

Direct measurement of astrophysical ${}^8\text{Li} (d,t) {}^7\text{Li}$ reaction

Advanced Science Research Center (ASRC)
Japan Atomic Energy Agency (JAEA)
Takashi Hashimoto

Collaborators

JAEA	S. Mitsuoka, K. Nishio, T. K. Sato, A. Osa, S. Ichikawa, M. Matsuda, H. Ikezoe
KEK	H. Ishiyama, Y. X. Watanabe, Y. Hirayama, N. Imai, H. Miyatake, S. C. Jeong, M.-H. Tanaka, N. Yoshikawa, T. Nomura, M. Okada, S. Arai
O.E.C.U	S. K. Das, Y. Mizoi, T. Fukuda
RIKEN	S. Bishop
Osaka Univ.	A. Sato, T. Shimoda

Table of Contents

1. Introduction

Motivation of this work

2. Experiment

TRIAC

^8Li beam profile provided by TRIAC

Experimental setup

3. Discussion

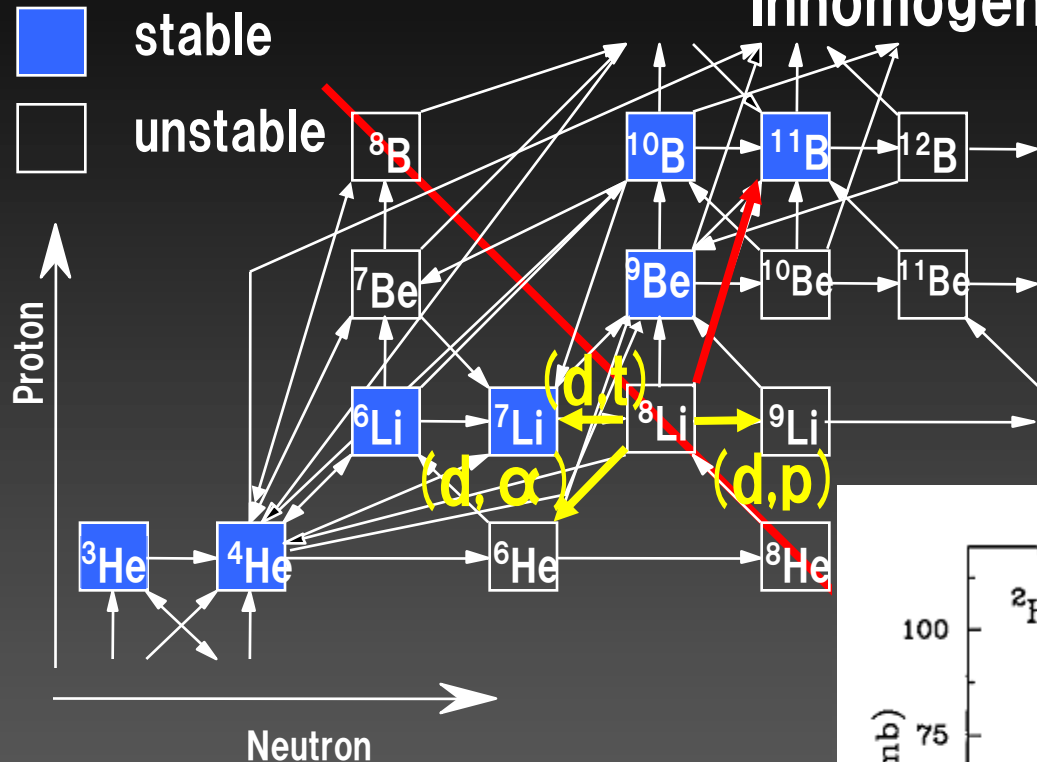
Differential and total cross sections

Reaction flow via ^8Li

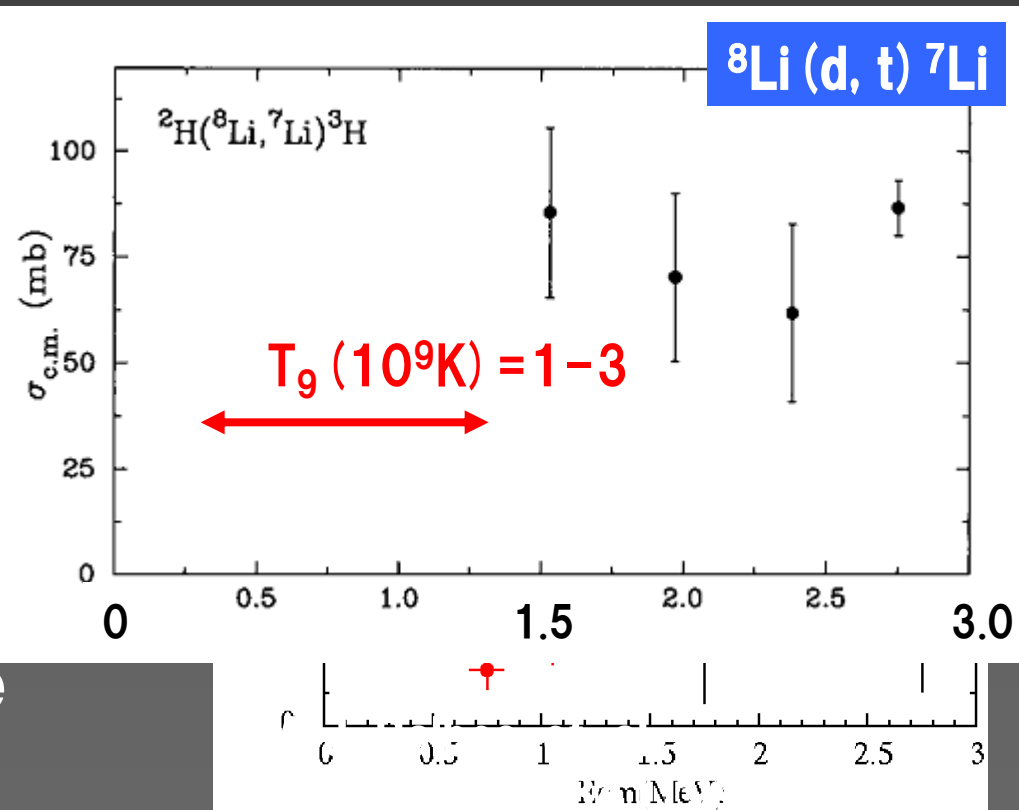
4. Summary

1. Introduction

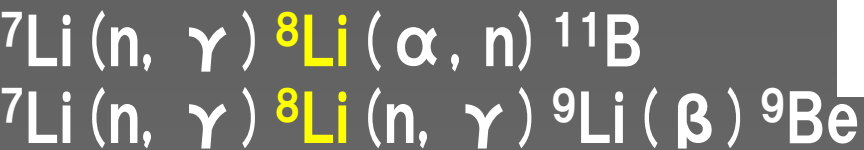
Inhomogeneous Big-Bang Model (IBBM)



