Experimental Study on the ^{7}Be destruction reaction relevant to Big Bang Nucleosynthesis

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NEWS Colloquium

About me and Today's topic

About me

- ✧ Azusa Inoue
- ✧ Obtained Ph.D. in Science in Mar. 2024 at Osaka University, Japan.
- ✧ Postdoctoral fellow at University of Oslo, Norway from Oct. 2024.

Today's topics

- ✧ Experimental works relevant to the Big Bang Nucleosynthesis. (My Ph.D. works)
- ✧ Extension of the study and open questions, and Prospects.

Experimental work

Overview & Keywords

- This research is about the **Cosmological Lithium Problem** (CLP) in the Big Bang Nucleosynthesis (BBN).
  -> A discrepancy between the theoretical calculation and observations in **^{7}Li abundance**.

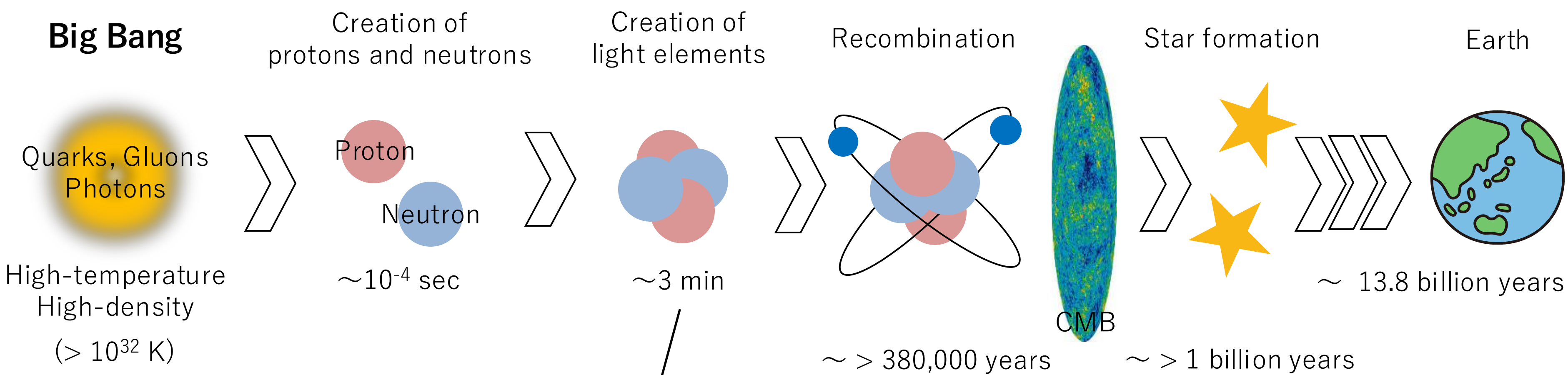
- Find a solution in the **Nuclear astrophysics**.
  -> Measured the cross section of a nuclear reaction.
  -> The result will be included in the theoretical model to understand the nucleosynthesis.

- Measured **^{7}Be(d, p)^{8}Be reaction cross section** to resolve the CLP.

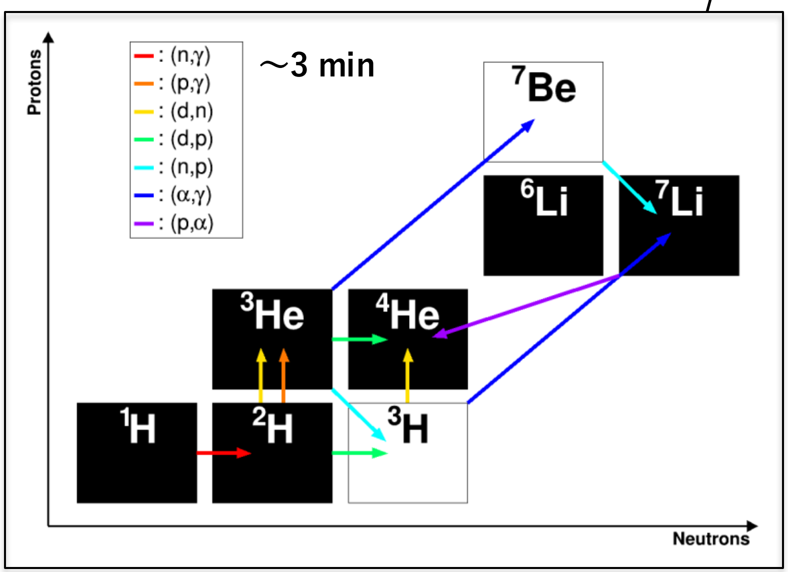
- Radioactive **^{7}Be target production** was one of the challenging parts of this research.

- **^{7}Be(d, p)^{8}Be reaction has limiting impact to the CLP** but an important measurement data for the BBN theory, and the CLP is still a fascinating, mysterious topic in Astrophysics.

Big Bang and its Aftermath

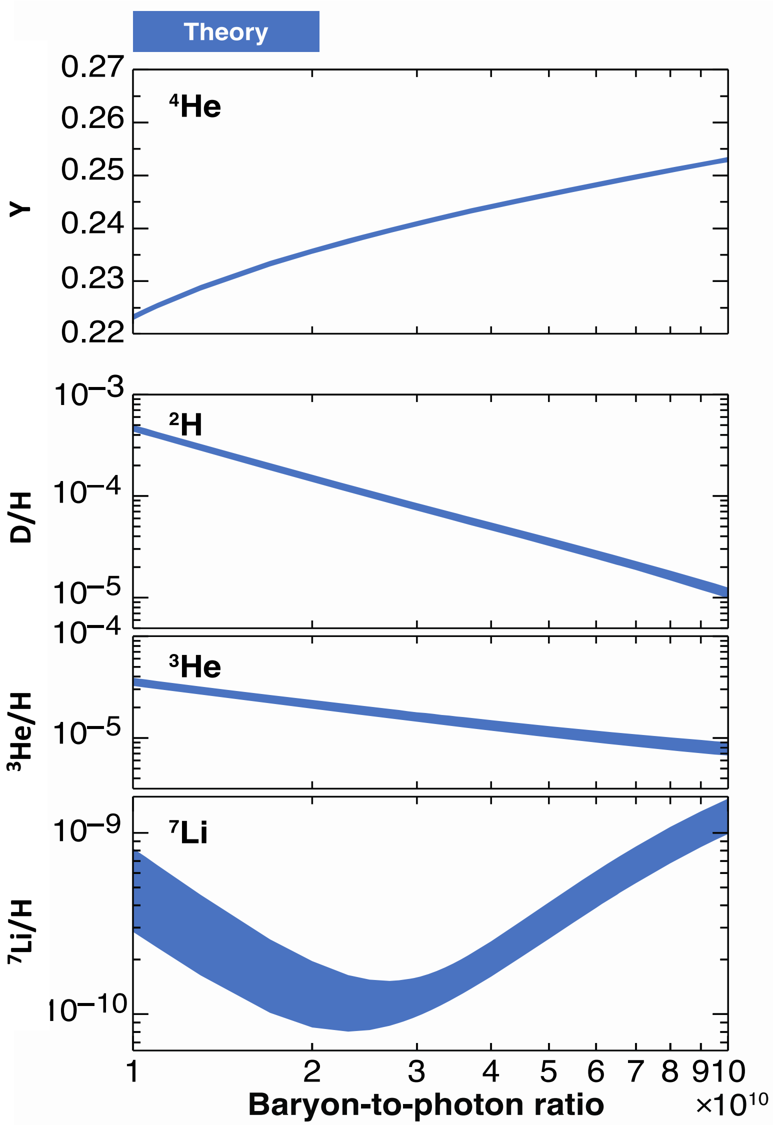


Big Bang Nucleosynthesis (BBN)



S. Q. Hou et al., The Astrophysical Journal 834.2 (2017).

What is the Cosmological Lithium Problem ?



⇨ **Standard BBN model**

R. H. Cyburt *et. al.*, J. Cosmol. Astropart. Phys. **11**, 012 (2008).
Brian D. Fields *et. al.*, J. Cosmol. Astropart. Phys. 03(2020)010.

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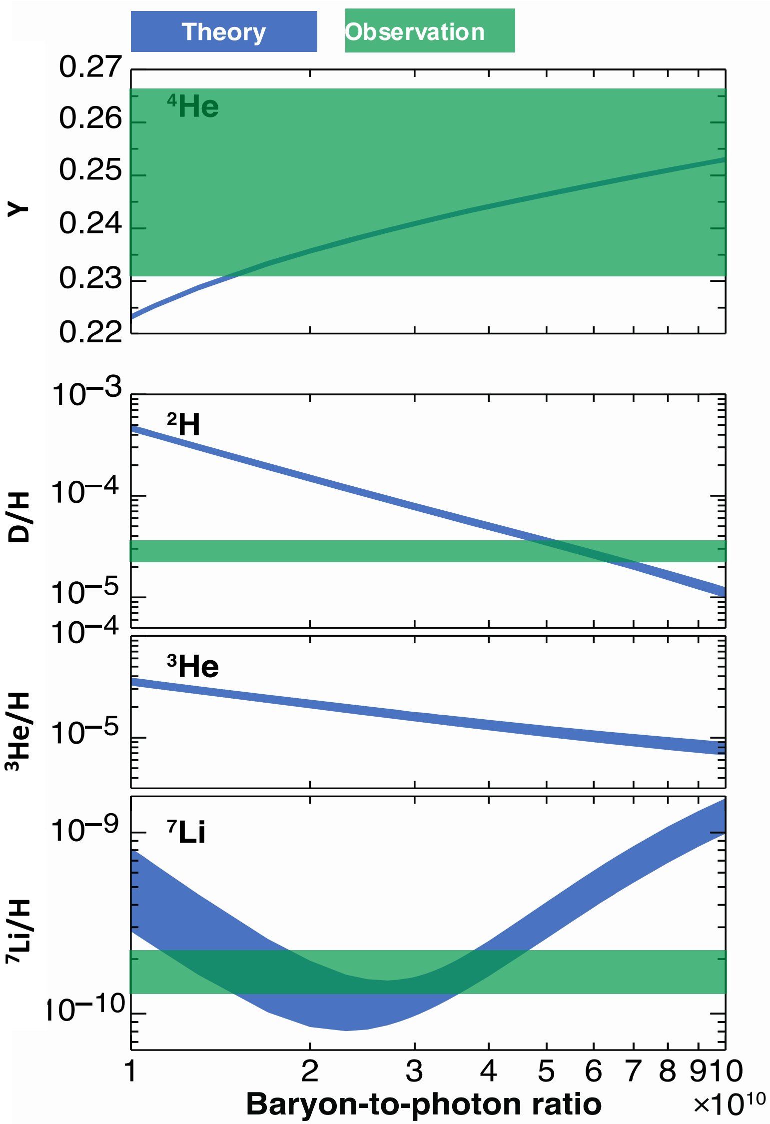

- Derived from observations of metal-poor stars using spectroscopic method (and other methods).
  → Reflect primordial abundances with minimal stellar processing.

R. H. Cyburt *et. al.*, J. Cosmol. Astropart. Phys. **11**, 012 (2008).
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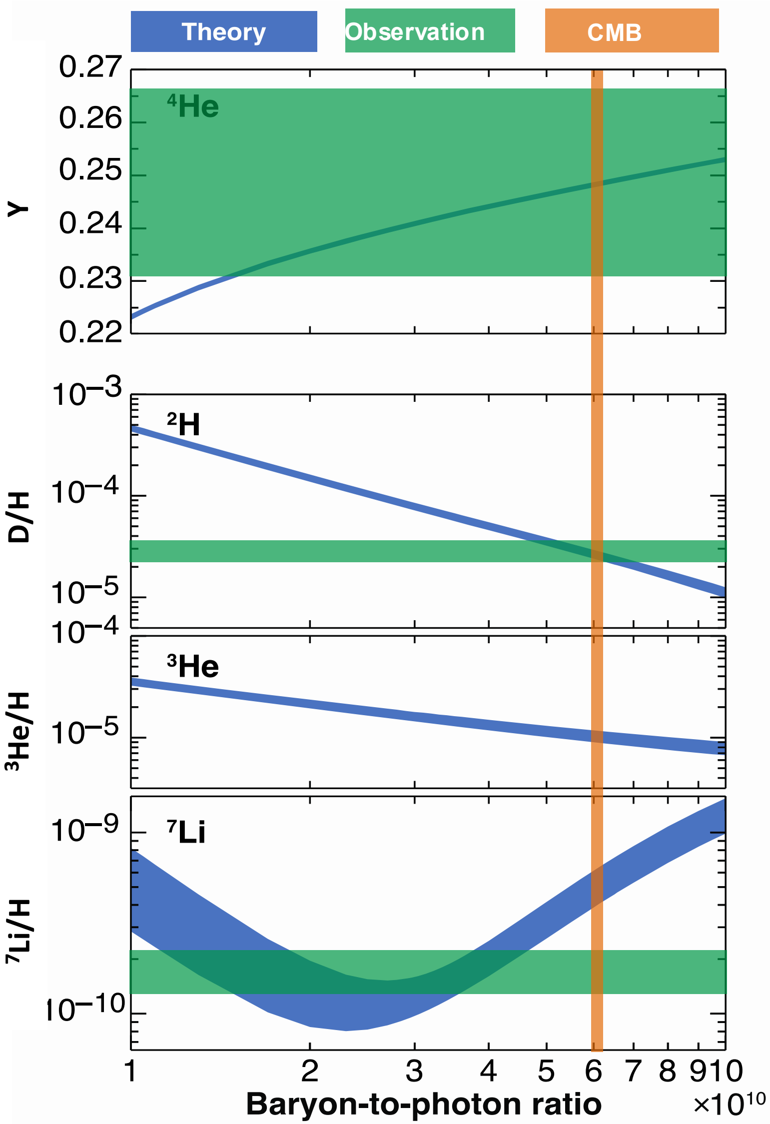

- Cosmic Microwave Background measurement (WMAP)
  → Baryon-to-photon ratio was determined based on CMB temperature fluctuation.

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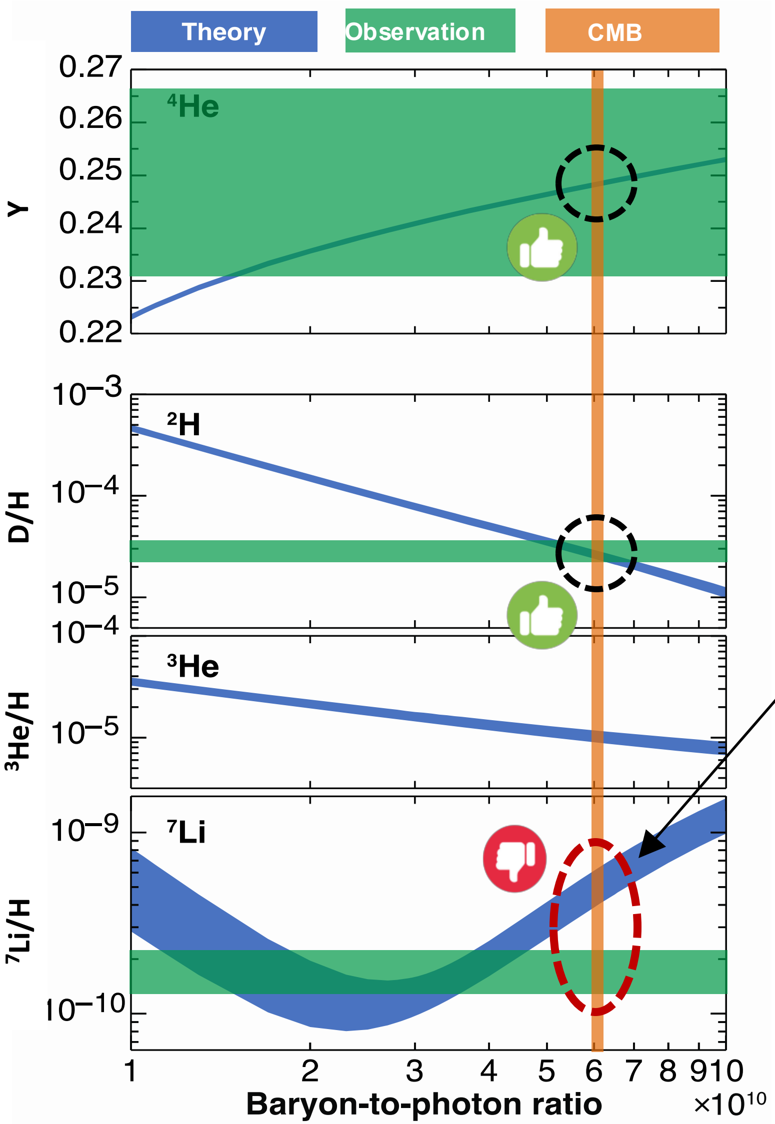

Abundance of ^{7}Li

Theoretical calc.

