Nuclear experimental approach to cluster correlation and nucleosynthesis in the universe

Search for Rare γ-decay Modes in ^{12}C

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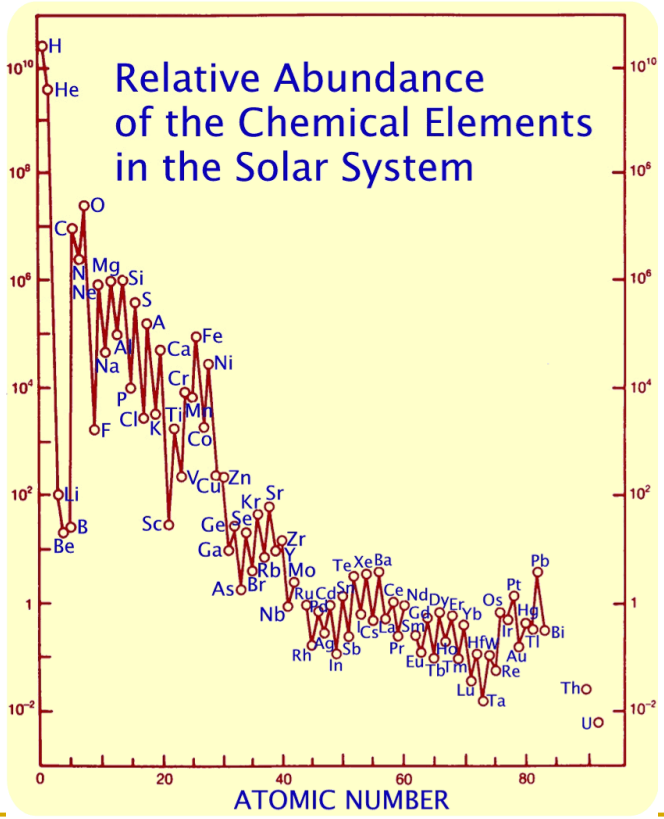
Cluster Correlation and Nucleosynthsis

^{4}He (α particle) is the second abundant element in the universe

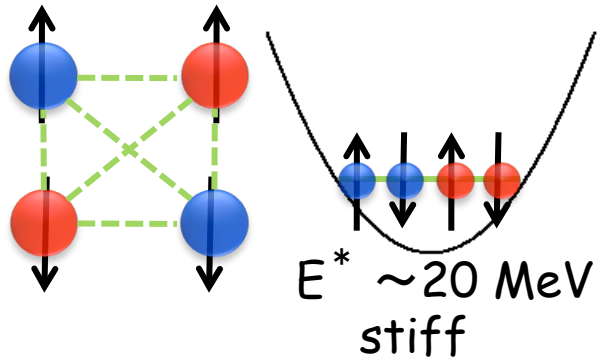
$\rightarrow$ α induced reaction is important



α clustering is the most important correlation in nuclei.

The most tightly bound light cluster

α particle (quartet)

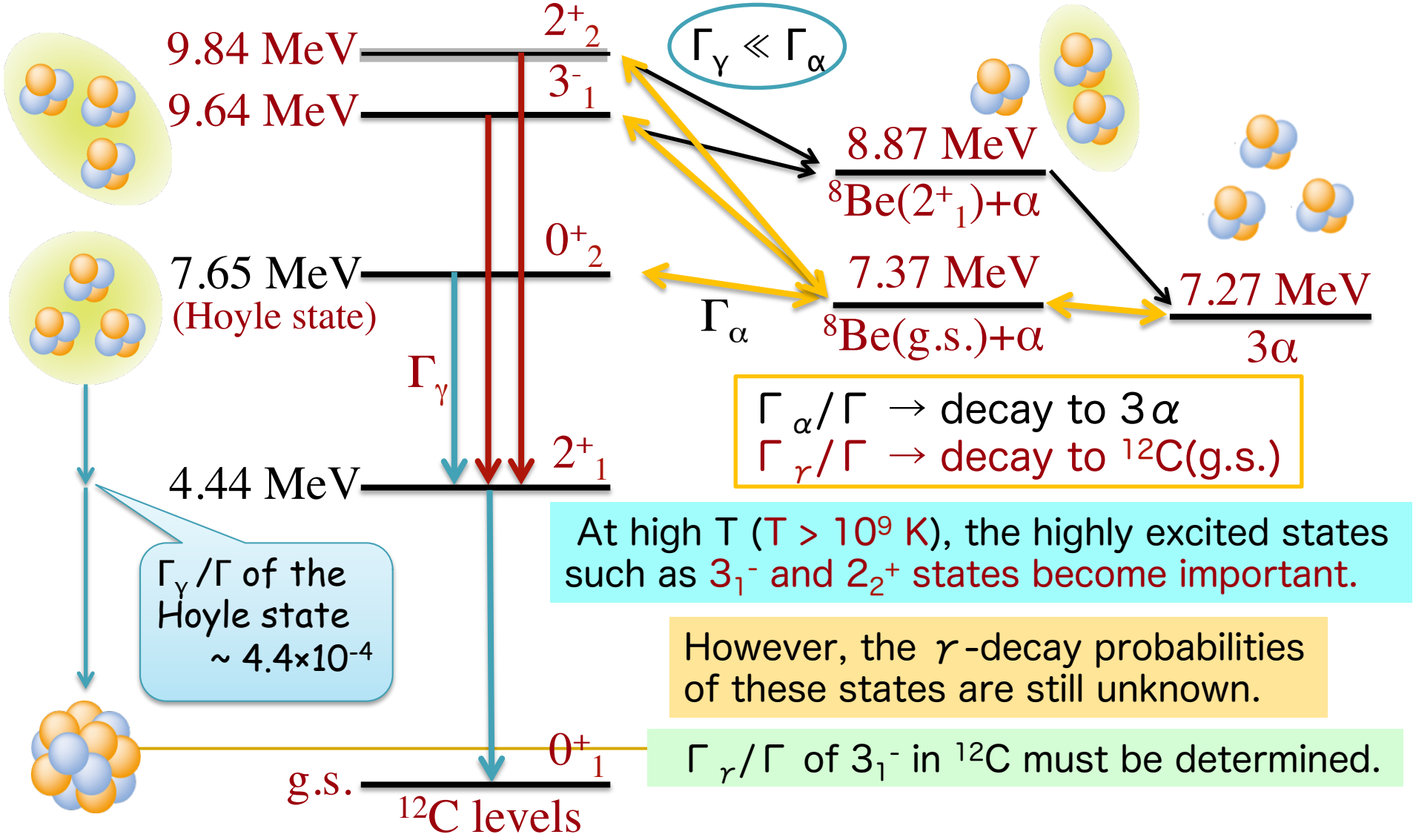


The most elemental subunit in nuclear cluster structures.

Cluster correlation plays an important role in nucleosynthesis

Triple Alpha Reaction

The triple a reaction plays a crucial role in the nucleosynthesis.