IBBM:
 heavy elements beyond
 lithium are produced more
 than the Standard model

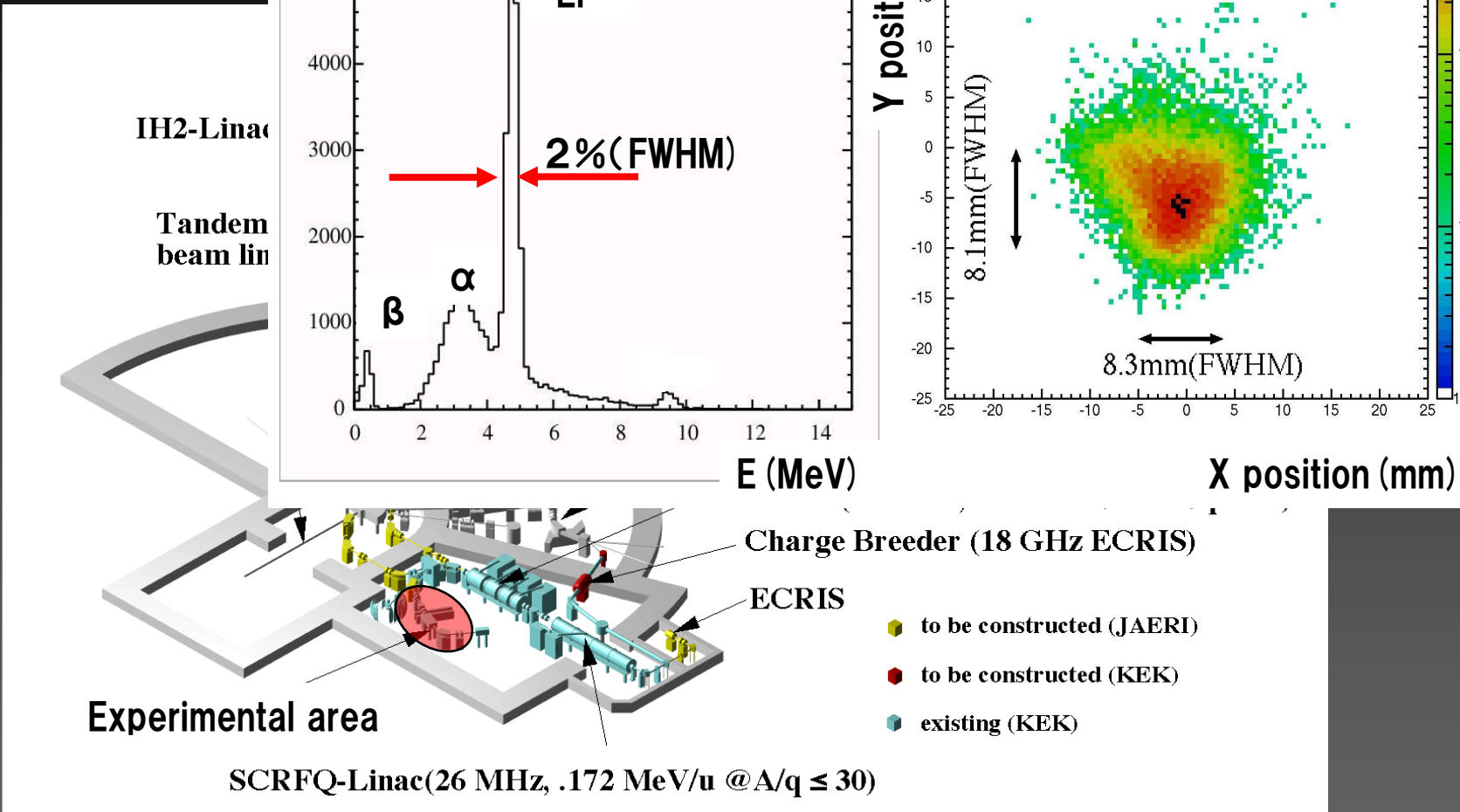


Key Reaction



Experiment

TRIAC ; Tokai Ra



RNB can provided with variable out put energy from 0.18 to 1.1MeV/u