3 times higher than observation

→ The Cosmological Lithium Problem

R. H. Cyburt *et. al.*, J. Cosmol. Astropart. Phys. **11**, 012 (2008).
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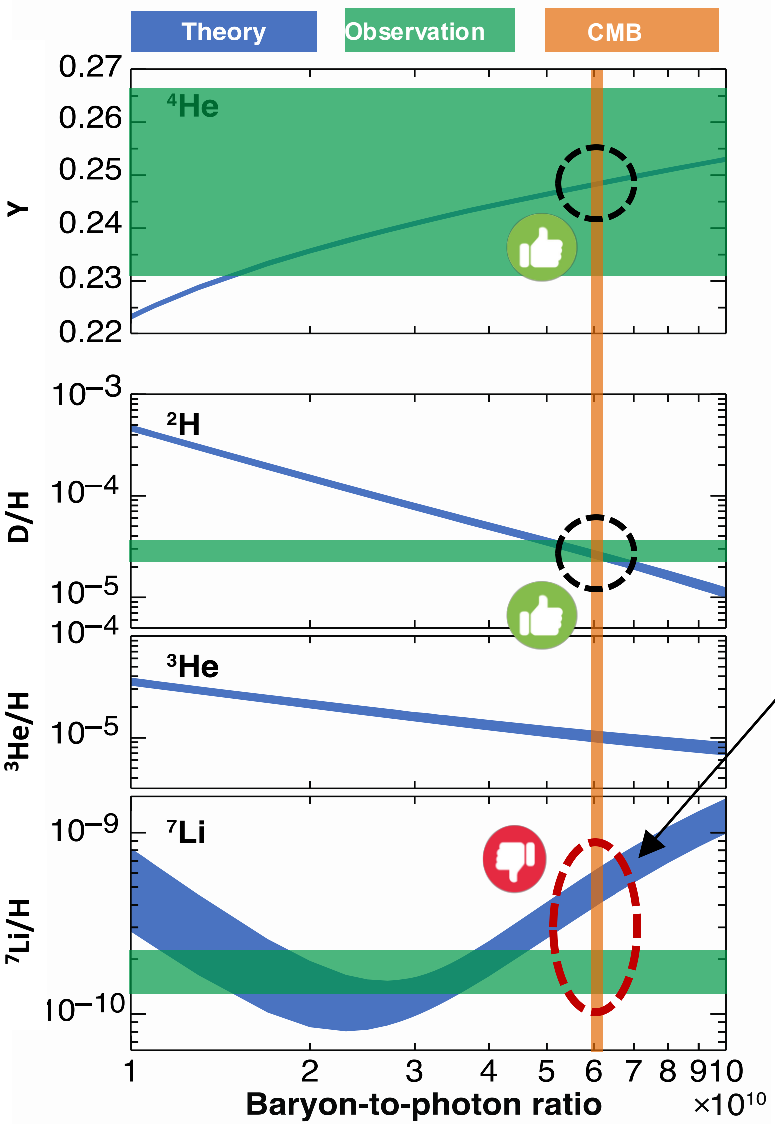


Abundance of ^{7}Li

Theoretical calc.

3 times higher than observation

3 times..? Is it really a problem??

YES!

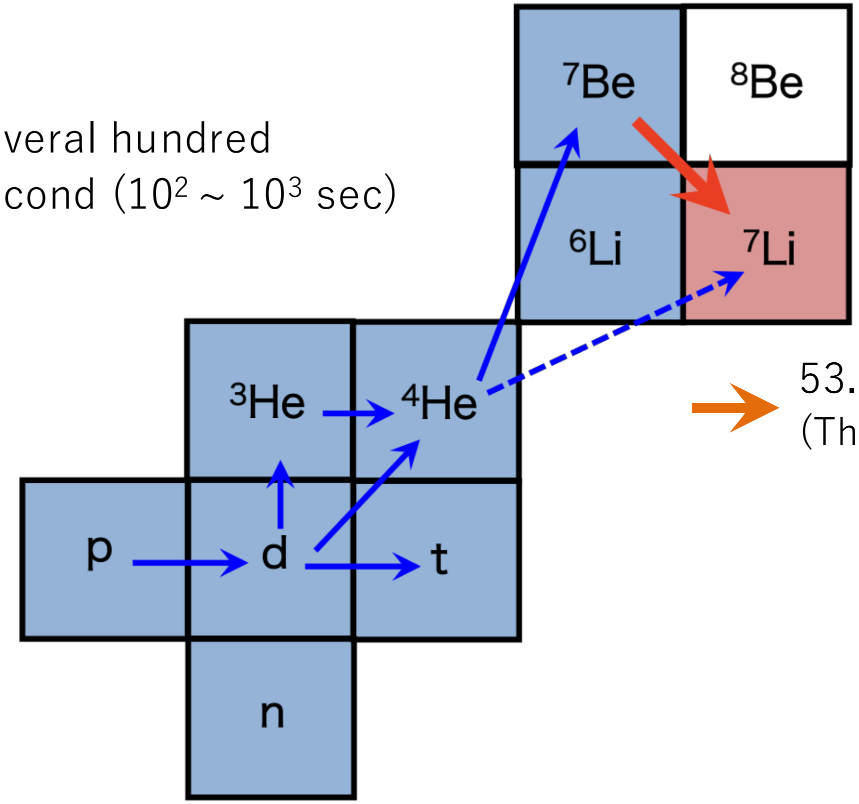
- ^{7}Li is the 3rd element.
- Modern cosmology has entered precision era.

R. H. Cyburt *et. al.*, J. Cosmol. Astropart. Phys. **11**, 012 (2008).
Brian D. Fields *et. al.*, J. Cosmol. Astropart. Phys. 03(2020)010.

BBN and ^{7}Li production

- Main channel of the ^{7}Li production?

several hundred second ($10^2 \sim 10^3$ sec)



53.2 days = 4.5×10^6 sec
(The half life of electron capture decay)

A possible scenario is...

If ^{7}Be was destroyed in the BBN before it decays into ^{7}Li → The abundance of ^{7}Li was also decreased

→ **Search (= measure) a destruction reaction of ^{7}Be in the BBN energy!**

^{7}Be destruction processes and Why are we focusing on ^{7}Be(d, p)?

Present status of ^{7}Be destructive reactions

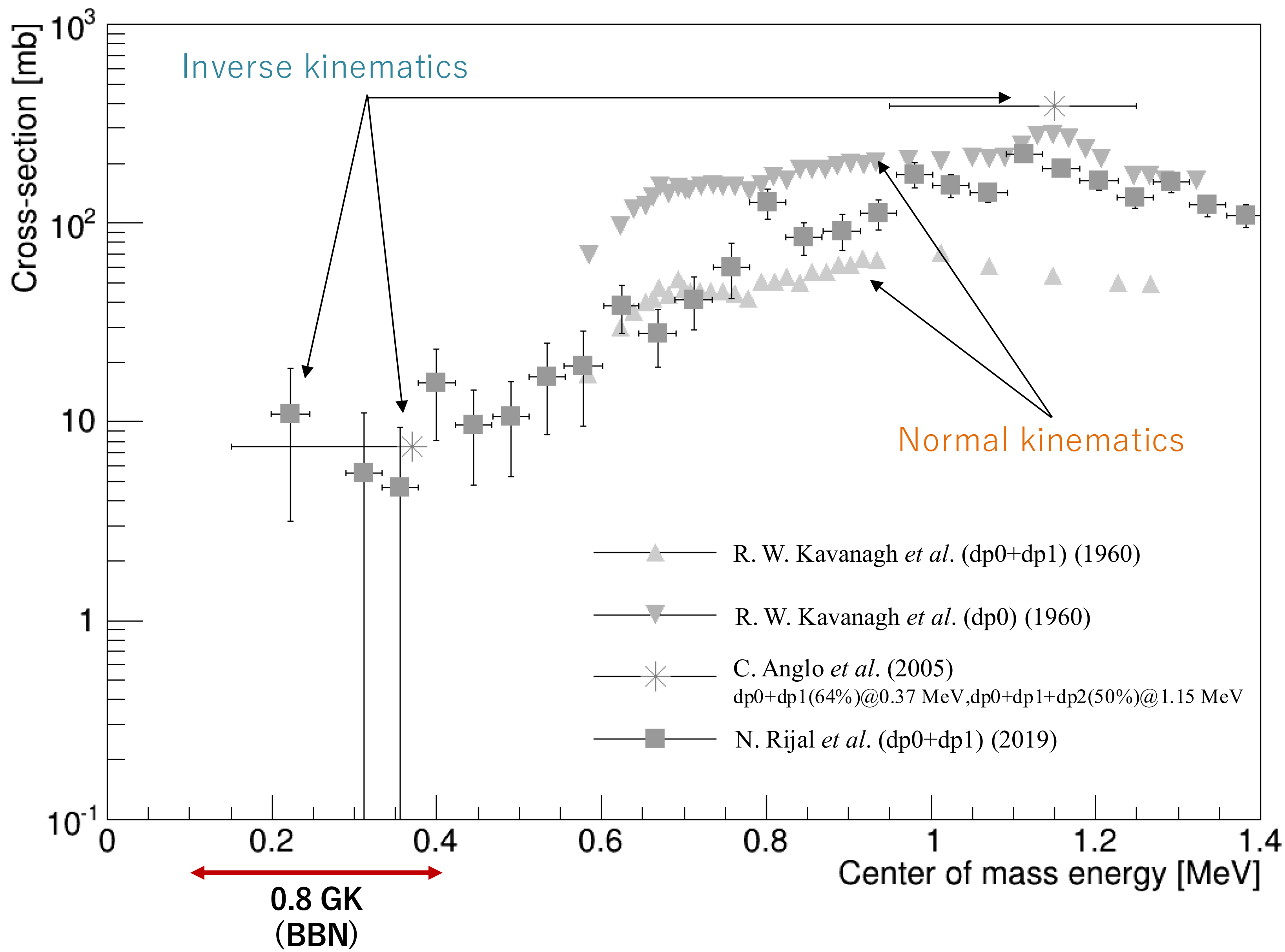
- ✓ ^{7}Be(n, α)^{4}He
  M. Barbagallo *et al.* (2016), T. Kawabata *et al.* (2017), L. Damone *et al.* (2018), L. Lamia *et al.* (2019)
  -> **10 %** of ^{7}Li reduction
- ✓ ^{7}Be(n, p)^{7}Li
  S. Hayakawa et al. (2021)
  -> **10 %** of ^{7}Li reduction
- ✓ ^{7}Be(d, α)^{7}Li
  N. Rijal *et al.* (2019)
  -> **14 %** of ^{7}Li reduction

We focused on **^{7}Be(d, p)^{8}Be.**

Why ^{7}Be(d, p)^{8}Be?
-> The ^{7}Be(d, p)^{8}Be reaction rate is not included the BBN calculation.
-> The importance of ^{7}Be(d, p)^{8}Be reaction was theoretically suggested.
S. Q. Hou et al., Phys. Rev. V91, 055802 (2015)

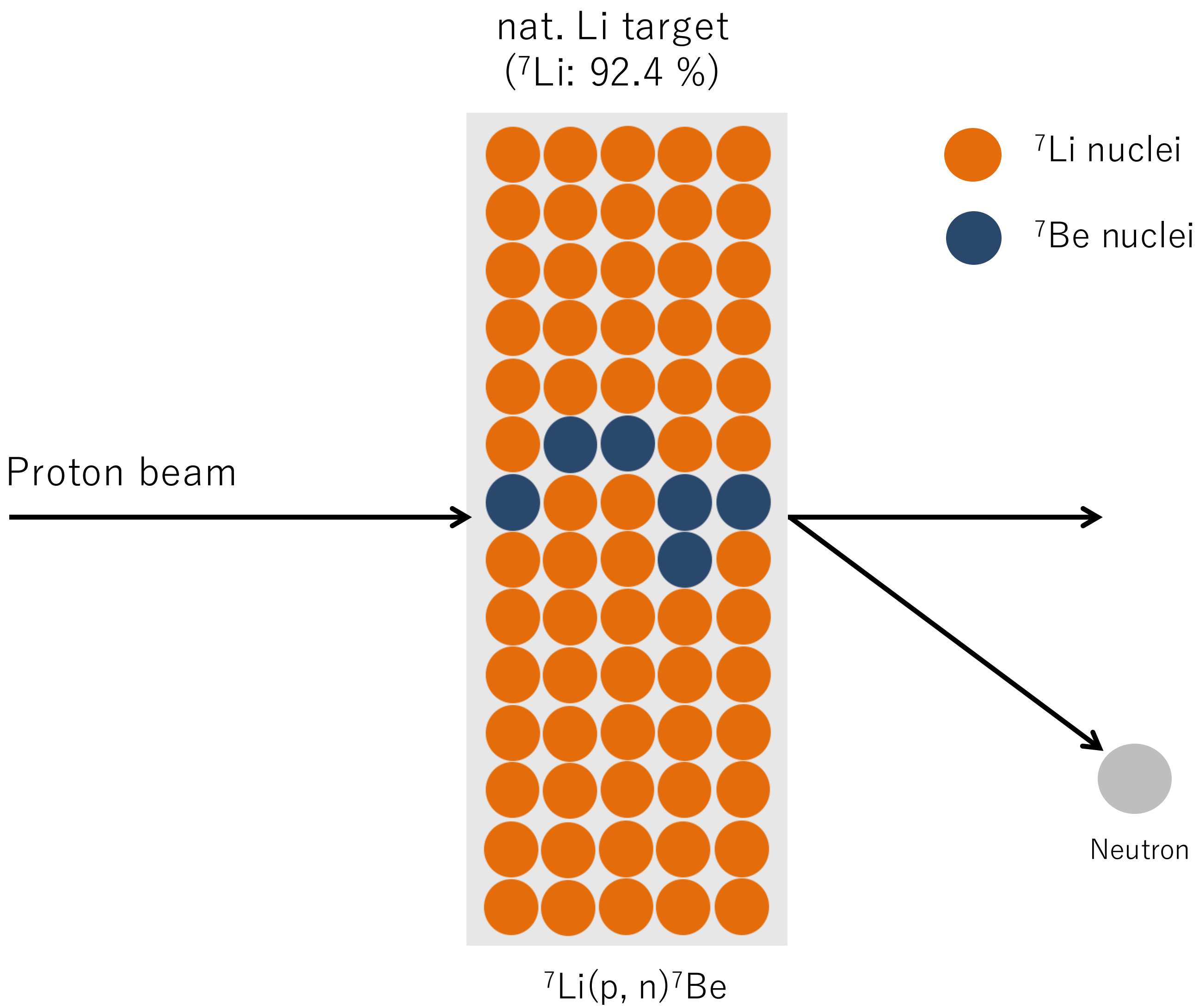
➡ The cross section must be measured at the Big Bang temperature (0.8 GK)
-> $E_{c.m.}$ = 0.1 – 0.4 MeV

