Triple alpha reaction rate under extreme conditions

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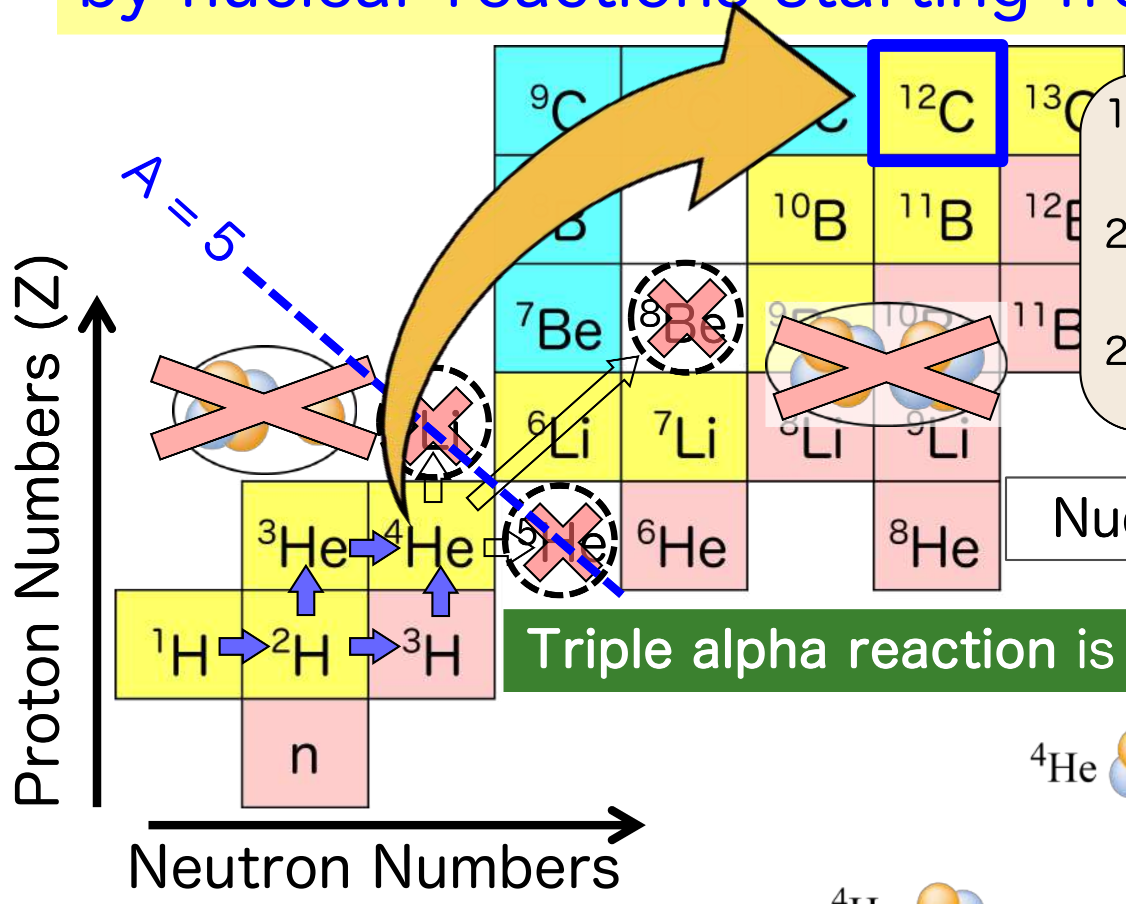
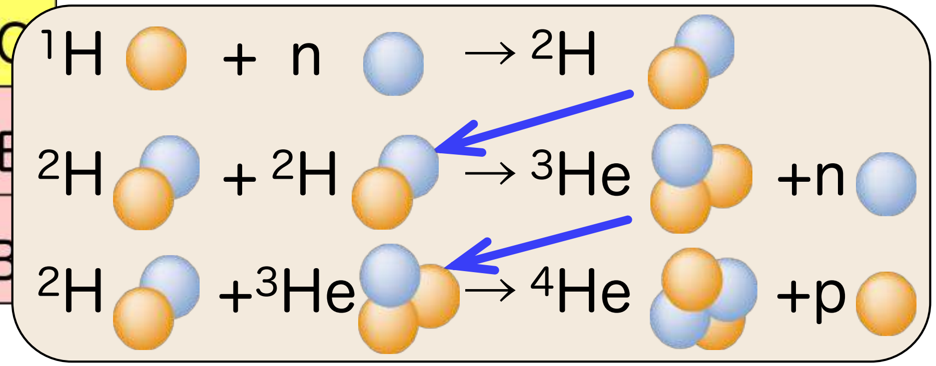
- Triple alpha reaction rate at high T
  - γ-decay probability of the 3^-_1 state in ^{12}C

- Triple alpha reaction rate at high ρ
  - Cross section for the $^{12}C(n,n')^{12}C^*$ reaction

Nucleosynthesis in the Universe

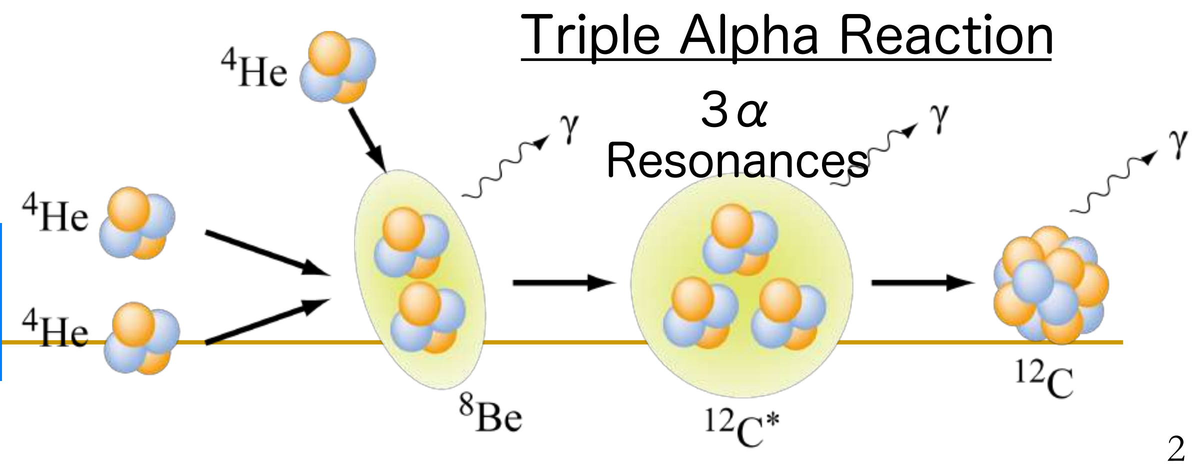
All chemical elements were synthesized
by nuclear reactions starting from protons and neutrons.





Nucleosynthesis suspended at A = 4.

Triple alpha reaction is the doorway for all heavy elements.



Are we fully understand
the Triple Alpha Reaction?

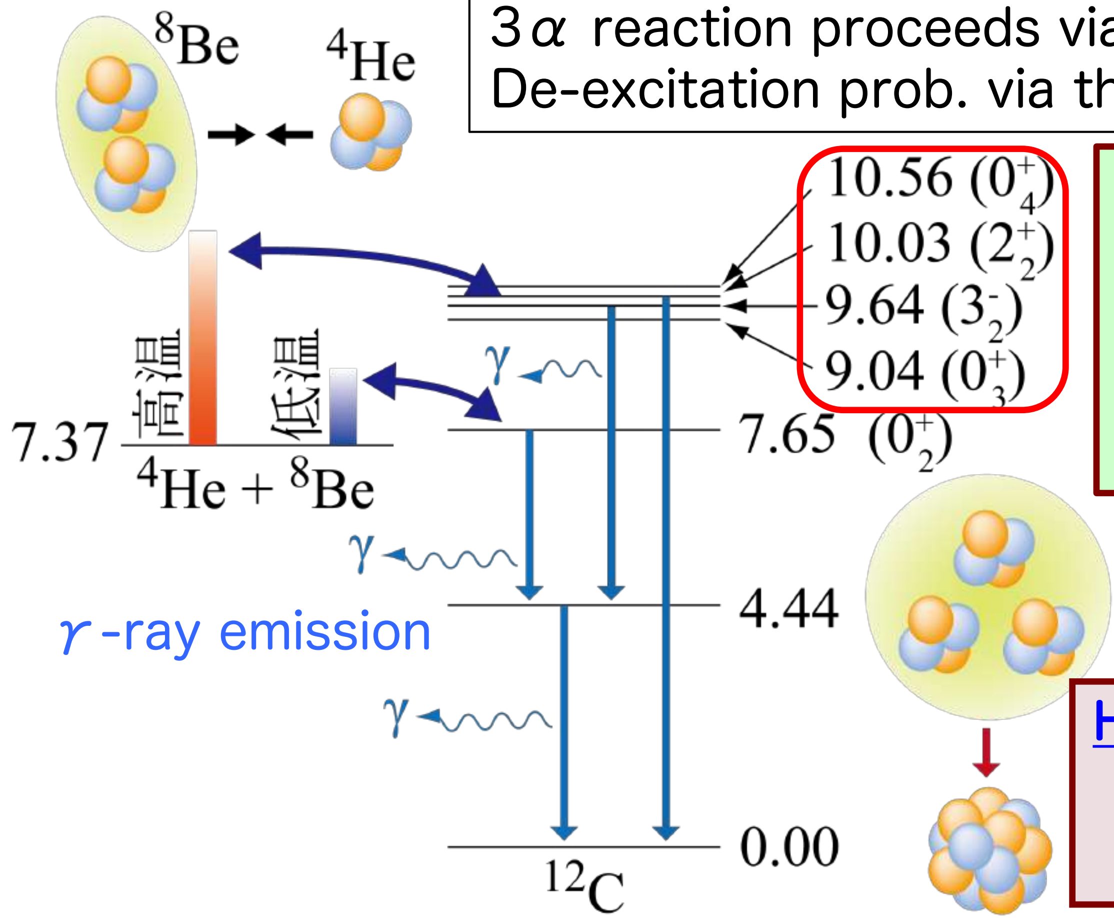
Triple Alpha Rate and De-Excitation Prob.

Most of 3α states decay back to 3α particles, **but rarely de-excite into ^{12}C**

→ De-excitation probability determines the 3α rate

<u>Normal Stellar Environments ($\rho \sim 10^{3-5}$ g/cm^3, T~10^8 K)</u>

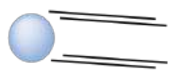
3α reaction proceeds via the 0^+_2 state at E_x = 7.65 MeV
De-excitation prob. via the γ decay is known [$4.4(5)\times10^{-4}$].