 $E_{\text{cm}} = 1.2, 1.1, 1.0, 0.8, 0.7, 0.5, 0.4, 0.3\text{MeV}$ ($T_9=1-3$)

^8Li beam : $I = 10^5\text{pps}$ on target (max $3 \times 10^5\text{kpps}$)

Purity : almost 100%

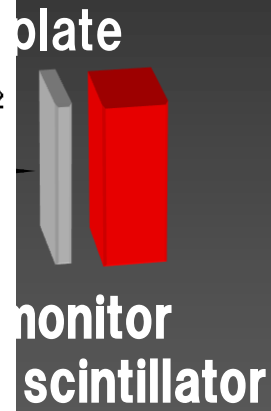
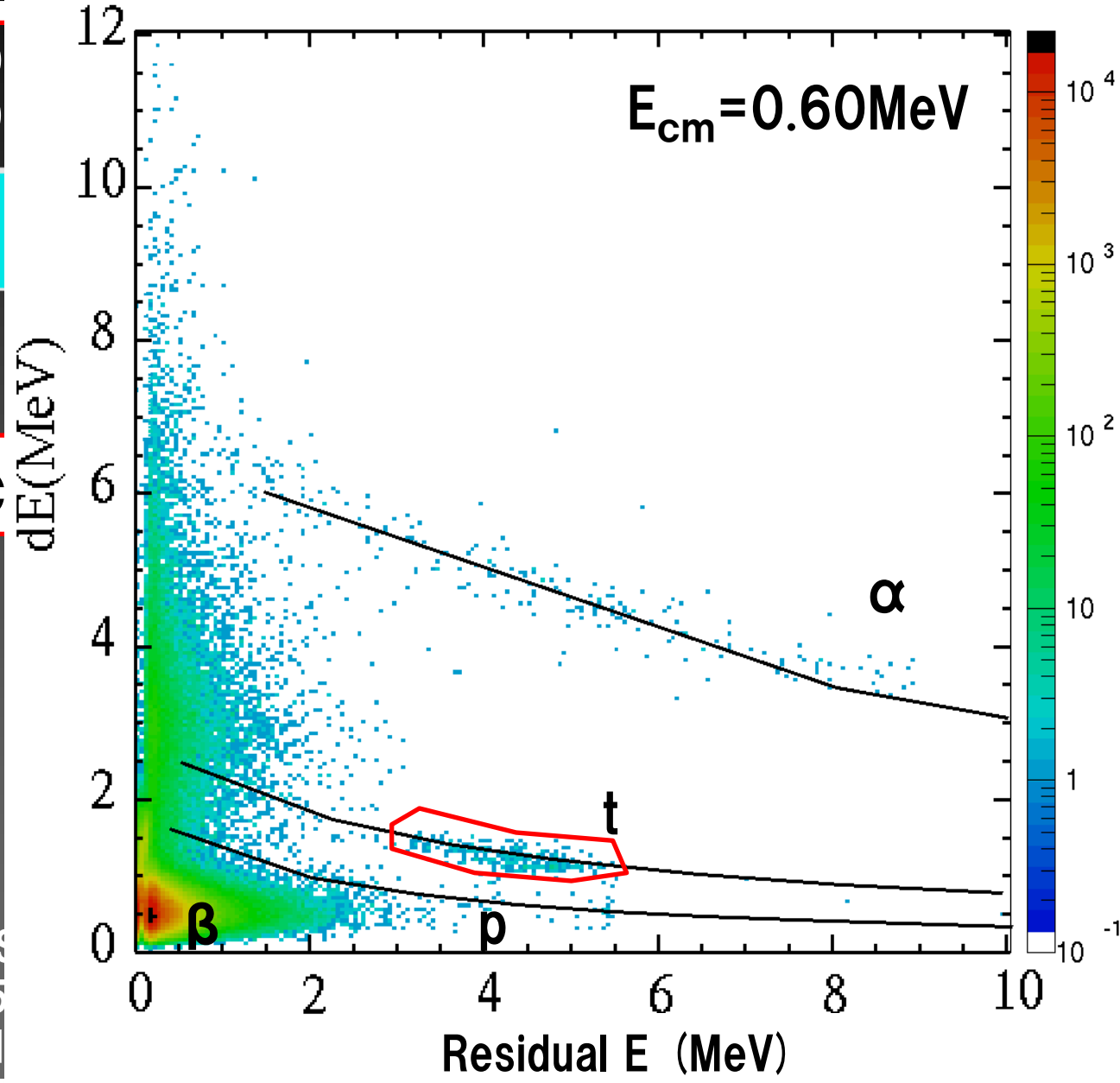
Angular distribution of triton from 22.7 to 120 deg