Previous published data of $^{7}Be(d, p)$

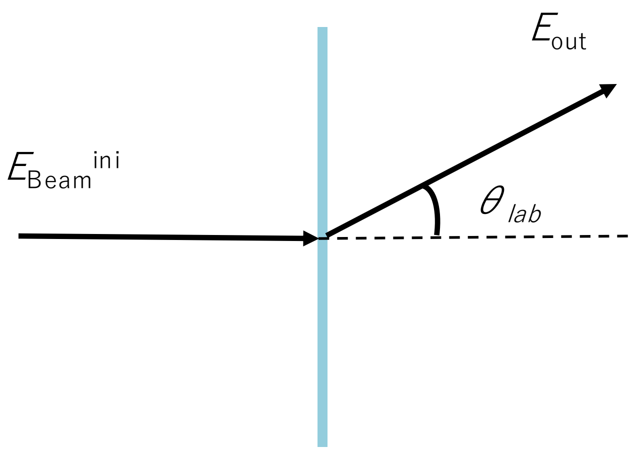


Experimental Technique (1) – Activation Method -

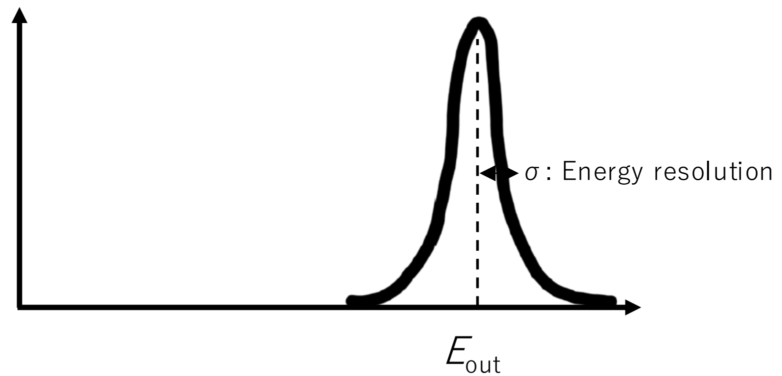
- Activation method for the ^{7}Be target production



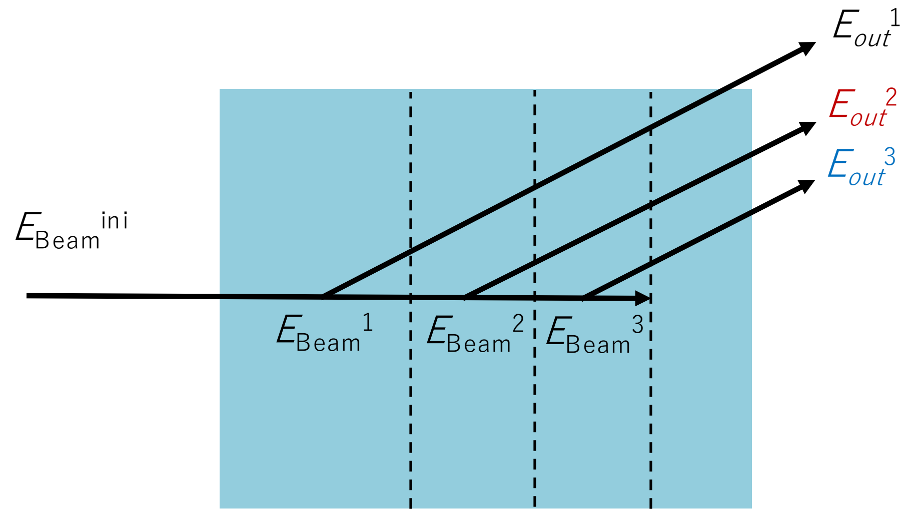
- Thin target



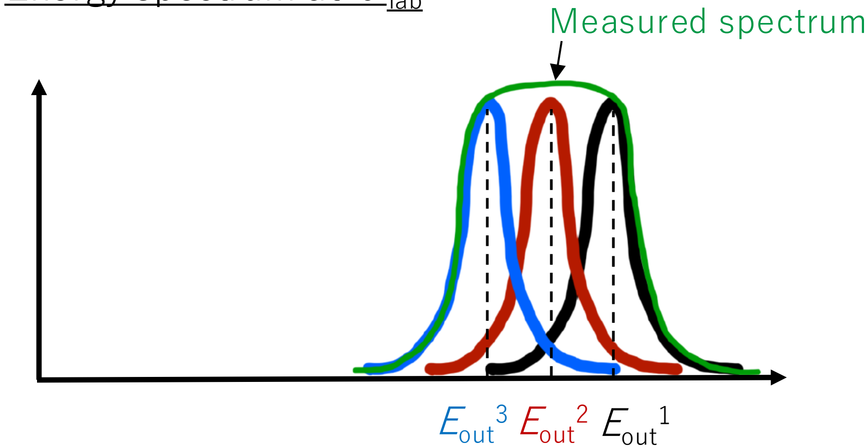
Energy spectrum at θ_{lab}



- Thick target
  (Very schematic)

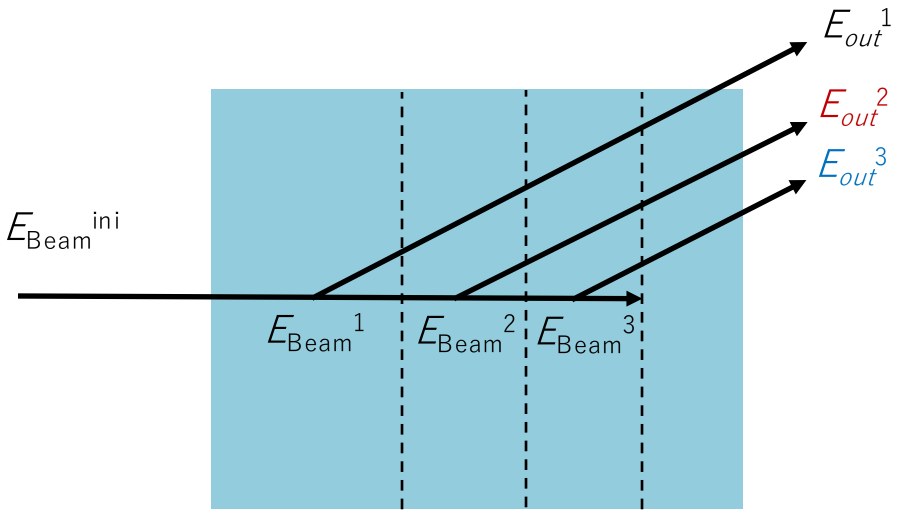


Energy spectrum at θ_{lab}



Experimental Technique (2) – Thick Target Method -

- Thick target
  (Very schematic)



<u>Advantage</u>

✓ Low energy measurement

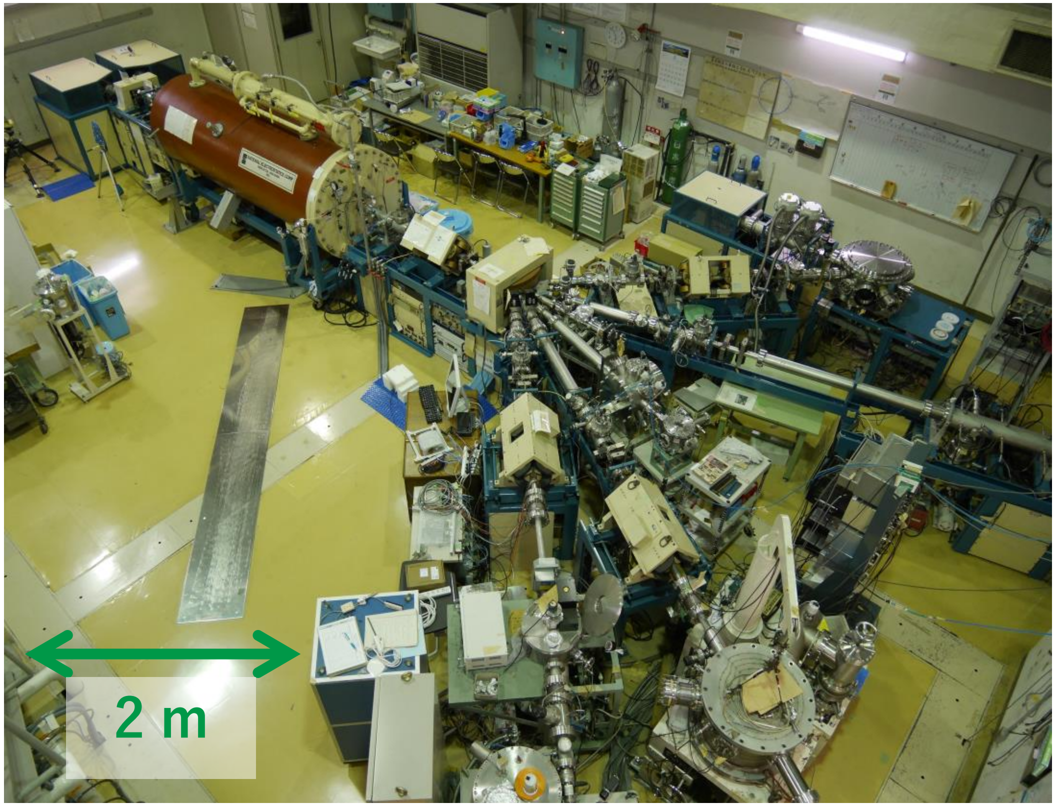
-> Low energy : Beam almost stopped in the target.

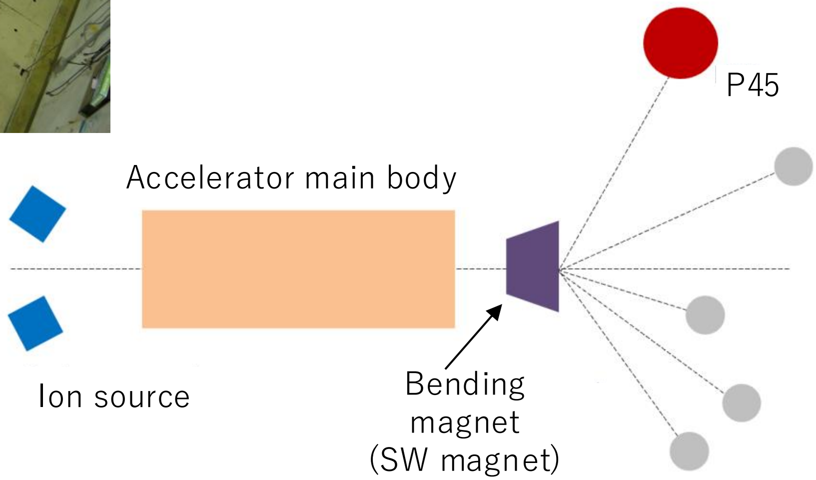
✓ Large yield

→ **Simulations are necessary to obtain the cross section energy dependence.**

Facility and Beam Line

- Tandem accelerator facility, Kobe University, Japan

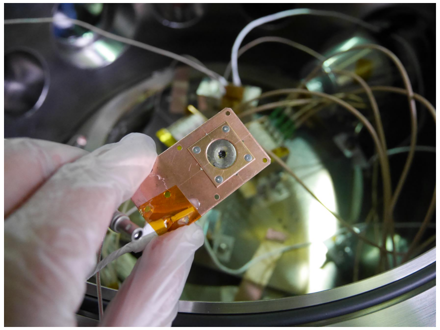




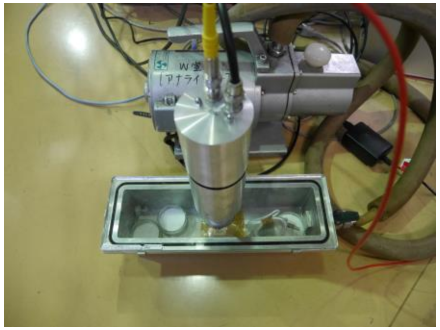
Experimental Steps

Step1

^{7}Be target production

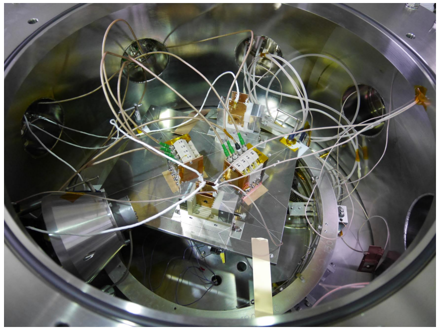


Measurement of the produced ^{7}Be target nuclei number



Step2

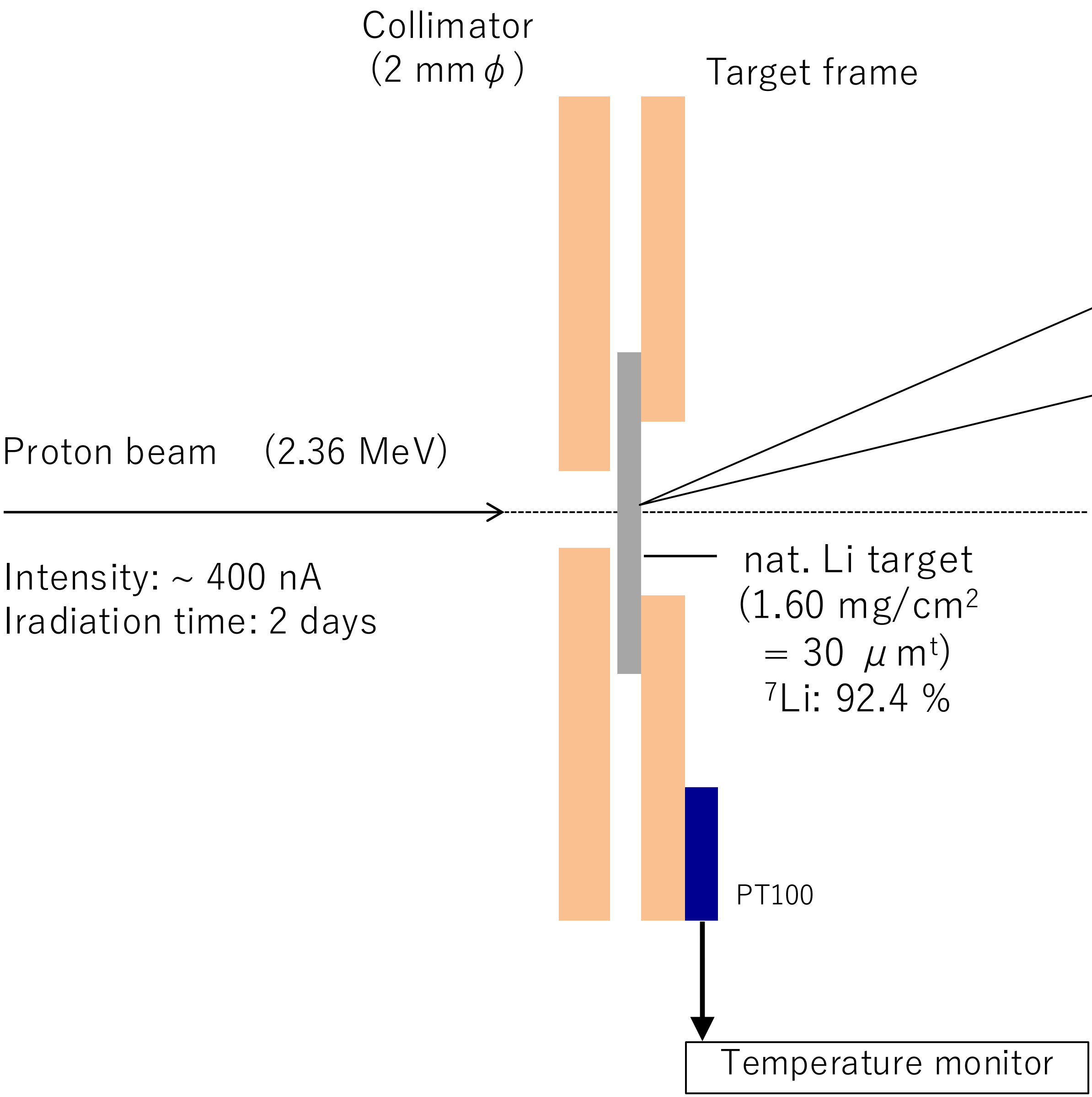
^{7}Be(d, p)^{8}Be measurements

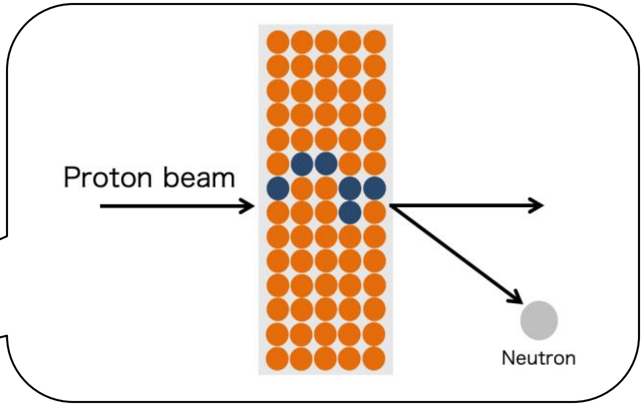


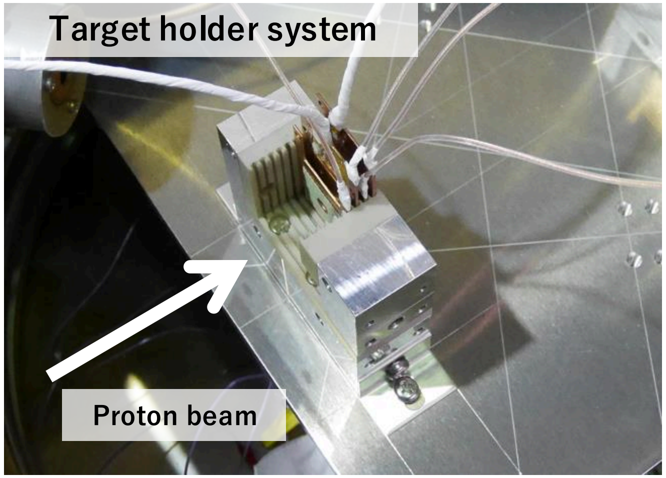
Step1: ^{7}Be Target Production

Proton beam (2.36 MeV)