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

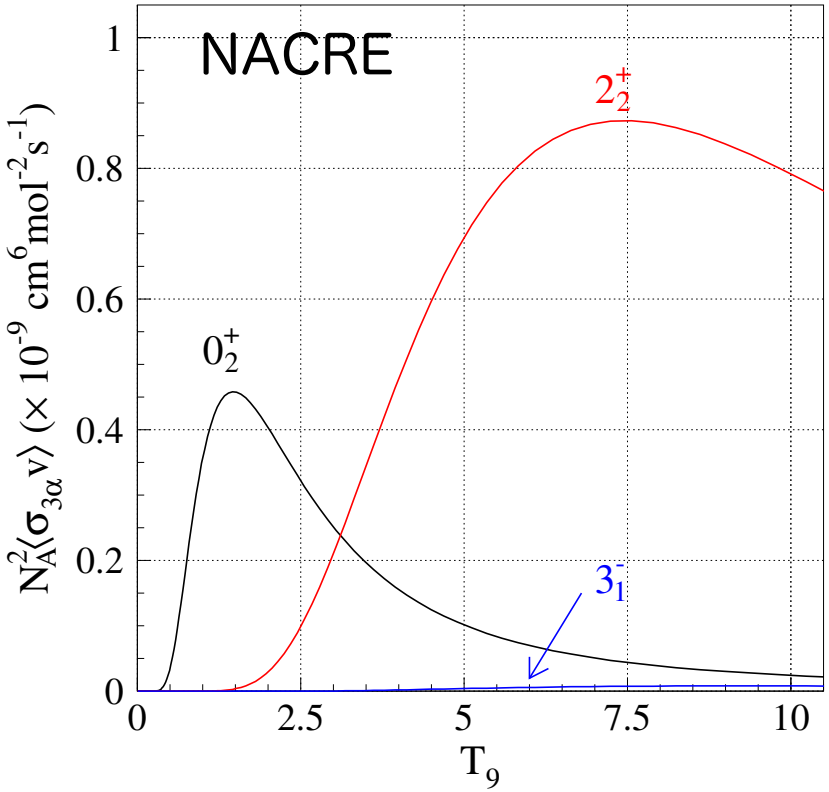
At high T ($T > 10^9$ K), the highly excited states such as 3_1^- and 2_2^+ states become important.

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 $T_9 \sim 5$.

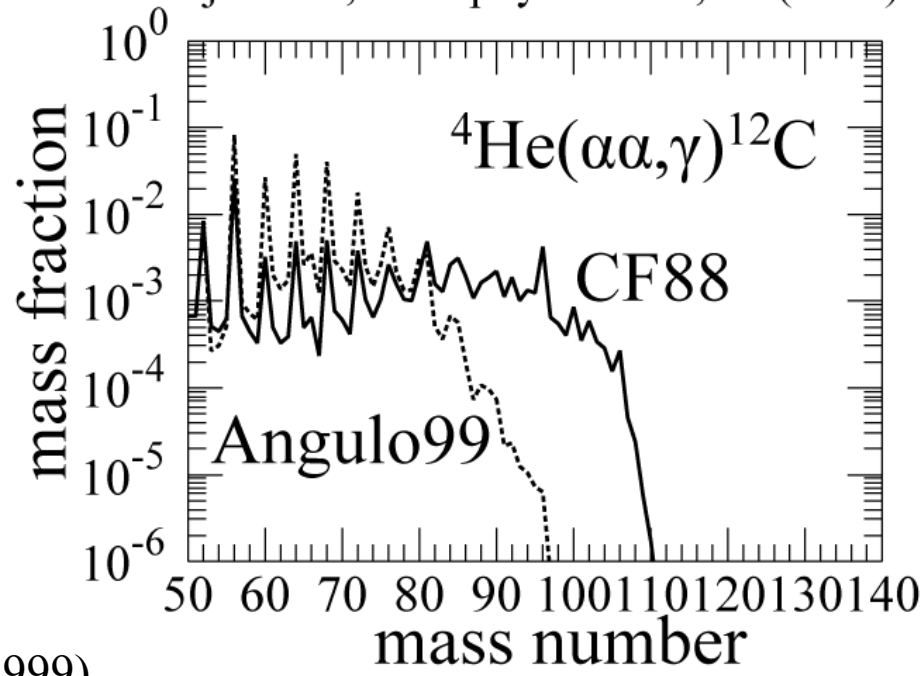


C. Angulo et al., Nucl. Phys. A**656** 3—187 (1999).

Large Impact on Heavy element abundance by νp process

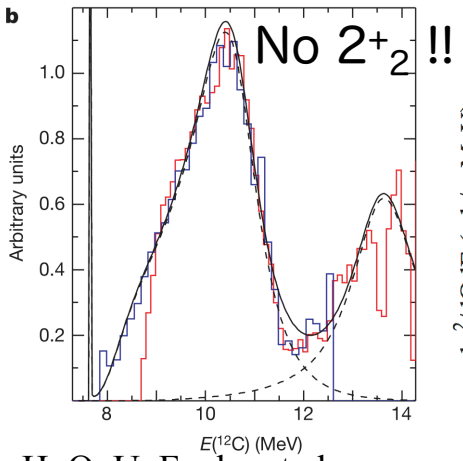
Angulo99: Include 3^-_1 and 2^+_2
CF88: 0^+_2 only

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

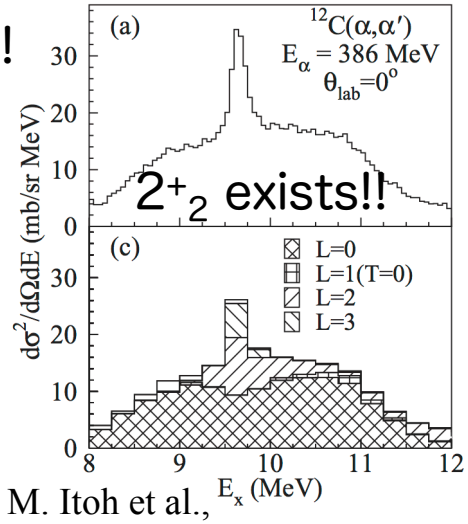


Recent Update

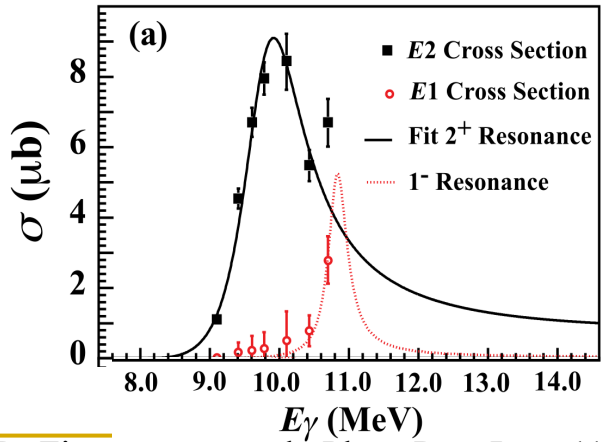
New data on the 2^+_2 were published.



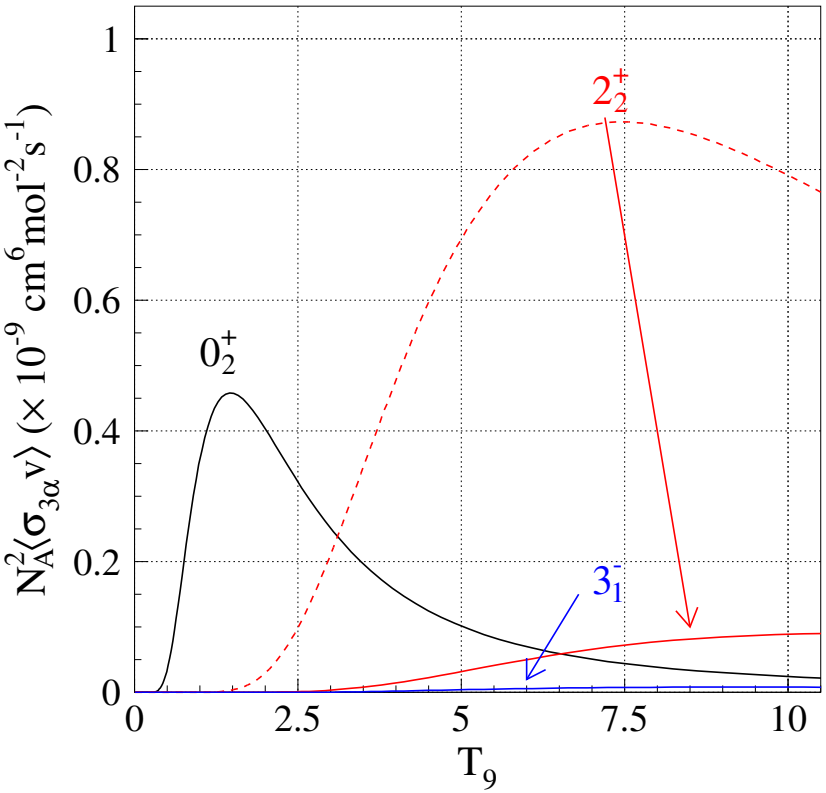
H. O. U. Fynbo et al., Nature **433**, 136 (2005).