<u>High Temp. (T > 10^9 K)</u>

High-lying 3α resonances (2^+_2, 3^-_1, 0^+_3, 0^+_4) are important.
De-excitation by γ decays.
γ-decay prob. are unknown.

Scattering with BG particles



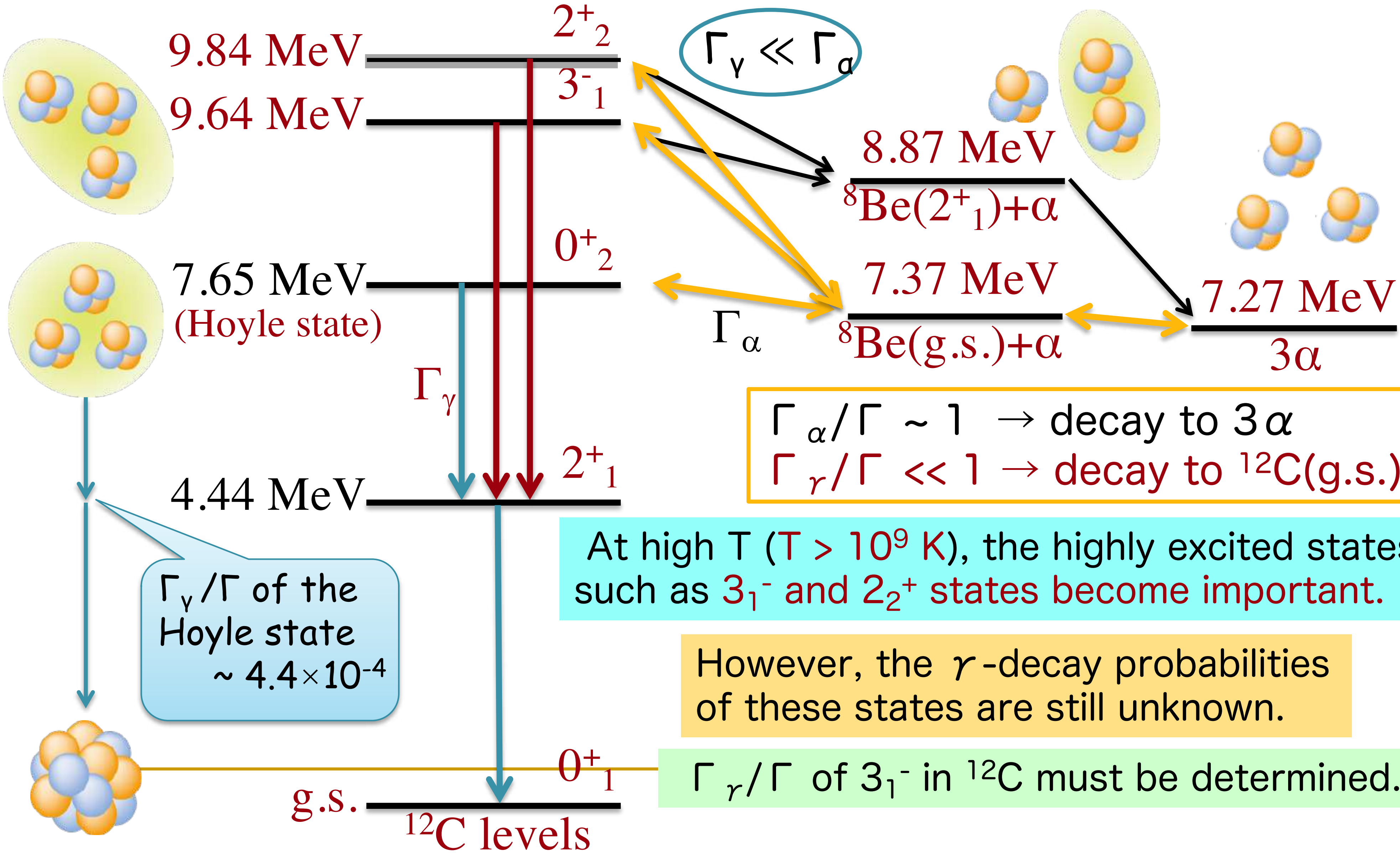
<u>High Density (ρ > 10^6 g/cm^3)</u>

Scattering with BG particles
Cross sections are unknown.

3α reaction under extreme conditions (High T and ρ) has never been fully understood.

3α Reaction and γ-decay Probability

The 3α reaction rate strongly depends on γ-decay probablity.



$\Gamma_\alpha/\Gamma \sim 1$ → decay to 3α
$\Gamma_\gamma/\Gamma \ll 1$ → decay to ^{12}C(g.s.)

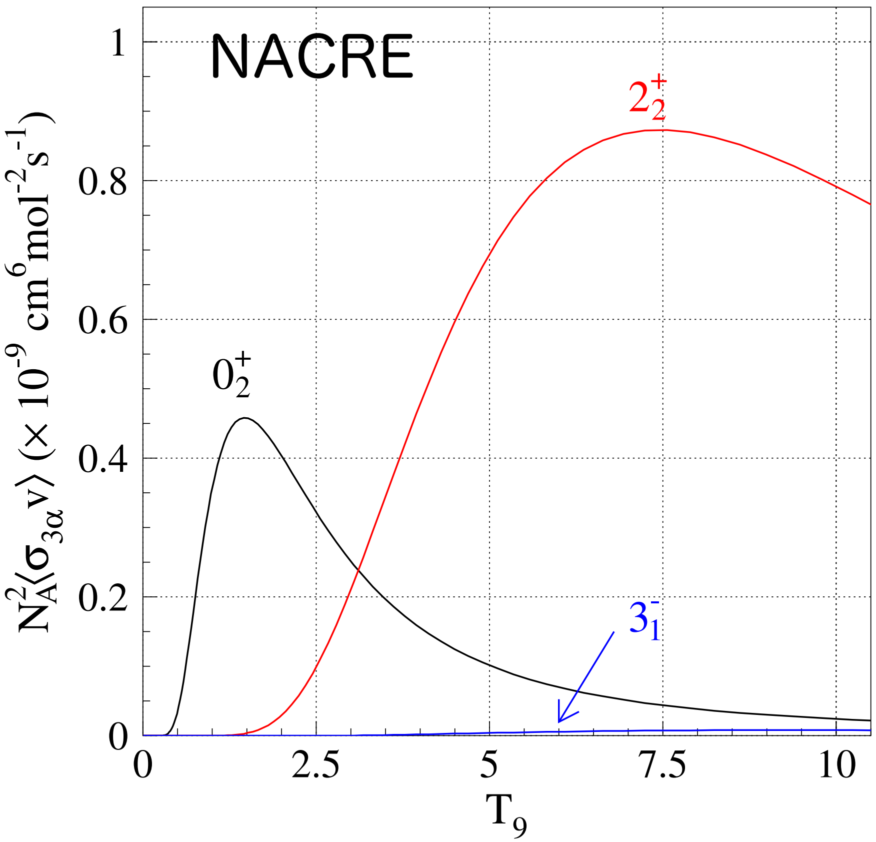
At high T ($T > 10^9$ K), the highly excited states such as 3_1^- and 2_2^+ states become important.

However, the γ-decay probabilities of these states are still unknown.

Γ_γ/Γ of 3_1^- in ^{12}C must be determined.

Triple alpha reaction rate

First star is massive and temperature reaches $T_9 \sim 5$.



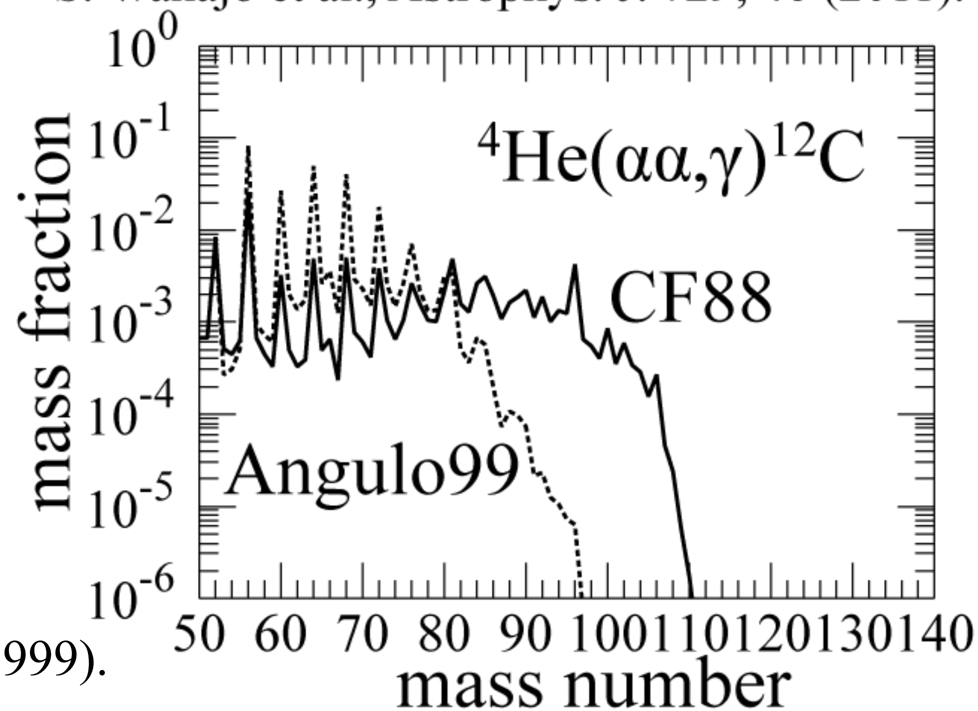
C. Angulo et al., Nucl. Phys. A**656** 3—187 (1999).