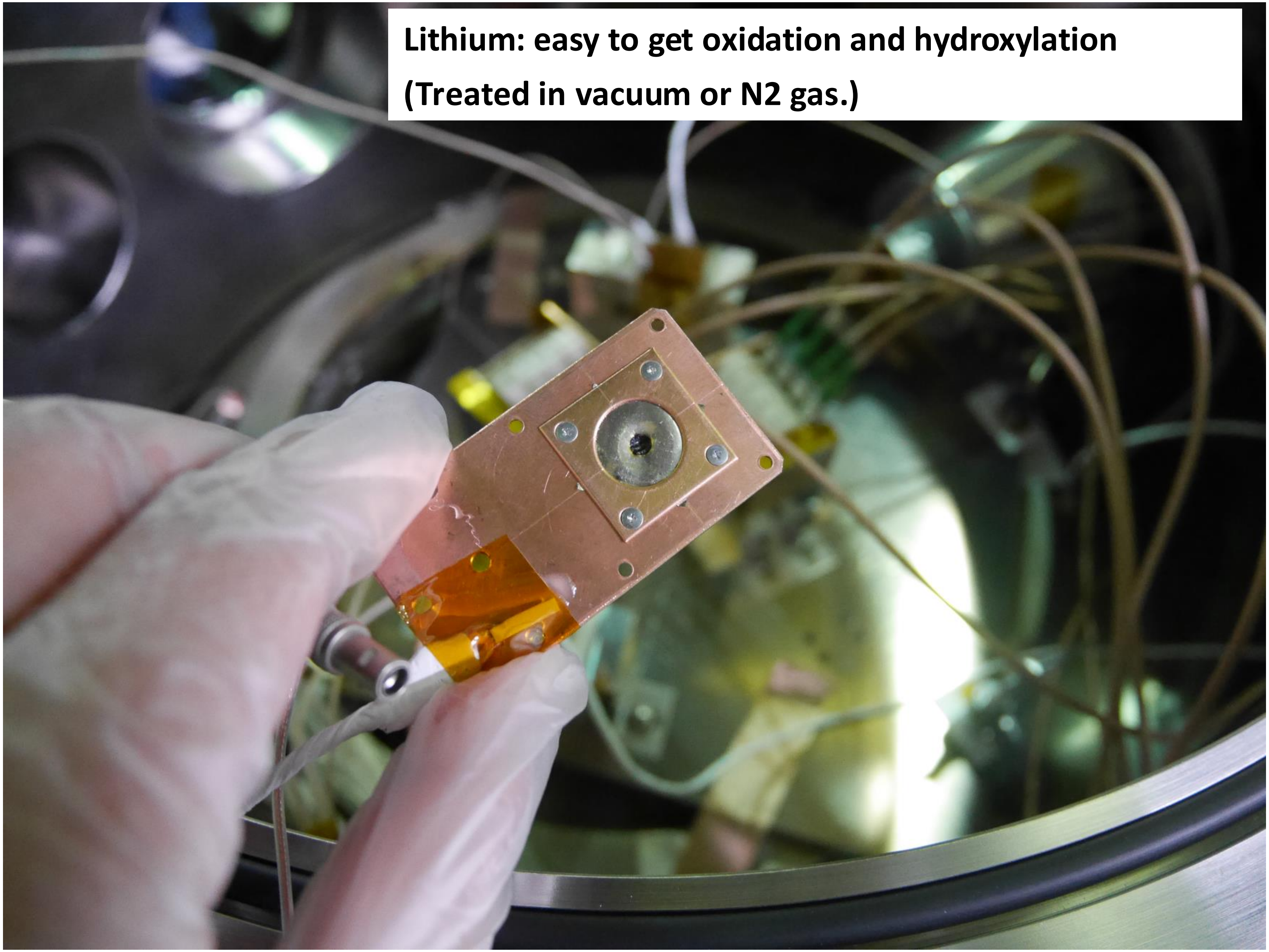
Intensity: ~ 400 nA
Iradiation time: 2 days





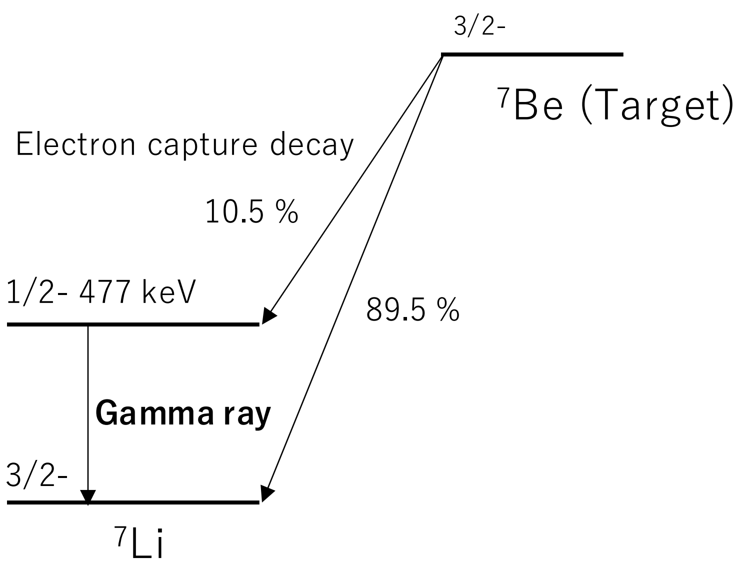


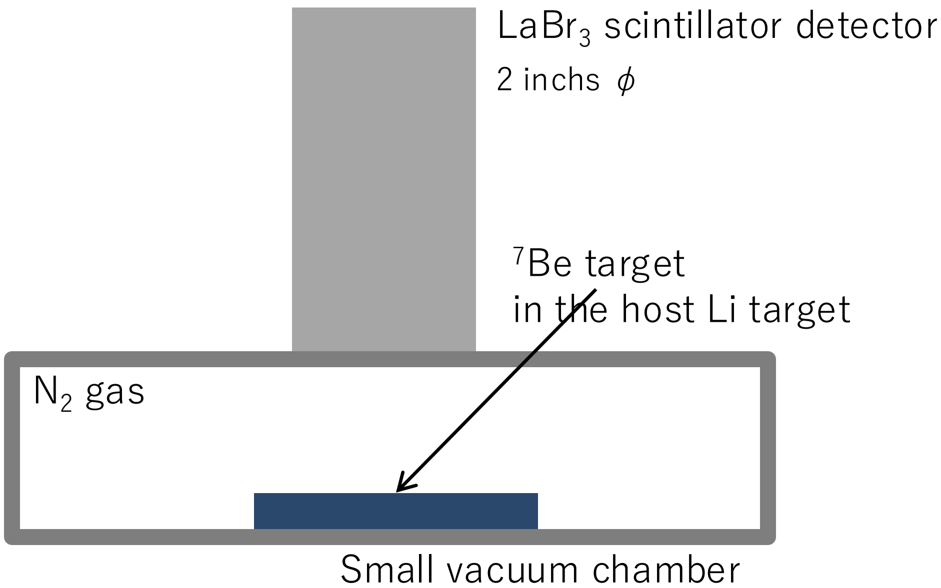
Step1: ^{7}Be target production



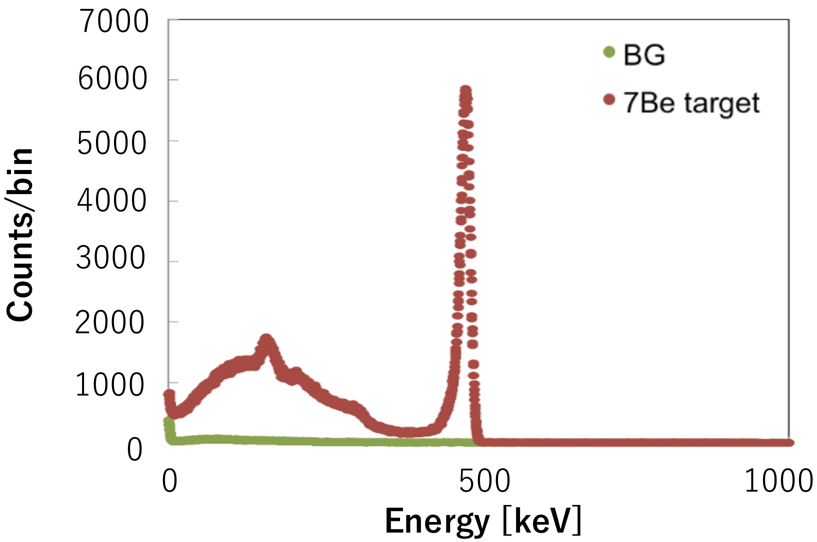
Lithium: easy to get oxidation and hydroxylation
(Treated in vacuum or N2 gas.)

Measured the ^{7}Be Target Nuclei Number





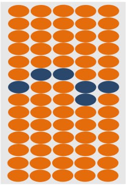
✓ $LaBr_3$ detector efficiency was determined by ^{137}Cs and ^{60}Co source measurements.