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 ?

Recent Update

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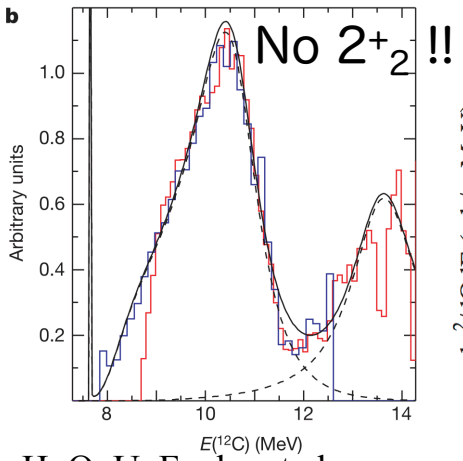

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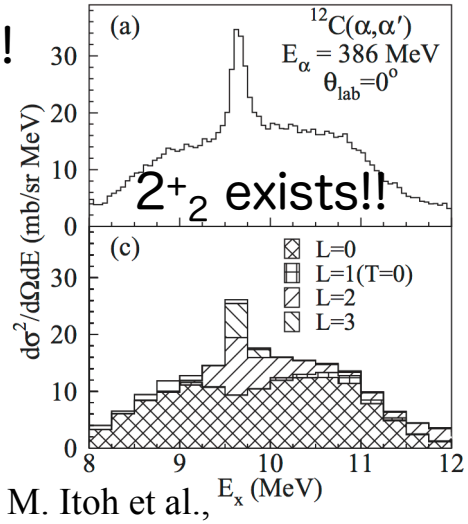

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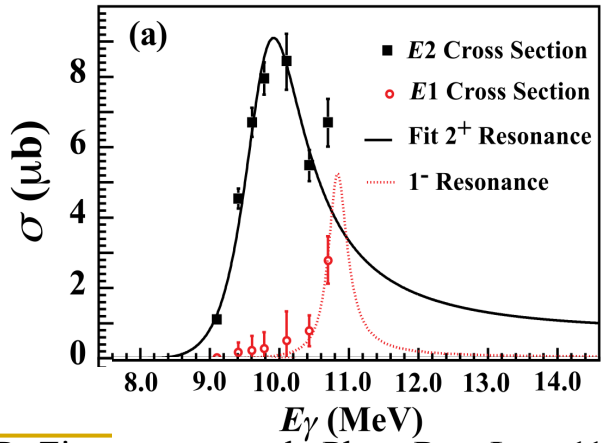

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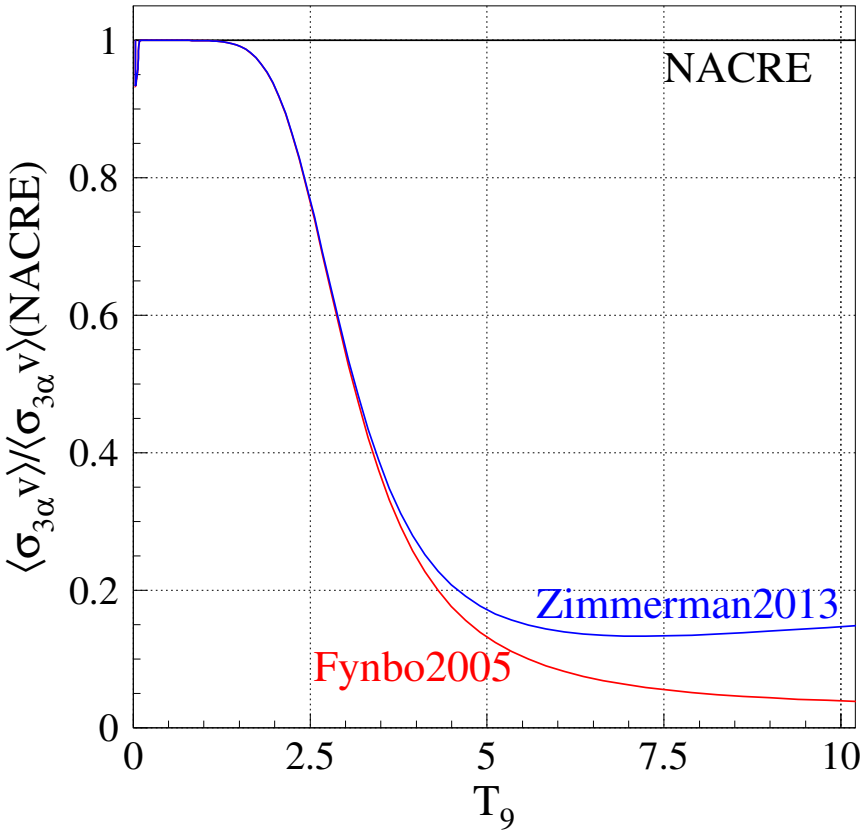


3α rate significantly suppressed at high T.

How about the 3^-_1 state ?

γ-decay probability of the 3_1^- state

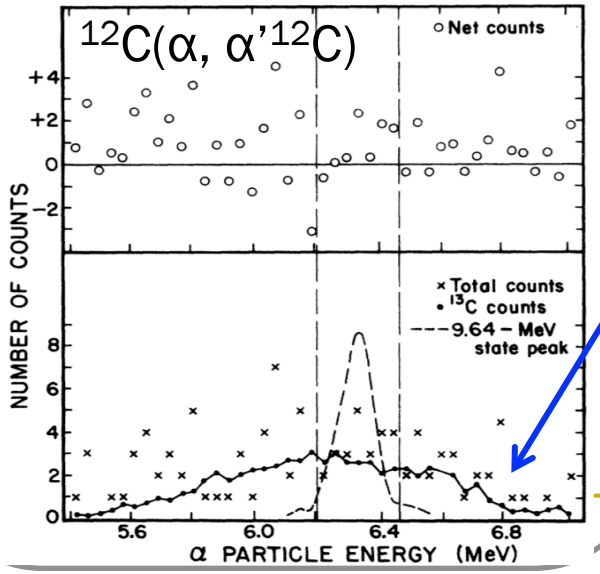
Difficult to measure the Γ_γ/Γ of the 3_1^- state because it is very small.

3^-_1 in ^{12}C	Total width Γ	γ-decay width Γ_γ	γ-decay probability Γ_γ/Γ
Lower limit	46(3) keV	0.31(4) meV	6.7×10^{-9}
Upper limit		38 meV (2σ C. L.)	8.2×10^{-7}

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

Difficult to measure!!

Previous experiment



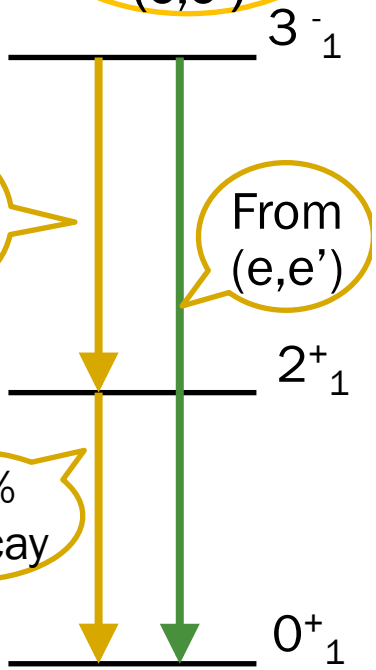
Background due to ^{13}C contaminants

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

?