Large Impact on Heavy element abundance by νp process

- Angulo99: Include 3^-_1 and 2^+_2*
- CF88: 0^+_2 and 3^-_1*

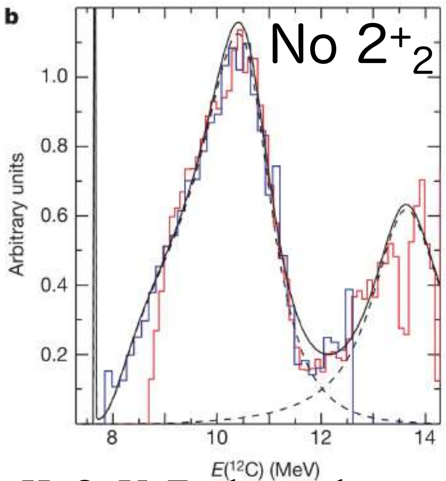
*Not experimental information

S. Wanajo et al., Astrophys. J. **729**, 46 (2011).

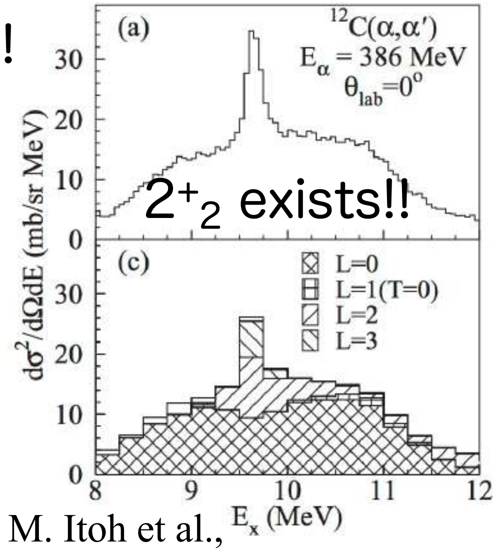


Recent Update

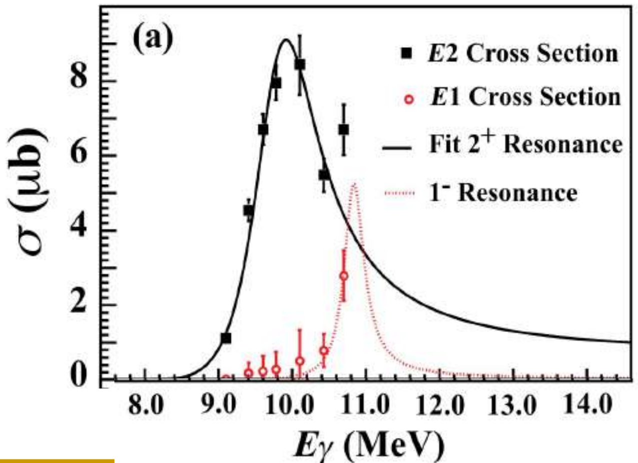
New data on the 2^+_2 were published.



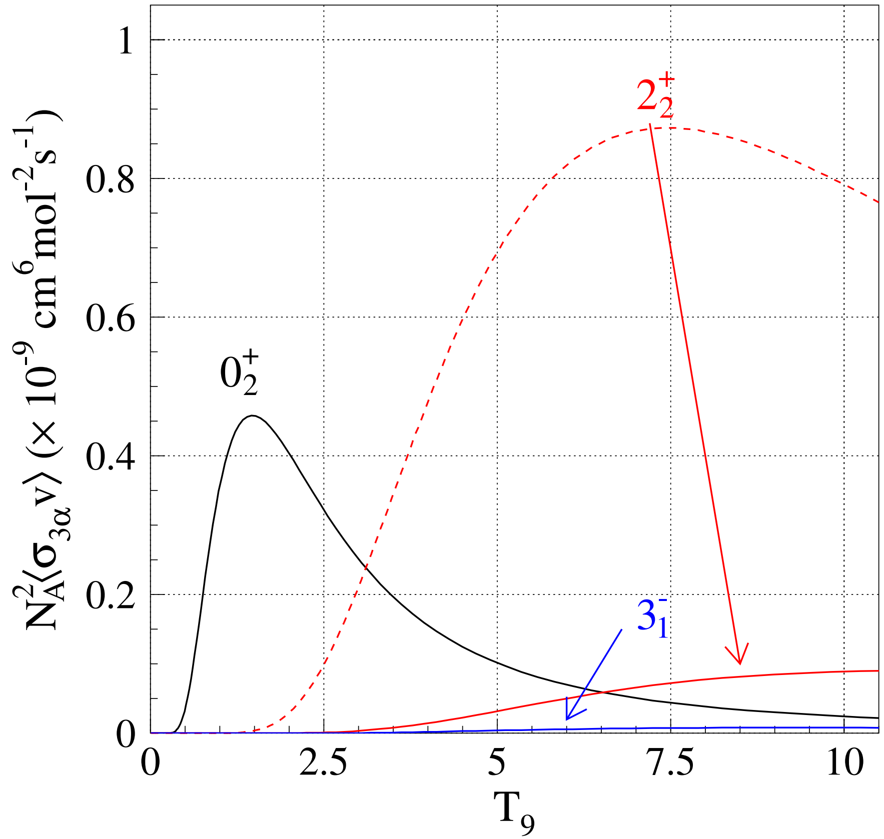
H. O. U. Fynbo et al., Nature **433**, 136 (2005).



M. Itoh et al., Phys. Rev. C **84**, 054308 (2011).



W. R. Zimmerman et al., Phys. Rev. Lett. **110**, 152502 (2013).



3α rate significantly suppressed at high T.

How about the 3^-_1 state ?

γ-decay probability of the 3_1^- state

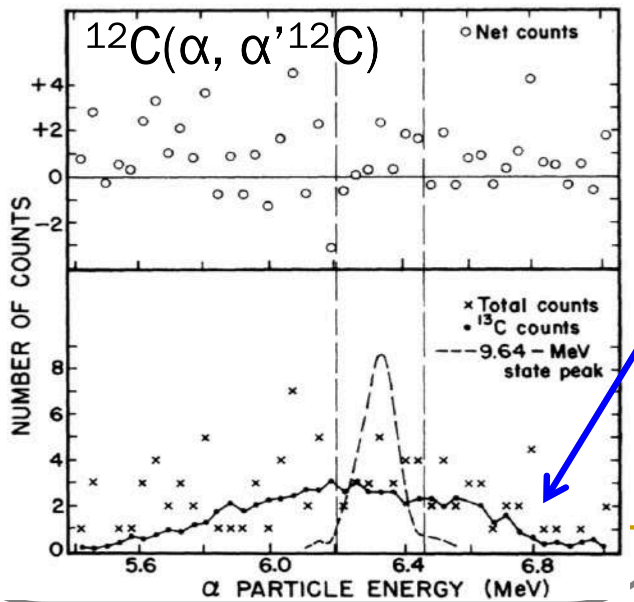
Difficult to measure the Γ_γ/Γ of the 3_1^- state because it is very small.

3^-_1 in ^{12}C	Total width Γ	γ-decay width Γ_γ	γ-decay probability Γ_γ/Γ
Lower limit	34(5) keV	0.31(4) meV	9.1×10^{-9}
Upper limit		28 meV (2σ C. L.)	4.1×10^{-7}

Direct γ-decay to the g. s. taken from (e,e')

Difficult to measure!!

Previous experiment



[D. Camberlin *et.al.*, Phys. Rev. C **10**, 2 (1974).]

Background due to ^{13}C contaminants

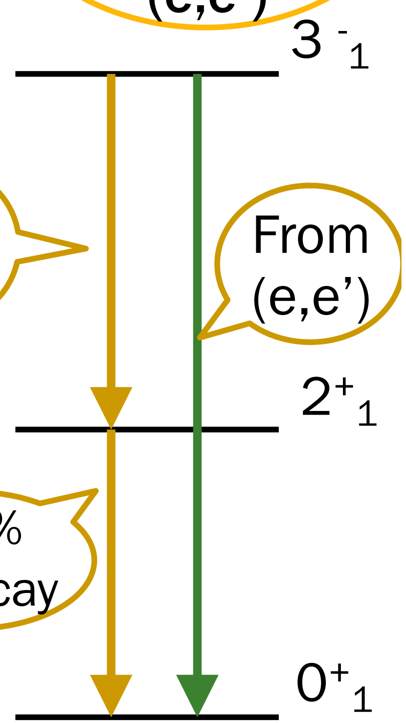
Use ^{12}C beam not ^{12}C Target !

No ^{13}C contaminants in ^{12}C beam!!

?

From (e,e')

100% γ-decay



Experimental procedure

Using the inverse kinematic reaction H(^{12}C, ^{12}C p), recoil protons and scattered ^{12}C will be measured simultaneously instead of γ-rays.

γ-decay probability Γ_γ / Γ

$$\frac{\Gamma_\gamma}{\Gamma} = \frac{\text{Number of } \gamma\text{-decay events}}{\text{Number of all excited events}}$$

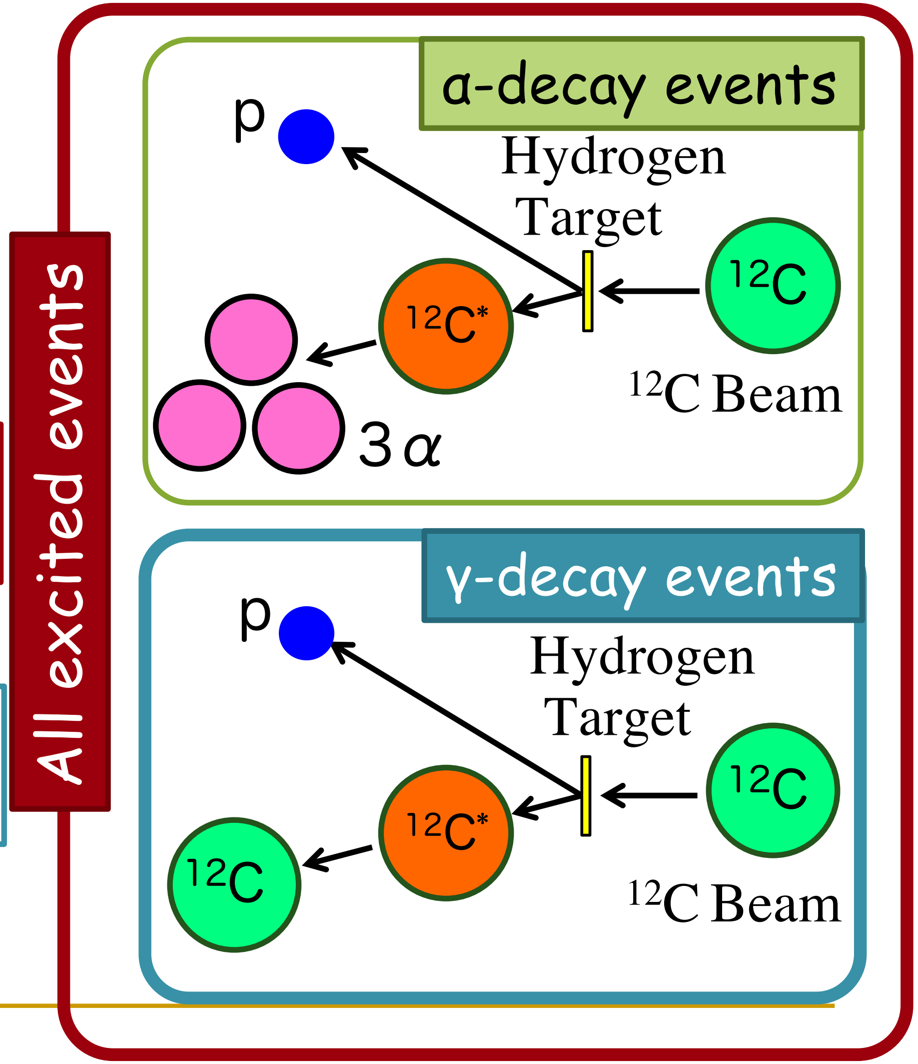
Number of all excited events

E_X in ^{12}C is determined from the energy and angle of the recoiled proton.