SSD1 θ
SSD2 θ

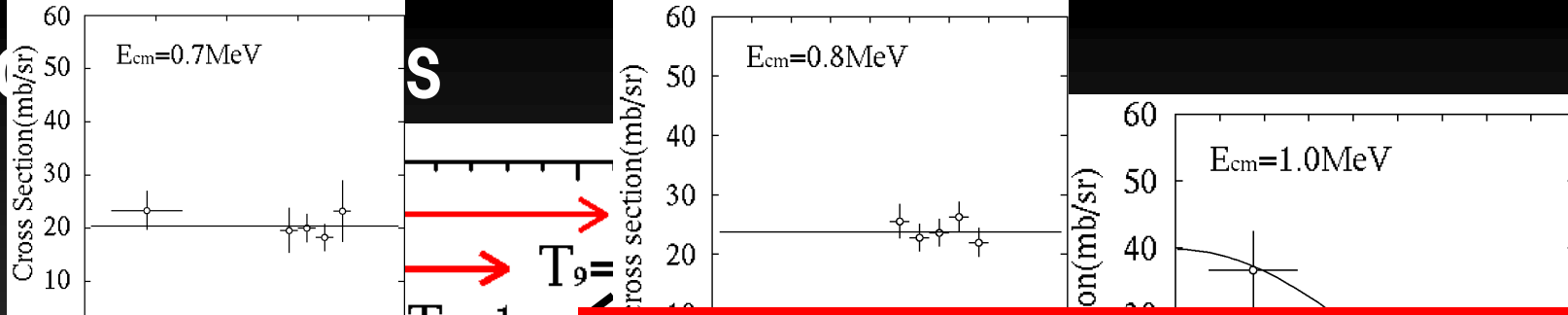
p, t, α

Coinc
 ^8Li beam

DSSD: Double S
50x50mm
SSSD: Single S
50x50mm, x=16strips

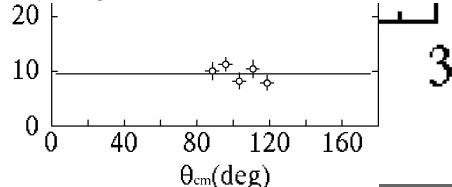
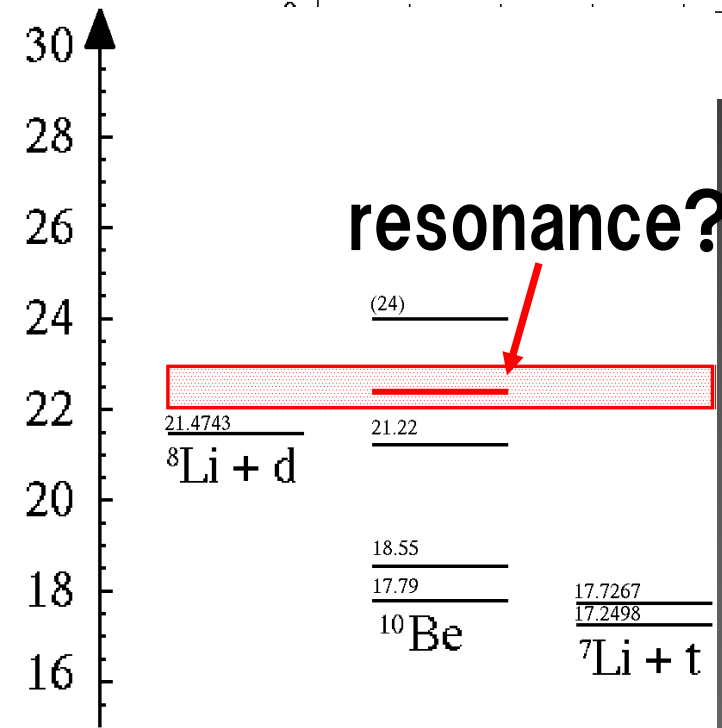
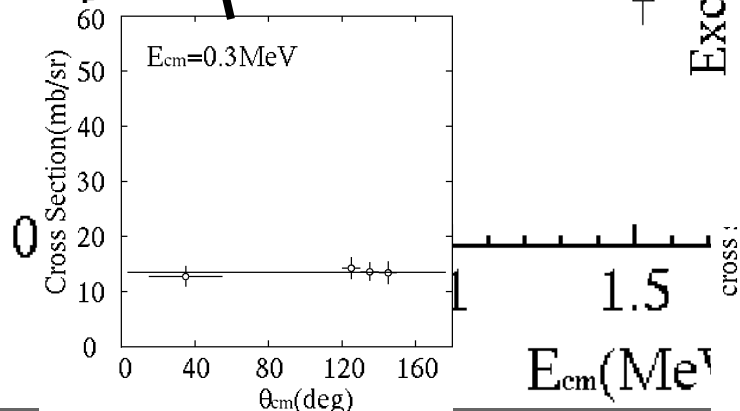
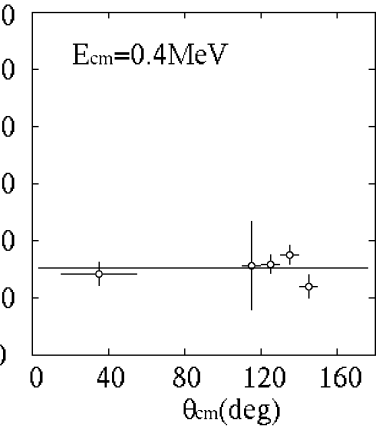
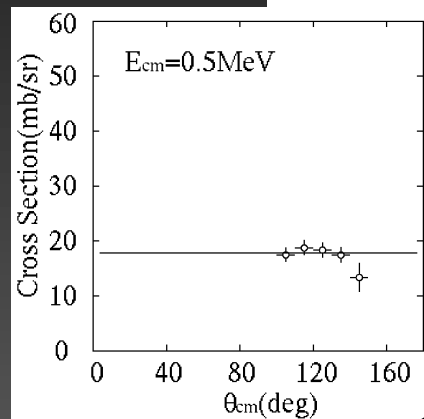


