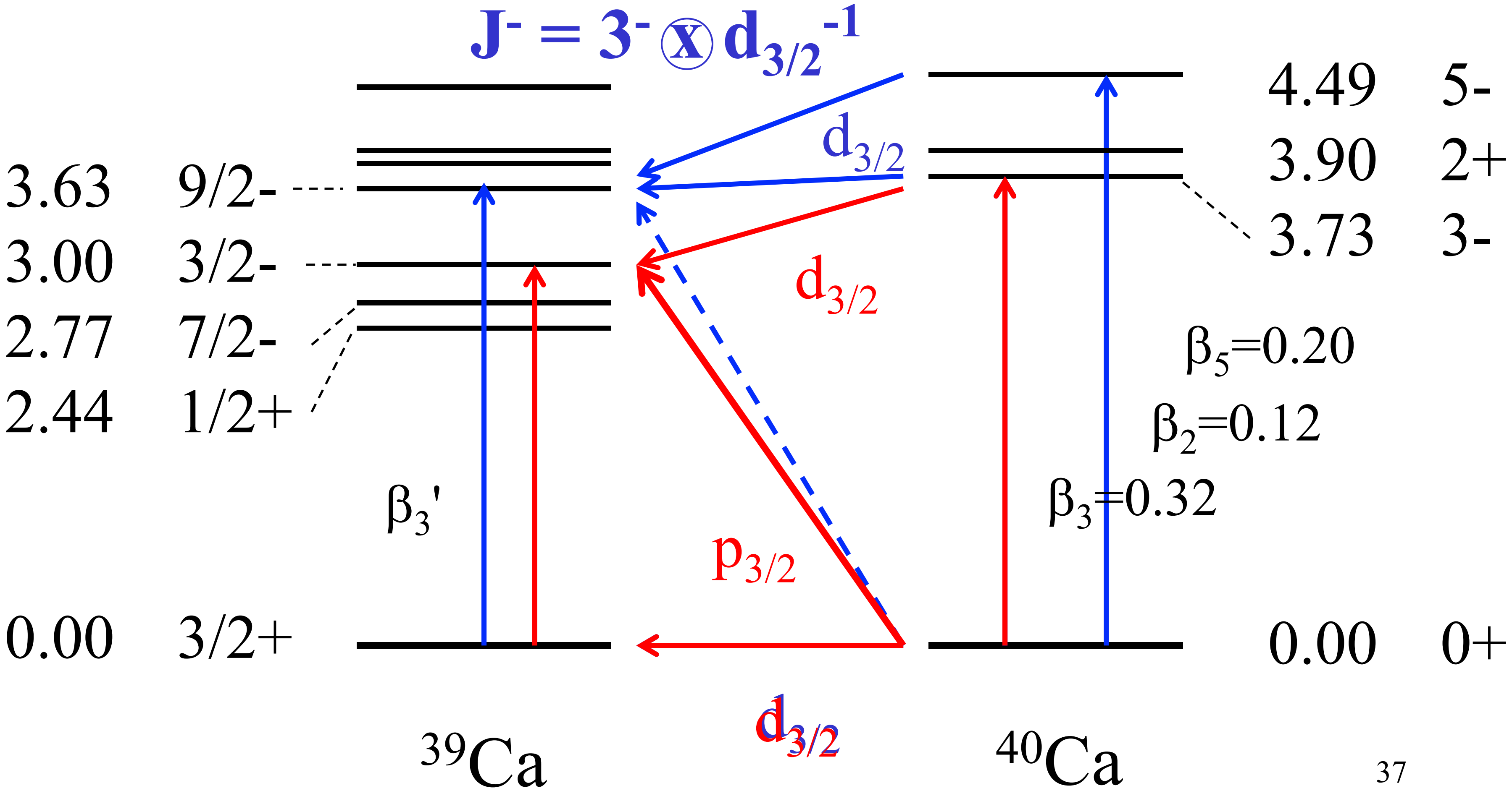


(Kubono, '75)