Number of γ-decay events

The scattered ^{12}C should be detected in coincidence with the recoiled proton.

- Thin solid hydrogen target.
- Recoil proton detector.



Experimental Setup

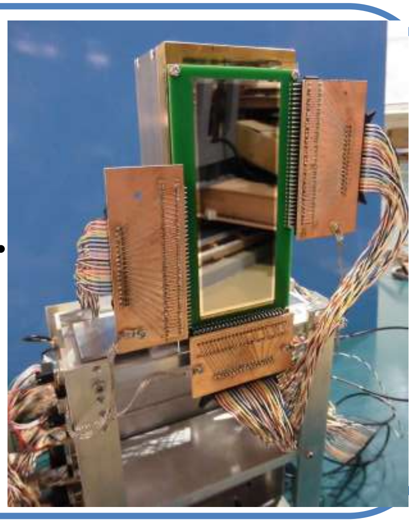
The experiment was performed at the cyclotron facility in RCNP.

Recoile proton detector

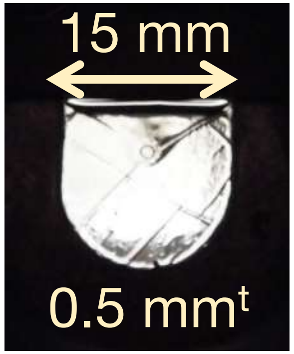
Particle-identified
by Gion (Si+GAGG telescope).

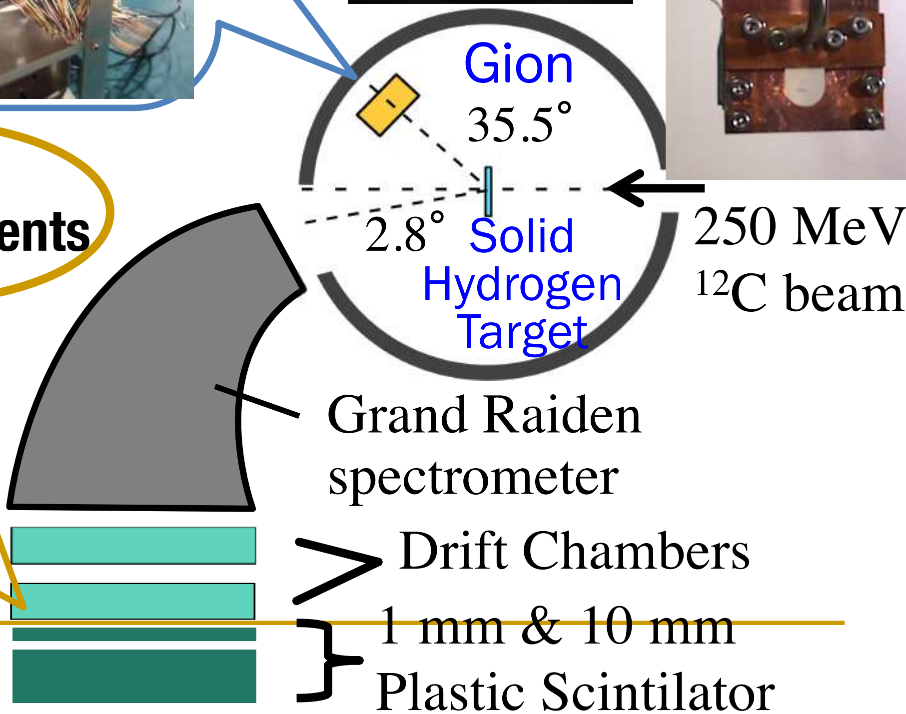
→ E_x of the scattered ^{12}C

Count the excited events



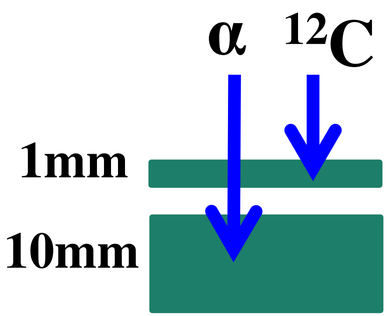
Solid Hydrogen Target





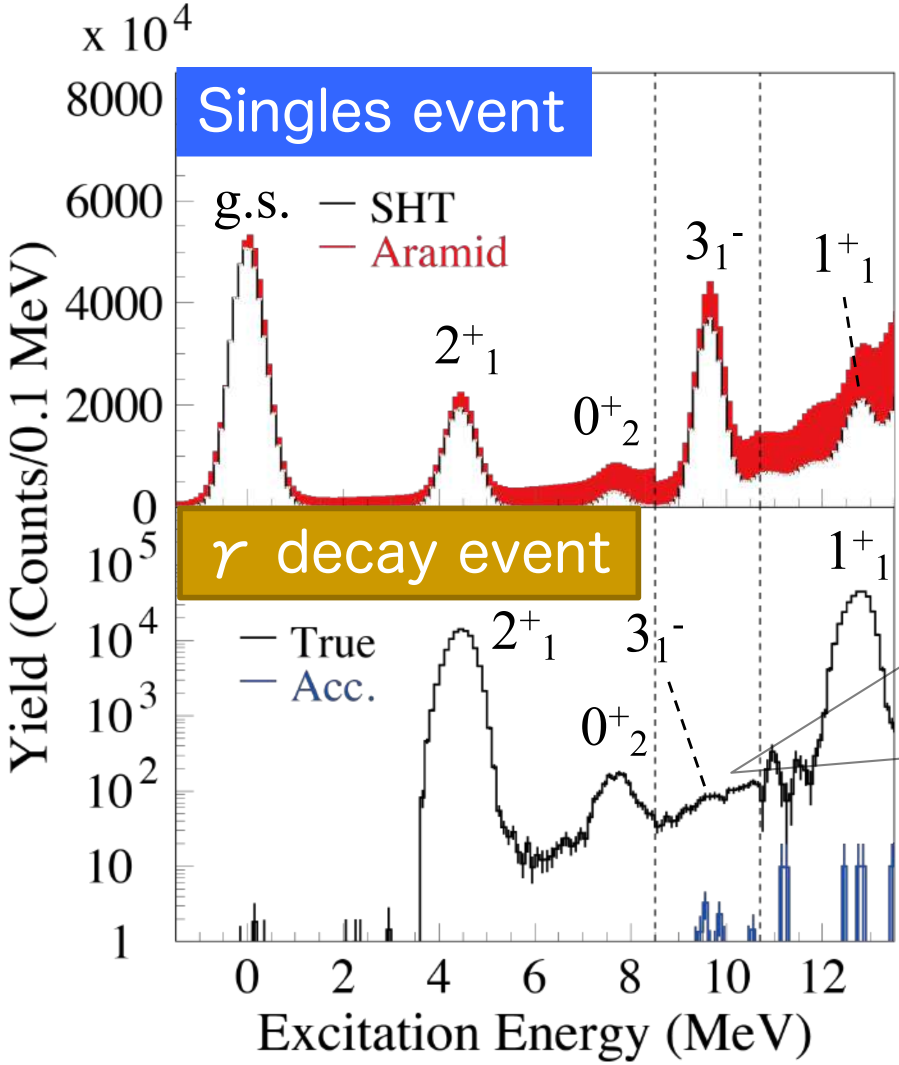
Select γ-decay events

Scattered ^{12}C detector

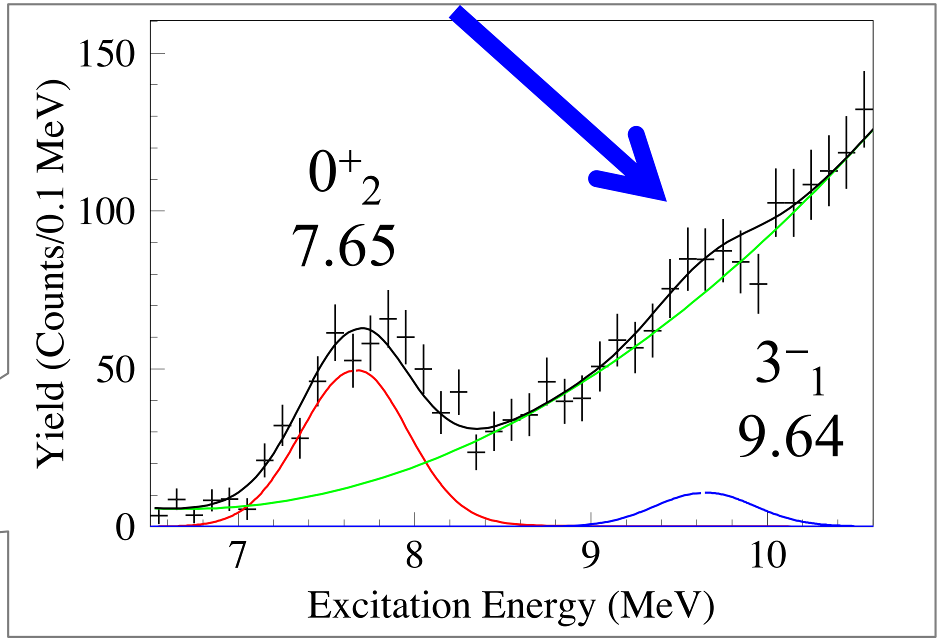


Anti-coin between 2 scintillators
→^{12}C trigger

Results



γ-decay from 3^-_1 was observed !



Peak significance: 91%

Gamma Decay Probability

γ-decay probability is given by

$$\frac{\Gamma_\gamma}{\Gamma} = \frac{\#\text{ of } \gamma \text{ decay events}}{\#\text{ of singles events}} \times \frac{1}{\text{geo. eff.}}$$

Geometrical efficiency should be estimated by MC calculation.