Total cross

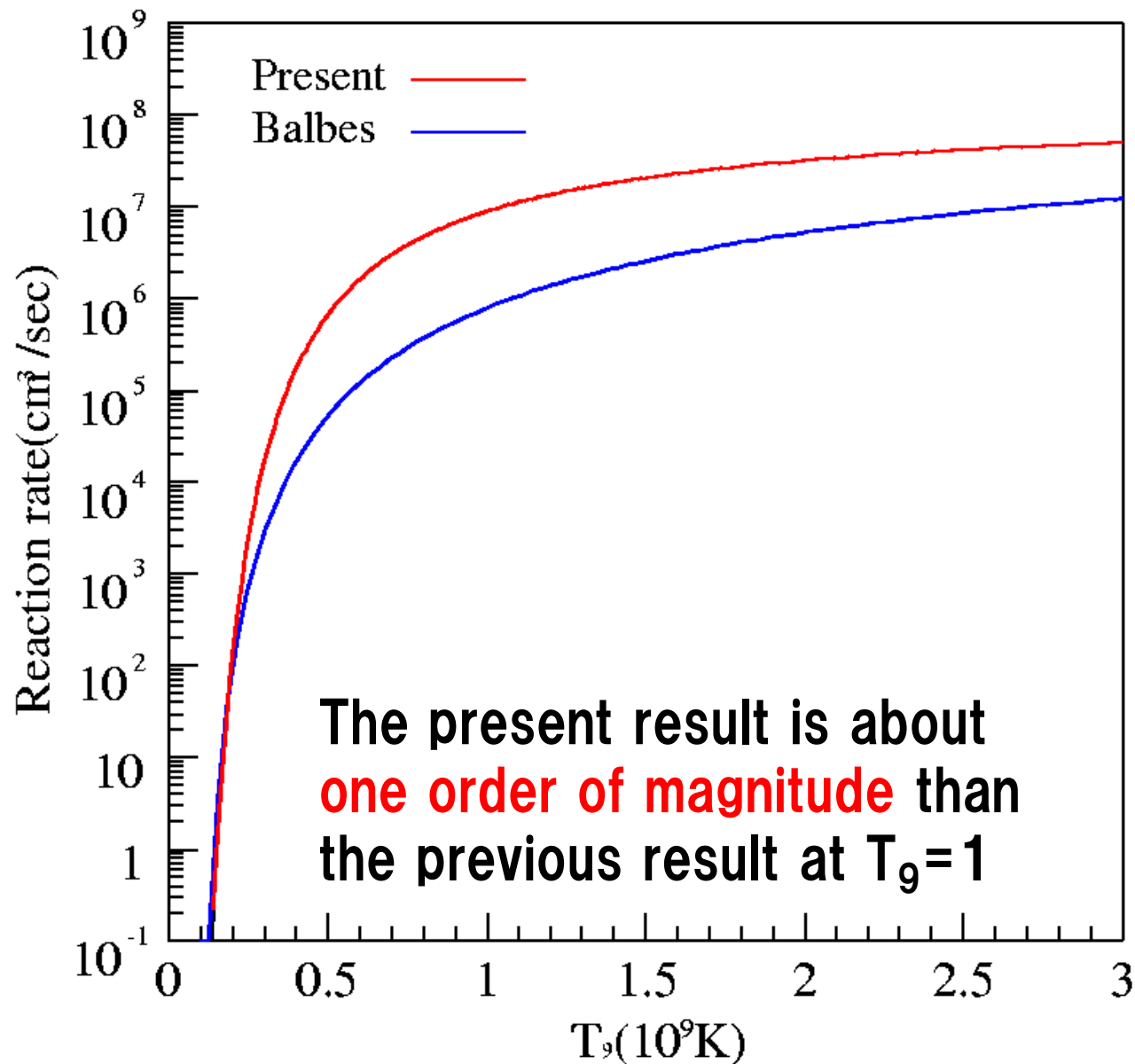


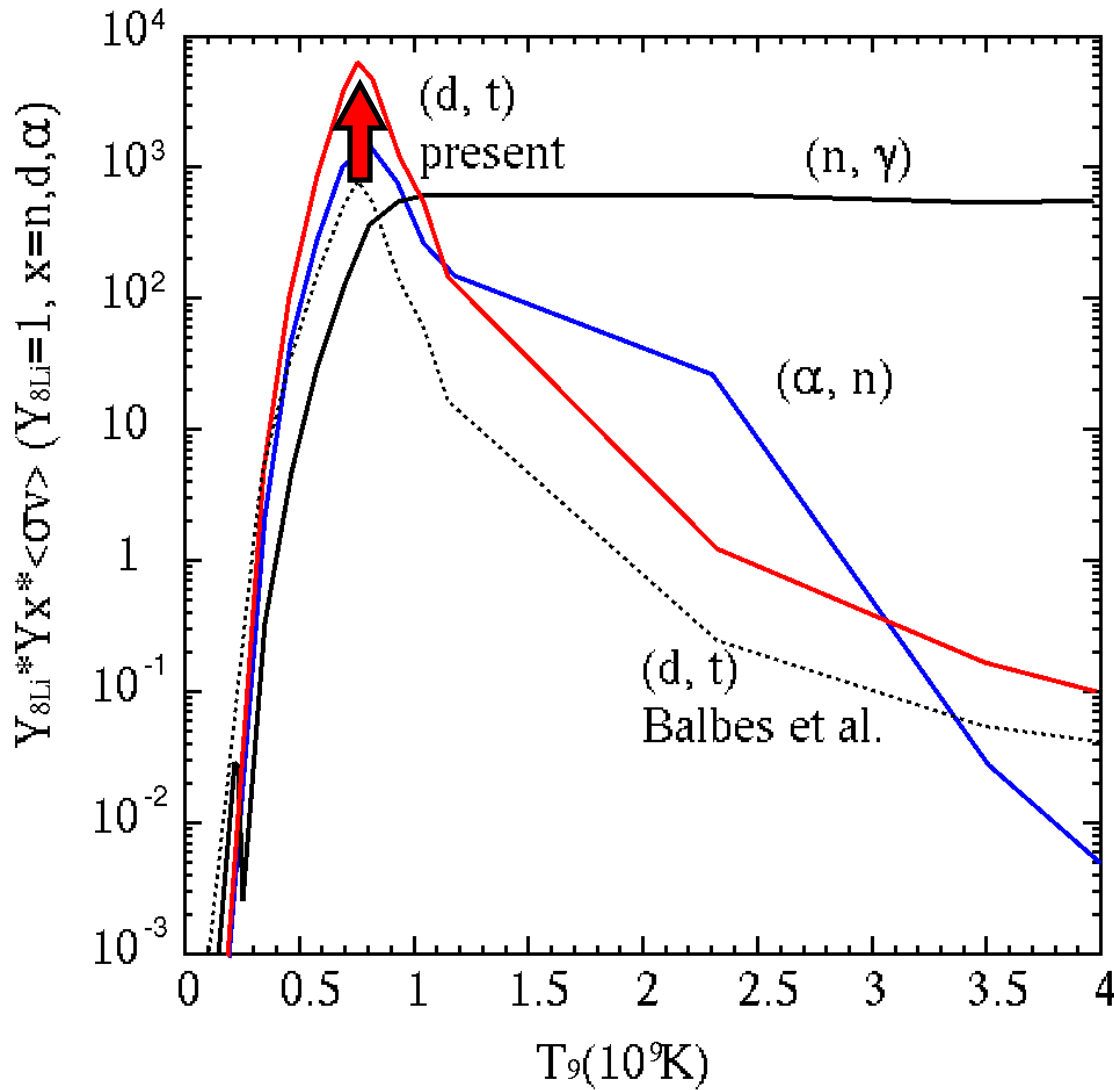
Existence of a new excited state around 22.4MeV in ^{10}Be

Unexpected cross section at $E_{cm}=0.8\text{MeV}$



Reaction rate





Nucleosynthesis model

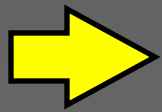
→ IBBN model

E. Keihanen, Phys. Rev. D66 (2002) 043512

The rate of ${}^8\text{Li} (d, t) {}^7\text{Li}$ reaction is not so larger than (n, γ) , (α, n) reactions

The rate of ${}^8\text{Li} (d, t) {}^7\text{Li}$ reaction below $T_9 = 1.0$ becomes larger than those of (n, γ) and (α, n) reactions

We are calculating the detail of the effect of the present result.



The calculated result will be presented at INPC2007