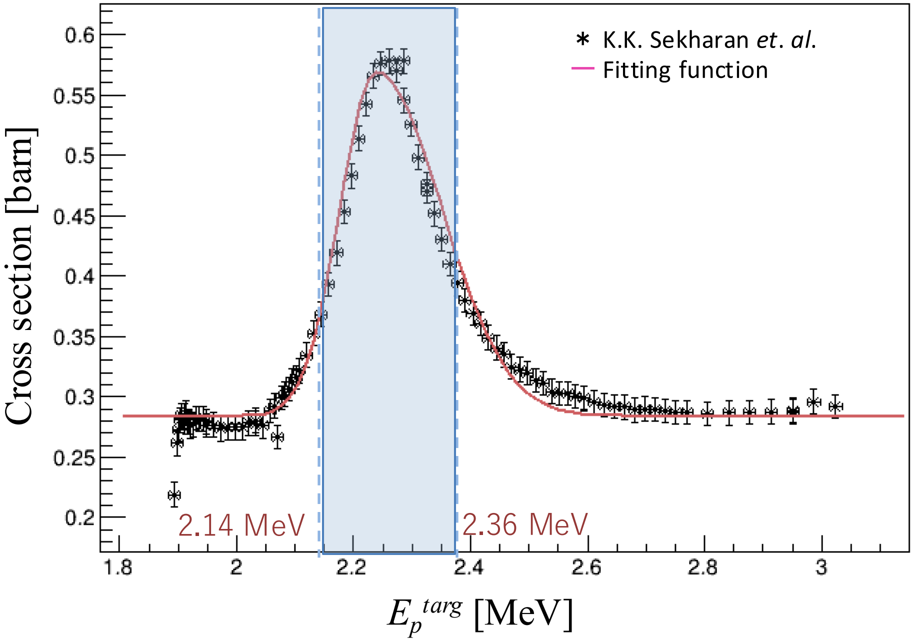


=> **2.80×10^{13} ^{7}Be particles**

^{7}Be target distribution

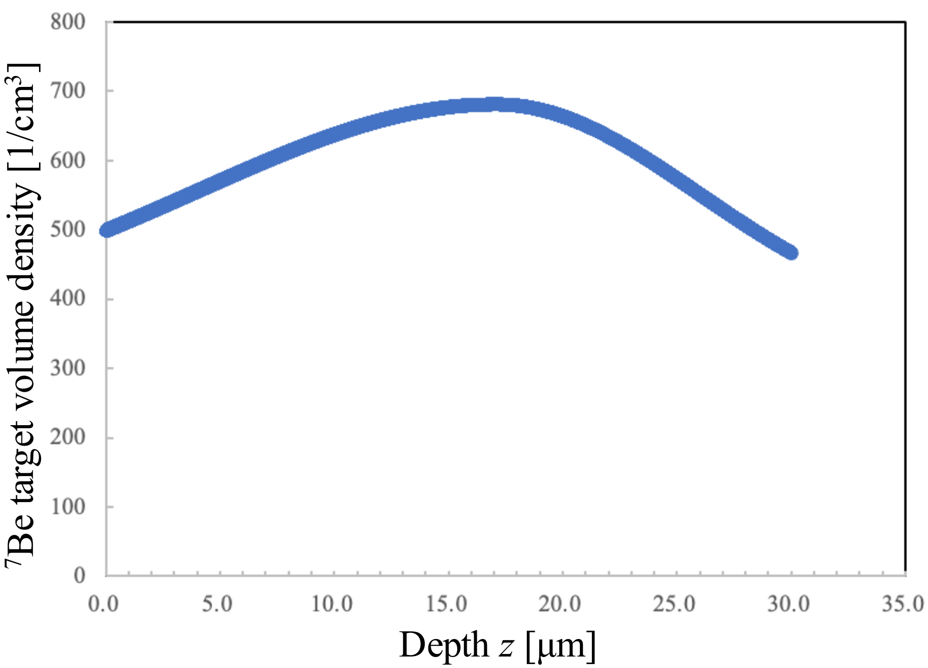
✧ $^7Li + p \to ^7Be + n$



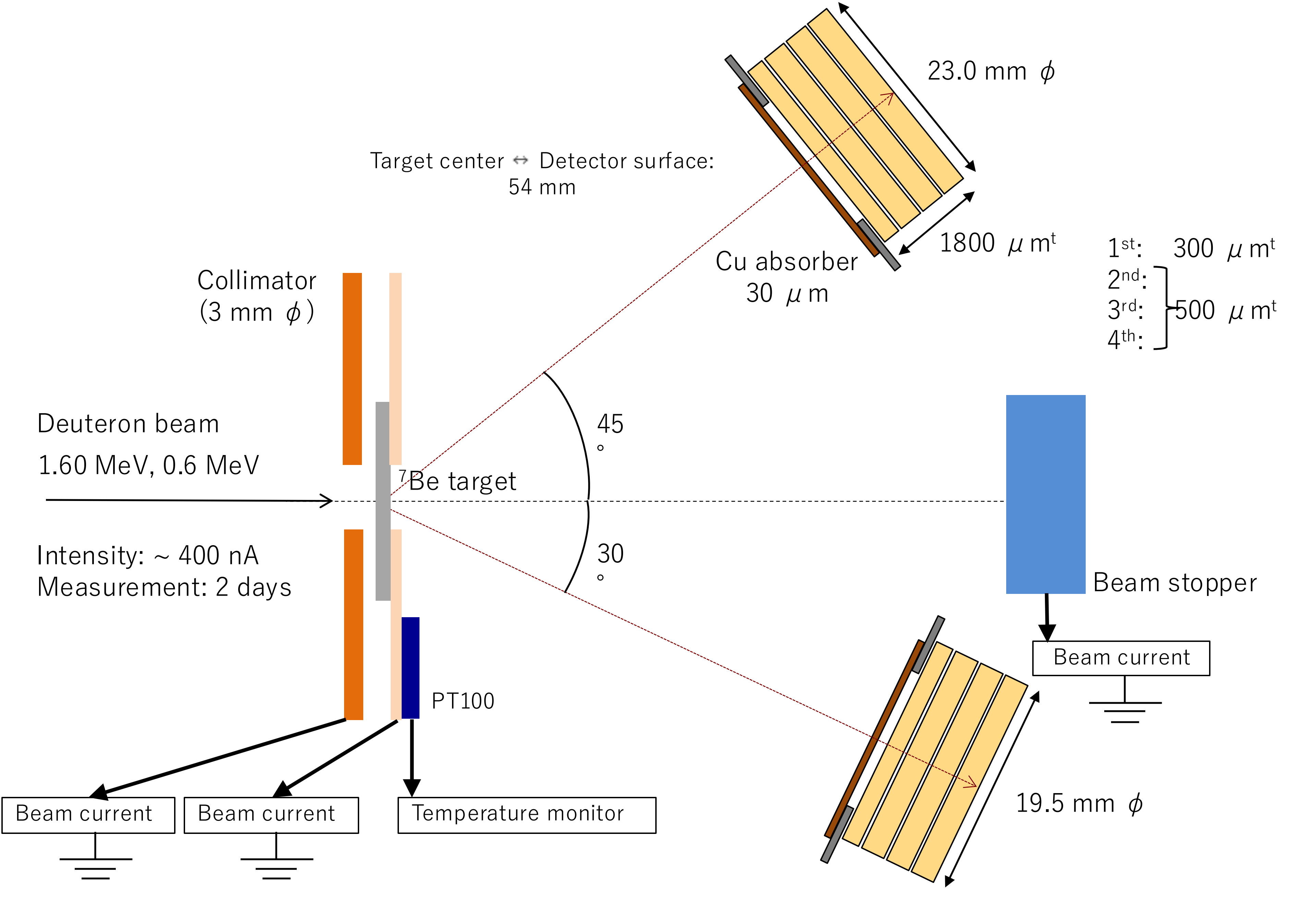


X: Energy loss function

Y: Proton beam current, Solid angle…



$^{7}Be(d, p)^{8}Be$ reaction measurement



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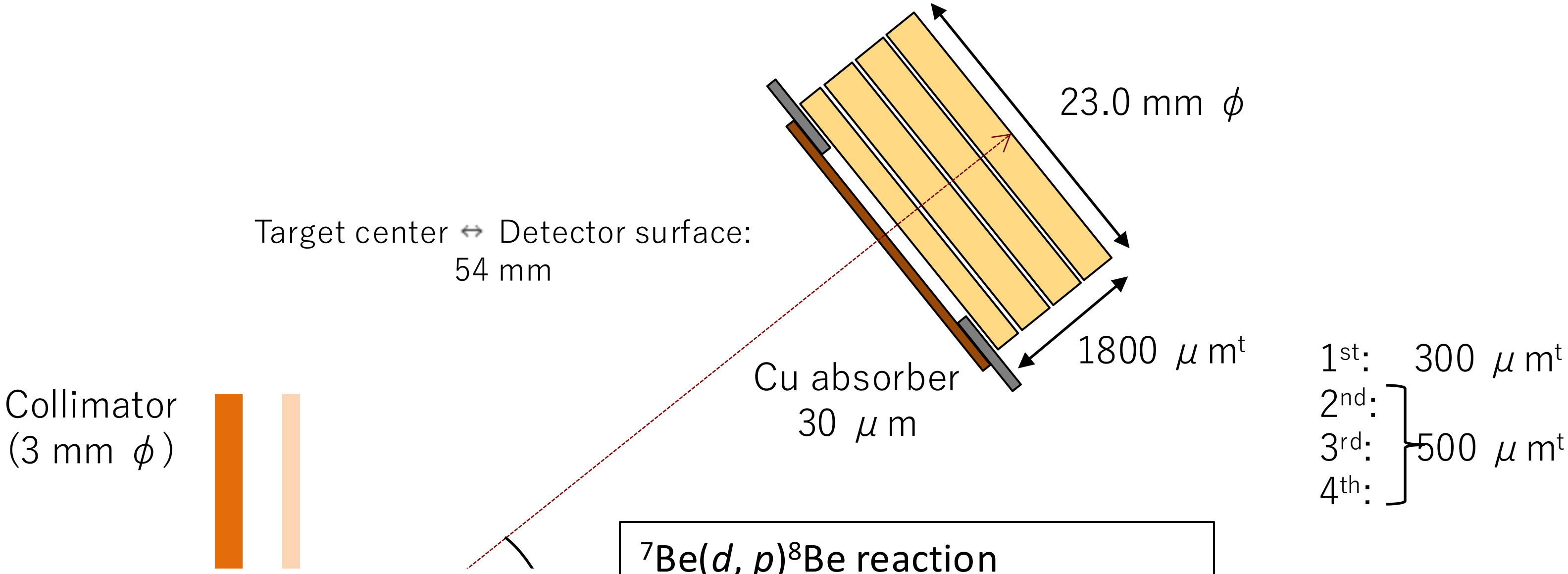


Deuteron beam

1.60 MeV, 0.6 MeV

Intensity: ~ 400 nA
Measurement: 2 days

$^{7}Be(d, p)^{8}Be$ reaction
Q-value: 16.7 MeV

Proton detection

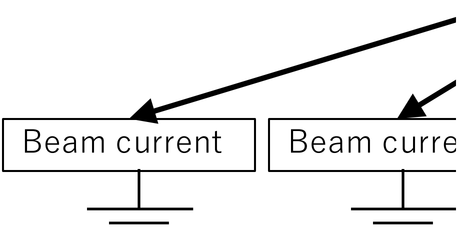
- ✓ Energy (~17 MeV)
- ✓ Number of particles

Detector out

- ✓ Charge out from each detector
  - -> Energy
  - -> Timing

Trigger condition

- ✓ Double coincidence
  - -> A trigger generated when 2 out of 4 detectors had signal.



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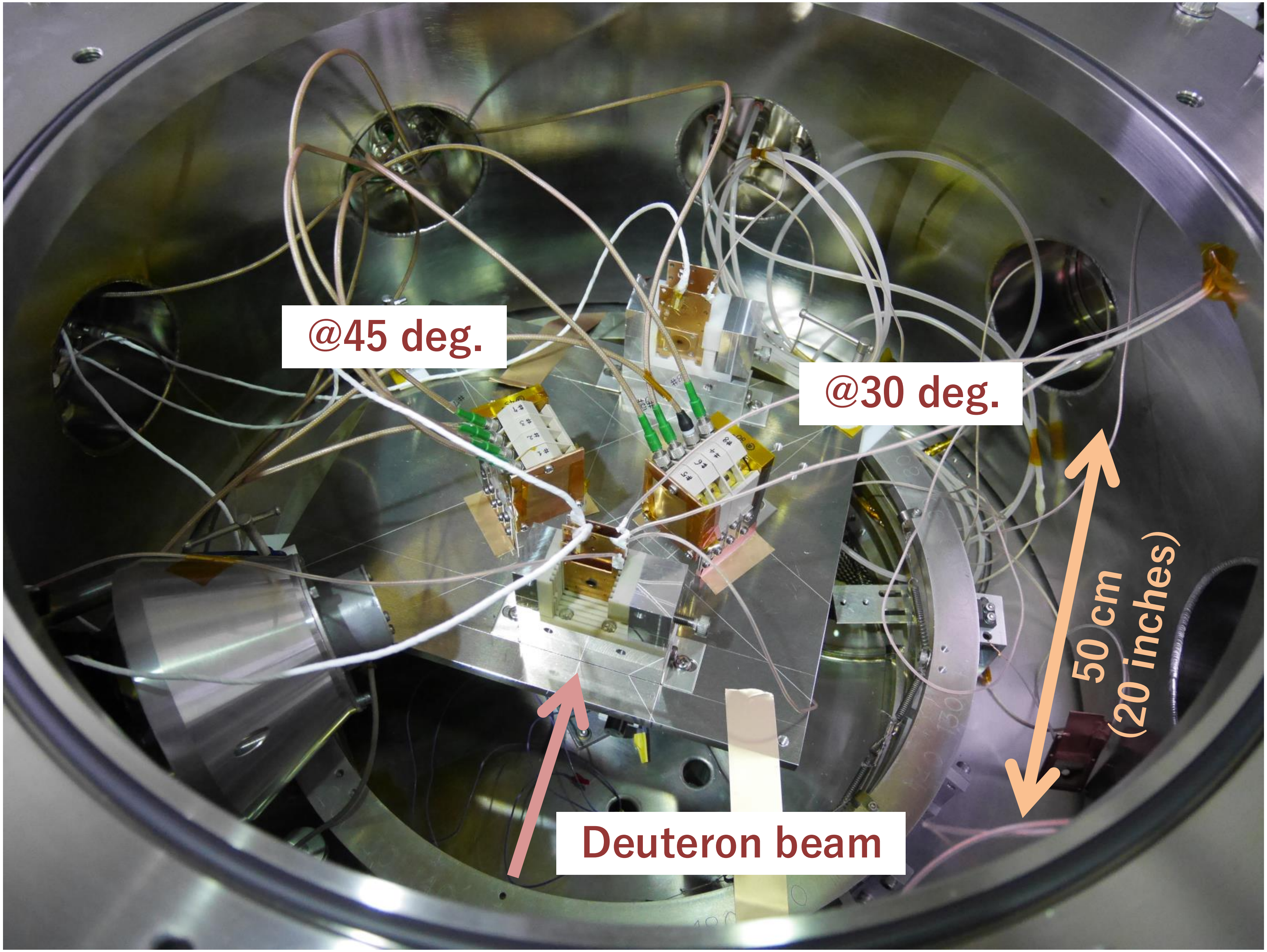
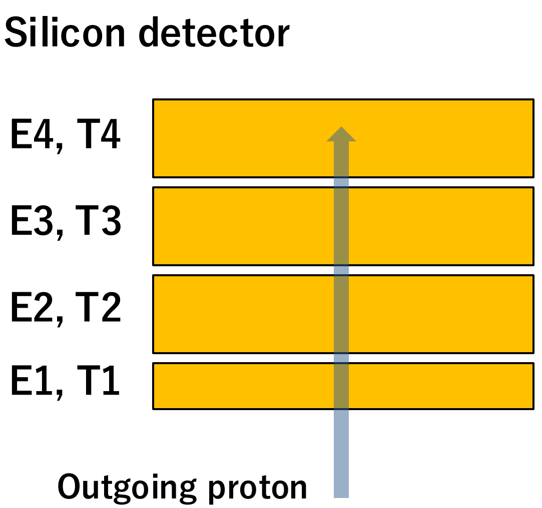
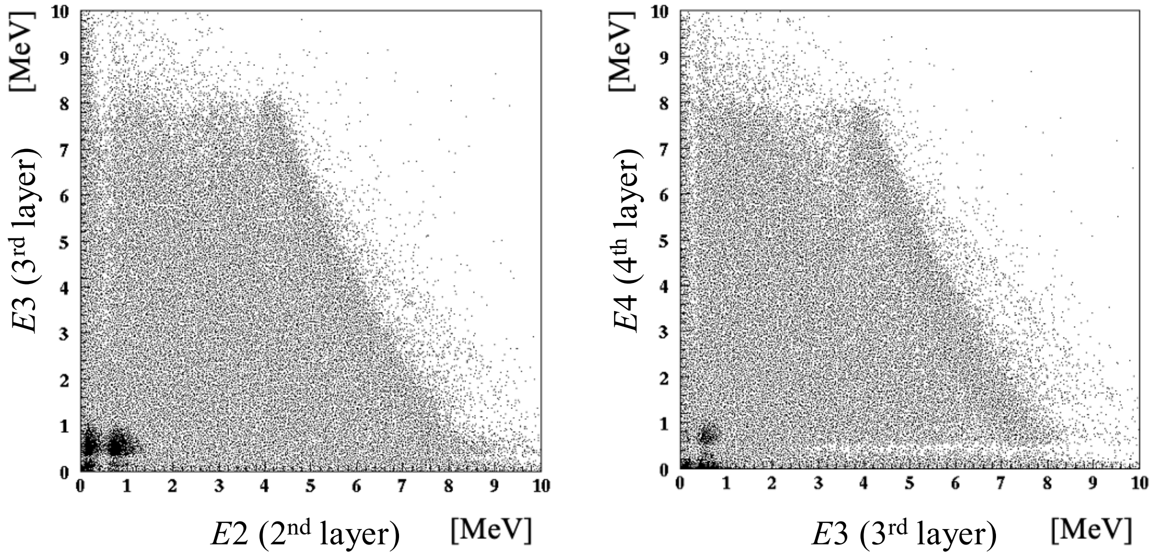
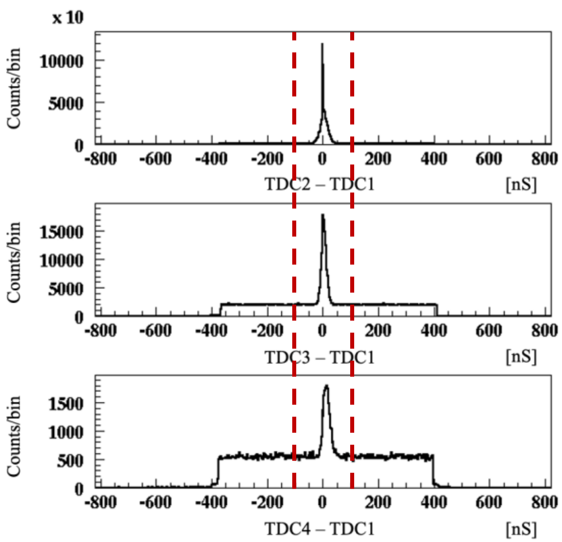




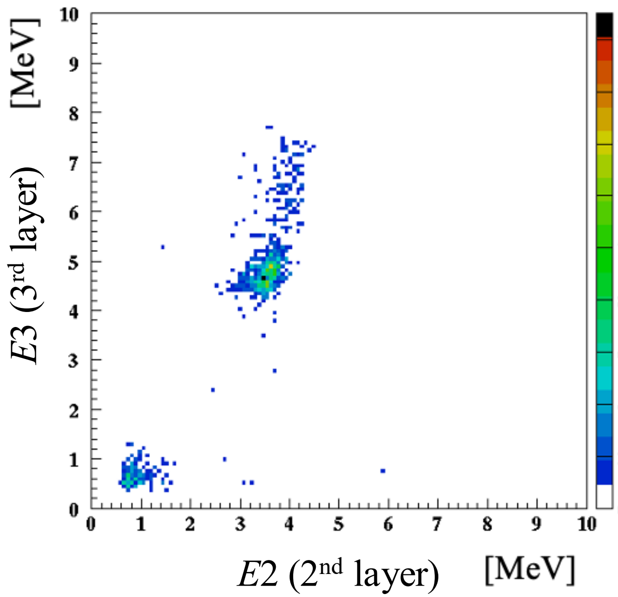
Energy (Raw data)