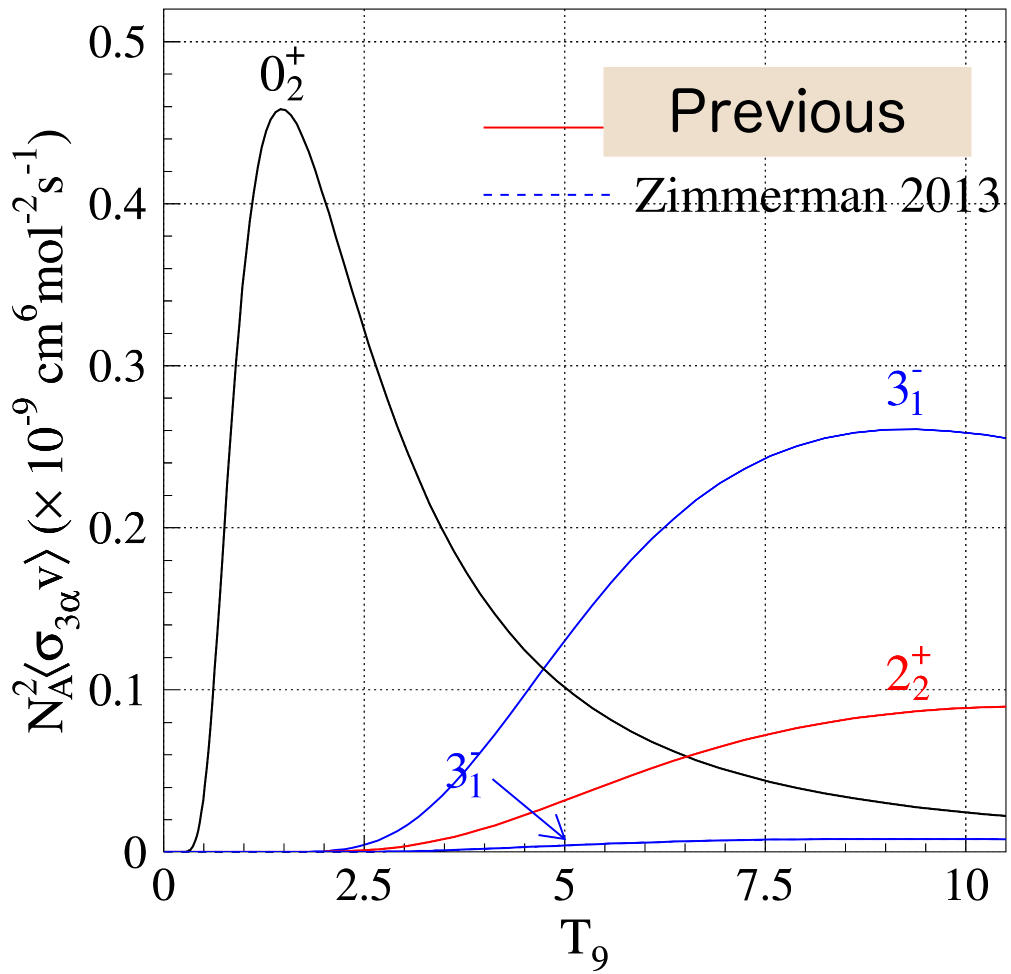
	0^+_2	1^+_1	3^-_1
Geo. Efficiency	0.117(2)	0.186(9)	0.229(3)
Γ_γ/Γ Previous	$4.16(11)\times10^{-4}$ ~~$6.2(6)\times10^{-4}$~~	$2.21(7)\times10^{-2}$	Unknown
Γ_γ/Γ Present	$4.3(8)\times10^{-4}$	$2.6(7)\times10^{-2}$	$1.3(8)\times10^{-6}$

The present results are consistent with the previous result on the 0^+_2 and 1^+_1 states, but not with the recent report for the 0^+_2 state by Kibedi et al.

Γ_γ for the 3^-_1 state is larger than the previous upper limit [8.2×10^{-7} (2σ)].

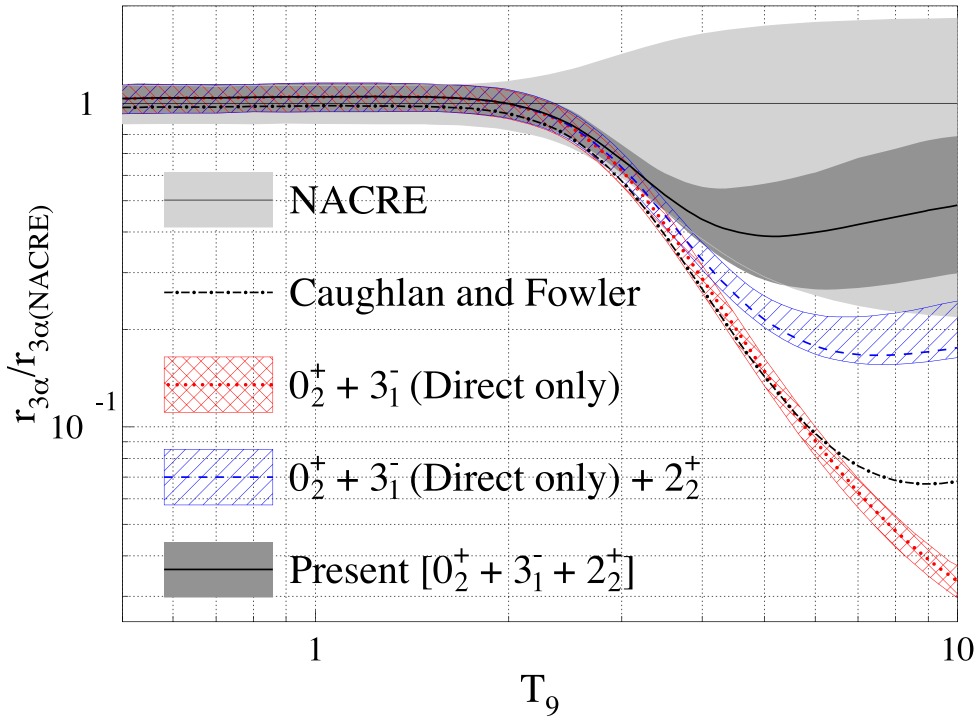
Triple Alpha Reaction Rate

Triple reaction rate was calculated using the measured Γ_γ/Γ



NACRE
3^-_1
Γ_γ = 2 meV

Present
3^-_1
Γ_γ = 44 meV



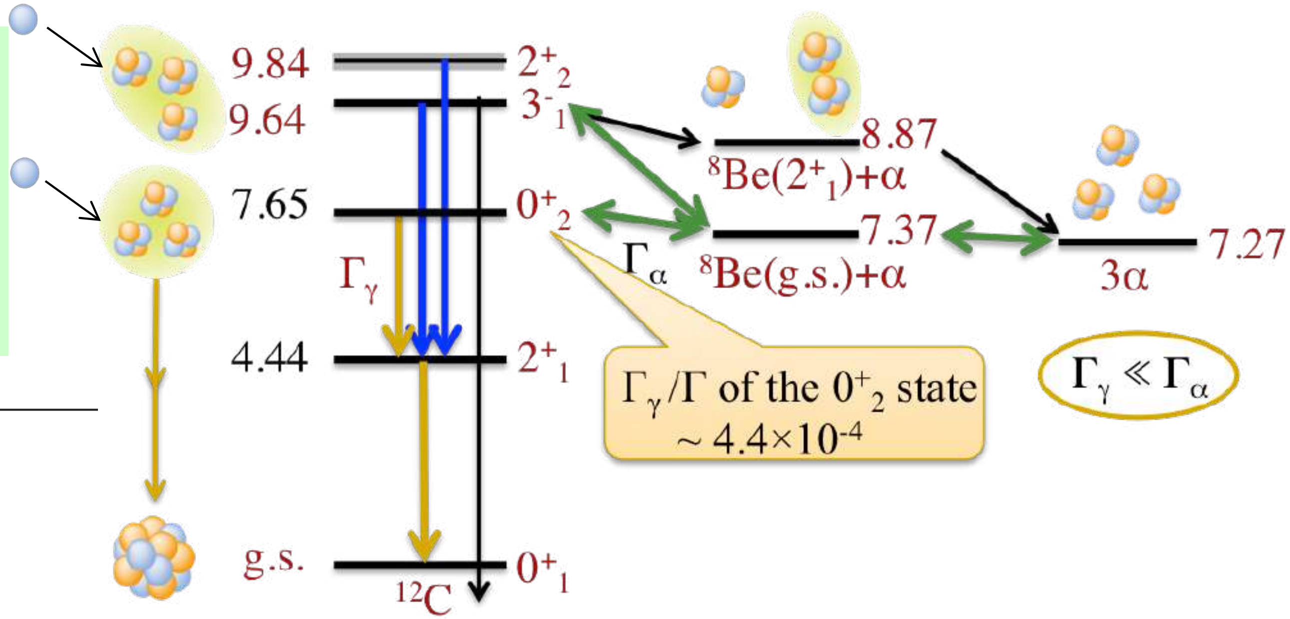
The 3α rate is partially restored, and consistent with NACRE...

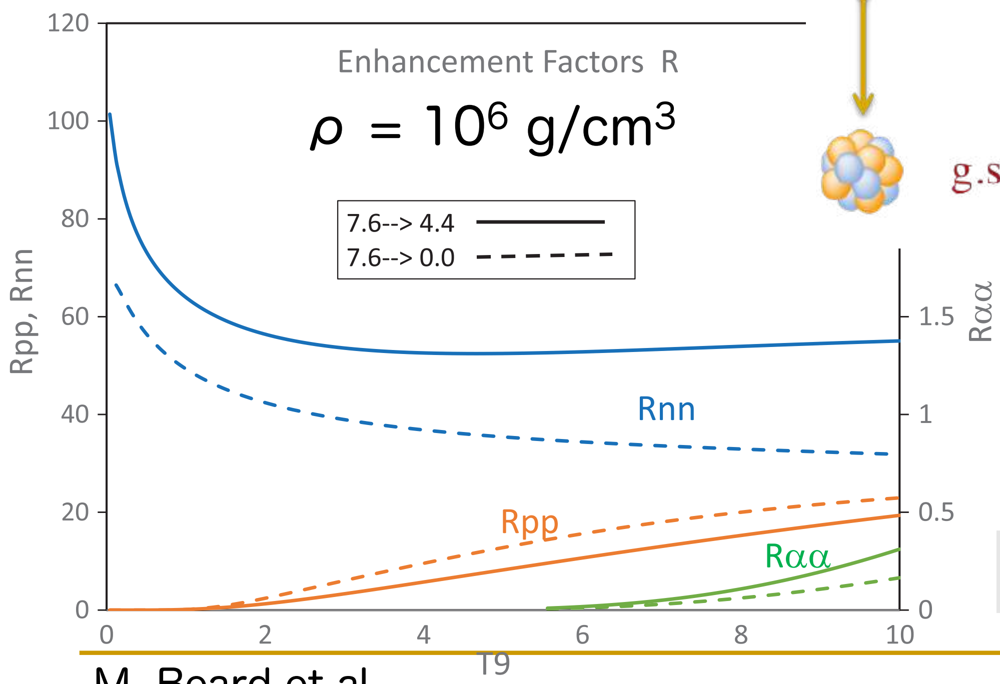
Recently published in M. Tsumura, T. K. et al., Phys. Lett. B 817, 136283 (2021).