From (e,e')

100% γ-decay



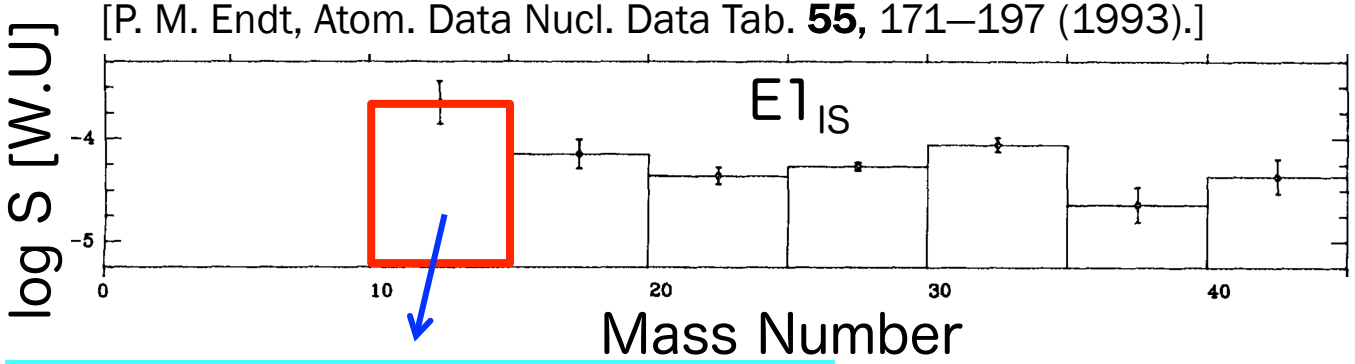
No ^{13}C contaminants in ^{12}C beam!!

[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	46(3) keV	0.31(4) meV	9.1×10^{-9}
Upper limit		38 meV (2σ C. L.)	8.2×10^{-7}

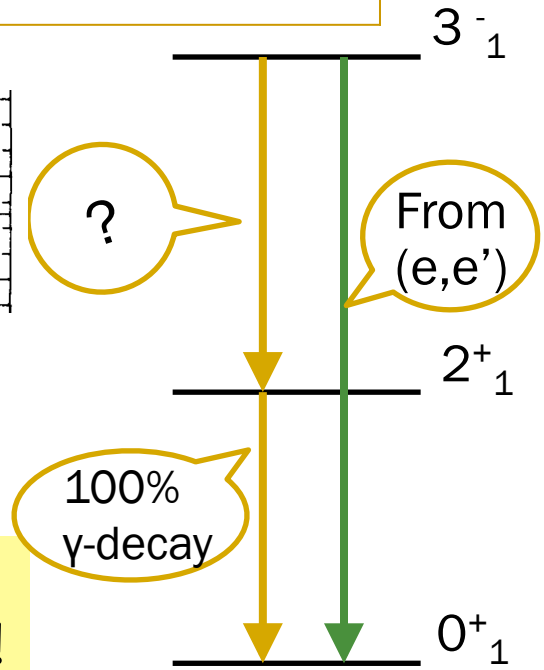
[P. M. Endt, Atom. Data Nucl. Data Tab. **55,** 171–197 (1993).]



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

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

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

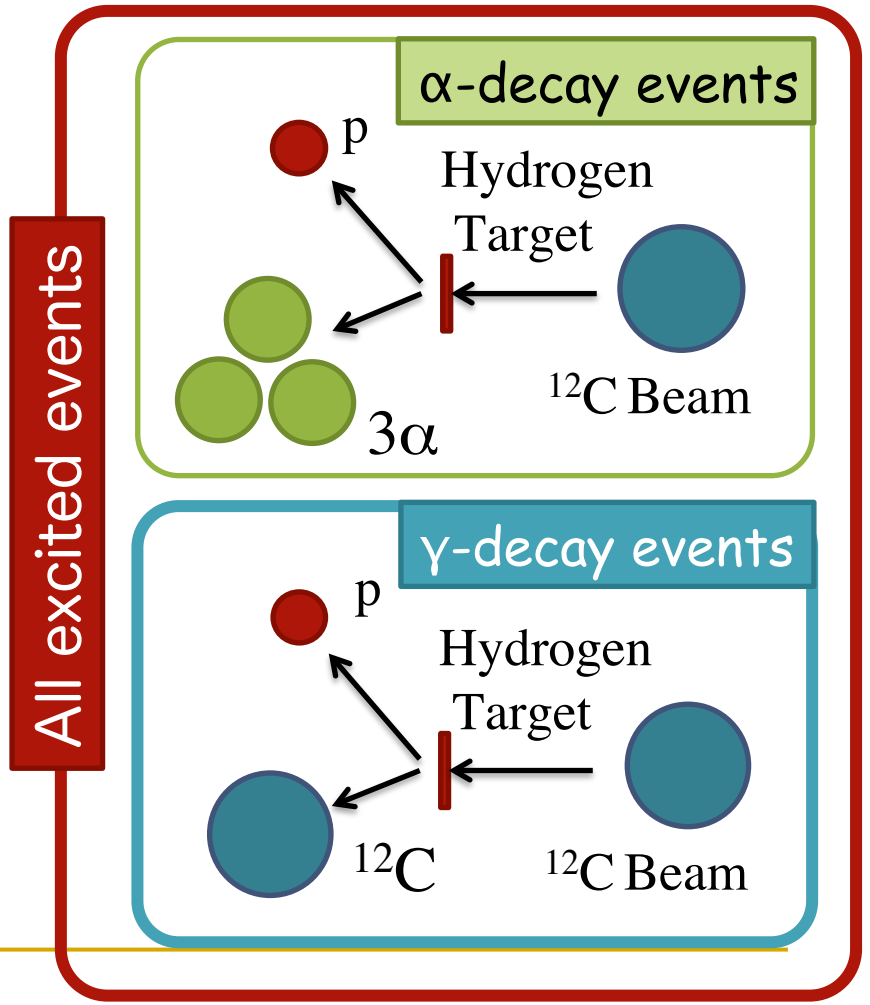
Number of all excited events

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

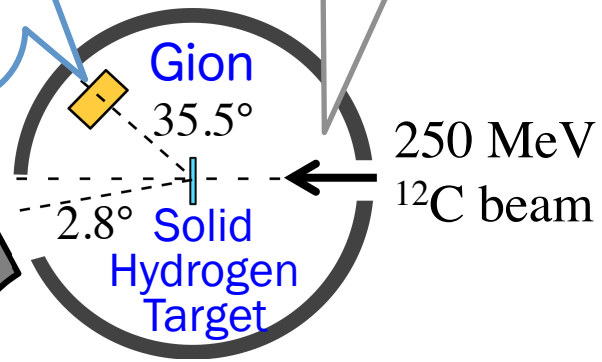
Count the number of the all excited events

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

Recoiled angle…The double-sided Si strip detector.
Energy…The GAGG crystal.