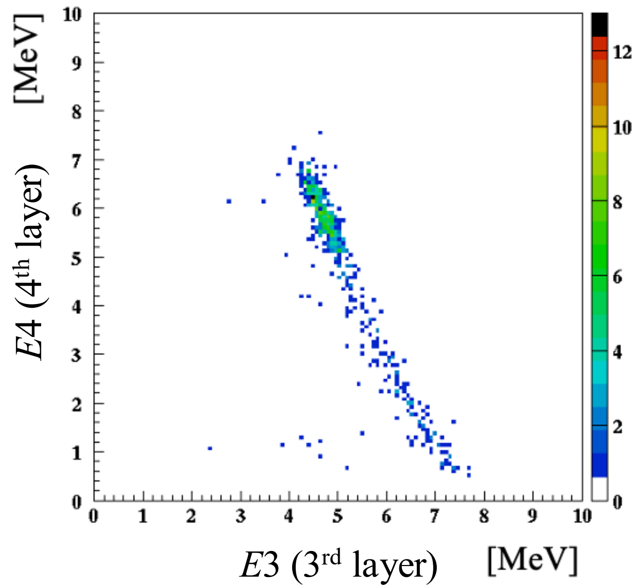


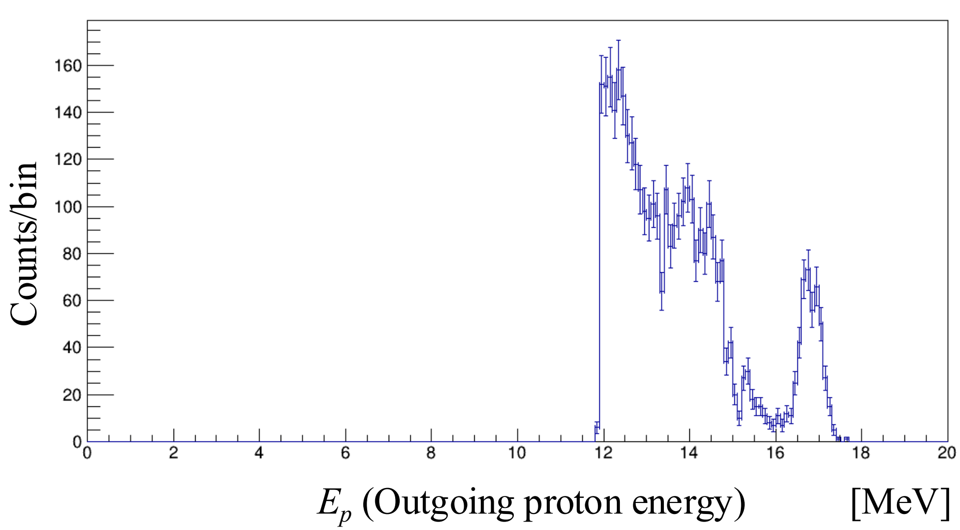
Timing



Energy



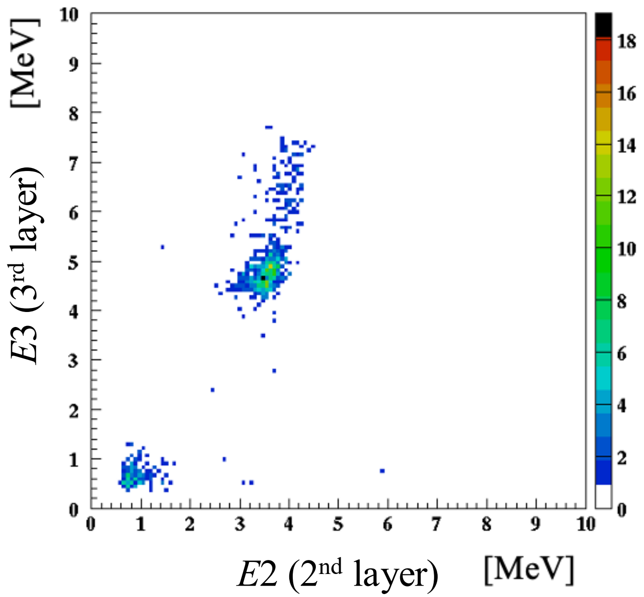


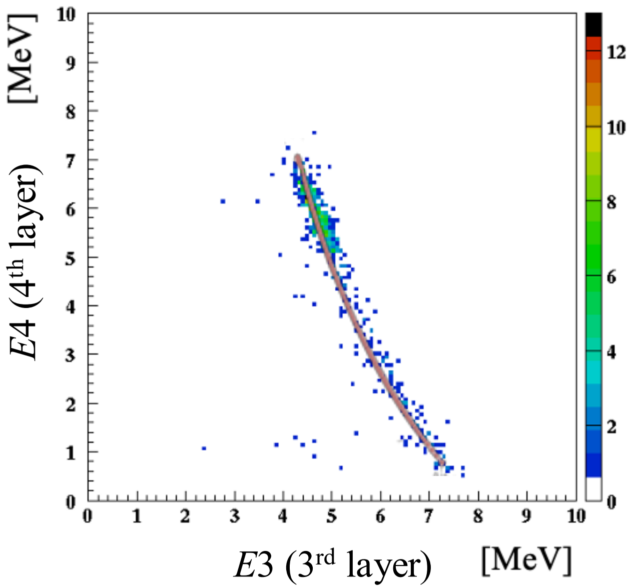


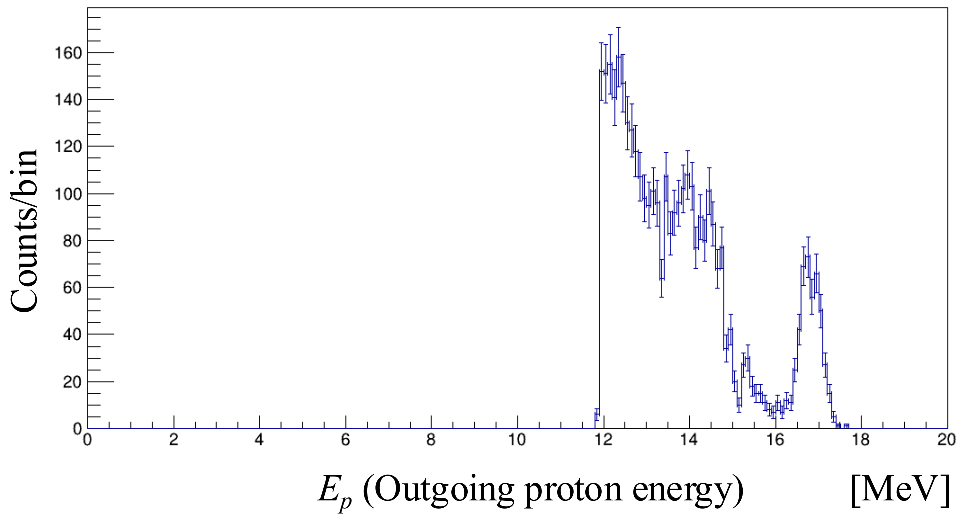
- E_p was calculated based on E4 and E3.
- $E2$ and $E1$ were not available due to the low energy protons from ^{6}Li(dp) or ^{14}N(dp)

Analysis

Energy







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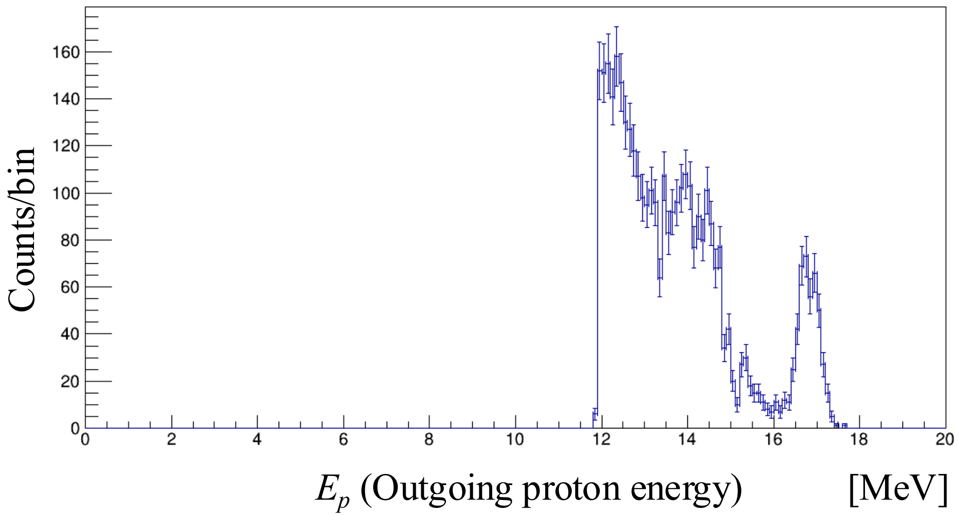
Keys of Analysis

E_p spectrum @E_d = 1.6 MeV

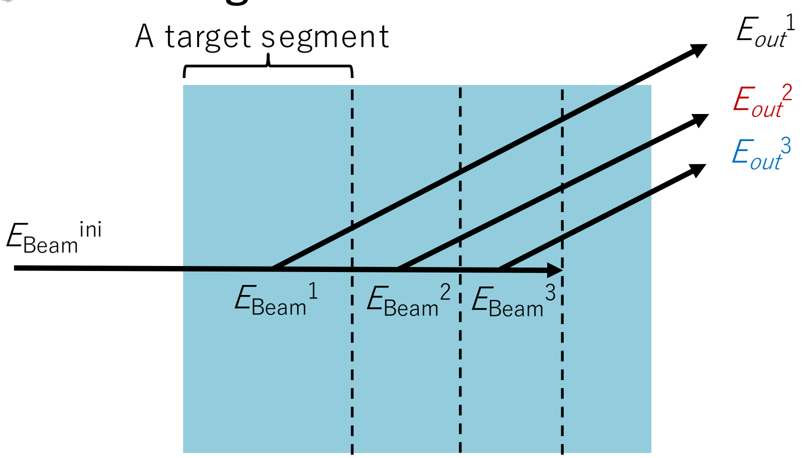


⭐ Q-Value = 16.7 MeV

$^7Be(d, p_0)^8Be^{g.s.}$
$^7Be(d, p_1)^8Be^{2+}$ (1st)
$^7Be(d, p_2)^8Be^{4+}$ (2nd)
…

=> Many states are measured at the same time.

⭐ Thick target method



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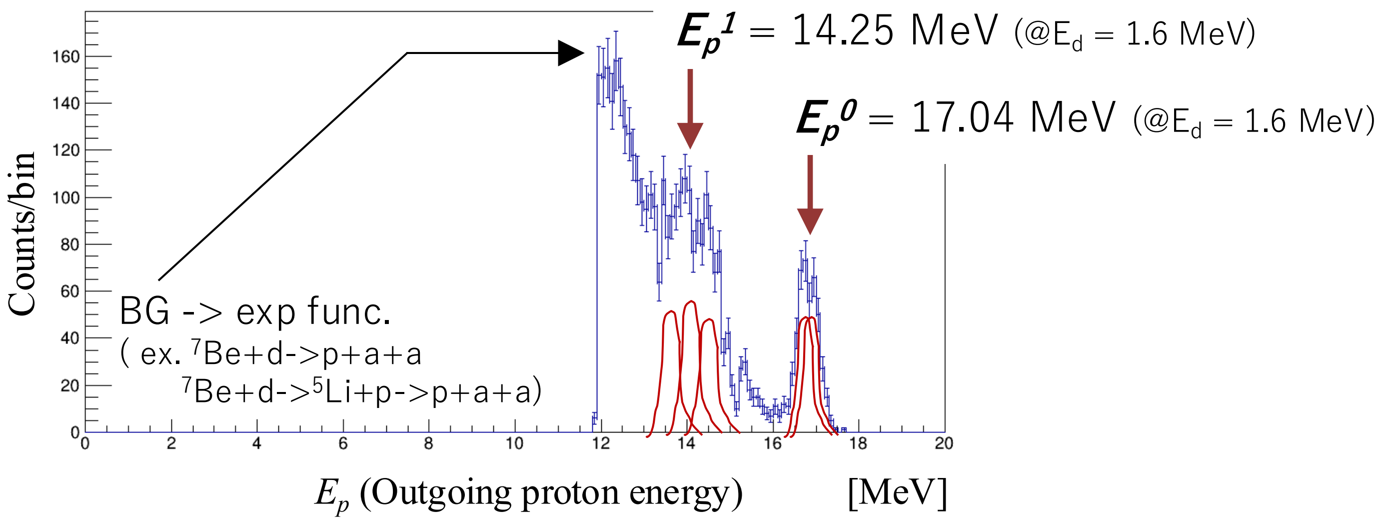

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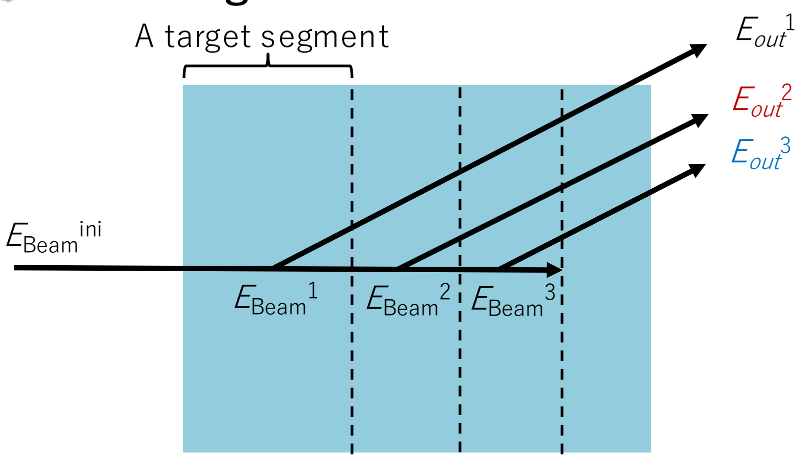
…

⭐ **Thick target method**



=> **Simulation was necessary** to get the response functions.

Simulations

- Measured values: Outgoing proton energy (E_p)
  Outgoing proton event number (Y_p)
  Number of the deuteron beam particles (I_d)
  Number of the ^{7}Be target particles (N_{7Be})

- Simulation

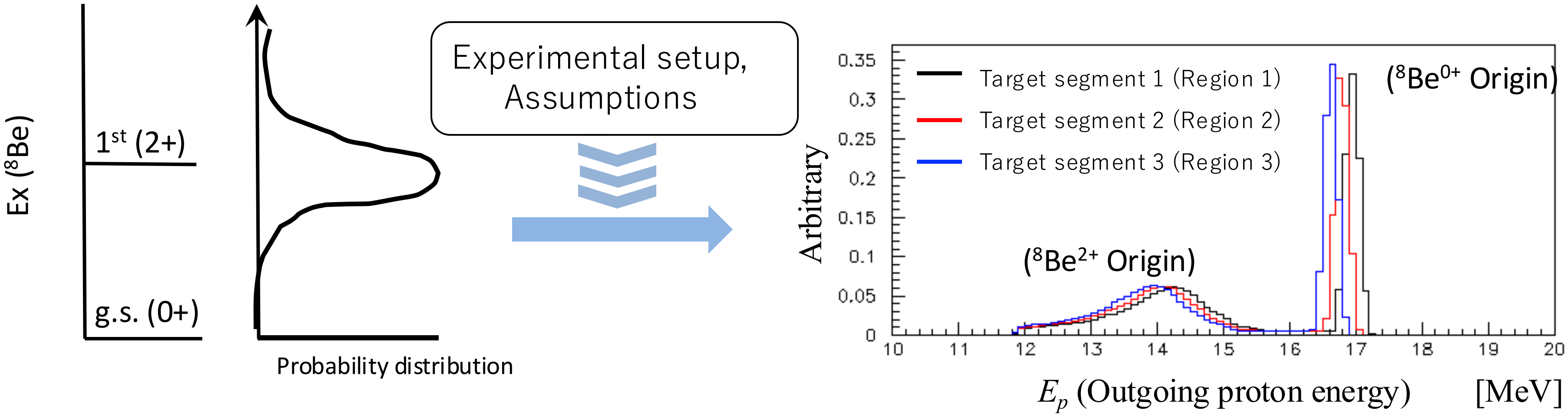
  What was simulated? -> The shapes of the E_p spectrum.

