Experimental determination of the triple-alpha rate

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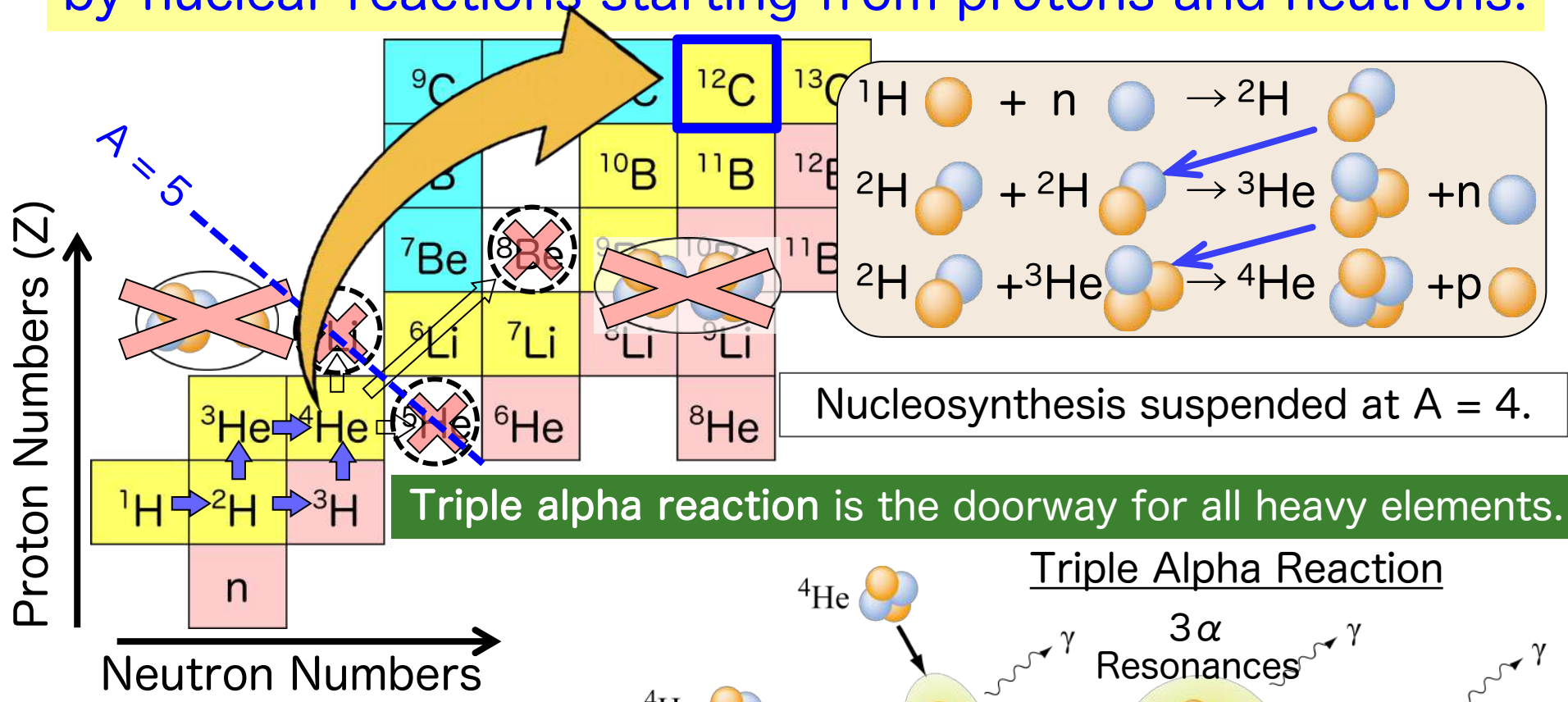
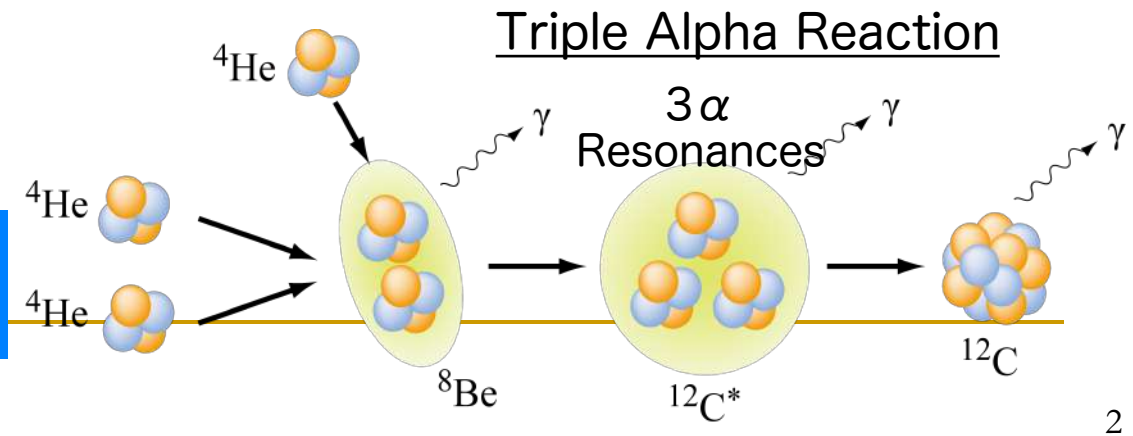
Nucleosynthesis in the Universe

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



Nucleosynthesis suspended at A = 4.

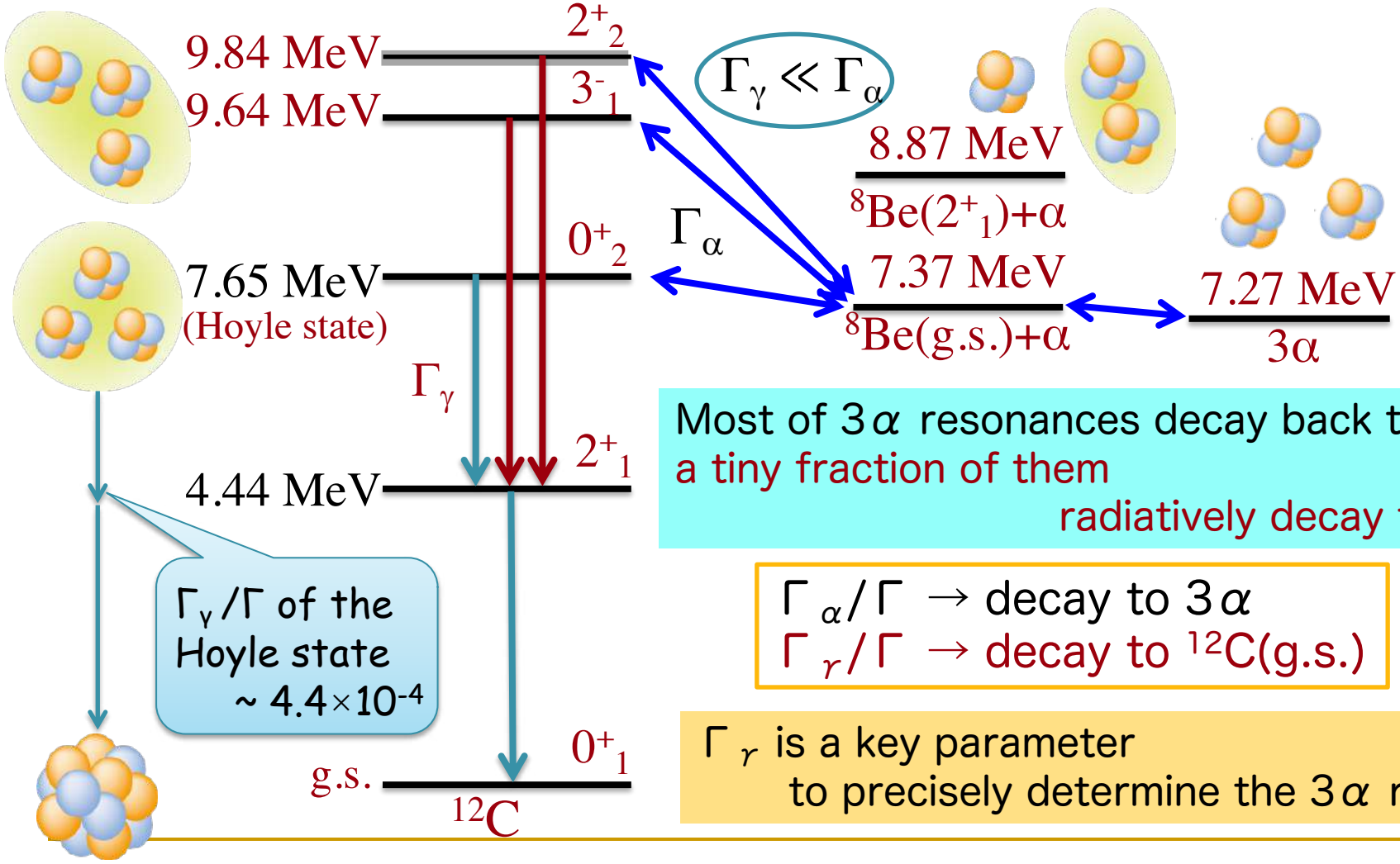
Triple alpha reaction is the doorway for all heavy elements.



Are we fully understand
the Triple Alpha Reaction?

Triple Alpha (3α) Reaction

The 3α reaction proceeds via 3α resonances in ^{12}C.



Most of 3α resonances decay back to 3α, a tiny fraction of them radiatively decay to g.s.

Γ_α/Γ → decay to 3α
Γ_γ/Γ → decay to ^{12}C(g.s.)

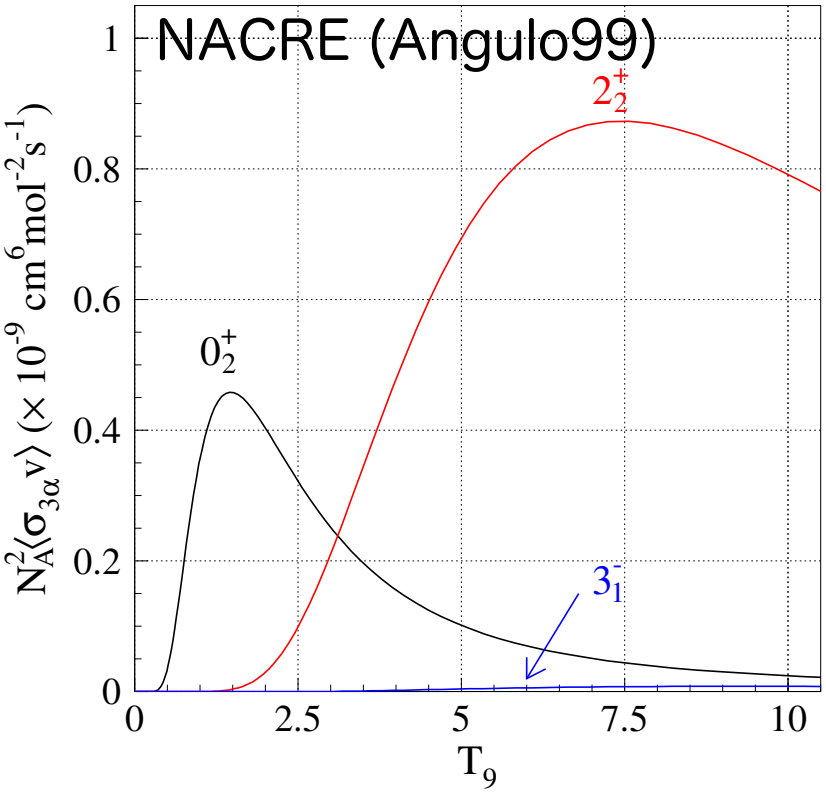
Γ_γ is a key parameter to precisely determine the 3α rate.

Triple Alpha Reaction at High T

(M. Tsumura, Y. Takahashi, Y. Honda, et al.)

Triple alpha reaction at High T

First stars are massive and temperature reaches $T_9 \sim 5$.

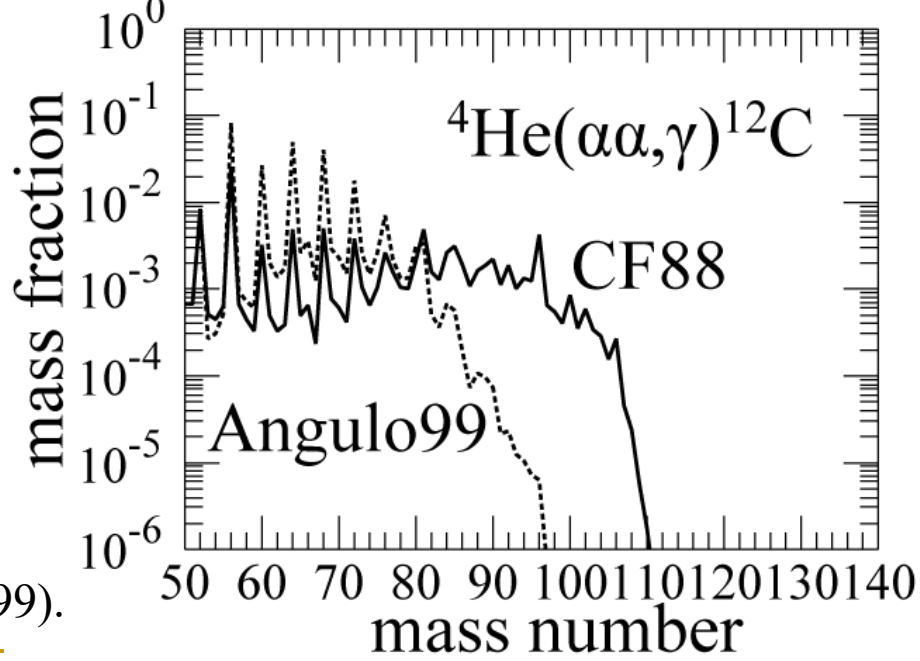


C. Angulo et al., Nucl. Phys. A**656** 3—187 (1999).

3α rate at high T is quite uncertain because Γ_γ for the 2^+_2 and 3^-_1 states were unknown.