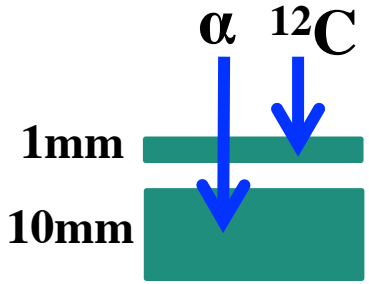
→ E_x of the scattered ^{12}C

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

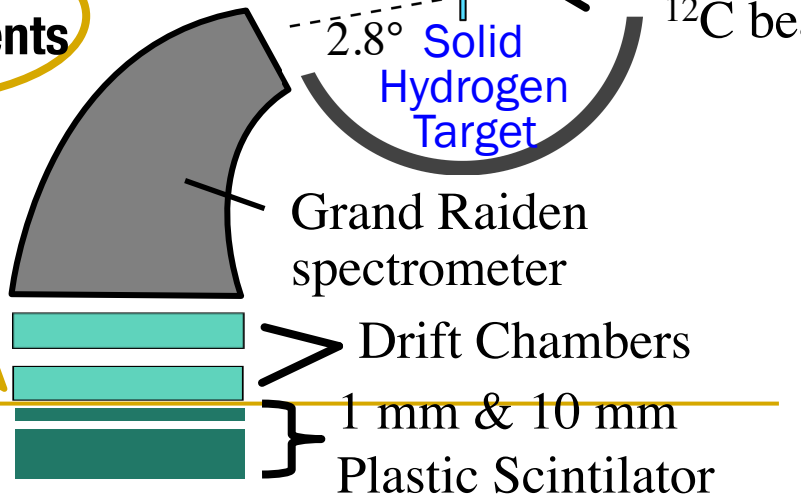


Scattered ^{12}C detector

Select γ-decay events



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

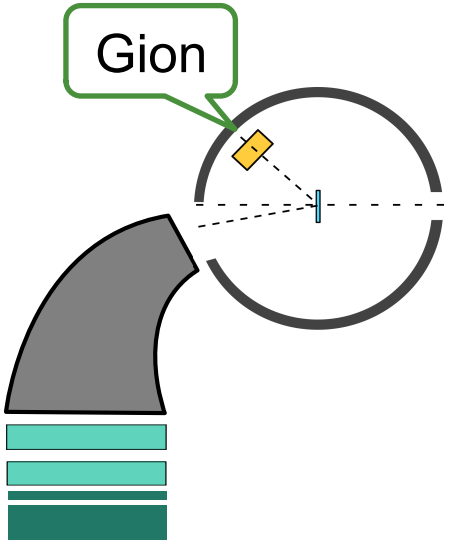


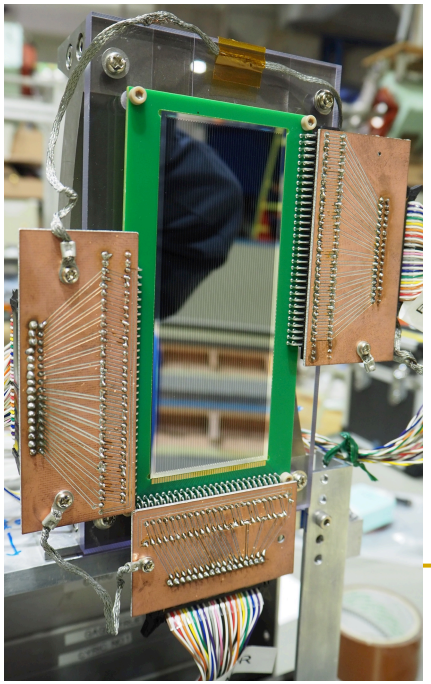
Gion Recoil proton counter

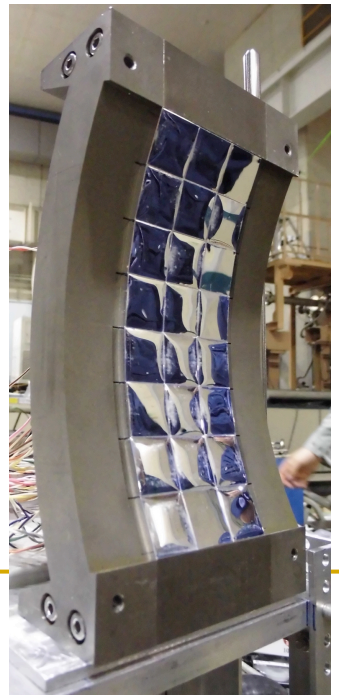
Gion = GAGG based light ion counter telescope

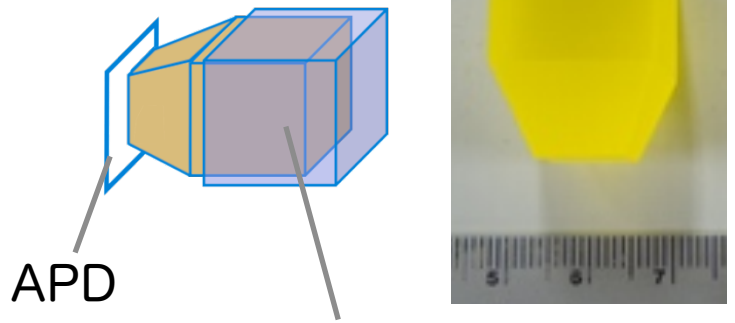
- GAGG .... $Gd_3Al_2Ga_3O_{12}$.

	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









✓ 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

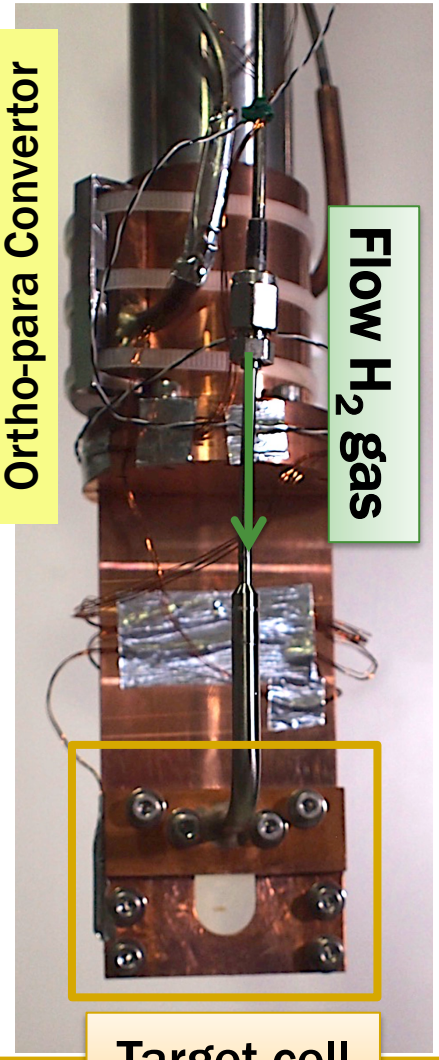
×23.4

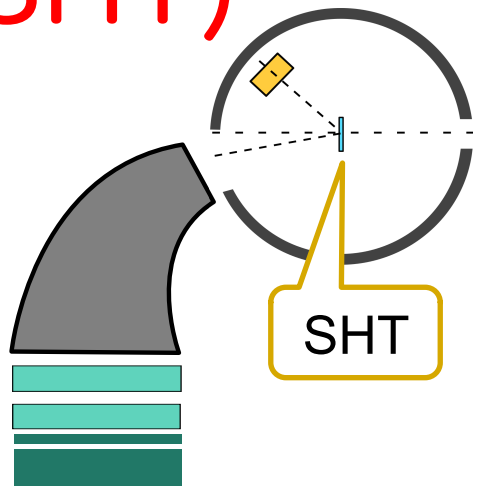
* Include gas-sealing Aramid film (4 um x 2)

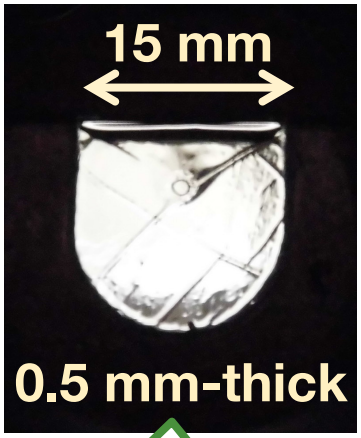
Thickness should be thinner than
0.5 mm for ΔE_x < 250 keV.

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).]