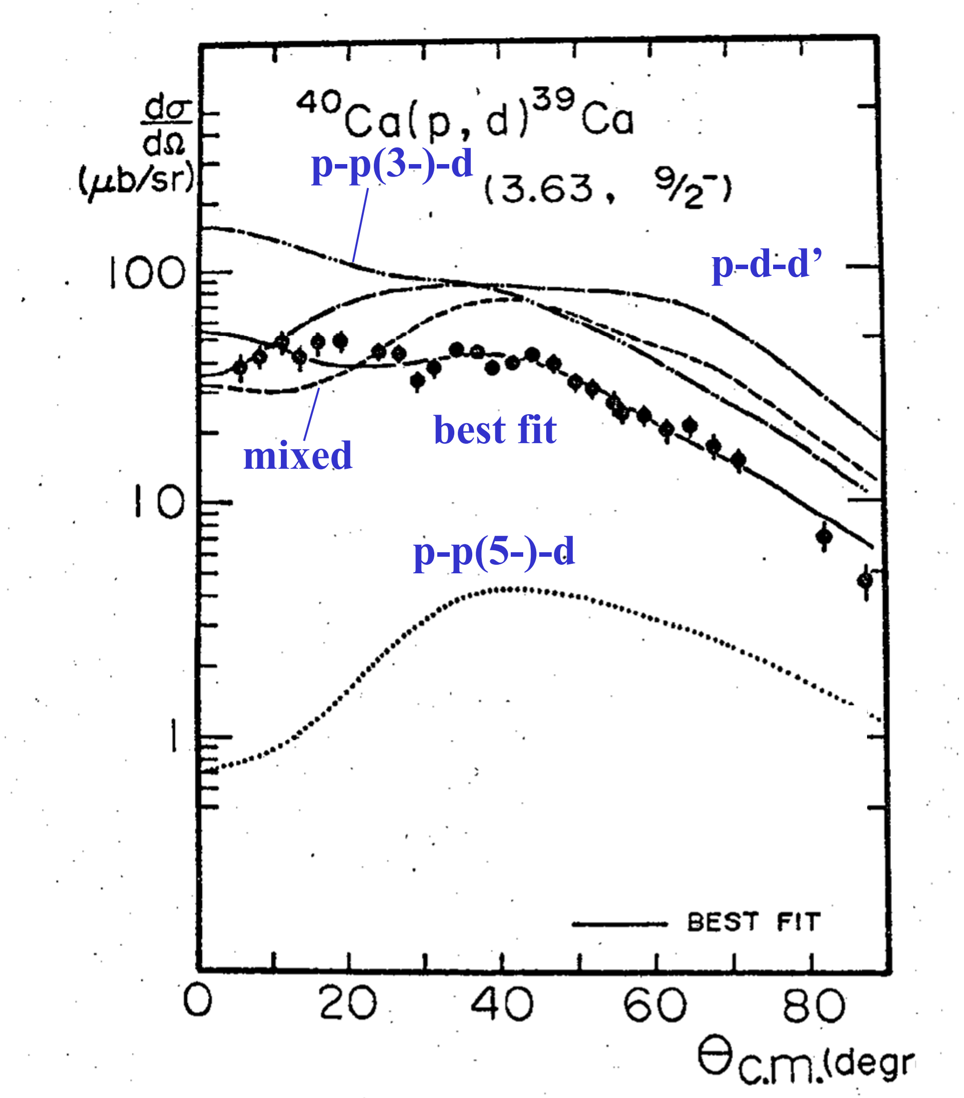
Two-step processes in ^{40}Ca(p,d)^{39}Ca

$$|^{40}Ca(g.s.,0^{+})> \approx 0.9\,|0p-0h> +0.4\,|2p-2h> +0.1\,|4p-4h>$$

Gerace, Green(NPA93)