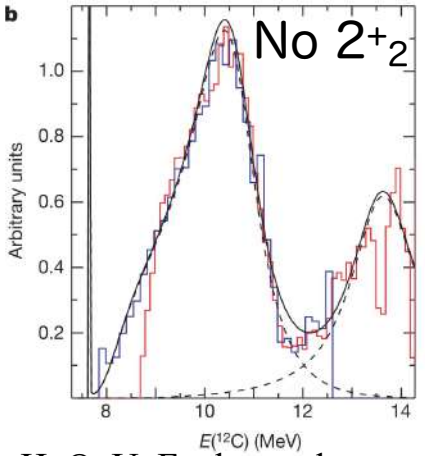
Large Impact on Heavy element abundance by νp process,

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

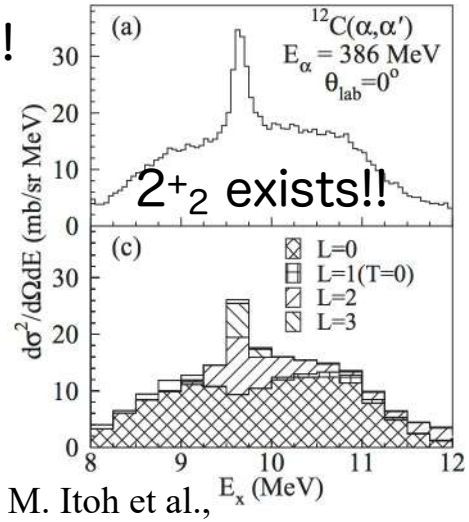


Recent Update on the 2^+_2 state

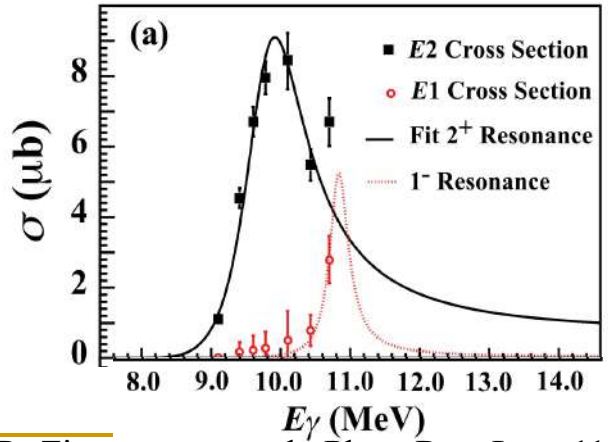
New data on the 2^+_2 were published.



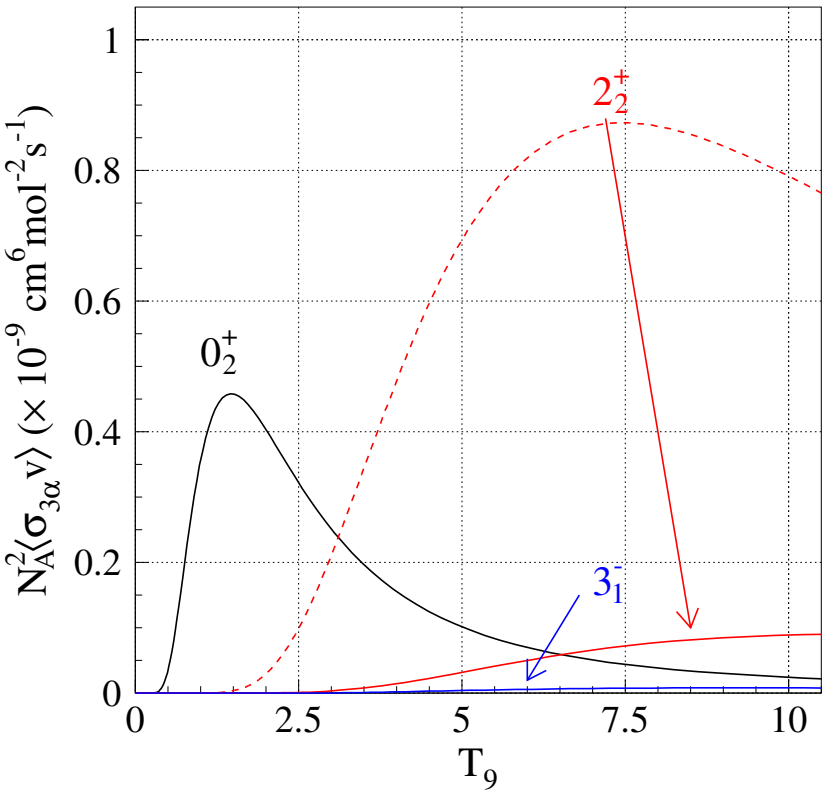
H. O. U. Fynbo et al., Nature **433**, 136 (2005).



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 ?

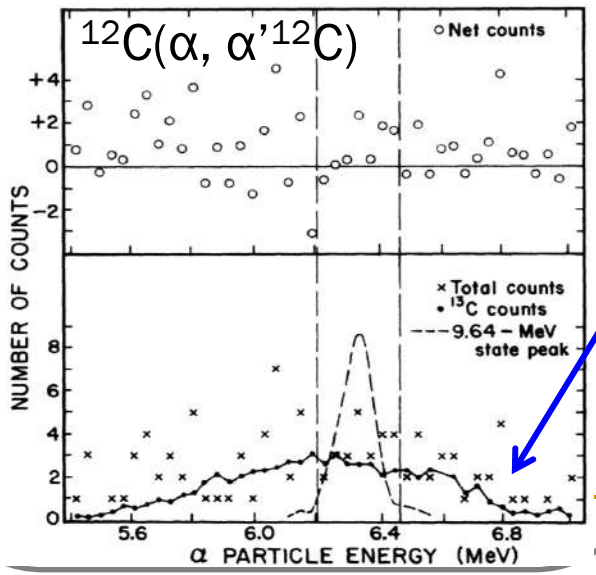
γ-decay probability of the 3_1^- state

Γ_γ/Γ of the 3_1^- state is very small, only its upper limit was reported

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')

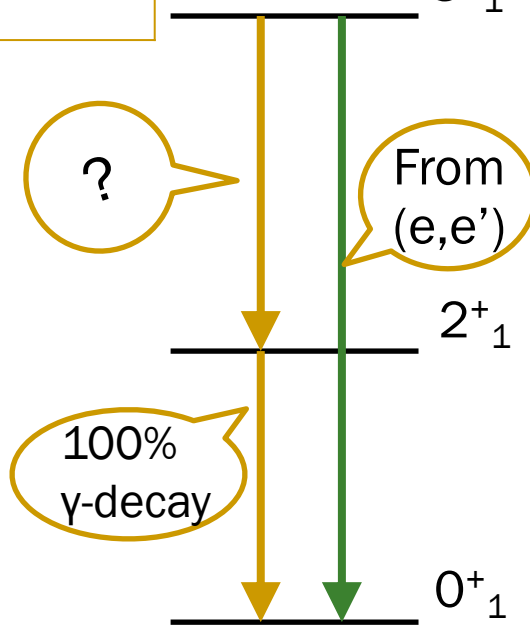
Previous experiment



Difficult to measure!!

Background due to ^{13}C contaminants

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



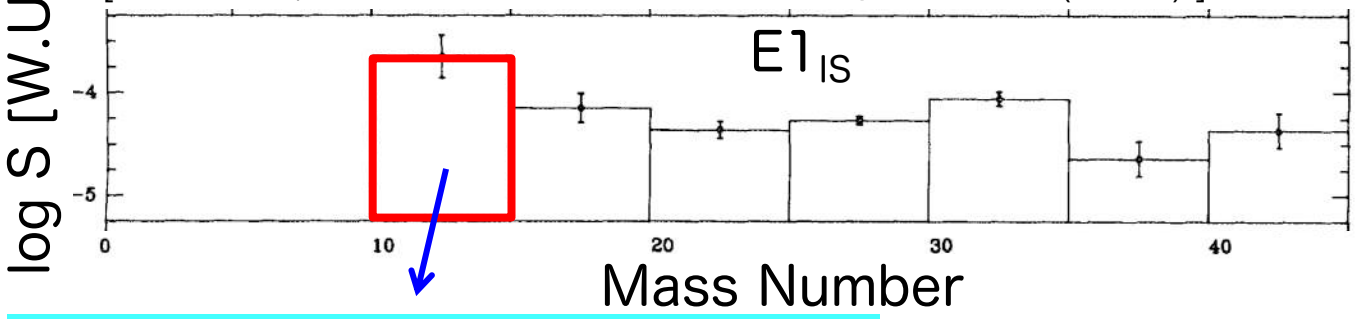
No ^{13}C contaminants in ^{12}C beam!!

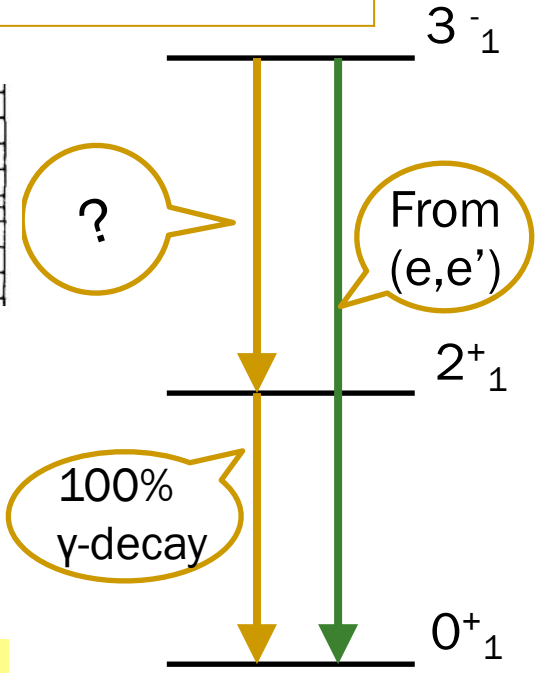
[D. Camberlin *et.al.*, Phys. Rev. C **10**, 2 (1974).]

Possible strength of isospin forbidden E1 strength

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}

[P. M. Endt, Atom. Data Nucl. Data Tab. **55,** 171–197 (1993).]





S ~ $10^{-3.6}$ W.u. around A ~ 12

IVE1 decay by isospin-symmetry breaking (α cluster dissolution)

Typiecal value: Γ_γ ~ 15 meV (~ 2 meV in NACRE)

3α rate could be enhanced at High T!

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

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

Number of all excited events

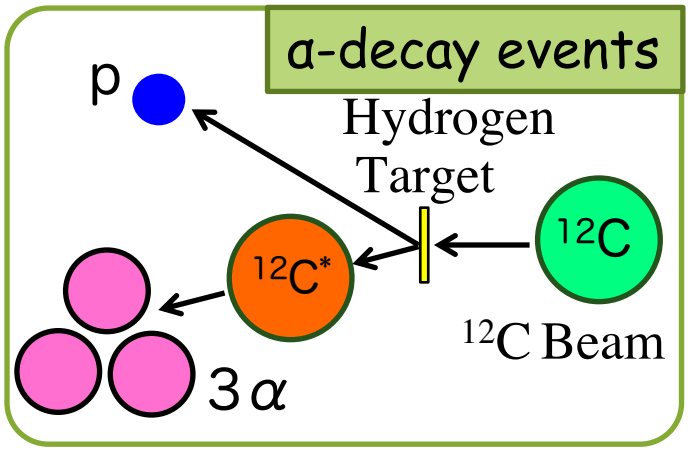
E_X in ^{12}C is determined from the energy and angle of the recoiled proton.