Summary

The direct measurement of the ${}^8\text{Li} (d, t) {}^7\text{Li}$ reaction have been performed at TRIAC

${}^8\text{Li}$ beam

Intensity 10^5 pps, purity 100%

$E_{\text{cm}} = 1.2, 1.1, 1.0, 0.8, 0.7, 0.5, 0.4, 0.3$ MeV

→ $T_9 = 1$ to 3

Unexpected large cross sections around $E_{\text{cm}} = 0.8$ MeV

→ It suggests existence of a new excited state

around 22.4MeV in ${}^{10}\text{Be}$.

Reaction Rate

The present result is about one order of magnitude than the previous result at around $T_9 = 1$

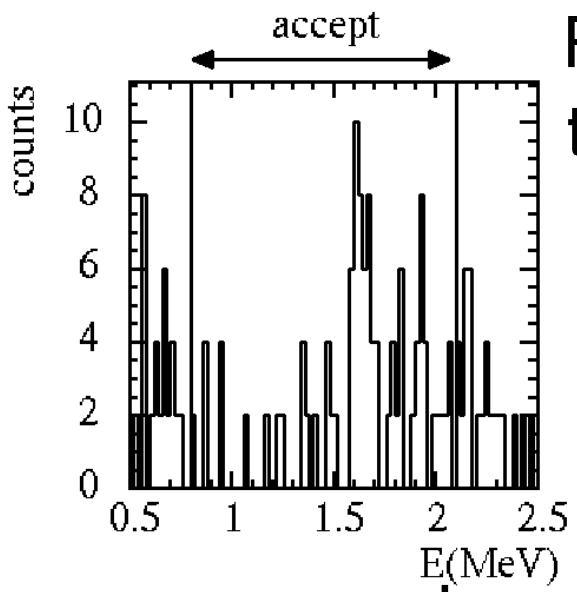
The detail of the effect of this result in a nucleosynthesis network calculation will be presented at INPC2007 (H1-4, H. Ishiyama et al.)