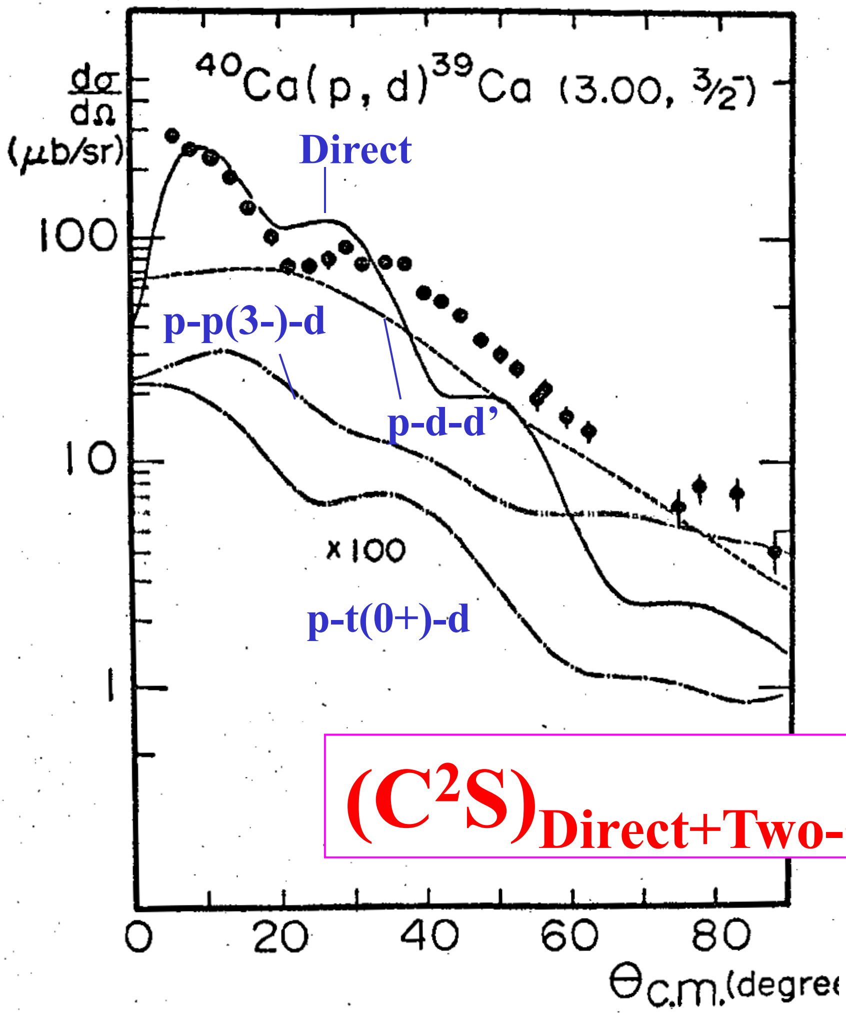


^{40}Ca(p,d) to states at 3.63(9/2$^-$) and 2.77(7/2$^-$)



(Kubono, '75)

Two-step processes in $^{40}Ca(p,d)^{39}Ca$



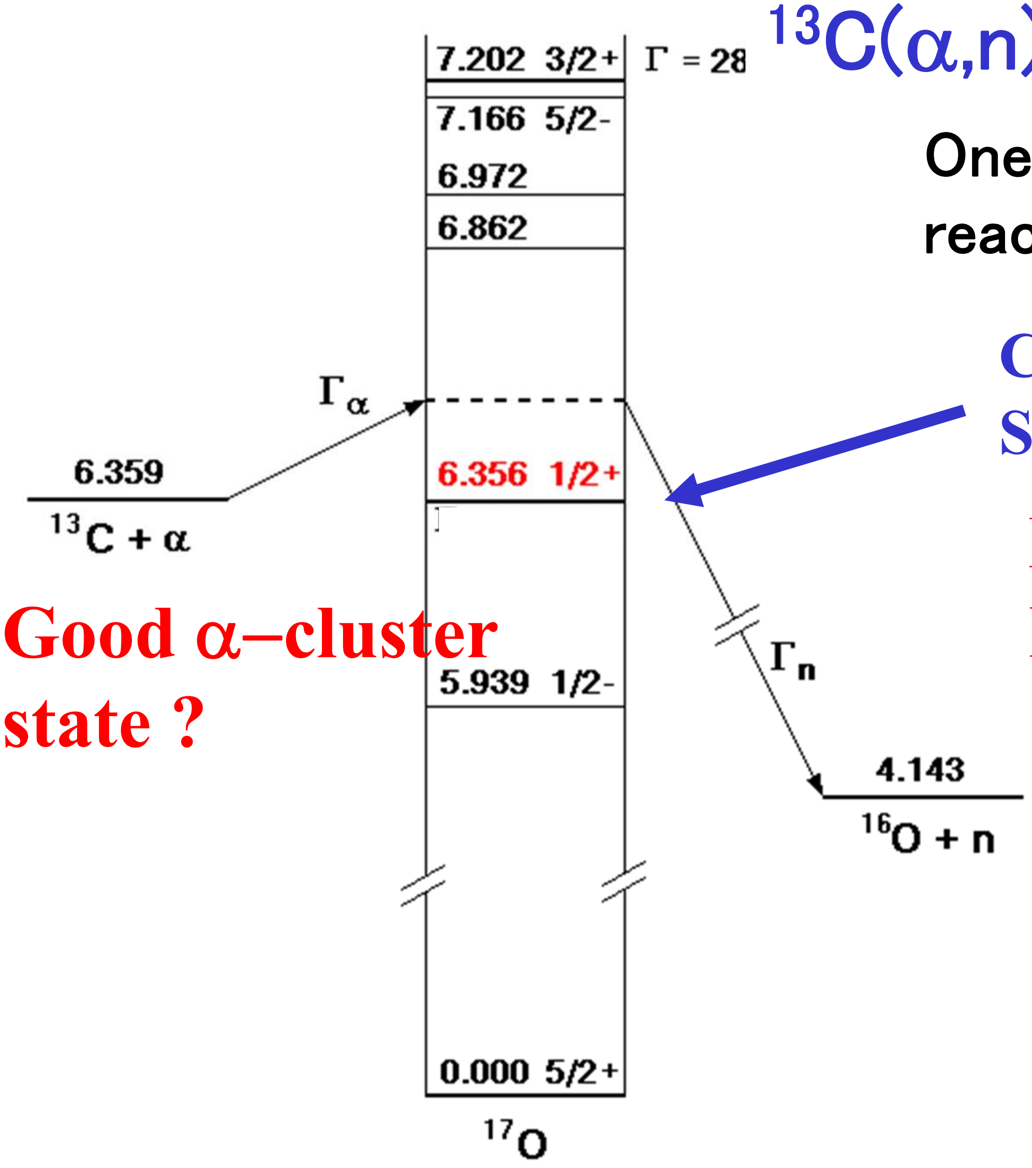
$$(C^2S)_{\text{Direct+Two-stp}} = 0.24(C^2S)_{\text{Direct only}}$$