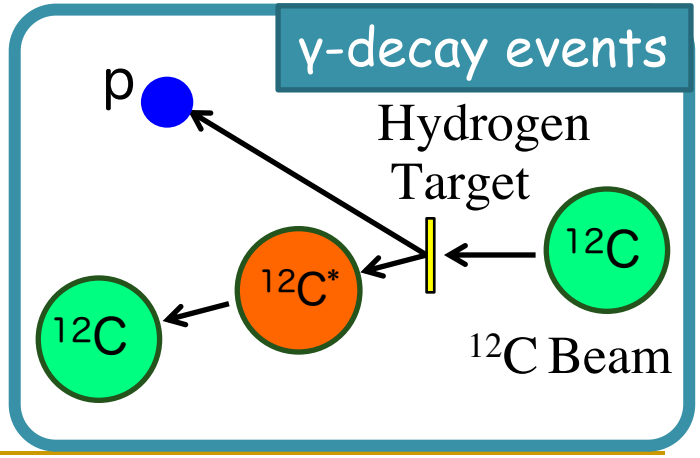
Number of γ-decay events

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

- Thin solid hydrogen target.
- Recoil proton detector.

All excited events





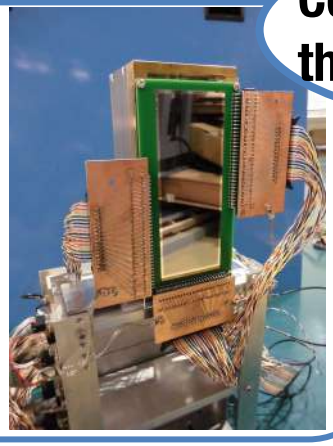
Experimental Setup

The experiment was performed at the cyclotron facility in RCNP.

Recoile proton detector

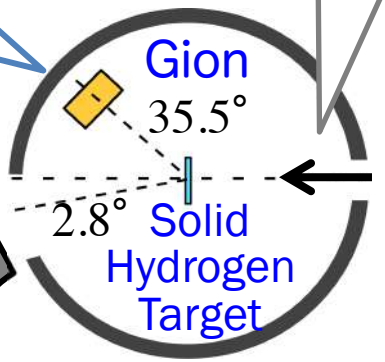
Gion (Si+GAGG telescope).

Double-sided Si strip detector
GAGG scintillator



Count the number of the all excited events

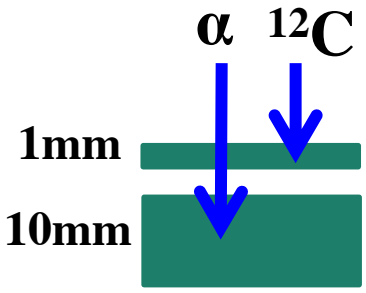
A solid H target is bombarded with a ^{12}C beam.



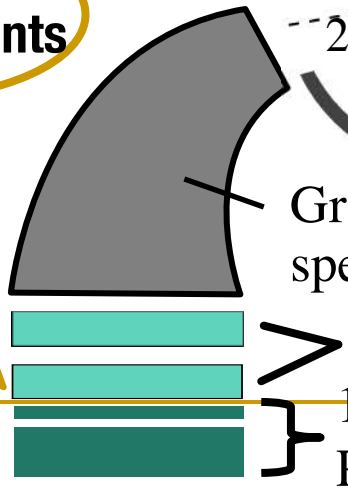
250 MeV
^{12}C beam

Scattered ^{12}C detector

Select γ-decay events



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



Grand Raiden spectrometer

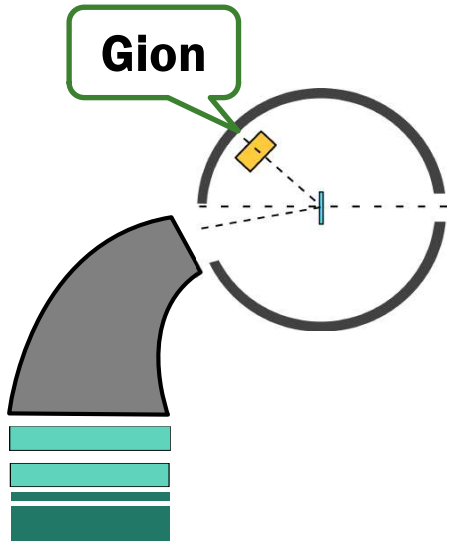
Drift Chambers

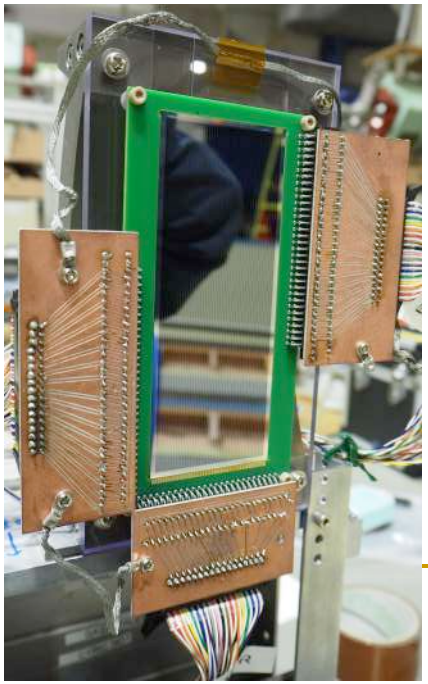
1 mm & 10 mm
Plastic Scintilator

Gion Recoil proton counter

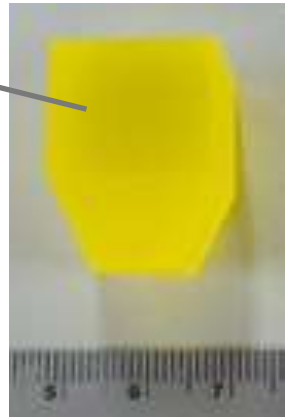
Gion = GAGG based light ion counter telescope

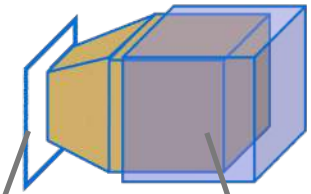
	Density (g/cm^3)	ΔE/E (FWHM) @662 keV	Decay time (ns)	Light output (photon/MeV)
CsI(Tl)	4.51	~6%	~1000	~56000
GAGG(Ce)	6.63	5-6%	88	65000





GAGG
$(Gd_3Al_2Ga_3O_{12})$





APD

Wrapped by 65-μm ESR film (3M)

✓ Double sided Si strip (16 x 32) detector
✓18 x 18 x 18 mm^3 GAGG x 24

Solid Hydrogen Target (SHT)

Develop SHT
to suppress background.

Target	H/Contaminant
SHT*	3.913
CH_2	0.167

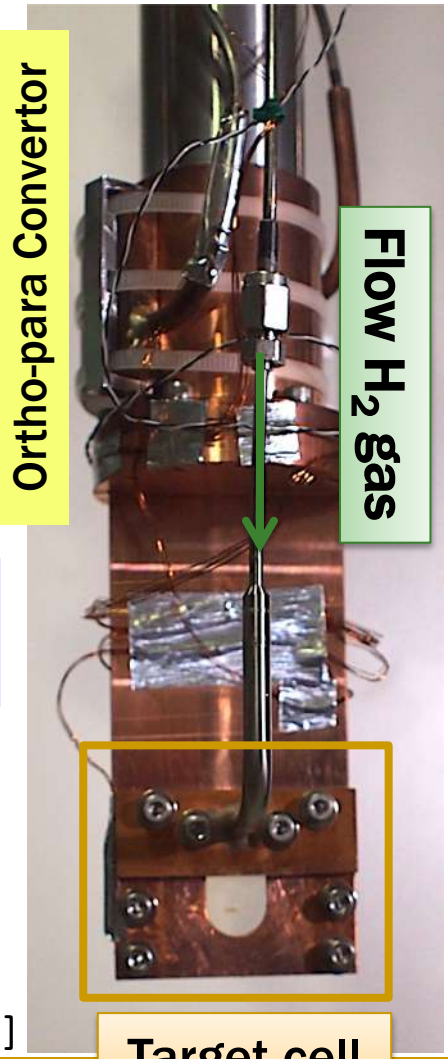
×23.4

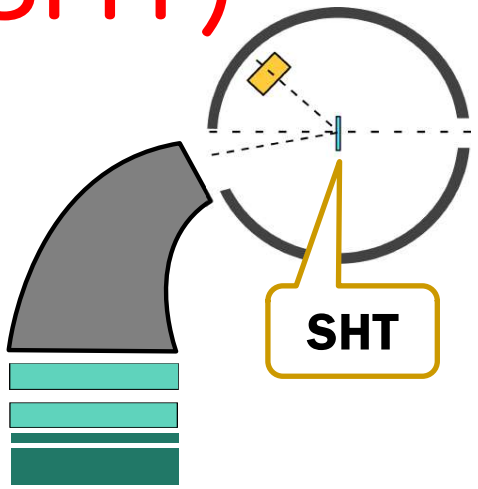
* Include gas-sealing Aramid film (4 um x 2)

Thickness should be thinner than
0.5 mm for ΔE_x < 250 keV.

Ortho-para convertor
→ Enhance thermal conductivity
of the solid hydrogen.

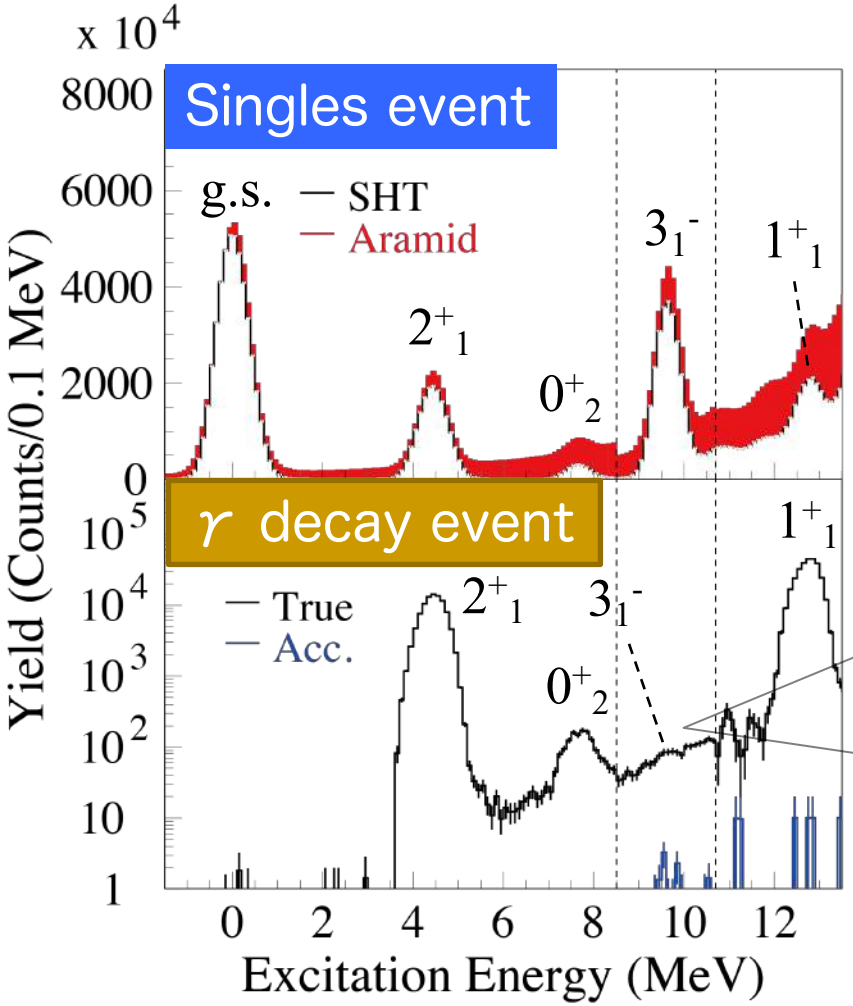
[Y. Matsuda, M. Tsumura, T. Kawabata *et.al.*,
J. Radioanal. Nucl. Chem. **305,** 897--901 (2015).]





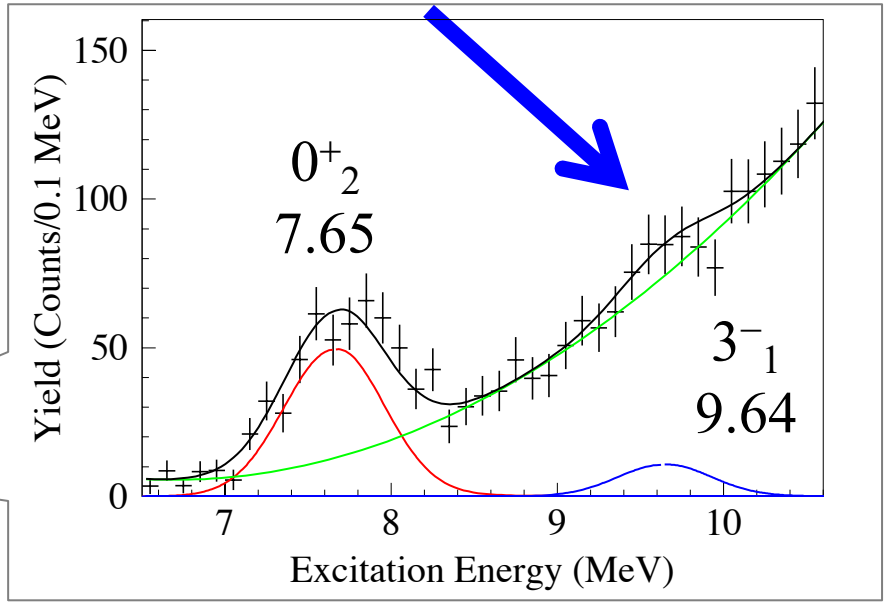
Thin!!