  Parameter -> Astrophysical S-factor

  Assumption -> Cross section does not have the angular dependence (Isotropic).
  -> Astrophysical S-factor is a constant at a target segment.

  Input -> Probability distribution of E_x (^{8}Be)
  (Assuming Breit-Wigner function)

Input



Simulation Segments

- How many segments of the ^{7}Be target can be divided?
  -> Depends Incident deuteron energy spread (ΔE_d) .
    -> Detected proton energy resolutions origin (ΔE_p).

<u>Factors determining the energy resolution</u>

- ✓ The silicon detector resolutions for protons. -> $\Delta E_p^{res.}$
- ✓ The proton straggling in the silicon detectors. -> $\Delta E_p^{str.}$
- ✓ The proton detector angular spread due to the lack of the angler sensitivity in the silicon detector. -> $\Delta E_p^{ang.}$

-> Proton energy resolutions were converted to the deuteron energy spread $\Delta E_d^{res.}$, $\Delta E_d^{str.}$, and $\Delta E_d^{ang.}$.

<u>Total deuteron energy spread</u>

$$\Delta E_d^{total} = \sqrt{\Delta E_d^{res.2} + \Delta E_d^{str.2} + \Delta E_d^{ang.2}}$$

$\underline{= 150 \sim 270\ \mathrm{keV}}$ ⟷ ex.) Deuteron energy loss in the target $\underline{= 460\ \mathrm{keV}}$ @E_d = 1.6 MeV

➡ 2～3 segments were available.

Simulation and Fitting Function

Simulations -> Fitting function (Response function)

$$P(E_p)\cdot dE_p = \int_0^t F(E_p; E_d)\cdot dE_p \cdot I_d \cdot N_t(z)\cdot S \cdot dz$$

E_p distribution

Yield per dE_p

Simulated part

Astrophysics S-factor was the fitting parameter.

t: $Target\ depth$

I_d: $Deuteron\ beam\ current$

N_t: ${}^7Be\ target\ number\ (volume\ dencity)$

Cross section

$$\sigma_{dp}(E_{c.m.}) = S(E_{c.m.})\cdot\frac{1}{E_{c.m.}}\cdot exp(-2\pi\eta)$$

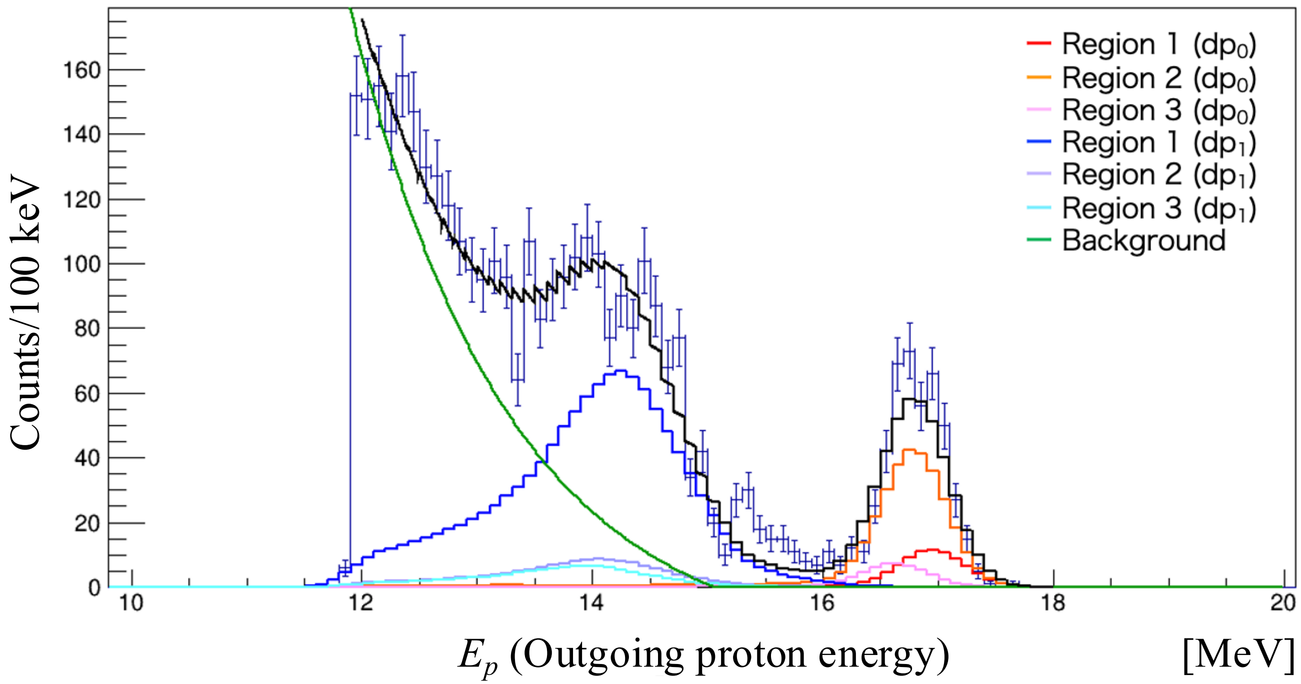
Astrophysical S-factor

Sommerfeld parameter

-> $S(E_{c.m.})$ was assumed to be constant within a target segment.

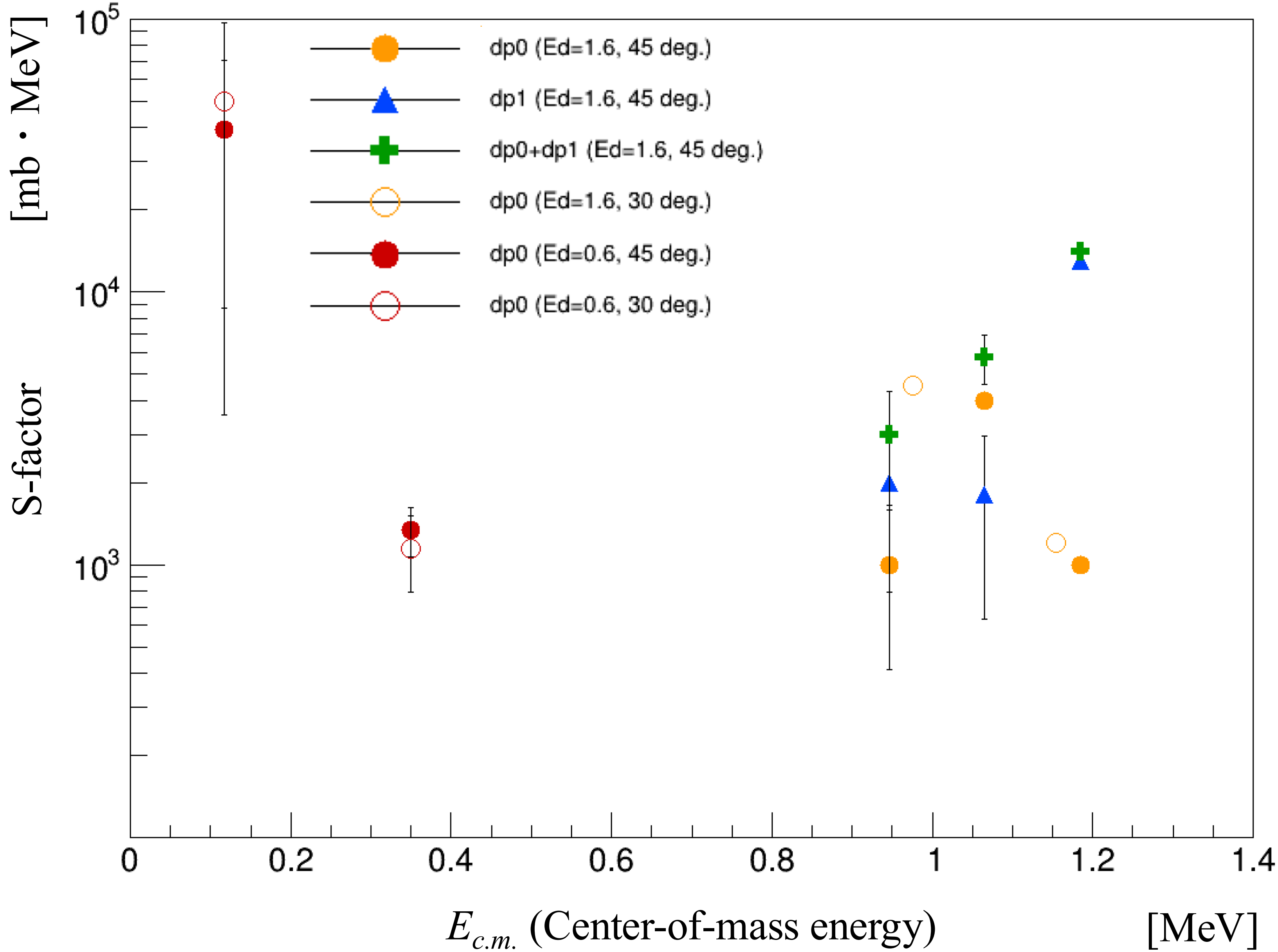
Fitting Results

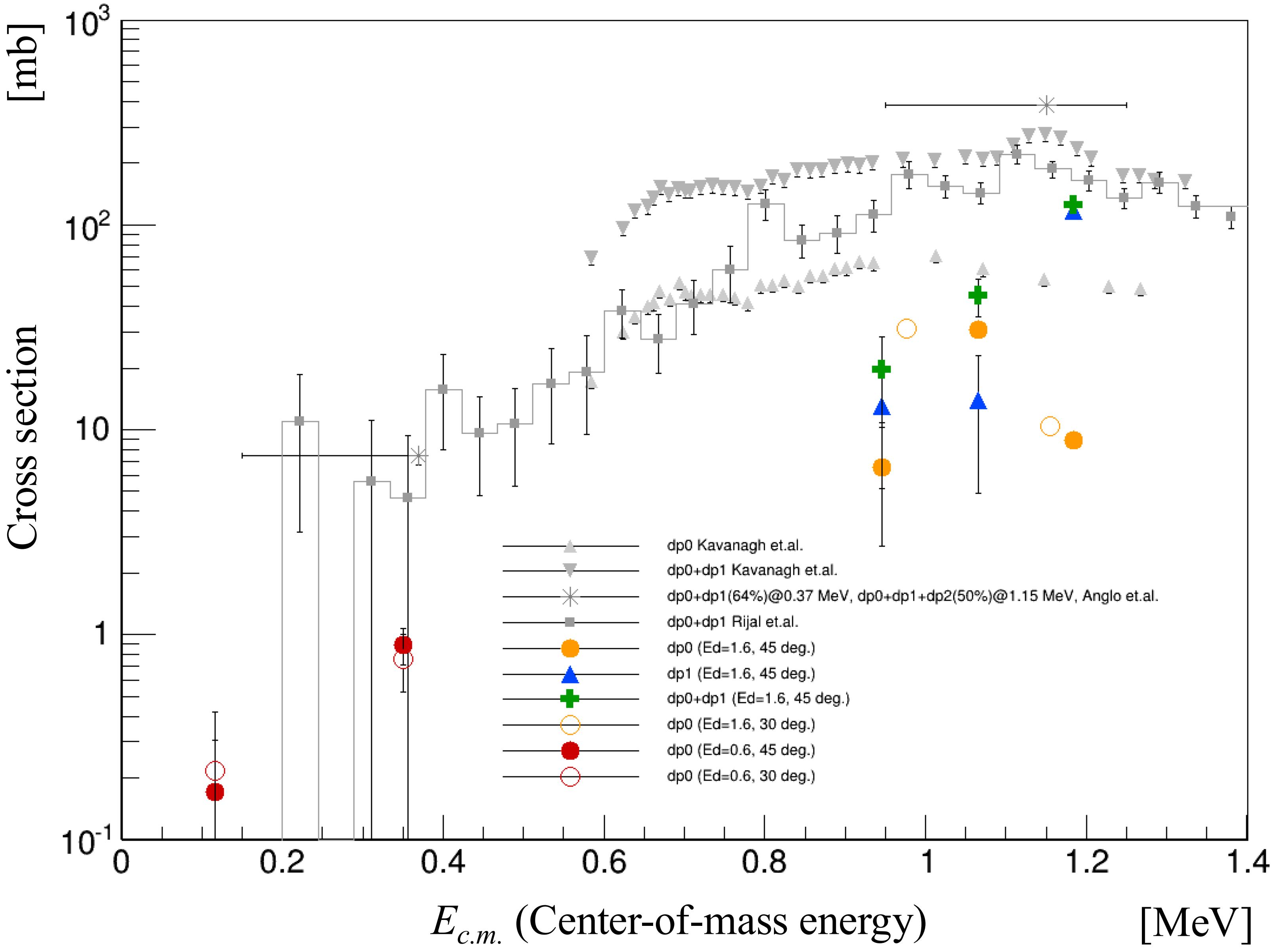
- E_d = 1.6 MeV @45° detector



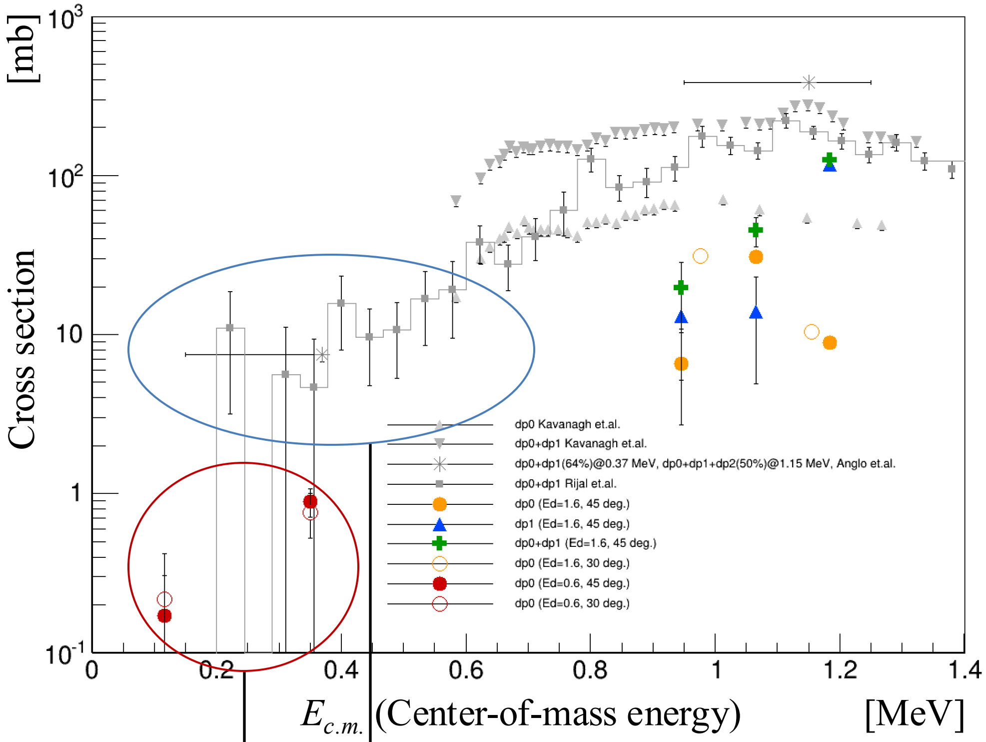
Reaction	S-factor [mb・MeV]	Fiting error	%
	1000.02	56.358	5.64
dp_0	3980.41	256.84	6.45
	1000.07	584.75	58.5
	13001.5	528.61	4.07
dp_1	1800.32	1169.0	64.9
	2000.04	1206.4	60.3

Astrophysical S-factors




Cross section [mb]
10^3
10^2
10
1
10^{-1}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
$E_{c.m.}$ (Center-of-mass energy) [MeV]
dp0 Kavanagh et.al.
dp0+dp1 Kavanagh et.al.
dp0+dp1(64%)@0.37 MeV, dp0+dp1+dp2(50%)@1.15 MeV, Anglo et.al.
dp0+dp1 Rijal et.al.
dp0 (Ed=1.6, 45 deg.)
dp1 (Ed=1.6, 45 deg.)
dp0+dp1 (Ed=1.6, 45 deg.)
dp0 (Ed=1.6, 30 deg.)
dp0 (Ed=0.6, 45 deg.)
dp0 (Ed=0.6, 30 deg.)