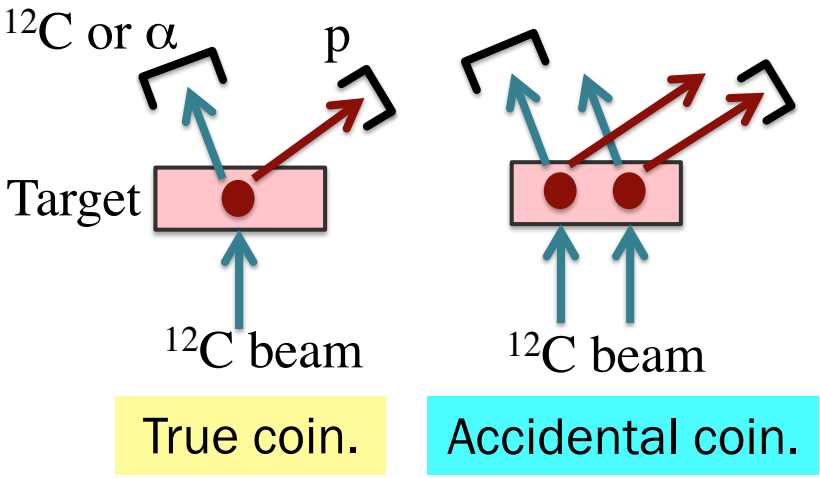


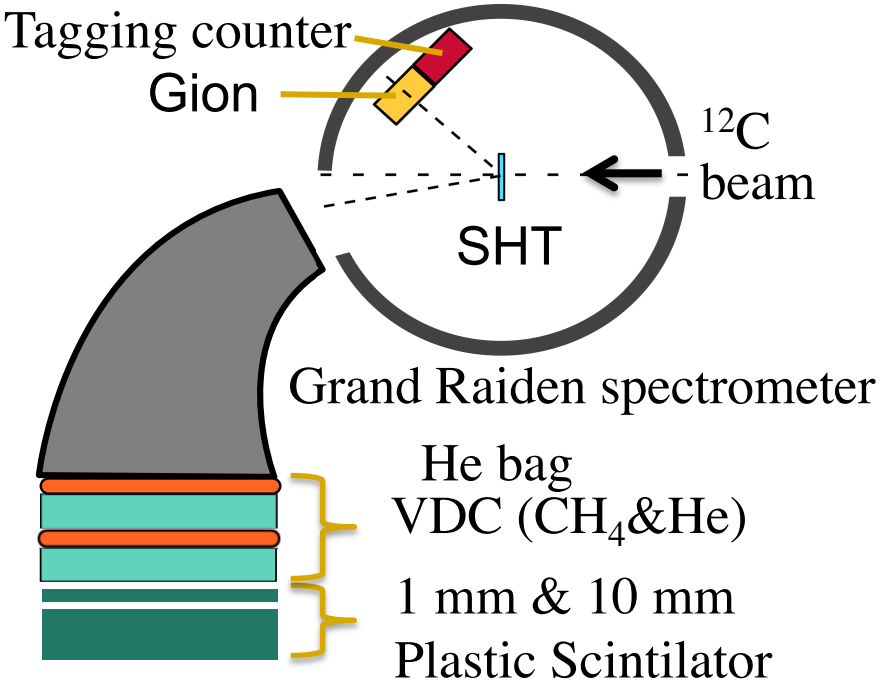
Thin!!

Improvement of the S/N

Accidental coincidence events cause serious background.

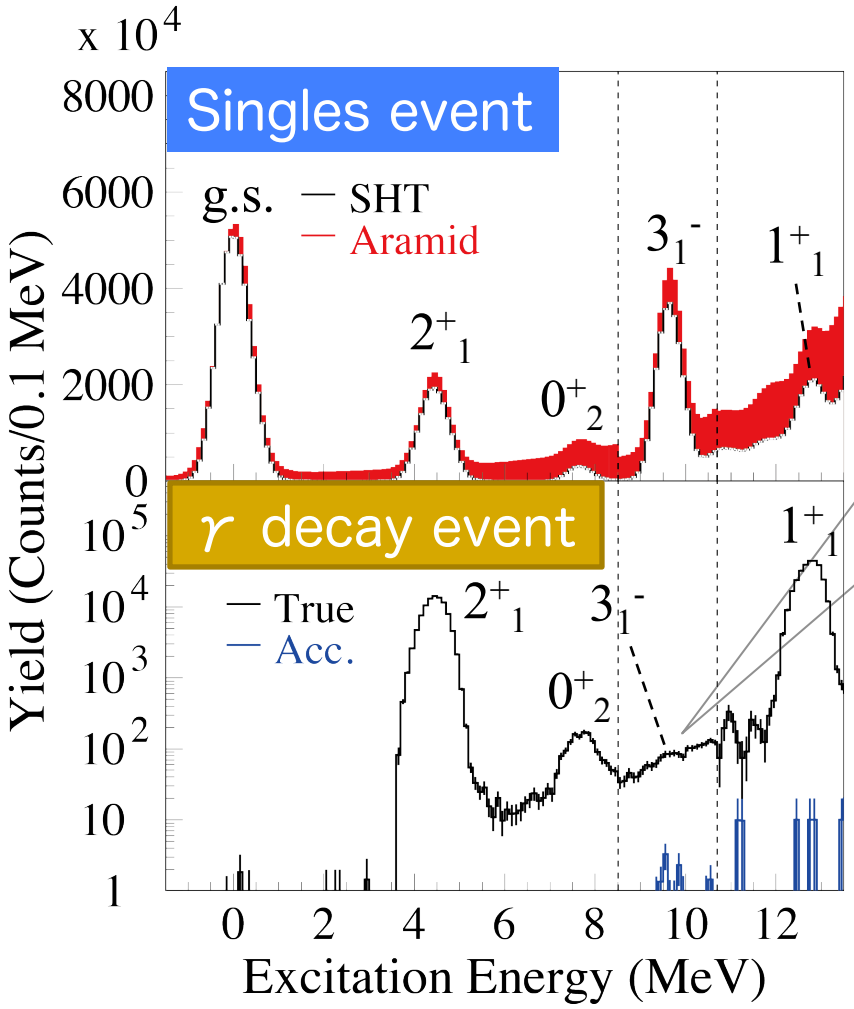
What's accidental coin. event?





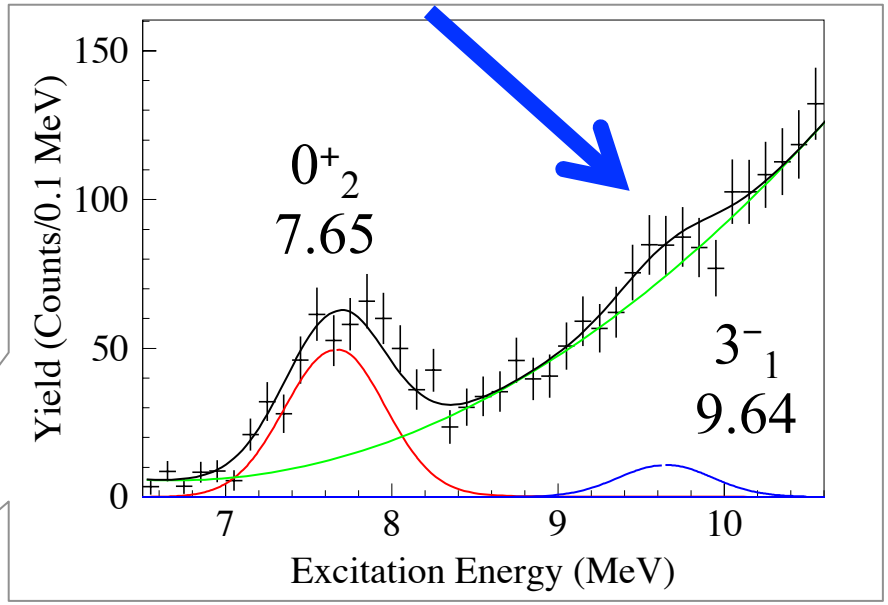
- Tagging counter (Gion)
  …To remove accidental coincidence events.
- Data reduction gate
  - Angular correlation between p and ^{12}C.
  - Energy correlation between p and ^{12}C.