Results



Peak significance: 91%

γ-decay from 3^-_1 was observed?



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.

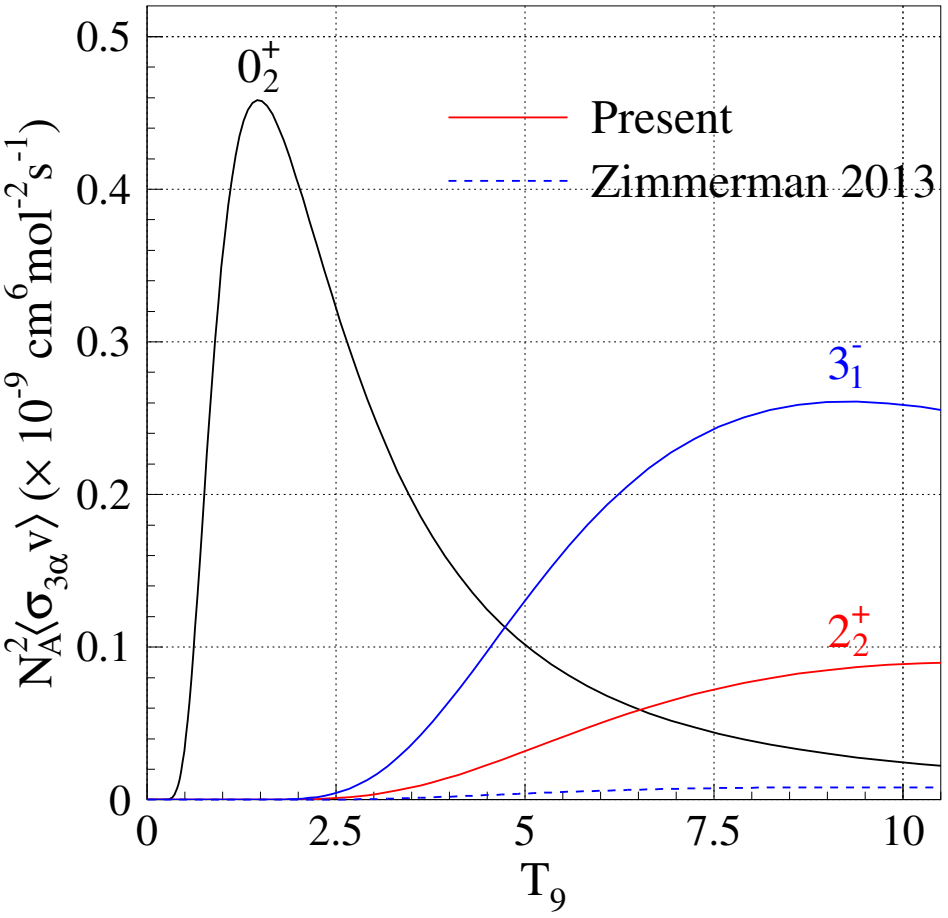
	0^+_2	1^+_1	3^-_1
Geo. Efficiency	0.117(2)	0.186(9)	0.229(3)
Γ_γ/Γ Previous	$4.16(11)\times10^{-4}$	$2.21(7)\times10^{-2}$	Unknown
Γ_γ/Γ Present	$4.3(8)\times10^{-4}$	$2.6(7)\times10^{-2}$	$1.3(8)\times10^{-6}$

The present results are consistent with
with the previous result on the 0^+_2 and 1^+_1 states.

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

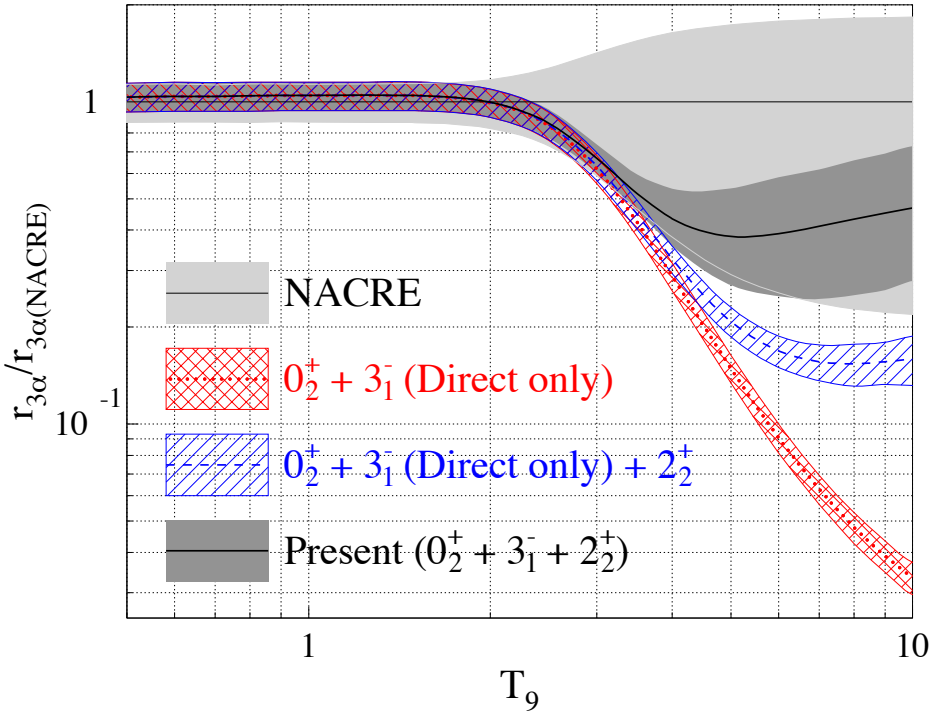
Triple Alpha Reaction Rate

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...

M. Tsumura, T. Kawabata et al., Phys. Lett. B **817**, 136283 (2021).

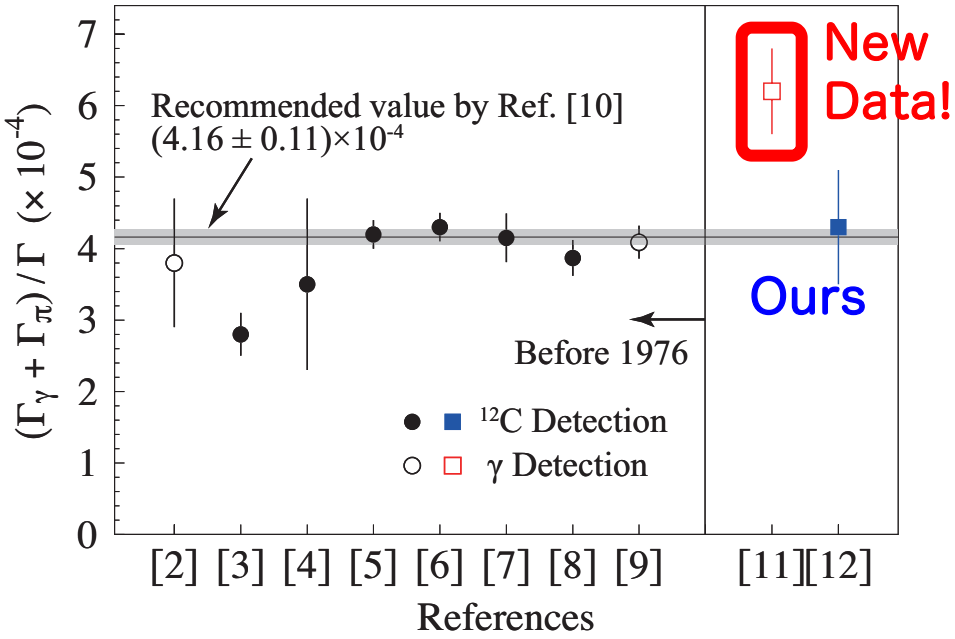
Triple Alpha Reaction via the Hoyle state

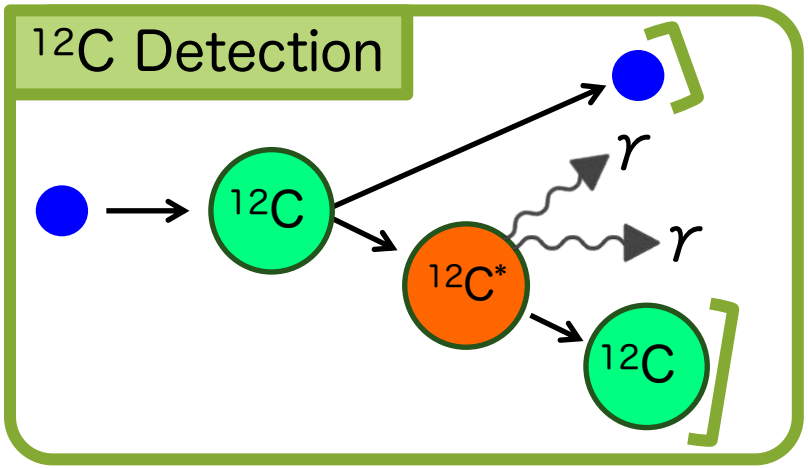
(K. Sakanashi, S. Tsuji, et al.)

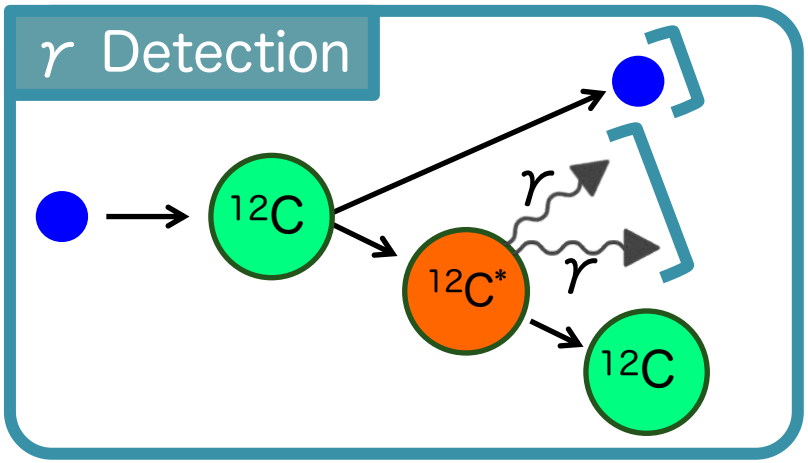
Hoyle state ~ the 0^+_2 state in ^{12}C

The Hoyle state is the most important state in the 3α reaction, but its width is recently controversial.

Previous measurements are classified into two types.





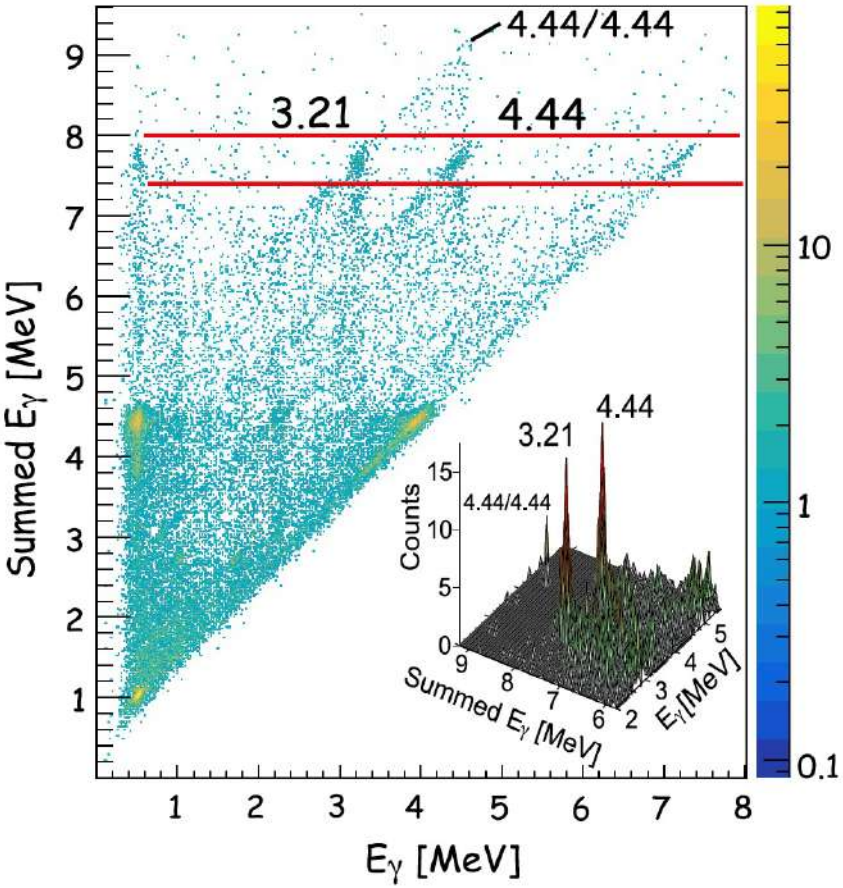


A new striking data has been reported from γ detection.