Triple Alpha Reaction Rate at high ρ

Only de-excitation by gamma decay was considered so far.

Exothermic inelastic scattering with background particles should be considered at high density environment.





^{12}C(Hoyle)(n,n')^{12}C(g.s.) might enhances the triple alpha reaction rate by a factor of 60—100.

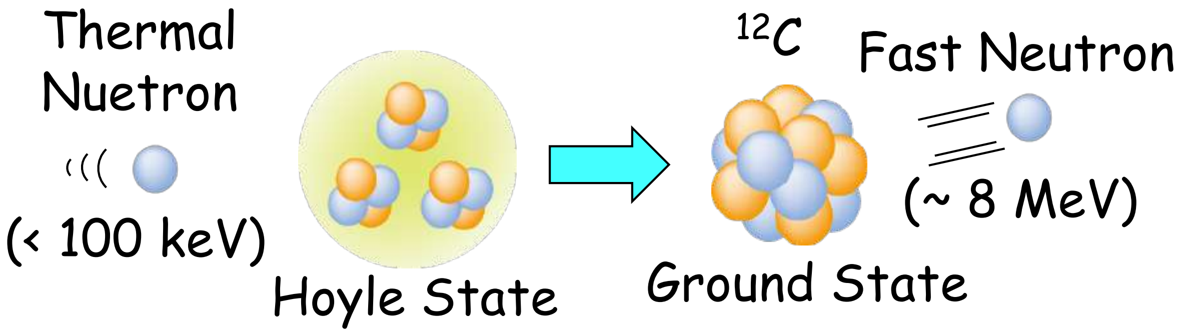
Need to determine the cross sections.

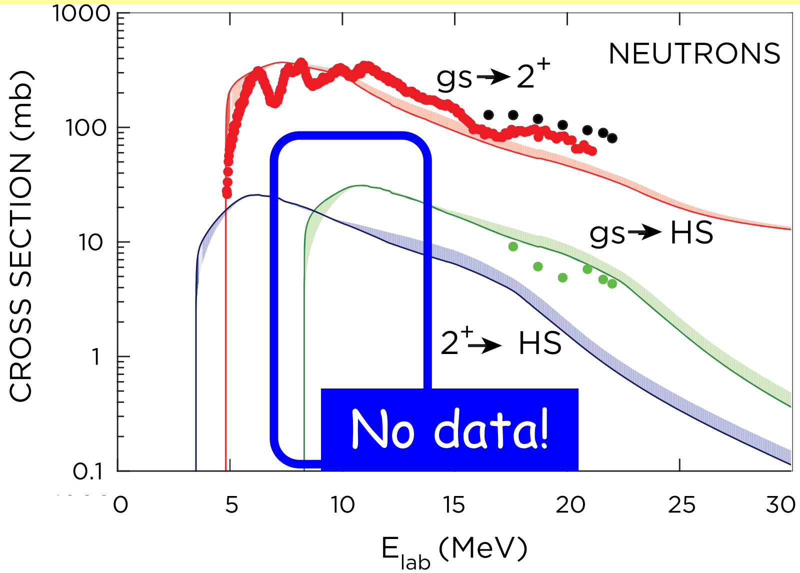
M. Beard et al.,
Phys. Rev. Lett. 119, 11701 (2017).

Time Inverse Reaction

Direct measurement of ^{12}C(Hoyle)(n,n')^{12}C(g.s.) is impossible.
→ Time inverse reaction should be measured.

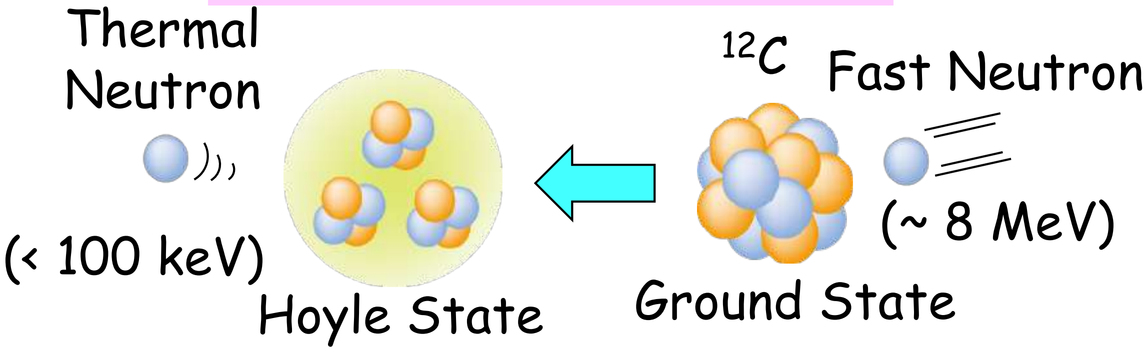
Astrophysical Reaction





M. Beard et al., PRL 119, 112701 (2017).

Time Inverse Reaction

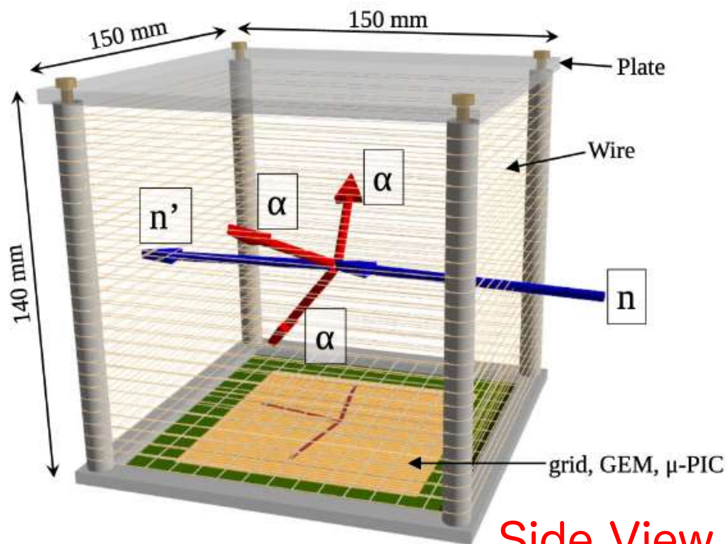


However,
measurements of low-E neutrons or alpha particles are not easy.
→ MAIKo Active Traget

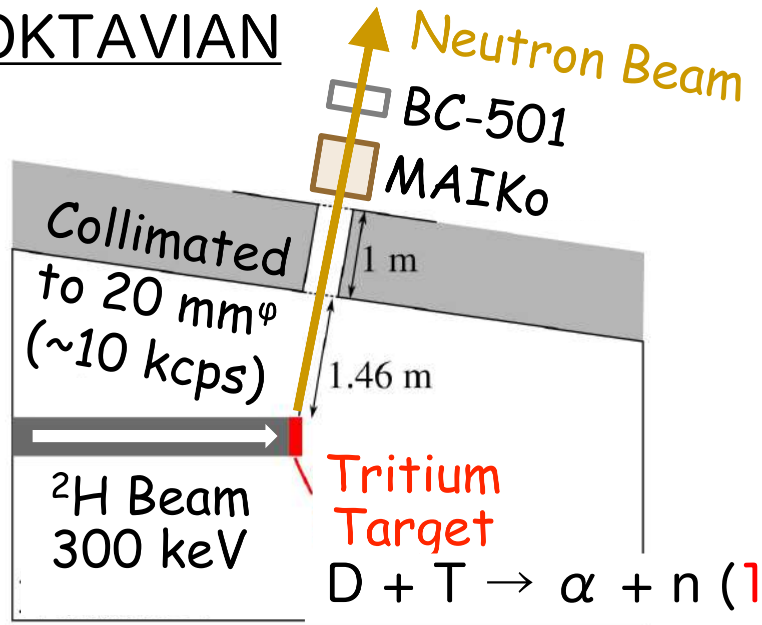
Test Measurement with MAIKo

Test measurement was carried out at OKTAVIAN, Osaka.

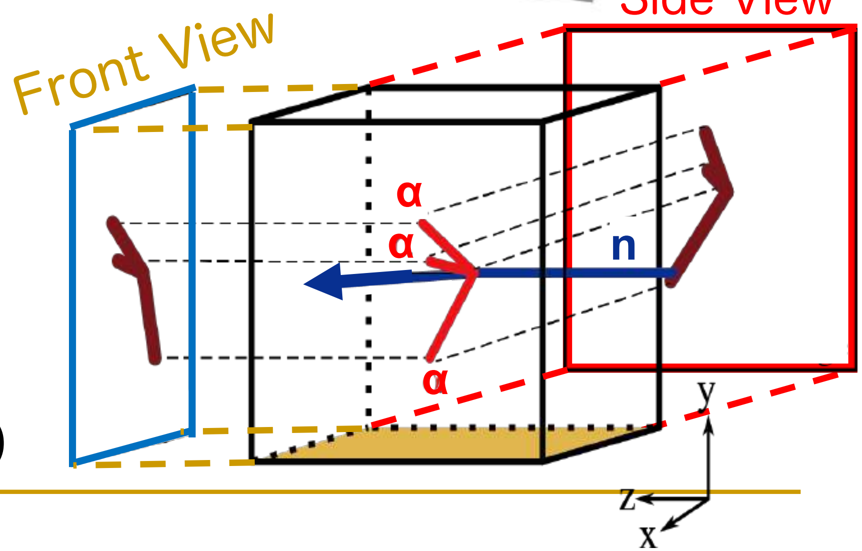
- MAIKo TPC
  - ✓ Two images of 2D-projected trajectories.
  - ✓ Detect low-E particles over large Ω
  - ✓ iC_4H_{10}(10%) + H_2 or He @100, 450 hPa
- BC-501 Liquid Scintillator
  - ✓ Determine the neutron flux.