(Kubono, '75)

α-Transfer Reactions on ^{13}C for S_α

$^{13}C(\alpha,n)^{16}O$ Stellar reaction

One of the main n-source reaction for the s-process



Contribution of the Sub-threshold state !

Good α–cluster state ?

Deduce S_α by α-transfer Reaction (^{6}Li,d)

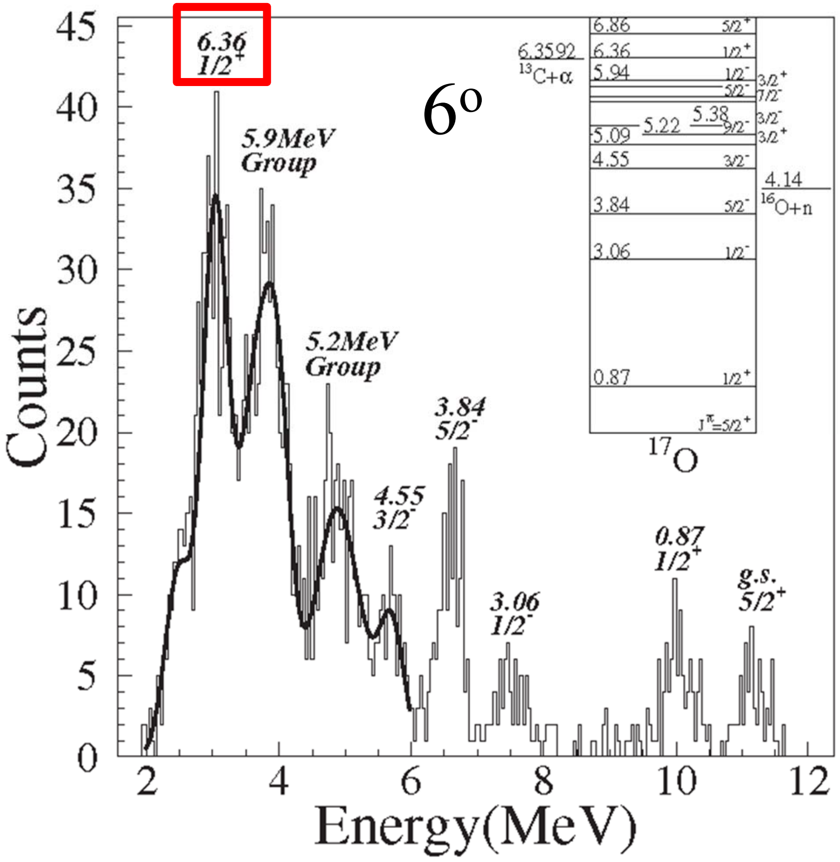
↓

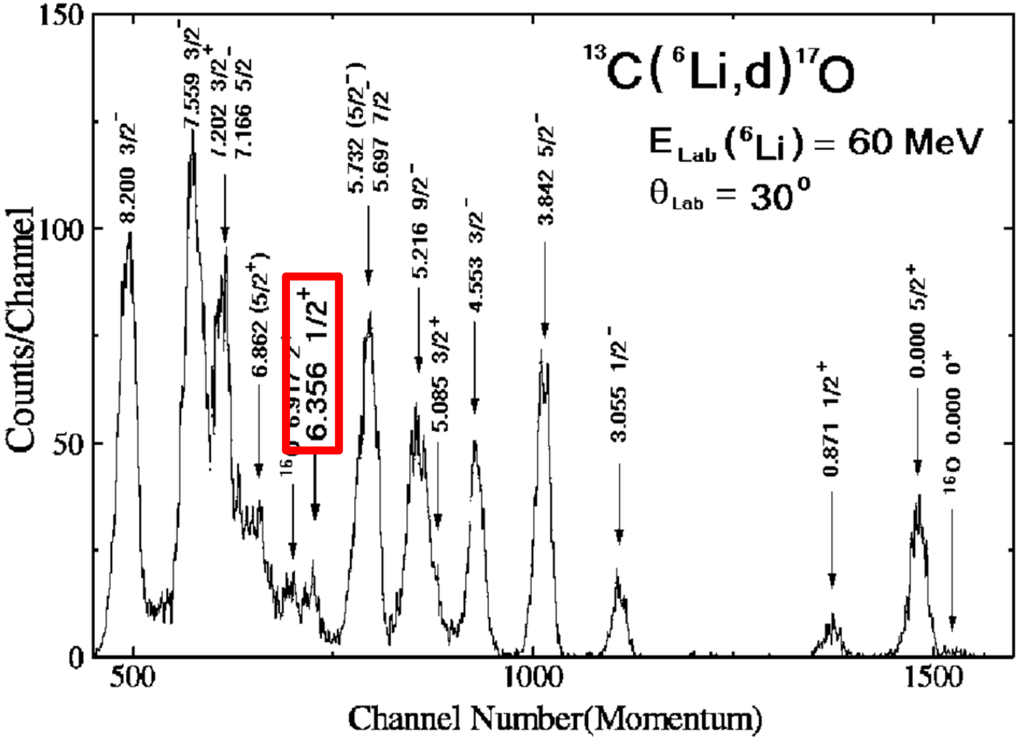
$\boxed{\langle \sigma \upsilon \rangle}$

$^{13}C(^{6}Li,d)\ ^{17}O$

$E_L(^{13}C) =$ 8.5 MeV
(E_{cm}=2.7 MeV)

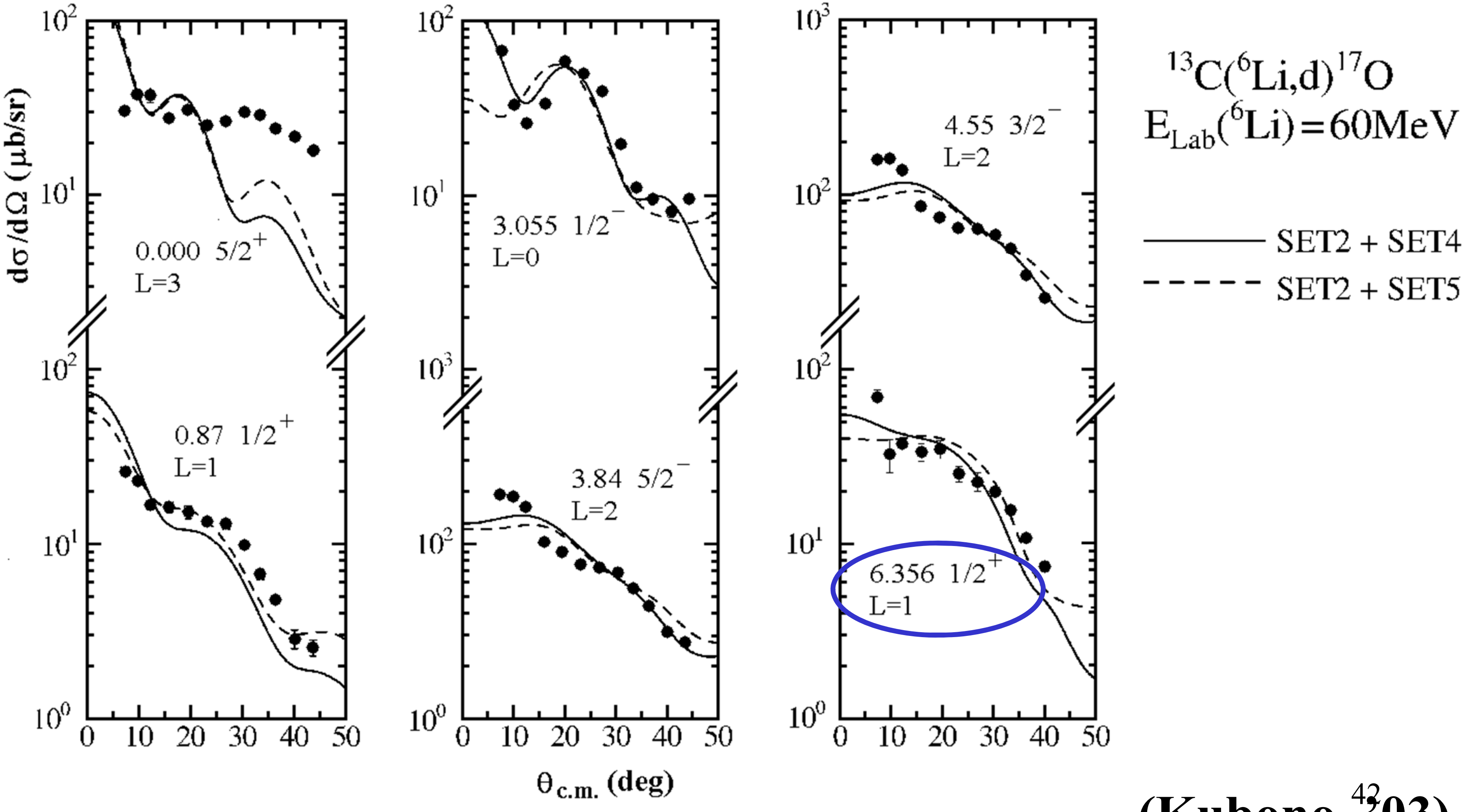
$E_L(^{6}Li)$=60 MeV
(E_{cm}=41.0 MeV)