T. Kibédi et al., Phys. Rev. Lett. **125**, 182701 (2020).

γ Detection by T. Kibédi et al.

New data reported by T. Kibédi et al.
is much larger than the currently accepted value.

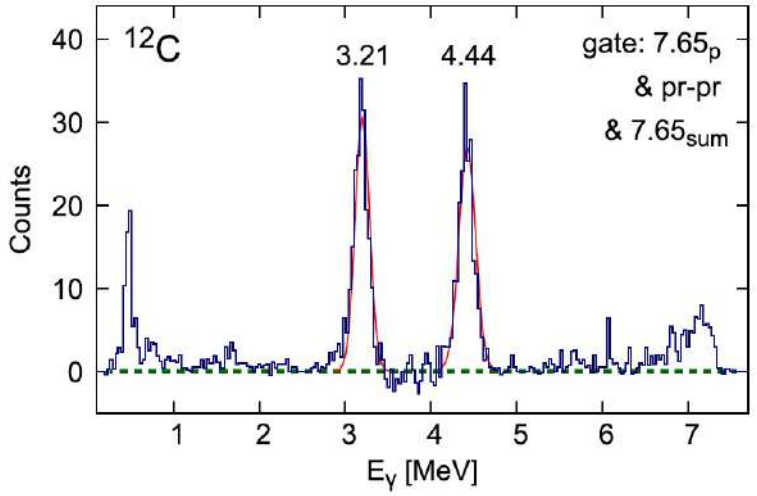


T. Kibédi et al., Phys. Rev. Lett. **125**, 182701 (2020).

$^{12}C(p,p'+2\gamma)$ @ E_p = 10.7 MeV

SiRi: 64 ΔE-E Si telescopes
ΔE: 130 um, E: 1550 um
$\Delta\Omega$ = 6% of 4π

CACTUS: 26 5" × 5" NaI(Tl)
ε = 14.2% @ 1.33 MeV



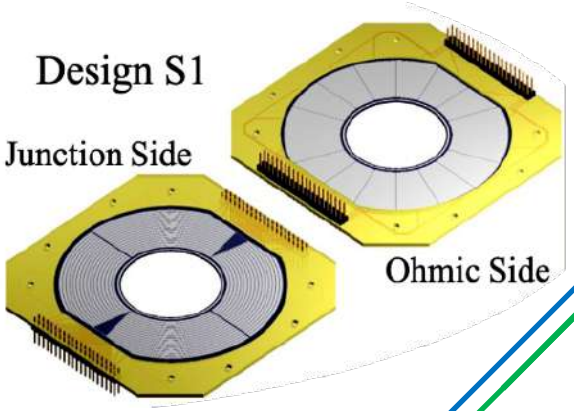
New data: Γ_{rad}/Γ = 6.2(6) × 10^{-4}
Accepted Value: 4.16(11) × 10^{-4}

50% larger than the accepted value!!

New Experiment@IFIN-HH, RO

$\alpha + {}^{12}C \rightarrow \alpha' + {}^{12}C + \gamma$ @ E_α = 25 MeV

Si: Charged particle



ROSPHERE: γ-ray

Data acquisition system

DAQ PC

Time information, Waveform, and Pulse height

V2495 (FPGA)

Timing out

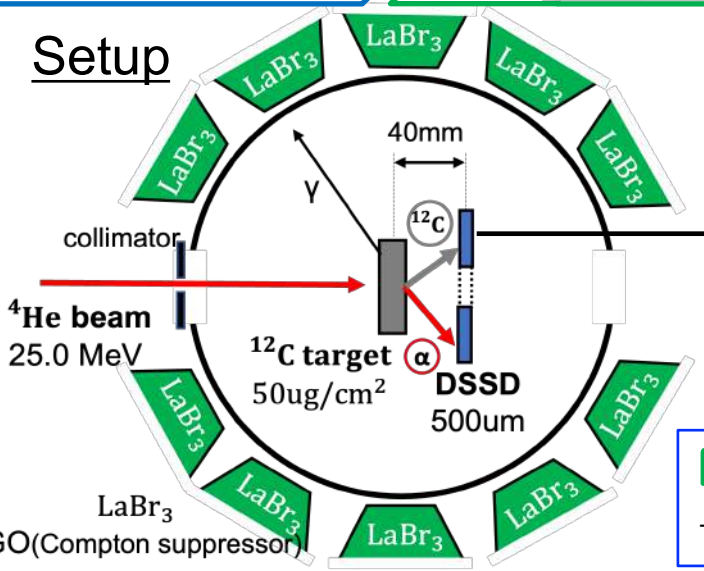
Trigger (all OR)

Busy

MSCF-16

Optical link cable

Setup



MPR

Rear

Front

V1730

Si : PHA firmware
→ Record waveform

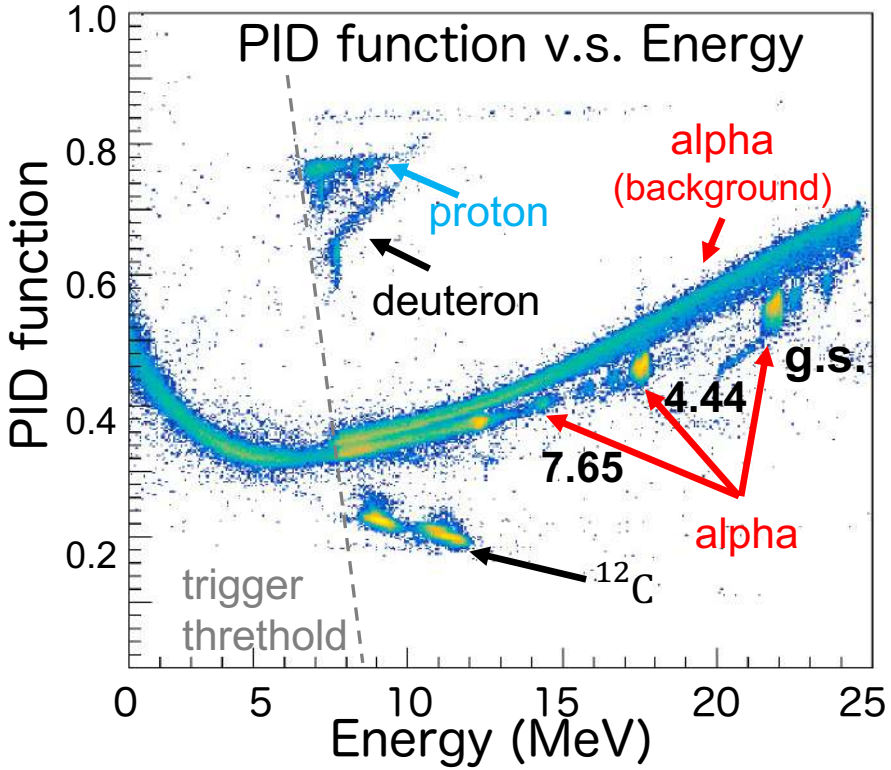
Self-trigger mode

ROSPHERE : PSD firmware
→ Record pulse height

V1730

Analysis

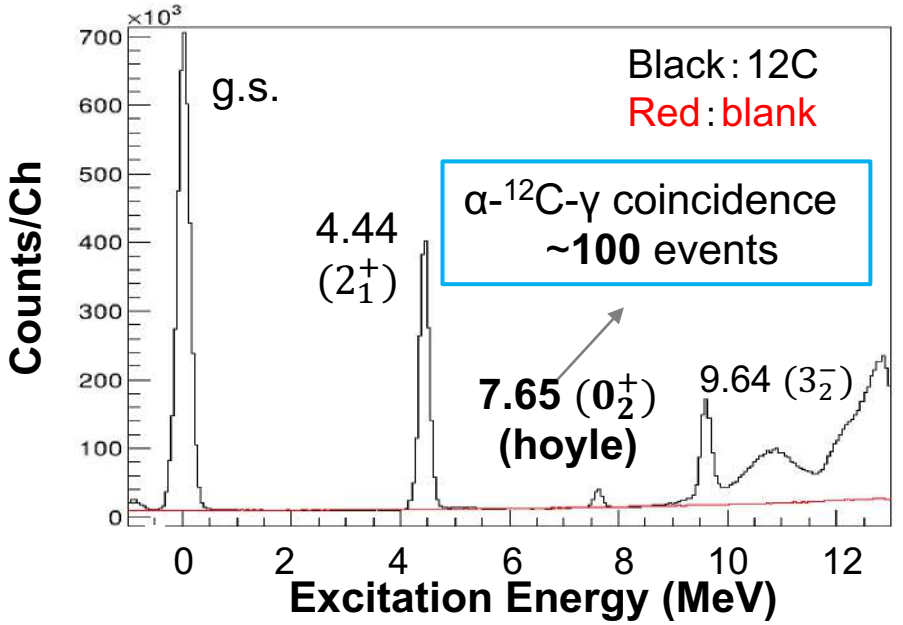
PID using Pulse Shape Analysis



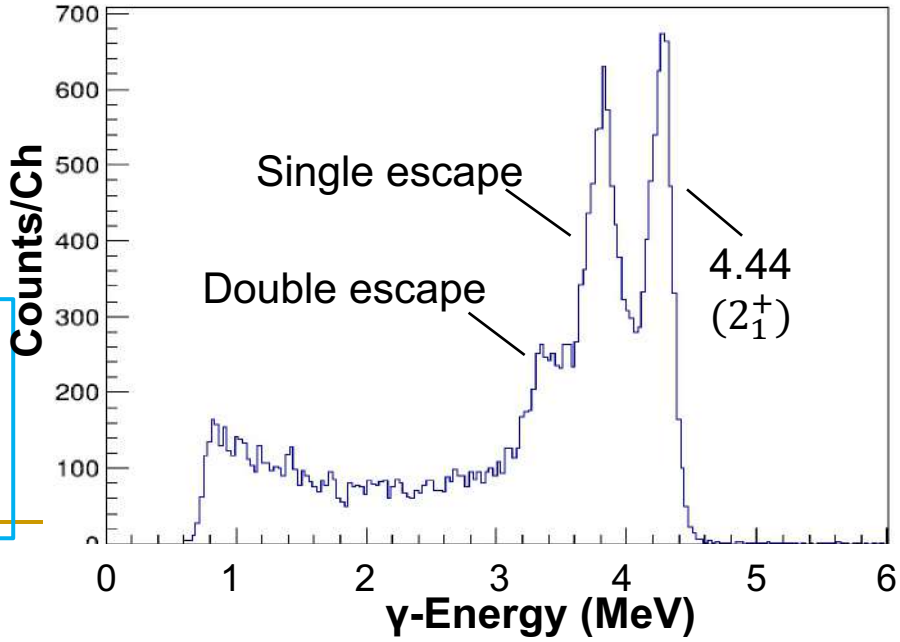
- ✓ Successfully separated α from p, d and ^{12}C
- ✓ Continuous background alpha particles

→ Beam scattered by upstream collimators

Analysis is still going on.