OKTAVIAN



D + T → α + n (14 MeV)



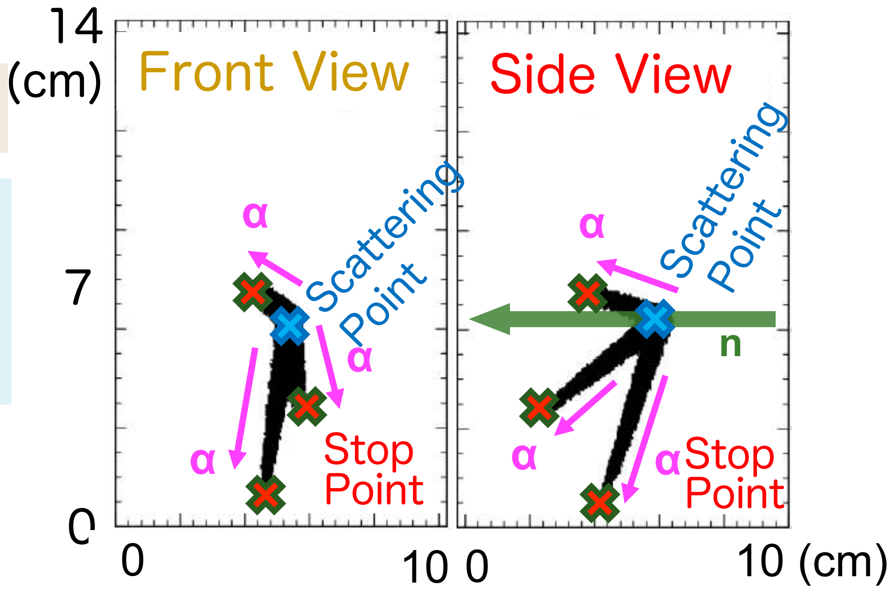
T. Doi, Master Thesis, Kyoto University (2020).

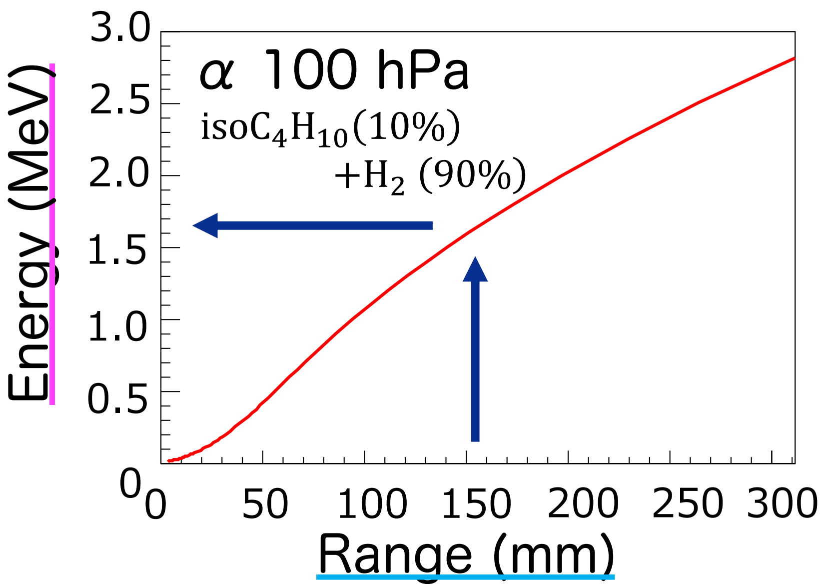
Eye-Scan Analysis

Two track images were analyzed by human eyes.

60K events by 11 people

- ✓ Number of trajectories
- ✓ Scattering point
- ✓ Stop positions

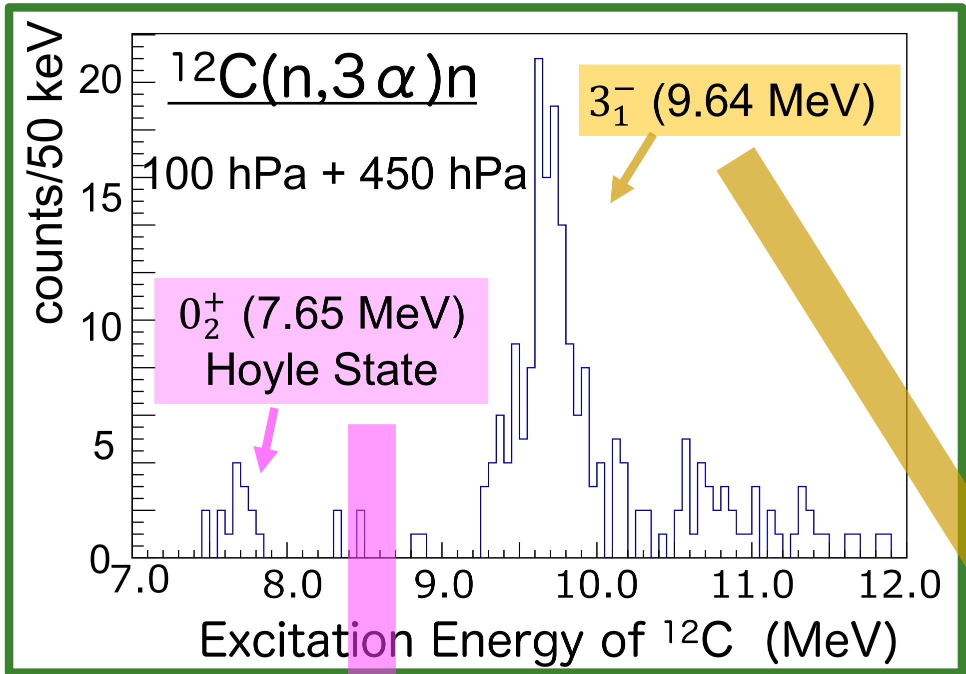




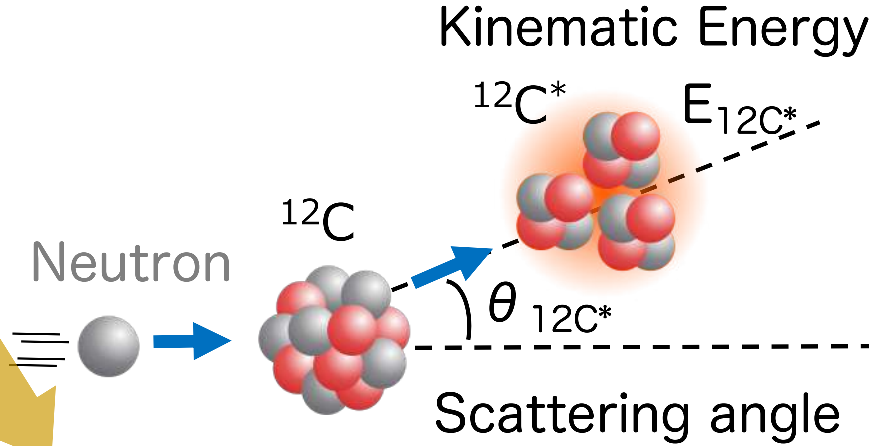
- ✓ Reconstruct 3D trajectories
  - → Ranges → Kinematic energies
  - → Emission angles

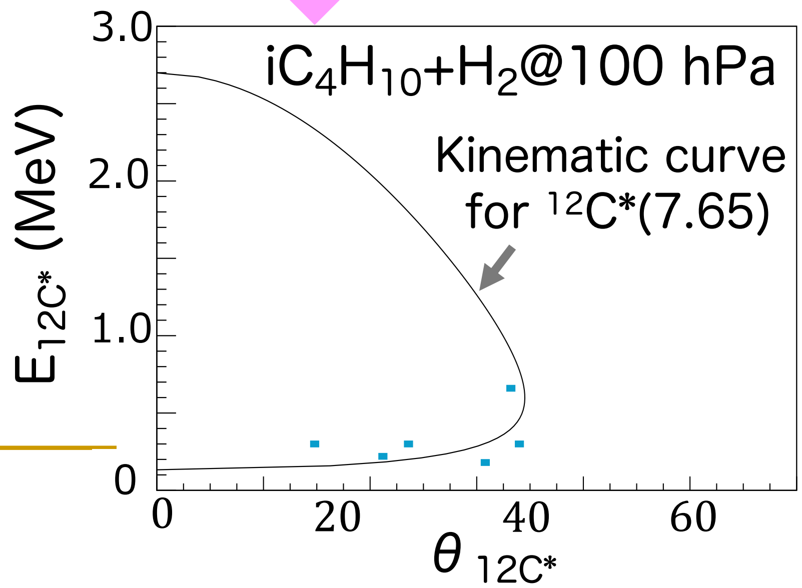
- ✓ Invariant mass spectroscopy of ^{12}C.

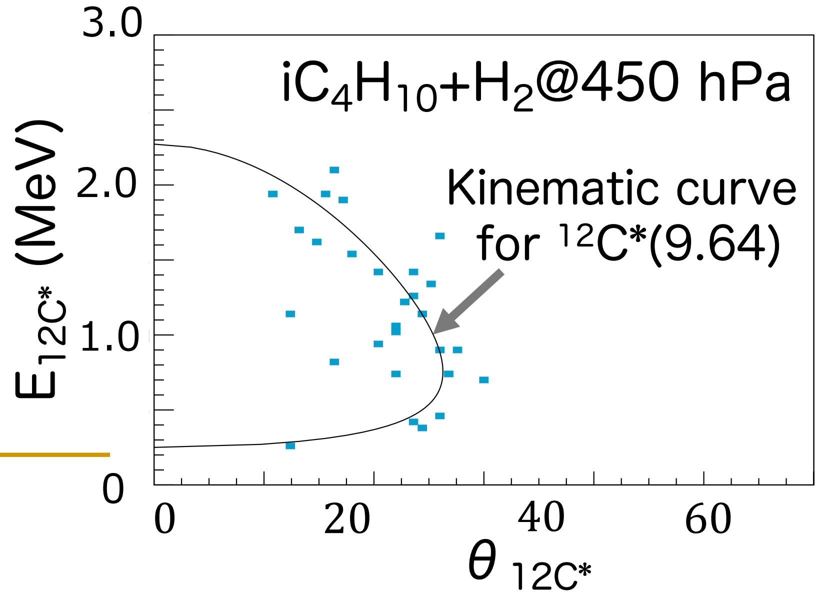
Event Reconstruction



Two peaks at 7.65 MeV and 9.64 MeV were successfully identified.