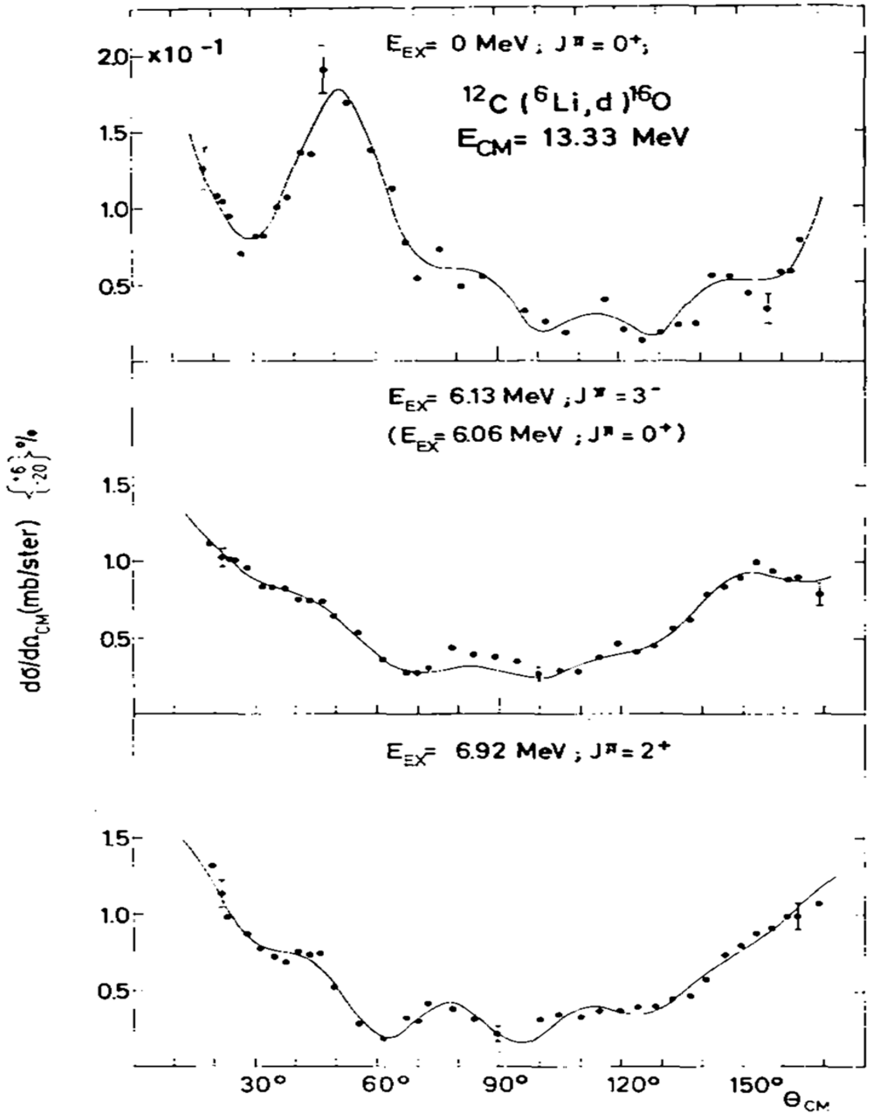
(Johnson, 2006)

Angular Distributions of $^{13}C(^{6}Li,d)^{17}O$



(Kubono, '03)

$^{12}C(^{6}Li,d)^{16}O$ E_{6Li}=20 MeV



(Meier-Evert, 1968)