α-γ coincidence events in ^{12}C(2^+_1)



Triple Alpha Reaction at High Density

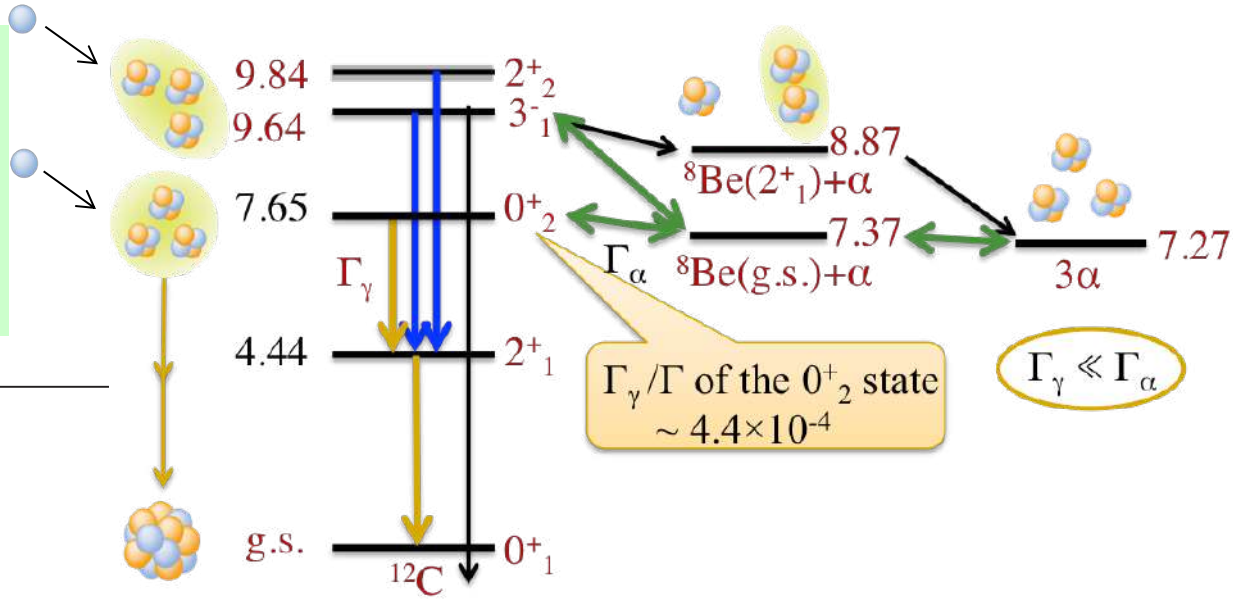
~ On going experiment with MAIKo+ ~

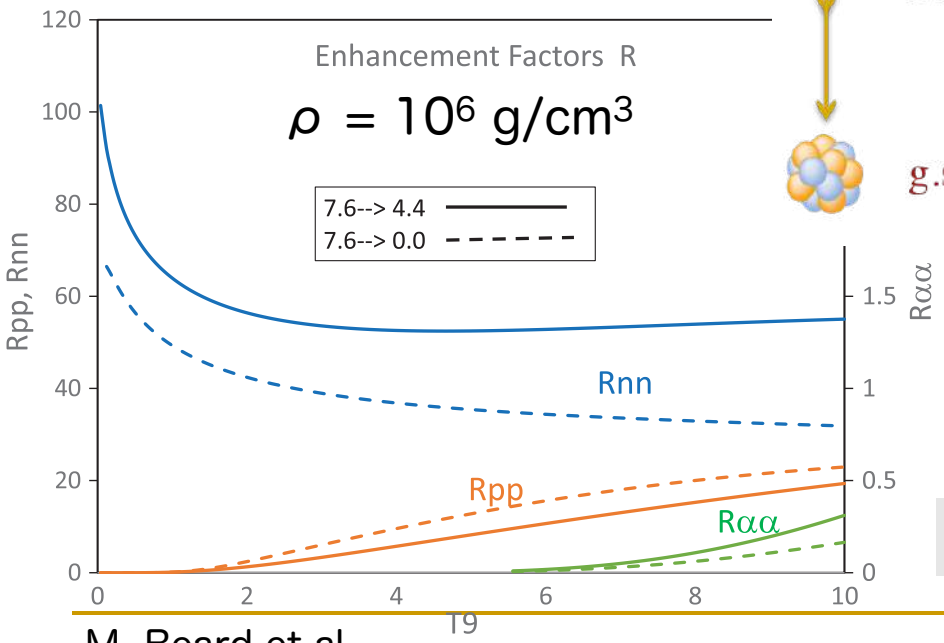
(T. Furuno, K. Himi, T. Doi et al.)

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.

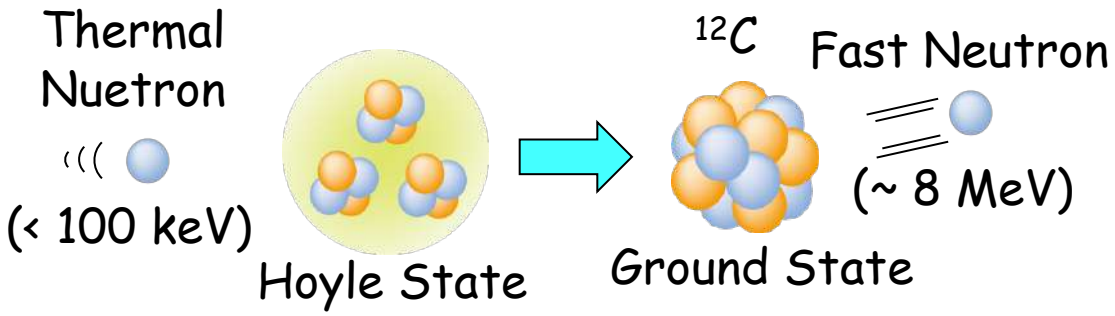
Need to determine the cross sections.

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

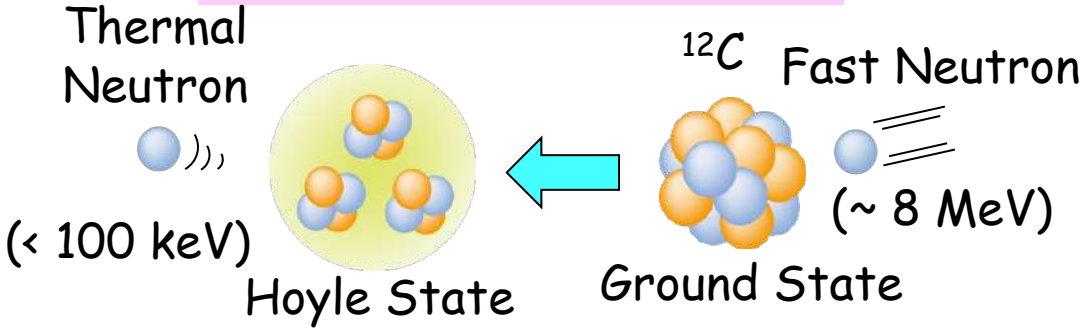
Time Inverse Reaction

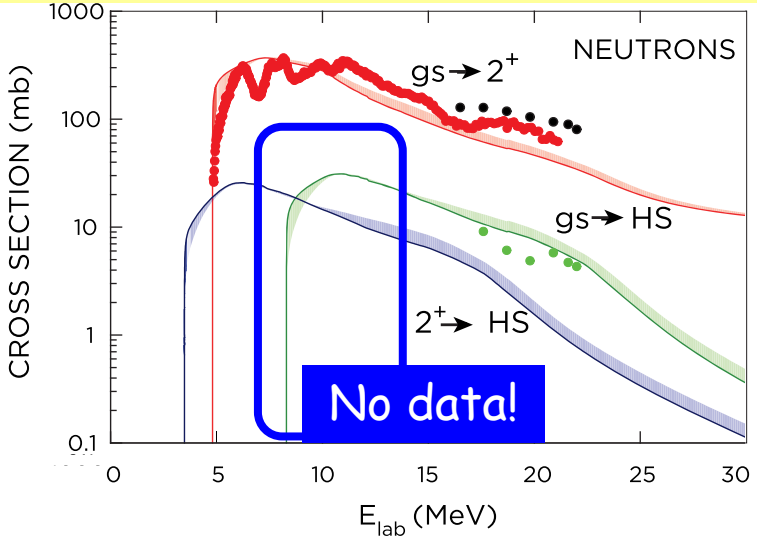
Direct measurement of ^{12}C(Hoyle)(n,n')^{12}C(g.s.) is impossible.
→ Time inverse reaction should be measured.

Astrophysical Reaction



Time Inverse Reaction





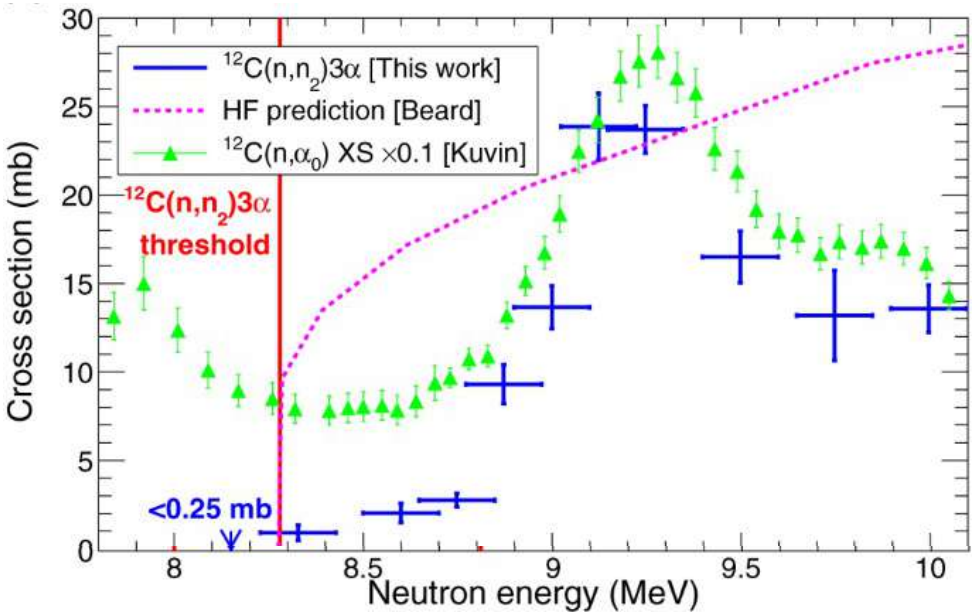
M. Beard et al., PRL 119, 112701 (2017).

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

Recent Data from TAMU

Recently, Texas A&M group published new data.

J. Bishop et al., Nature Comm. **13**, 2152 (2022).



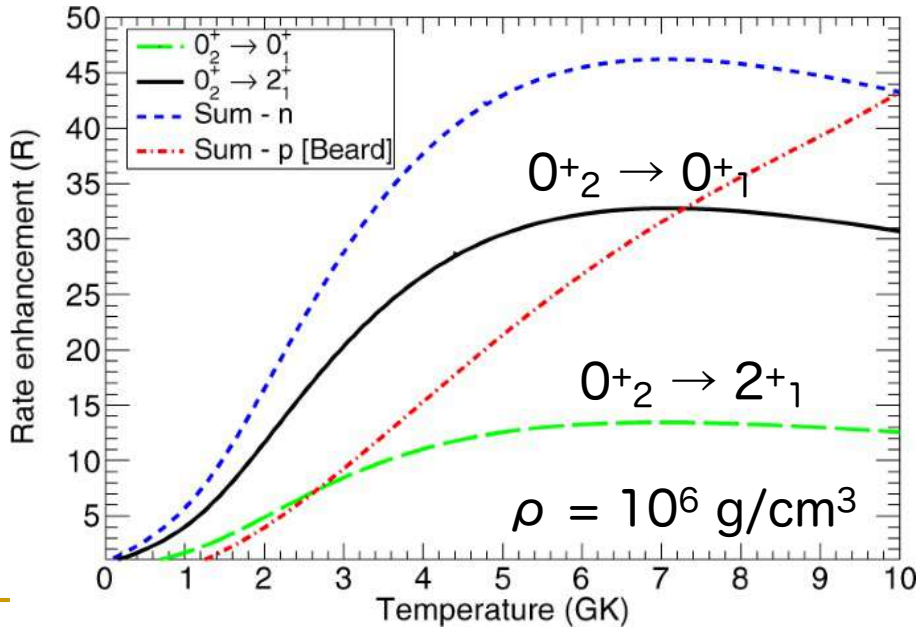
Measurement with TexAT TPC

Sensitive Volume:

224 × 245 × 130 mm^3

Detection gas: CO_2 at 50 Torr

Neutron beam at 7.2—10 MeV



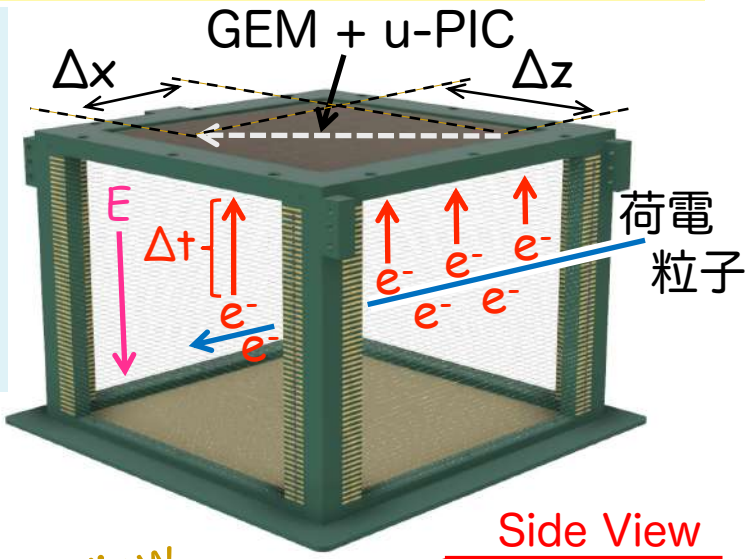
Enhancement at 7 GK: 46

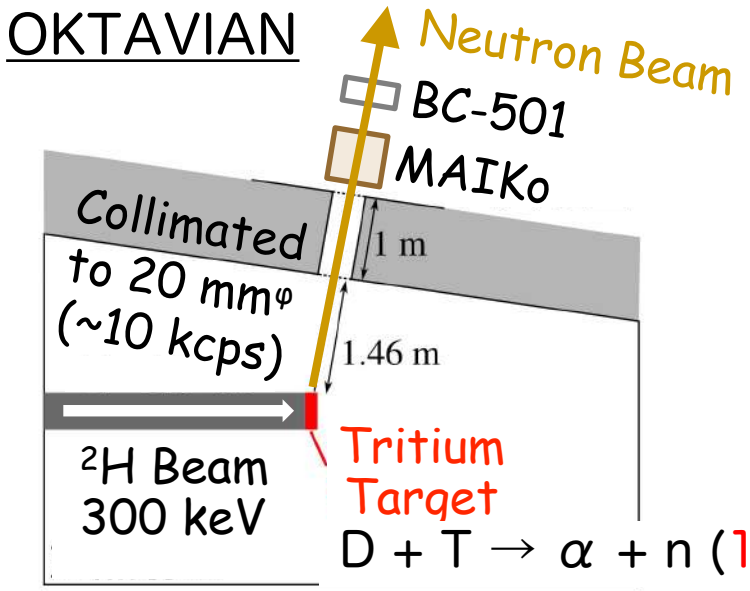
Smaller than expected (> 100)