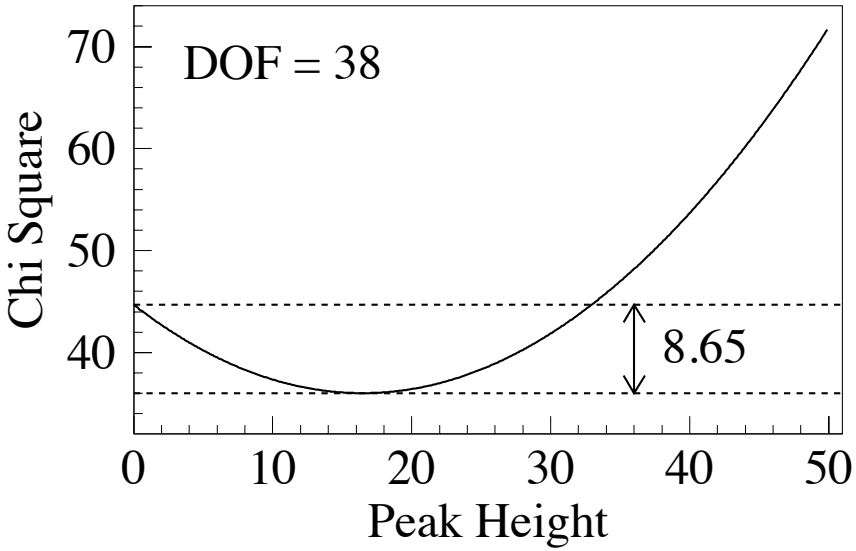
Results



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.

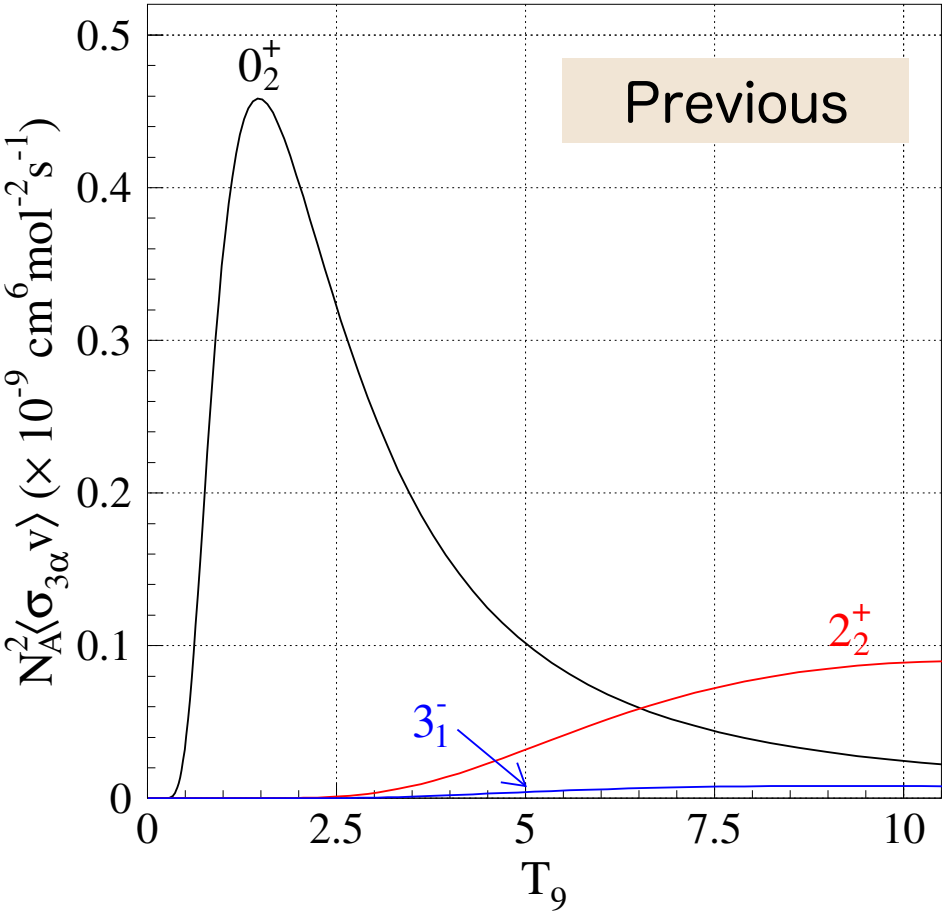
	0^+_2	1^+_1	3^-_1
Geo. Efficiency	0.117(2)	0.186(9)	0.229(3)
Γ_γ/Γ Previous	$4.4(5)\times10^{-4}$	$2.21(7)\times10^{-2}$	Unknown
Γ_γ/Γ Present	$4.3(3)\times10^{-4}$	$2.6(6)\times10^{-2}$	$1.3(6)\times10^{-6}$

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



$$N_A^2\langle\sigma v\rangle^{\alpha\alpha\alpha} = 3N_A\left(\frac{8\pi}{\mu_{\alpha\alpha}^2}\right)\left(\frac{\mu_{\alpha\alpha}}{2\pi k_B T}\right)^{3/2} \int_0^\infty \frac{\sigma_{\alpha\alpha}(E)}{\Gamma_\alpha\left({}^8\mathrm{Be},E\right)}\exp\left(-E/k_BT\right) N_A\langle\sigma v\rangle^{\alpha\,{}^8\mathrm{Be}} E\,dE$$

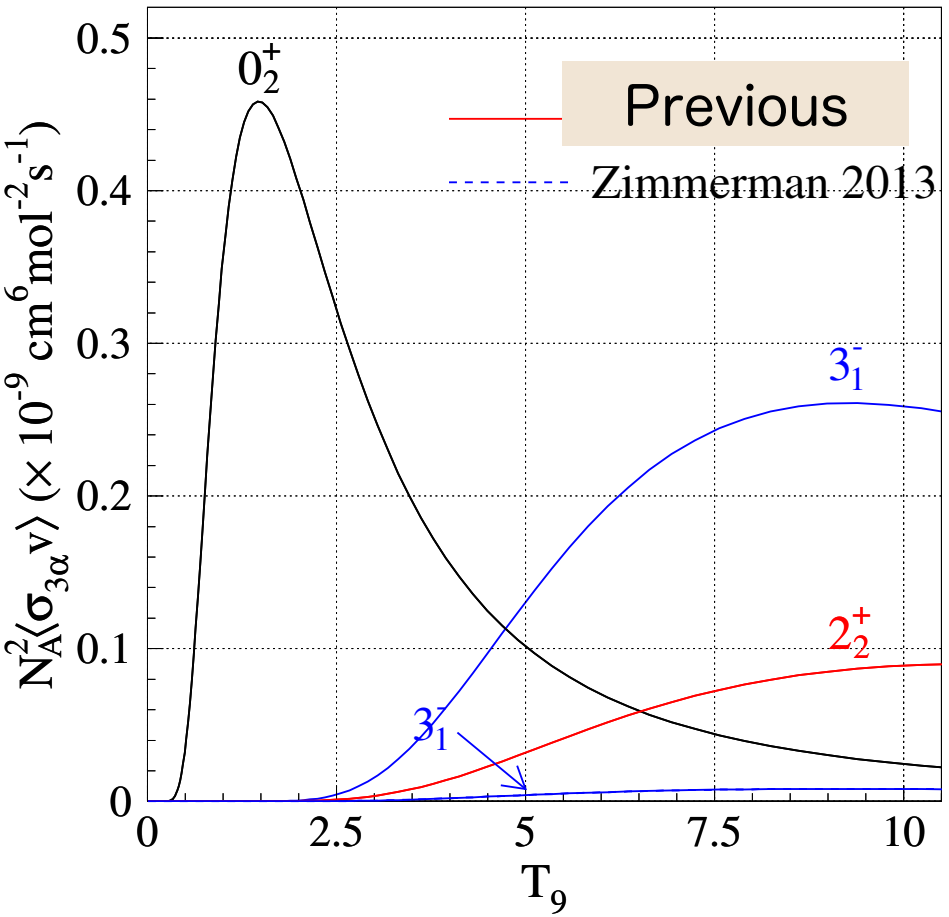
$$N_A\langle\sigma v\rangle^{\alpha\,{}^8\mathrm{Be}} = N_A\frac{8\pi}{\mu_{\alpha\,{}^8\mathrm{Be}}^2}\left(\frac{\mu_{\alpha\,{}^8\mathrm{Be}}}{2\pi k_BT}\right)^{3/2} \int_0^\infty \sigma_{\alpha\,{}^8\mathrm{Be}}(E';E)\exp\left(-E'/k_BT\right)E'\,dE'$$