(E_{cm}=13.3 MeV)

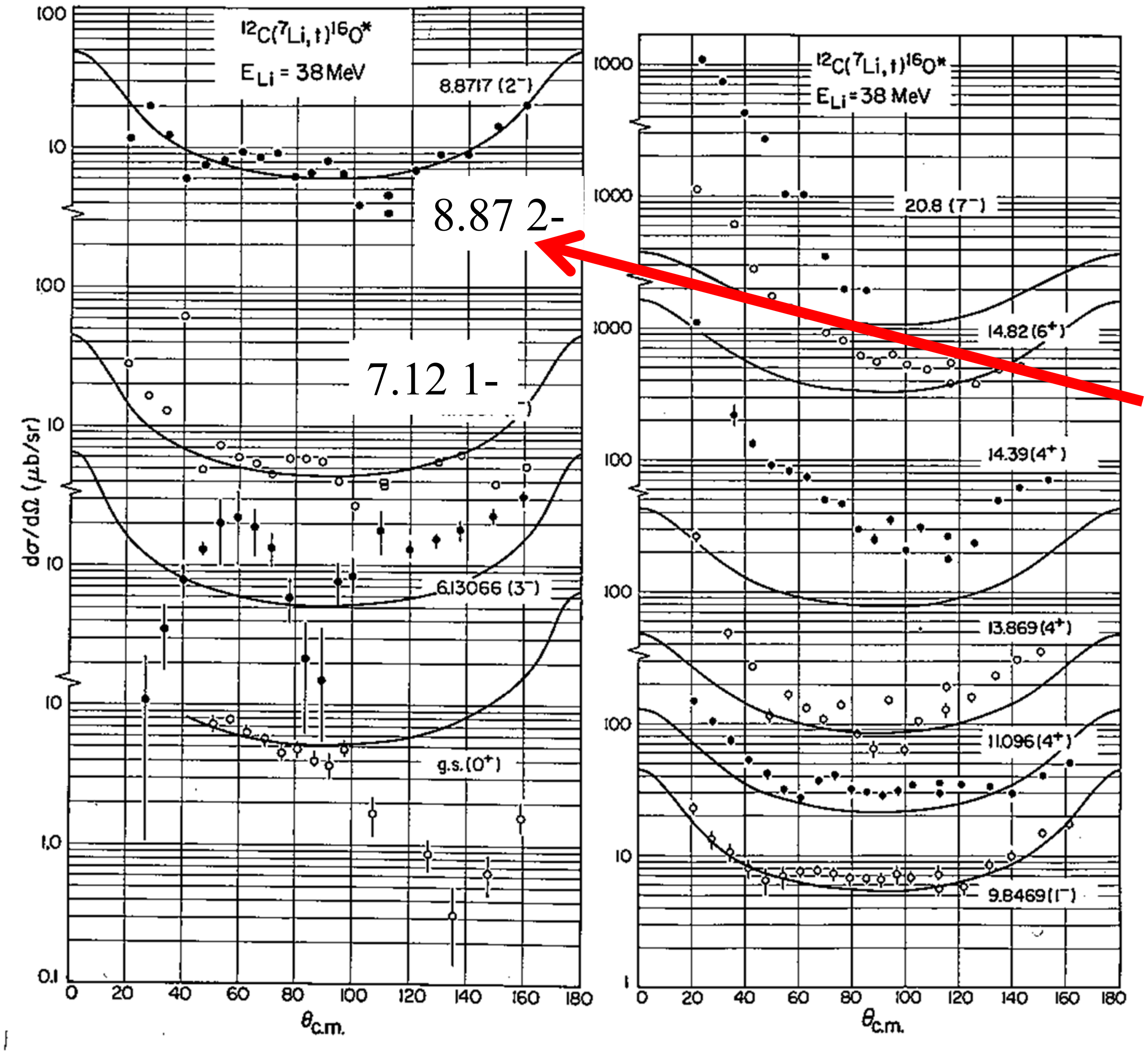
Fusion cross sections changes drastically at a few – several MeV/u by

$$\sigma_{fusion}(E_{cm}) \propto 1/E_{cm}$$

whereas c.s. of quasi-elastic processes increases instead.