Test Measurement with MAIKo+

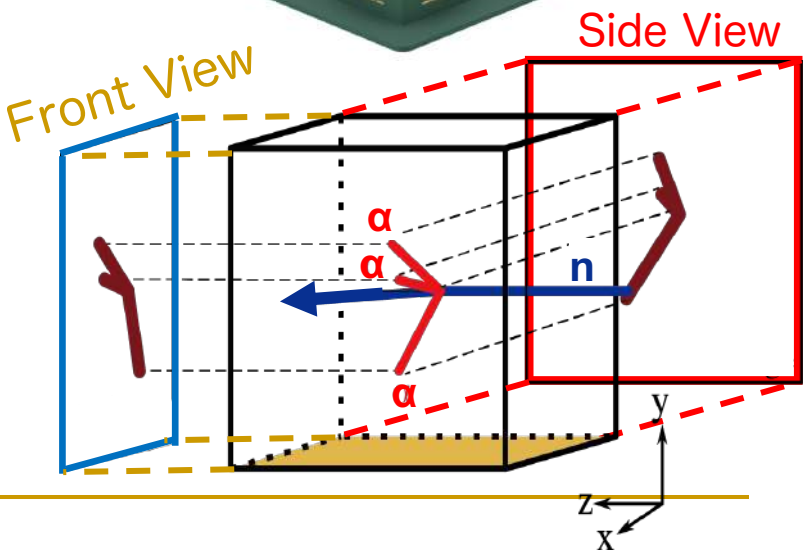
Test measurement was carried out at OKTAVIAN, Osaka.

- MAIKo+ TPC
  - ✓ Two images of 2D-projected trajectories.
  - ✓ Sensitive Volume 30 x 30 x 30 cm^3
  - ✓ iC_4H_{10}(10%) + H_2 @100 hPa
- BC-501 Liquid Scintillator
  - ✓ Determine the neutron flux.





D + T → α + n (14 MeV)

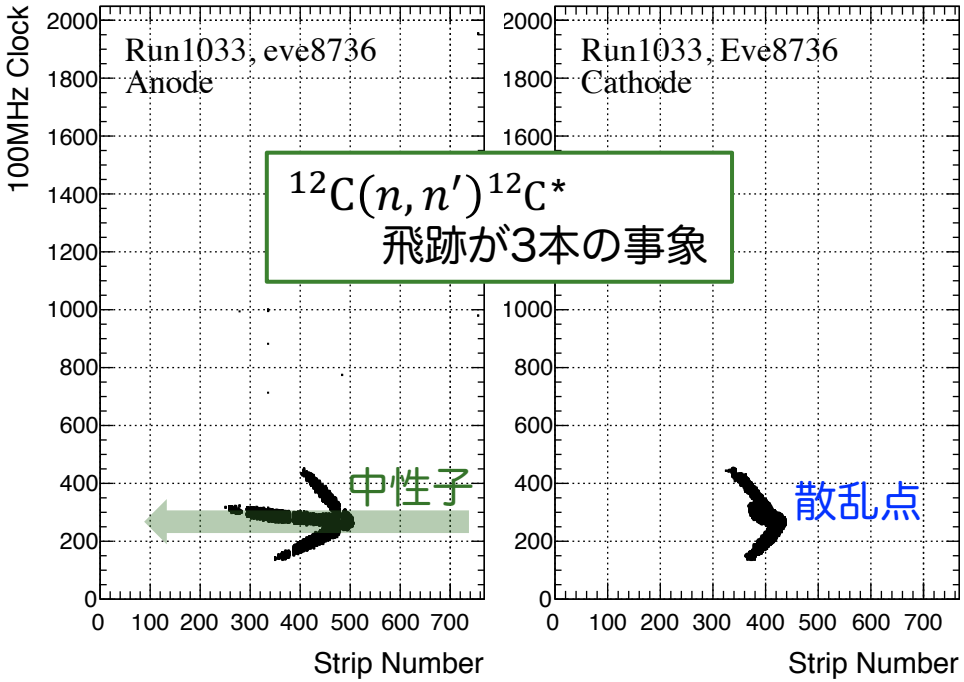


T. Doi, Master Thesis, Kyoto University (2020).

K. Himi, Master Thesis, Osaka University (2023).

Track Images

トラックの本数で信号事象とBG事象を弁別

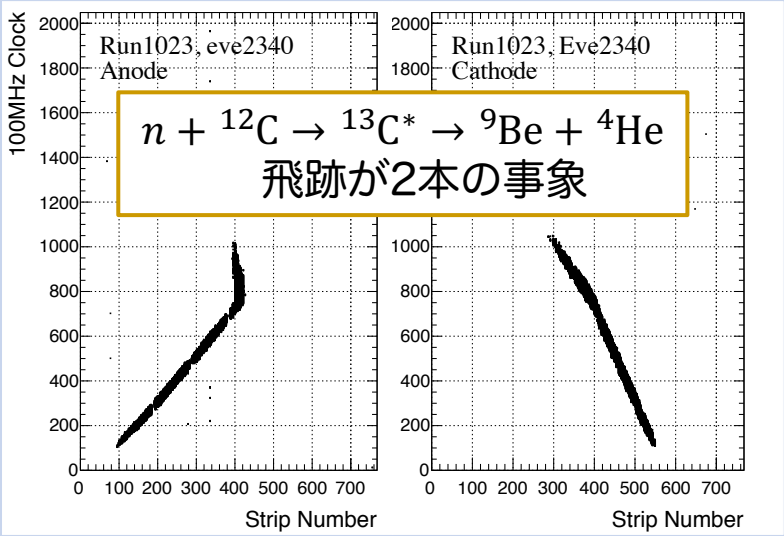


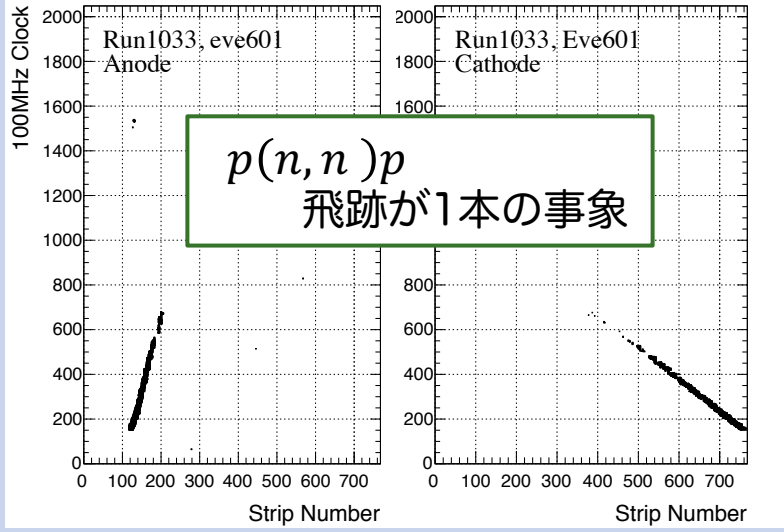
MAIKo+で記録された2枚の画像から人間の目で

- 飛跡の本数
- 中性子と^{12}Cの散乱点
- 各崩壊α粒子の飛跡の端点　の座標を抽出

ー 有感領域の端 から 2 cm 以内に端点が位置する事象は排除して解析

BG事象



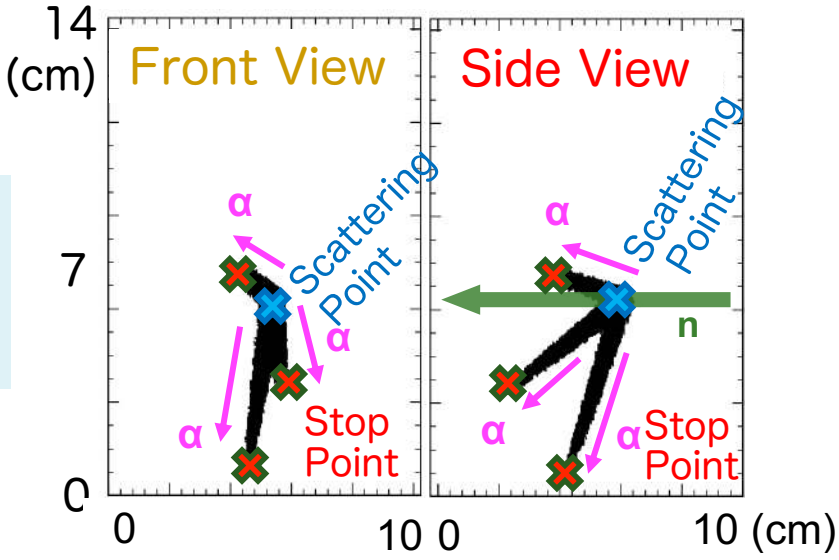


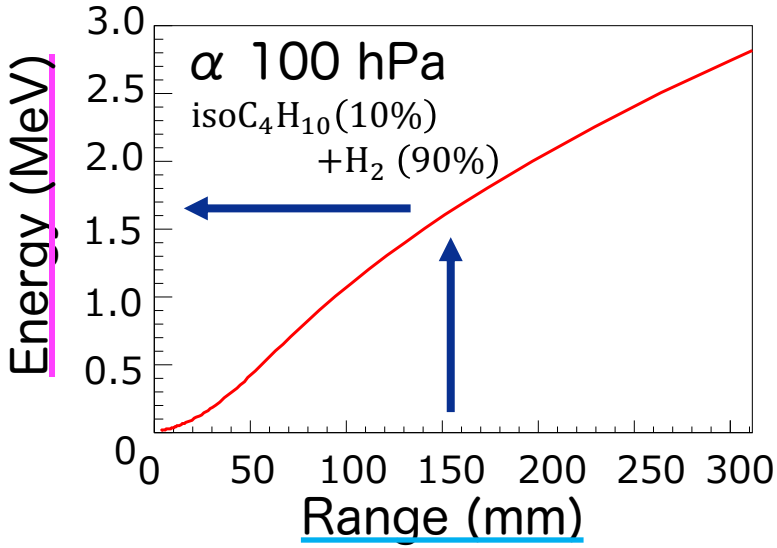
Eye-Scan Analysis

Two track images were analyzed by human eyes.

68K events (30% of total) by 14 people

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



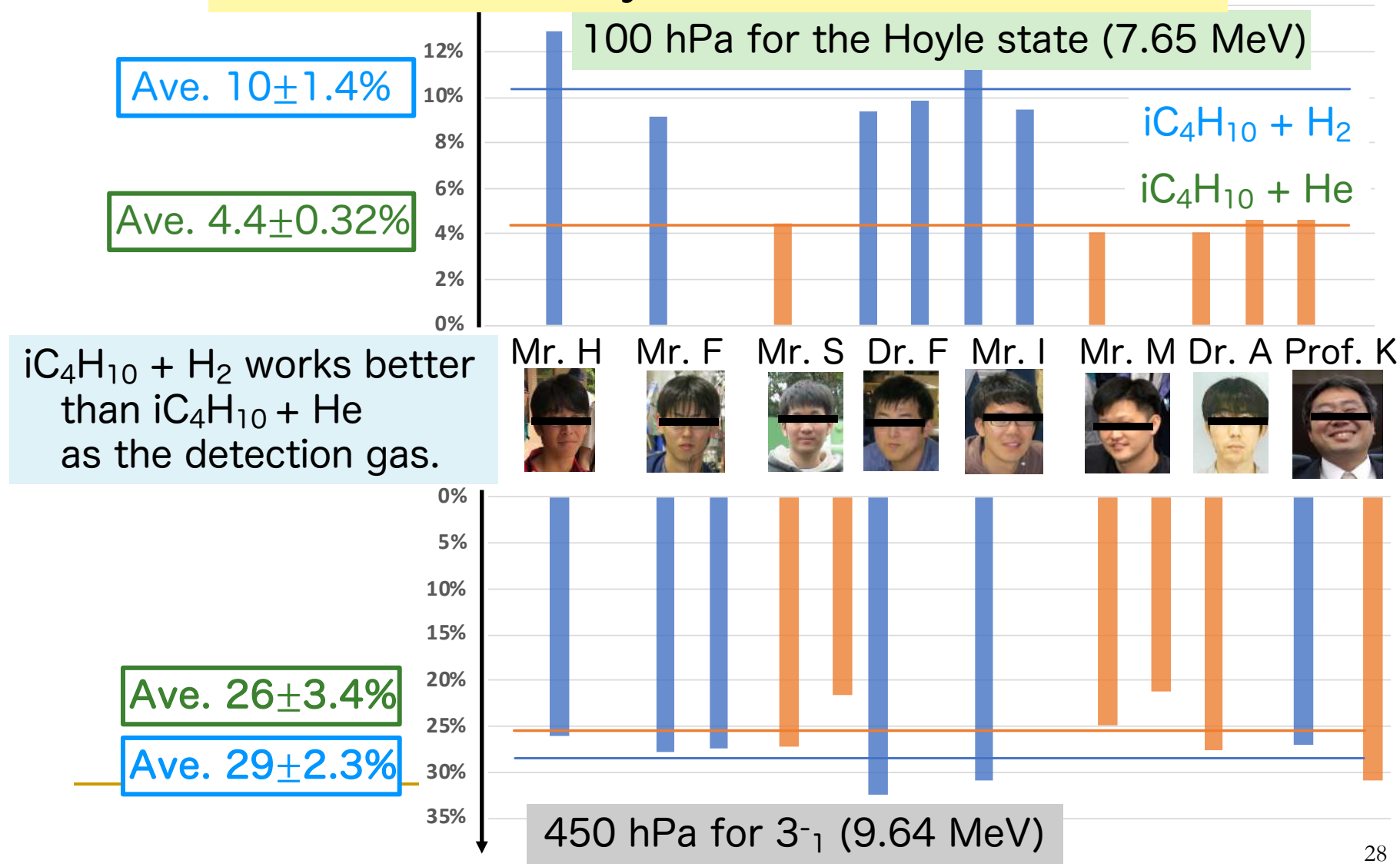


- ✓ Reconstruct 3D trajectories
  → Ranges → Kinematic energies
  → Emission angles

- ✓ Eye-scan efficiency must be examined by “dummy data”.