$$\sigma_{\alpha\,{}^8\mathrm{Be}}(E';E) = \sum_{J=0,2,3}(2J+1)\frac{\pi\hbar^2}{2\mu_{\alpha\,{}^8\mathrm{Be}}} \times \frac{\Gamma_\alpha\left({}^{12}\mathrm{C}^J,E'\right)\Gamma_\gamma\left({}^{12}\mathrm{C}^J,E'+E\right)}{\left(E'-E_r^J+E-E_{{}^8\mathrm{Be}}\right)^2+\frac{1}{4}\Gamma\left({}^{12}\mathrm{C}^J,E'+E\right)^2}$$

$$\sigma_{\alpha\alpha}(E) = 2\frac{\pi}{k^2}\frac{\Gamma_i(E)\Gamma_f(E)}{\left(E-E_r\right)^2+\Gamma(E)^2/4}$$

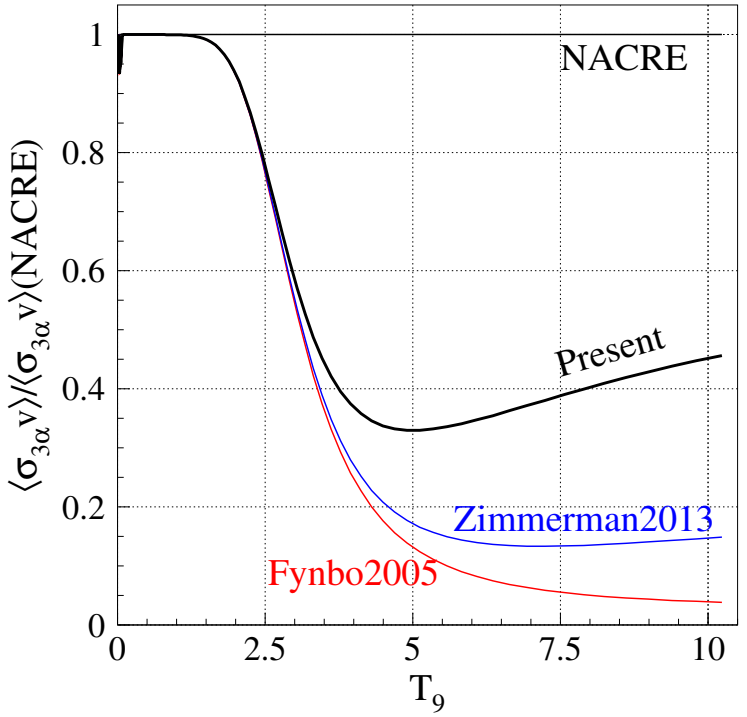
Triple Alpha Reaction Rate

Triple reaction rate was calculated using the measured Γ_γ/γ



NACRE
3^-_1
Γ_γ = 2 meV

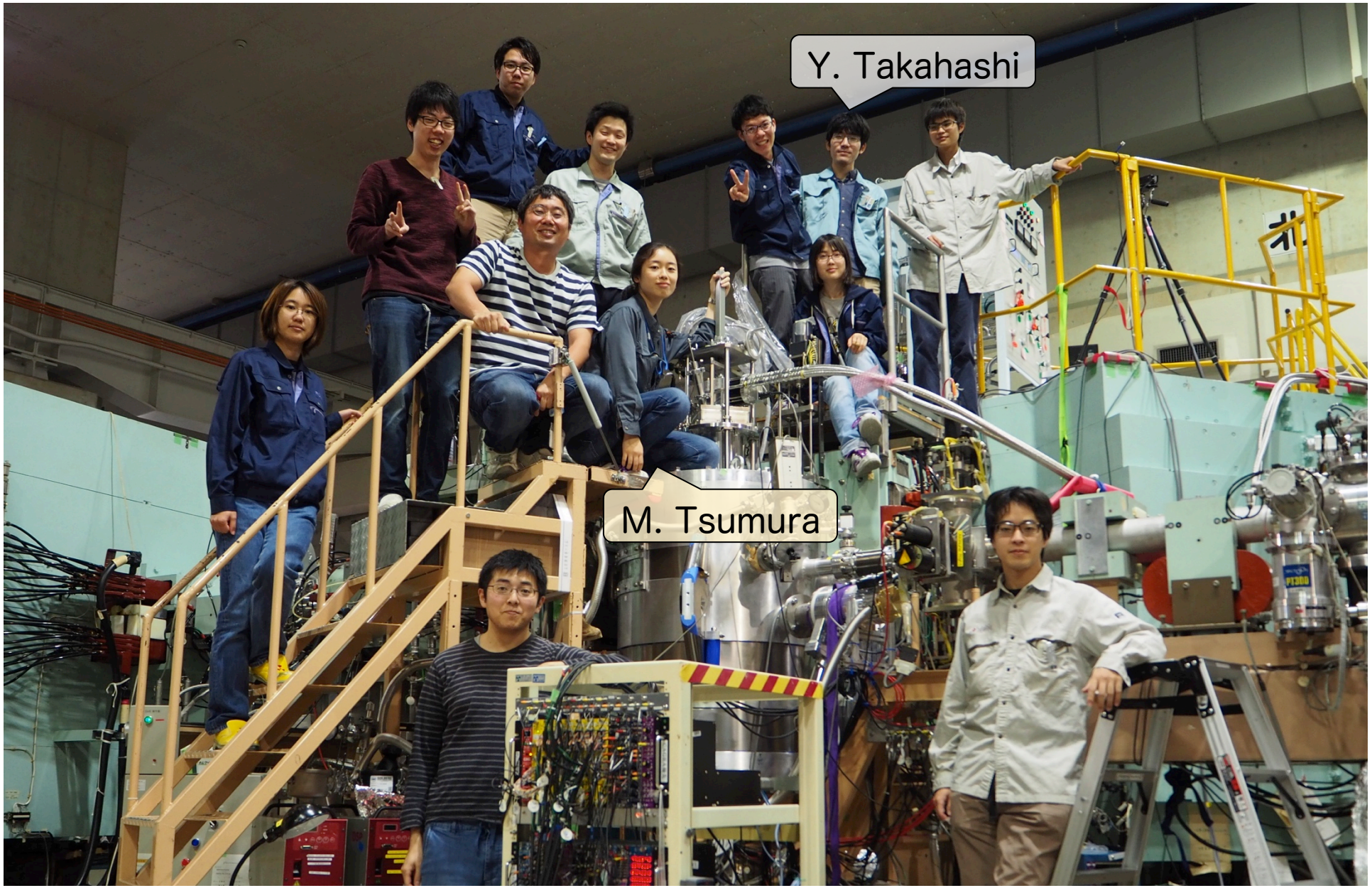
Present
3^-_1
Γ_γ = 60 meV



The 3α rate is partially restored, but still lower than NACRE...

Summary

- Measurement of the γ-decay probability of the 3_1^- state in ^{12}C.
  - Importance for the 3α reaction.
  - New detection scheme using the inverse kinematic reaction H(^{12}C, ^{12}C p) without γ-ray measuement.
- γ-decay events are successfully identified.
  - γ-decay events from the 3_1^- state were observed.
  - 3α reaction rate is partially restored but it is still lower than NACRE at high T.
  - 3α reaction via $^8Be(2^+_1)$ should be considered.



Thank you for your attention!!