$^{12}C(^{7}Li,t)^{16}O$　E_{7Li}=38 MeV

(E_{cm}=24MeV)



8.87 2-

7.12 1-

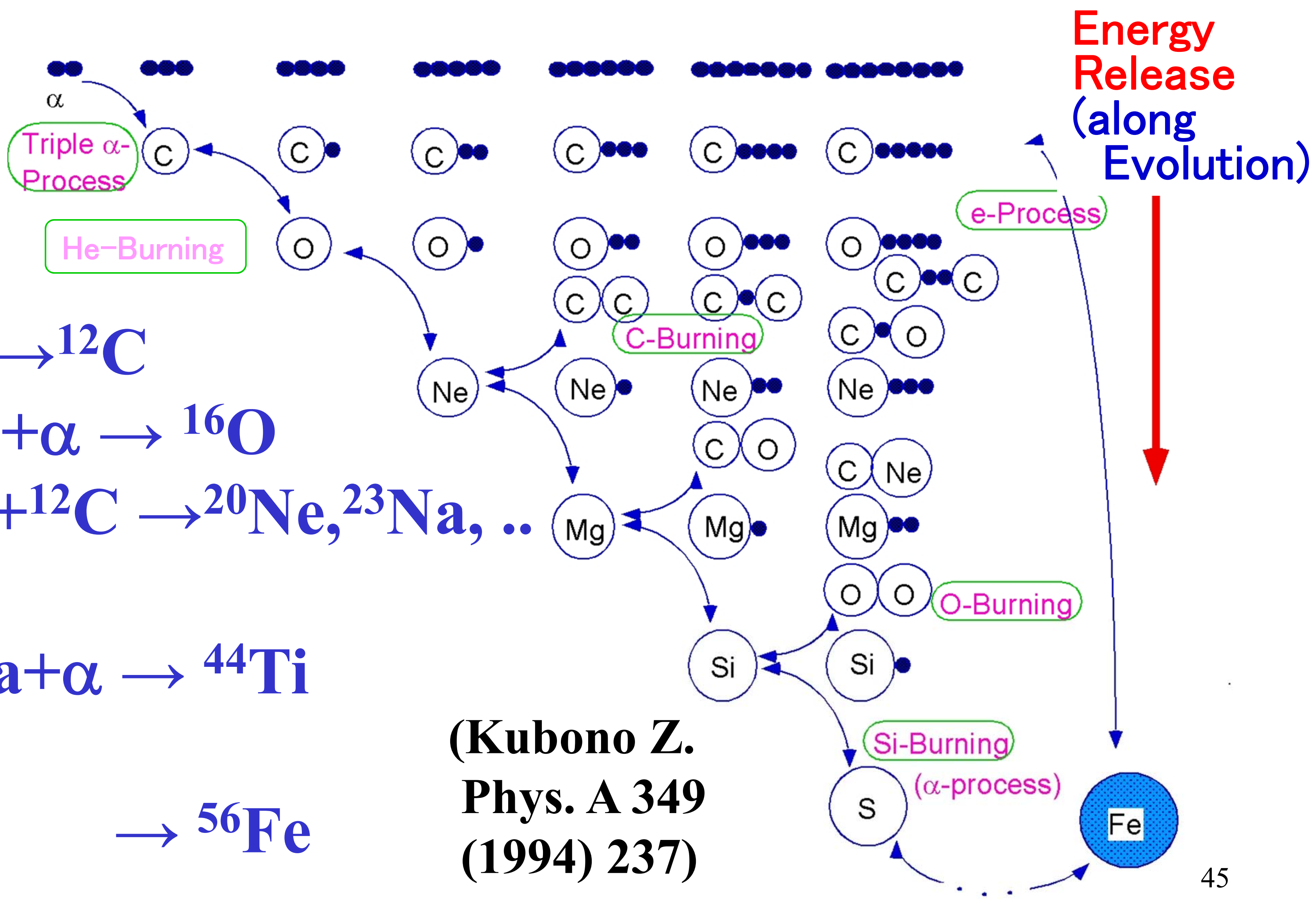
—— Statistical model calculation

- **Forbidden by the direct α-transfer**
- **90 deg. symmetry**

||

Compound nucleus process

Cluster Nucleosynthesis Diagram (CND)



- $3\alpha \rightarrow {}^{12}C$
- ${}^{12}C+\alpha \rightarrow {}^{16}O$
- ${}^{12}C+{}^{12}C \rightarrow {}^{20}Ne, {}^{23}Na$, ..

•....

- ${}^{40}Ca+\alpha \rightarrow {}^{44}Ti$

••••

→ ${}^{56}Fe$

(Kubono Z.
Phys. A 349
(1994) 237)

SUMMARY

1. α-cluster states play a crucial role in nuclear astrophysics.

2. α-cluster states can be investigated by resonant α scattering with the thick target method, and by direct α- transfer reactions.

3. Direct α transfer reactions need to be applied with cares, especially for the reaction mechanism.

4. Cluster Nucleosynthesis Diagram (CND) is a good guide for understanding nucleosynthesis flow after hydrogen burning in star evolution.