Eye-Scan Efficiency

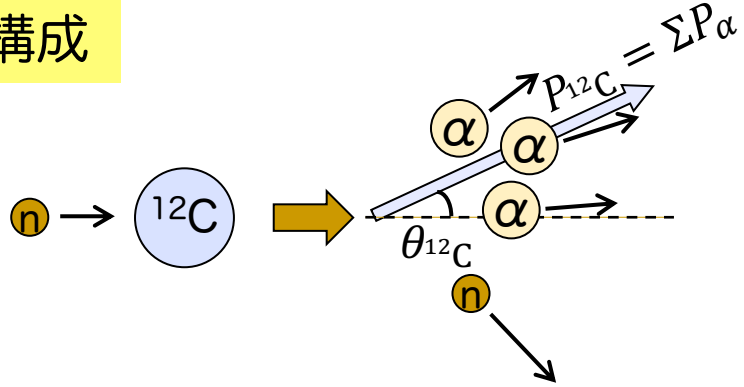
8 scanners analyzed the simulated data.

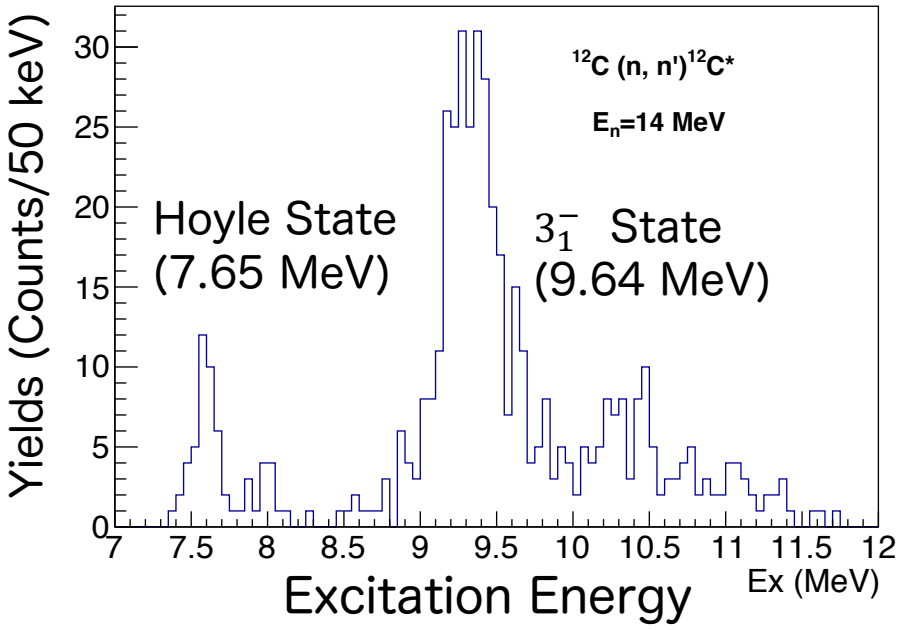


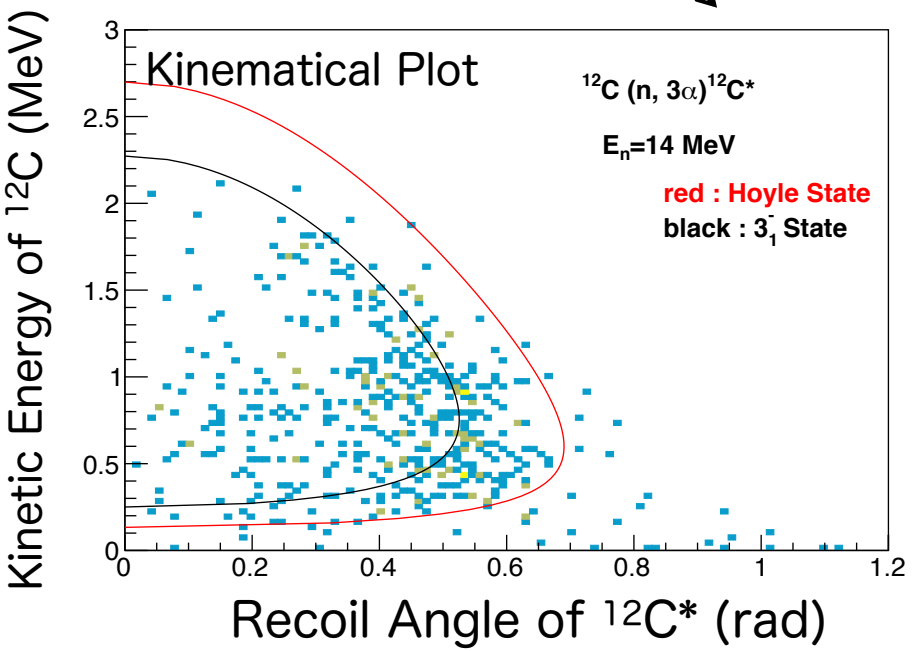
Excitation-Energy Spectrum

不変質量法により^{12}Cの励起エネルギーを再構成

崩壊α粒子の飛跡の長さ → **運動エネルギー**
＋散乱角度 → **運動量**







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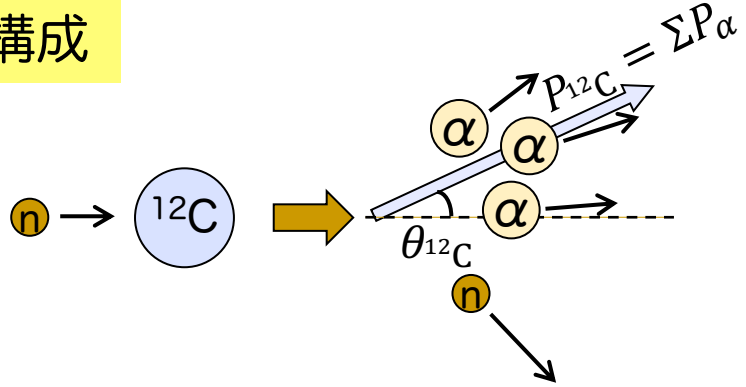

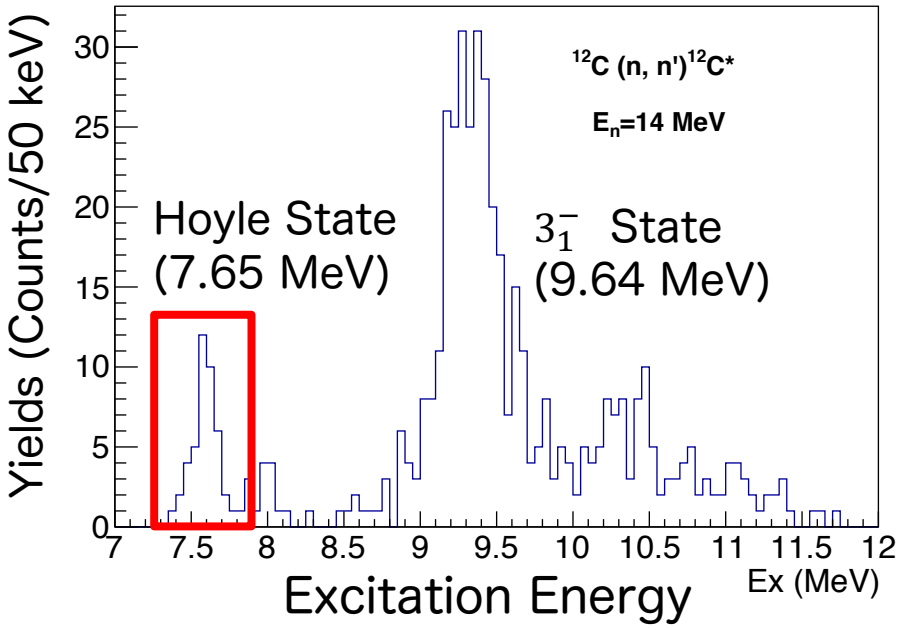

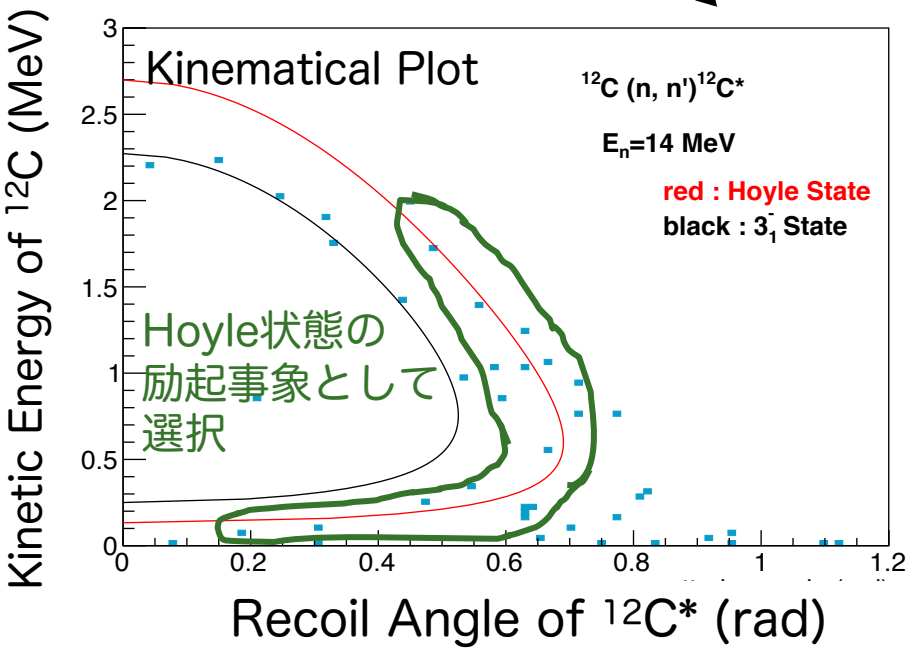

Cross Section

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

Y … 収量
N_{target} … 単位面積あたりの^{12}C標的の量 (個/cm^2)
N_{beam} … 入射中性子量 (個)
ε … 検出・解析効率 (%)

MAIKoテスト実験と比較して
収量は約10倍増加

En = 14 MeV 、100 hPa $\mathrm{isoC_4H_{10}}(10\ \%) + \mathrm{H_2}\ (90\ \%)$

	Y	N_{target} (/cm^2)	N_{beam}	ε	σ(mb)
Hoyle State	18	2.65×10^{19}	6.5×10^{8}	48%	**2.1** ± 0.5 (stat.) ± 0.1 (sys.)
3_1^- State	177			21%	**49** ± 5 (stat.) ± 1 (sys.)

先行研究との比較

K. Kondoらによる断面積　Hoyle状態 **8.9 mb** 、3_1^-状態 **69 mb**
K. Kondo et al., J. Nucl. sci. Tech. 45, 103 (2008)

MAIKoテスト実験　Hoyle状態 **14 ± 6 (stat.) ± 2 (sys.) mb**
3_1^-状態 **49 ± 10 (stat.) ± 11 (sys.) mb**

断面積の値が小さい
→ 運動学条件やトリガー条件による信号事象棄却の可能性を調査中

Summary

- We are experimentally studying triple alpha reaction rates at various conditions.
  - At high temperature,
    - Rare gamma-decay mode of the 3^-_1 state.
  - At normal temperature,
    - Puzzle about the radiative-decay width of the Hoyle state.
  - At high density,
    - Neutron inelastic scattering exciting the Hoyle state.