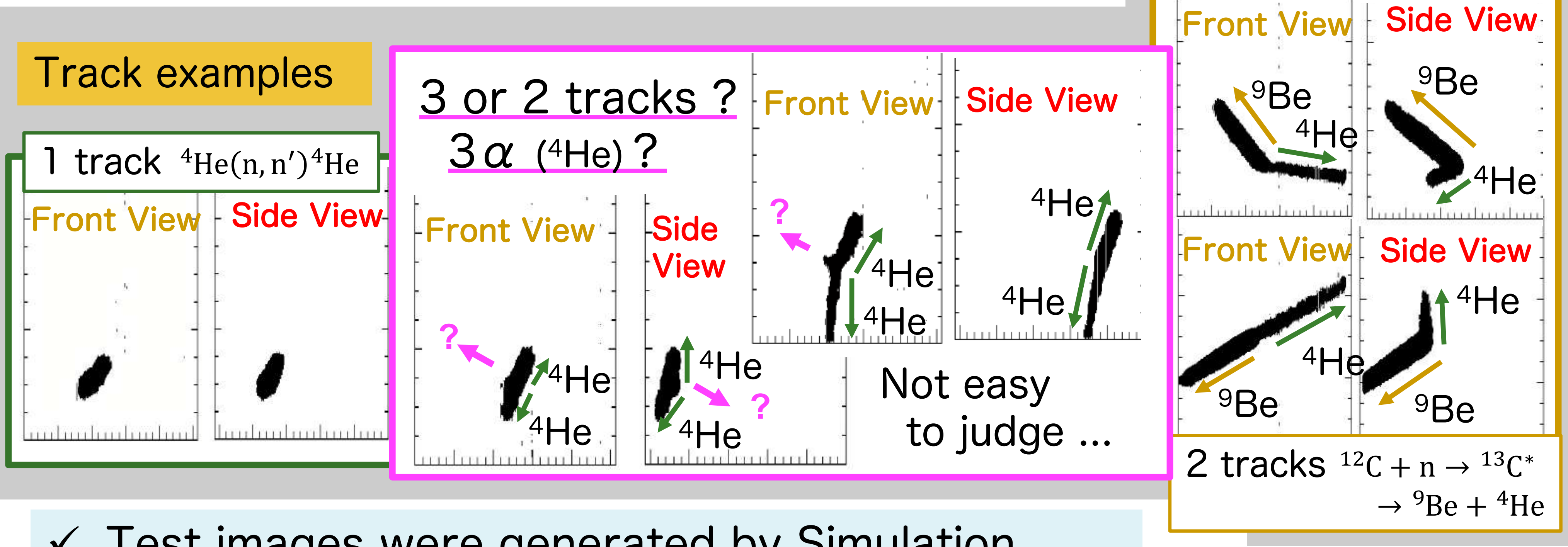






Reconstruction Efficiency

Requirements:
- ✓ 3αs stopped in the sensitive volume.
- ✓ Human eyes can find 3 tracks.



- ✓ Test images were generated by Simulation.
  → BG events were randomly mixed.
- ✓ **Eye-scan analysis** was carried out to estimate the reconstruction efficiency.

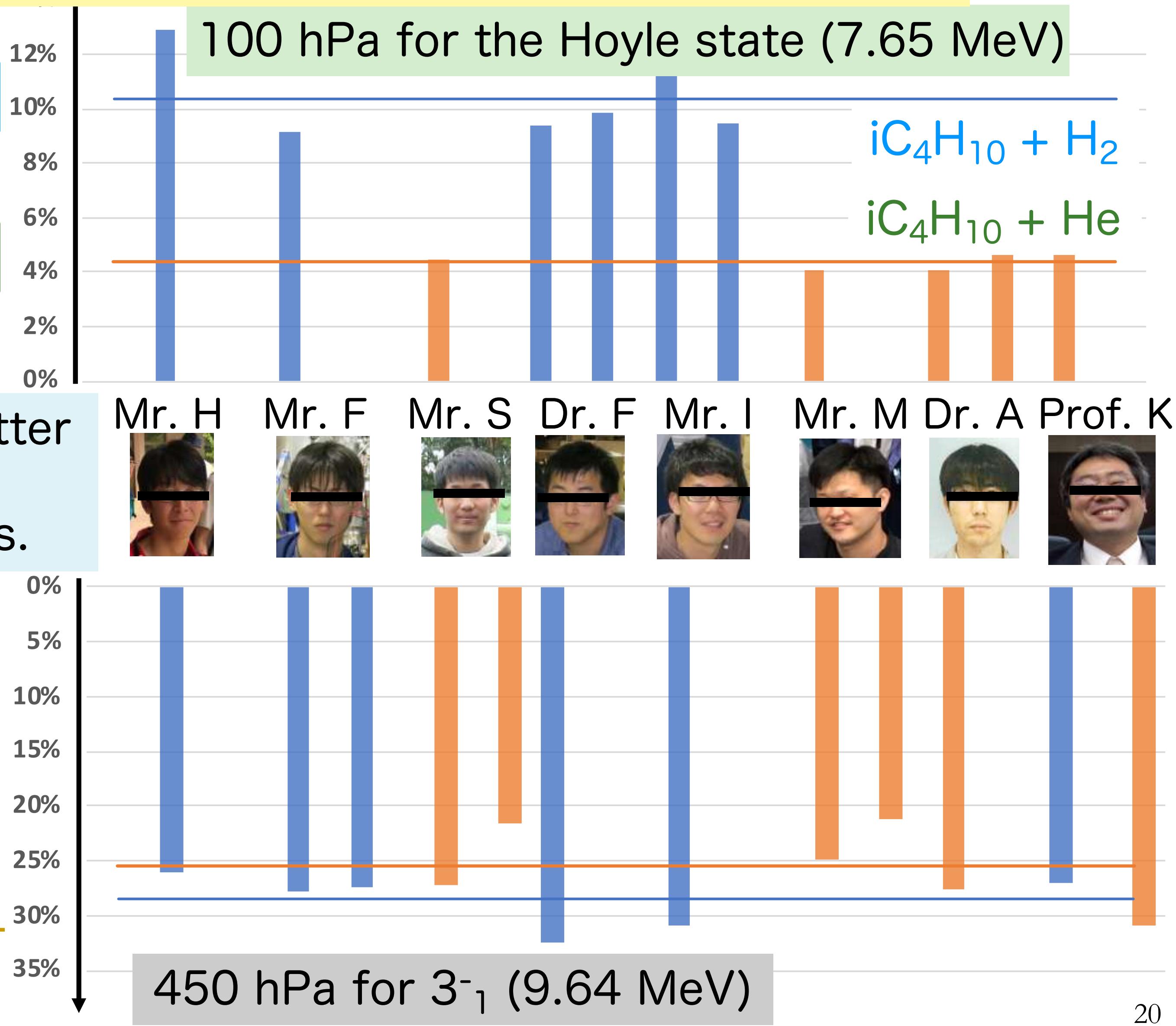
K. Himi, Bachelor Thesis, Osaka University (2021).

Eye-Scan Analysis, again

8 scanners analyzed the simulated data.

Ave. 10±1.4%

Ave. 4.4±0.32%



iC_4H_{10} + H_2 works better than iC_4H_{10} + He as the detection gas.

Ave. 26±3.4%

Ave. 29±2.3%

Measured Cross Section

$$\sigma(\mathrm{mb}) = \frac{Y}{N_t\, N_{beam}\, \varepsilon}$$

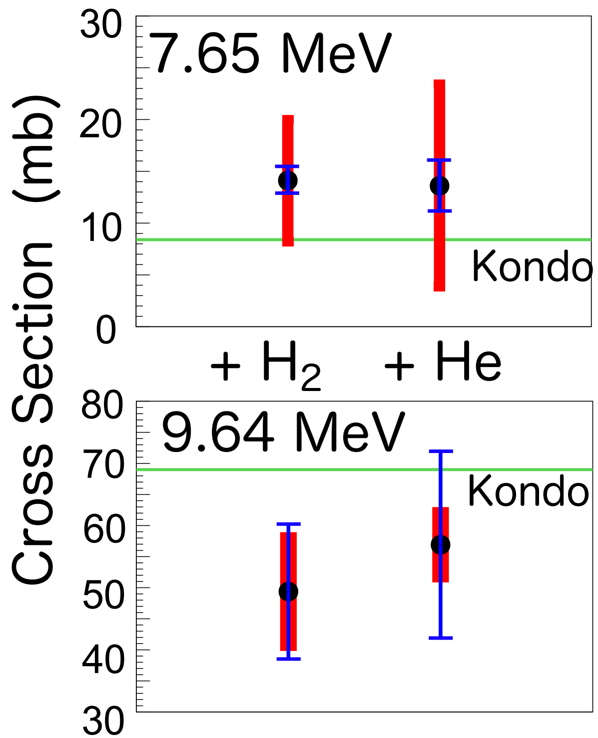
Y … Yield
N_t … Target Area Density (cm^{-2})
N_{beam} … Number of incident neutrons
ε … Efficiency

100 hPa Hoyle state (7.65 MeV)

	Y	ε	σ (mb)	Δσ$_{sta}$ (mb)	Δσ$_{sys}$ (mb)
+ H_2	6	0.10	14	5.8	1.2
+ He	2	0.044	14	9.6	2.4

450 hPa 3^-_1 (9.64 MeV)

	Y	ε	σ (mb)	Δσ$_{sta}$ (mb)	Δσ$_{sys}$ (mb)
+ H_2	28	0.29	49	9.6	11
+ He	111	0.26	57	6.1	15



Consistent with the previous data by K. Kondo et al.
[J. Nucl. sci. Tech. **45**, 103 (2008).]

8.4 mb for 7.65 MeV, 69 mb for 9.64 MeV

→ Experimental feasibility has been confirmed.

Summary

- Triple alpha reaction rates under extreme conditions were measured.
  - Measurement of the γ-decay probability of the 3_1^- state in ^{12}C
    - Triple alpha reaction rate at high T has been updated.
  - New measurement of the cross sections for the $^{12}C(n,n')^{12}C^*$ reaction is in progress.
    - Triple alpha reaction rate at high ρ.
    - Experimental feasibility has been confirmed.
    - Upgrade of MAIKo is now ongoing.
      (Sensitive volume 10 x 10 x 10 $cm^3 \rightarrow$ 30 x 30 x 30 cm^3)