Astrophysical Impacts



N. Rijal *et al*. reported

^{7}Be+*d* cross section reduced the ^{7}Li abundance by 14%.

(^{7}Be(d, α) was included.)

Our result of ^{7}Be(d, p_0) cross section was relatively low.

Small impact to the CLP.

^{7}Be(d, p_0) was not a solution for the CLP.

Summary for the experimental study

Motivation

- ✧ To find a solution for the Cosmological Lithium problem (CLP).
- ✧ Measurement of the ^{7}Be(d, p) reaction to obtain its cross section.
- ✧ The ^{7}Be(d, p) reaction was with the radioactive ^{7}Be target.

Achievements and Results

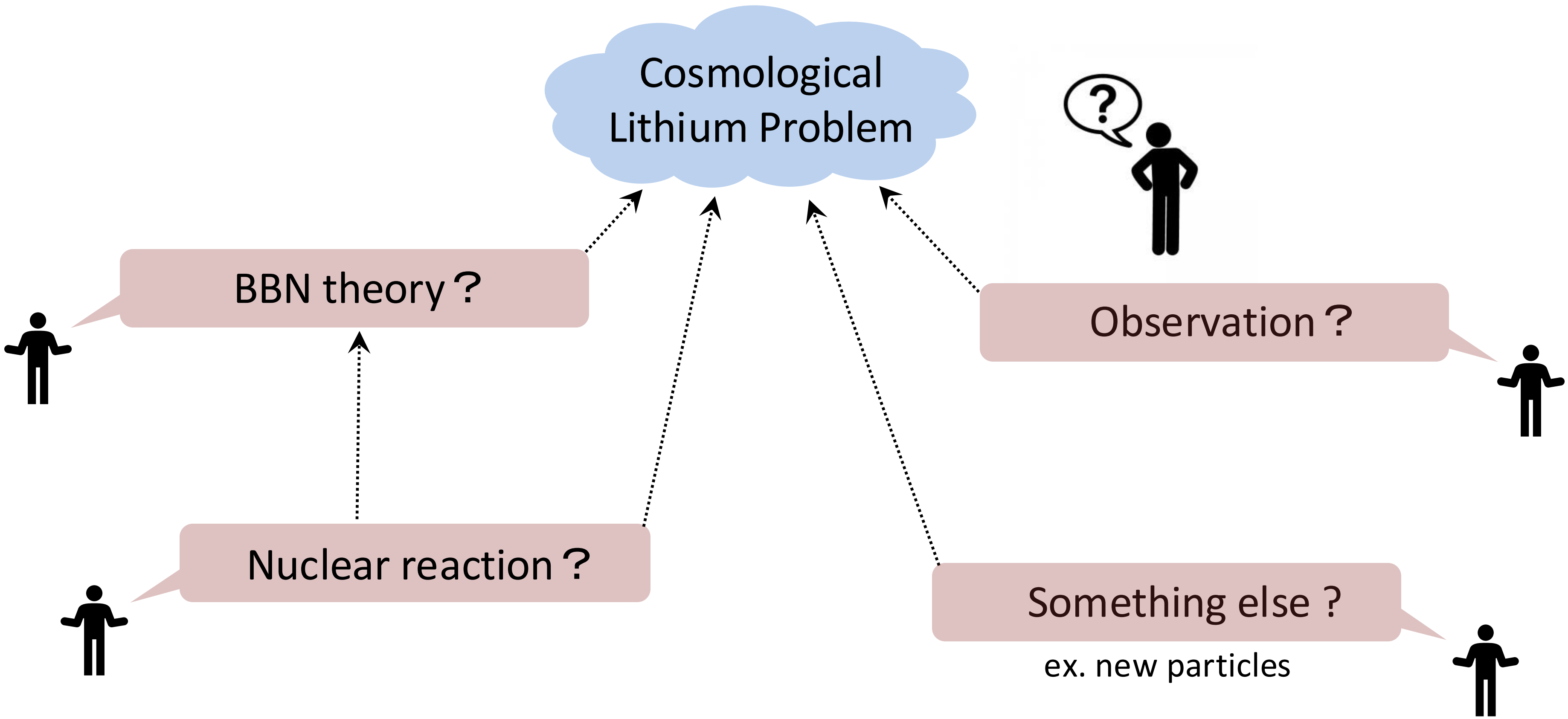
- ✧ **2.80×10^{13} ^{7}Be particles** were successfully produced.
- ✧ **The ^{7}Be(d, p)^{8}Be reaction cross sections were measured** in the Big Bang Nucleosynthesis energy region.
- ✧ The cross section at $E_{c.m.} = 0.12$ MeV exhibited the highest sensitivity and was measured at the lowest energy.

Astrophysical Impacts and Discussions

- ✧ The ^{7}Be(d, p)^{8}Be reaction had a **limiting impact on the CLP**.
- ✧ The CLP remained unsolved and mysterious problem in the cosmology.
- ✧ The CLP must be approached from other perspectives, such as astrophysical observations.

Extensions & Open questions

How to approach/solve the problem?



Points to be confirmed

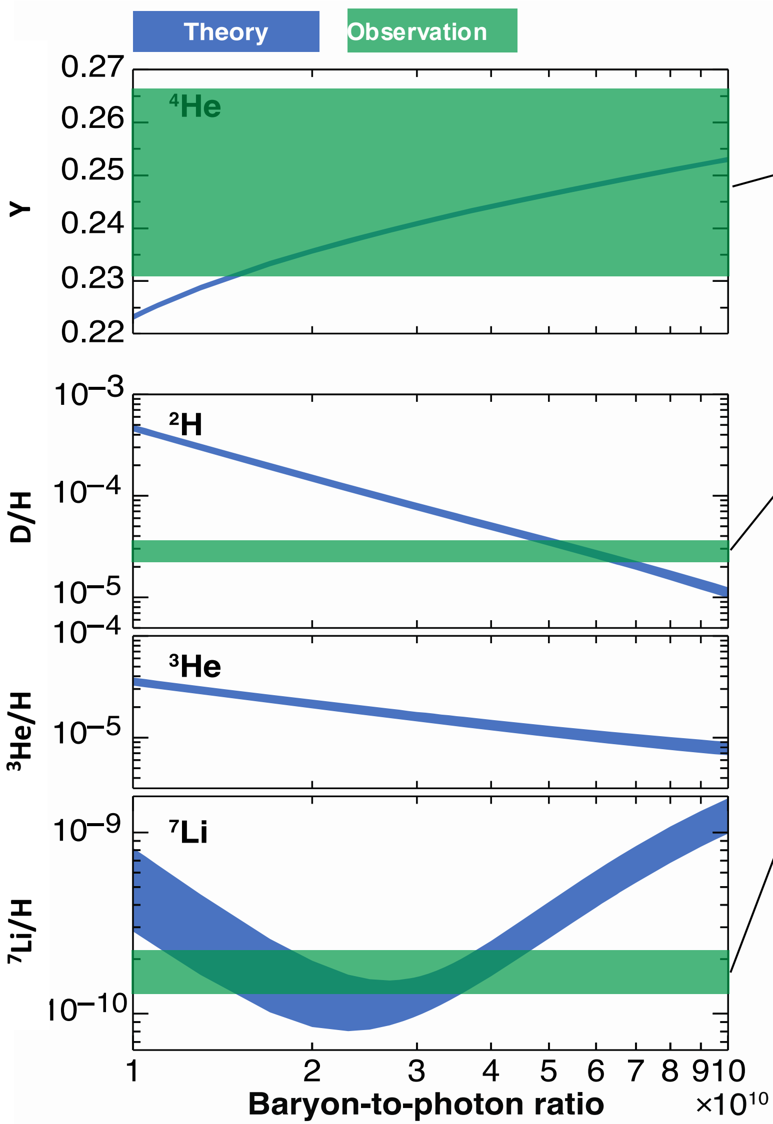
- ***Nuclear reaction data and the BBN Theory?***
  - Considerable all reactions in the BBN reaction chain must be measured.
  - Those results must be included systematically.
    - Correlations of nuclear reactions?
    - Sensitivity (of the nuclear reaction) search code. → My work at Oslo
  - Is the BBN theory perfect? Physical constants?

    -> Well-studied, but should be comprehensively re-evaluated.

- ***Astronomical observation?***
  - Metal-poor stats measurements?
  - CMB measurements?

  Details -> Next page

Astronomical Observation



- Emission line spectroscopy
- H II region stars

- Absorption line spectroscopy
- Primordial gas clouds behind quasers

- Absorption line spectroscopy
- Population II stars

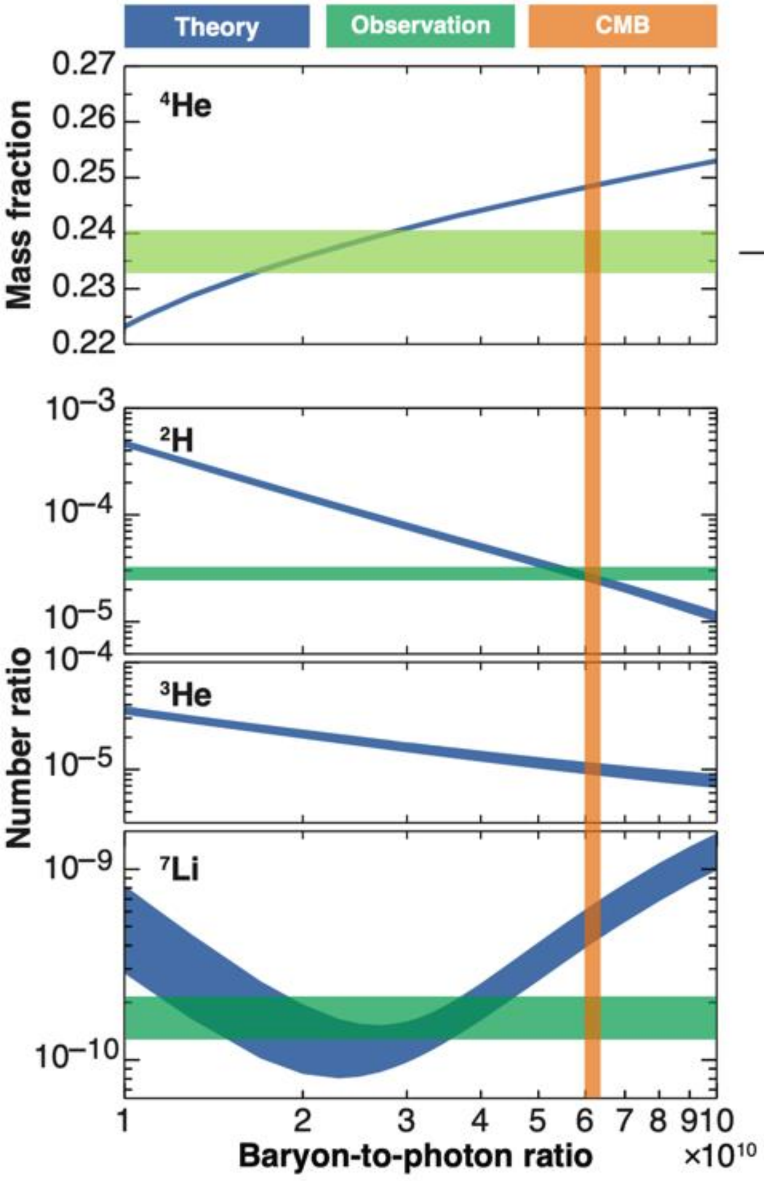
⇩

Obtained by different method and observational target.

→ May cause systematic error.

R. H. Cyburt *et. al.*, J. Cosmol. Astropart. Phys. **11**, 012 (2008).
Brian D. Fields *et. al.*, J. Cosmol. Astropart. Phys. 03(2020)010.

Posting a New Question



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→ New observation **"EMPGs"**

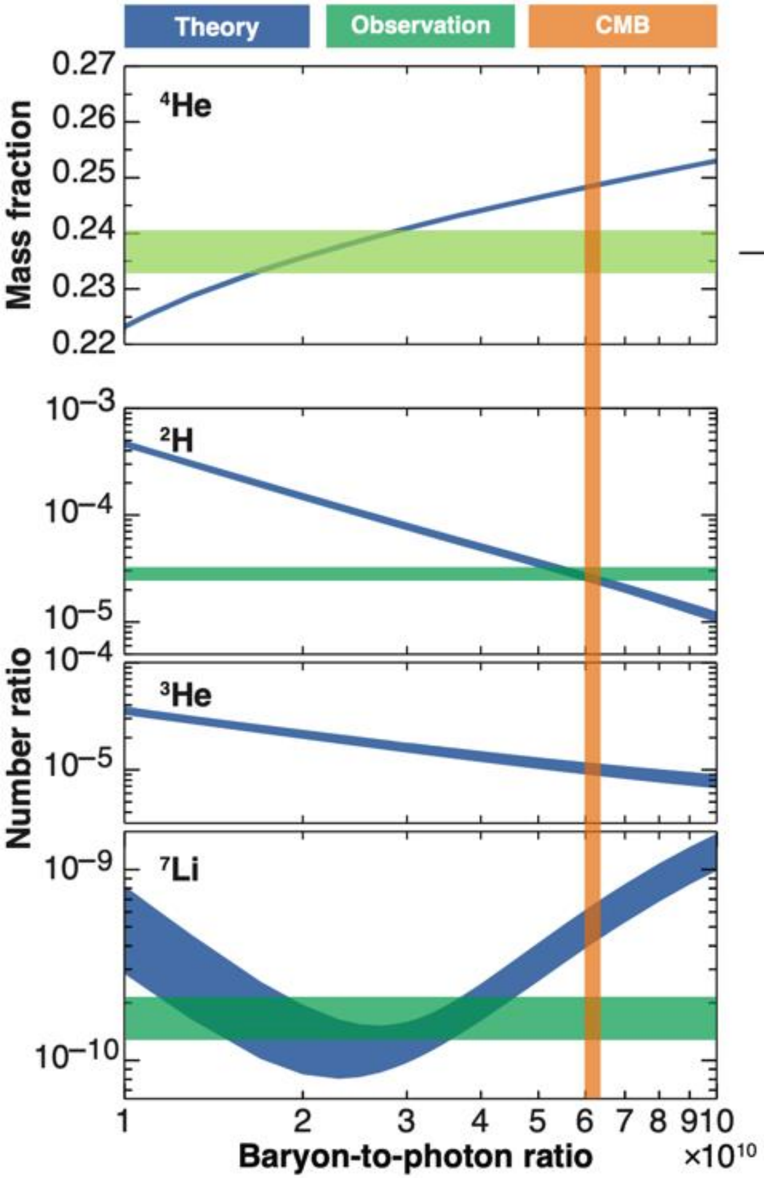
$$Y_p = {}^4\mathrm{He/H} = 0.2370^{+0.0033}_{-0.0034}$$

A. Matsumoto *et al.*, Astro. Phys. Jour. 941:167 (2022)

^{4}He problem...? 🤔

- CMB measurement？
  - ΛCDM model
- CMB measurement -> Baryon-to-photon ratio
  - ΛCDM model, Physical constants (*c*, *h*, *G*), thermal dynamics

Posting a New Question



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Comprehensive approach is necessary to solve the cosmological lithium problem.

A. Tamii, M. Asai, S. Hayakawa, N. Kobayashi, Y. Maeda, H. Makii, T. Shima, H. Shimizu, D. T. Tran , X. Wang, H. Yamaguchi, L. Yang, Z. Yang,
A.C. Larsen, S. Siem

Thank you for your attention!

Backup