Backup slid

Analysis(Upstream side)

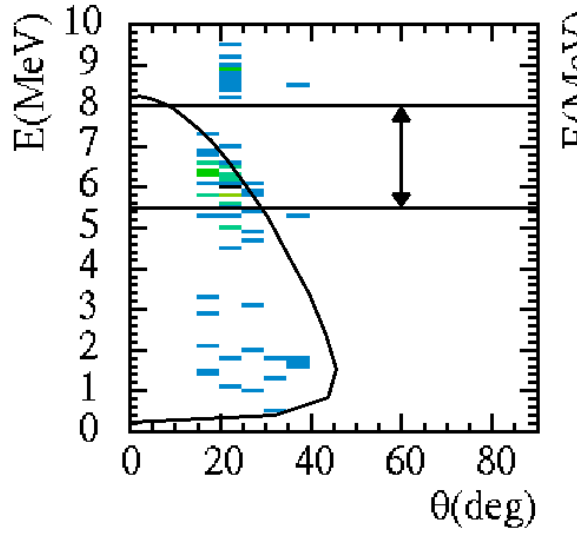
Coincidence events

Required kinematical condition of the ${}^8\text{Li}(d, t){}^7\text{Li}$ reaction

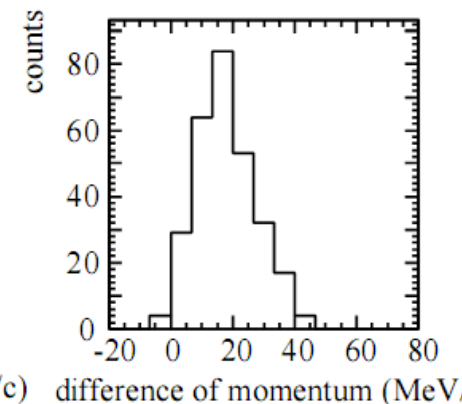
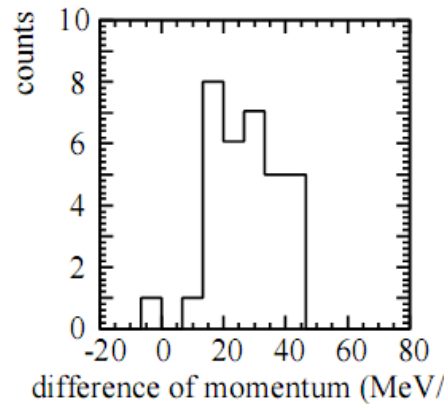
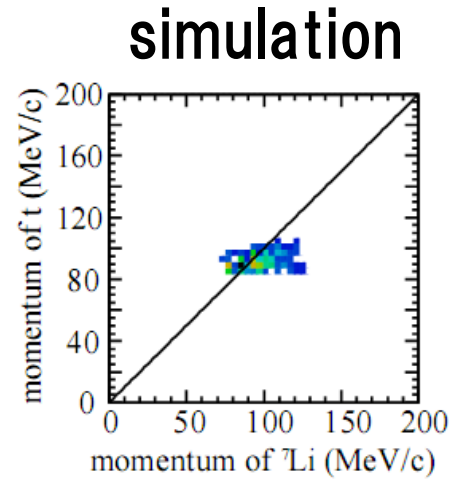
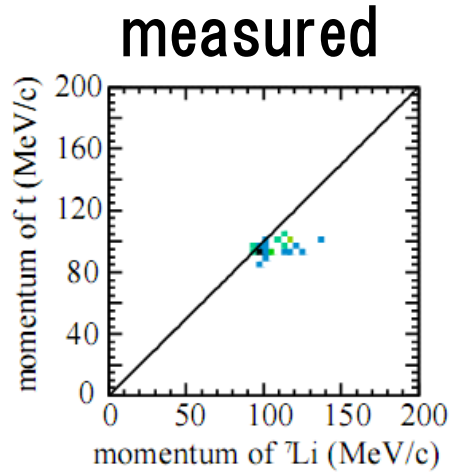


measured

transverse

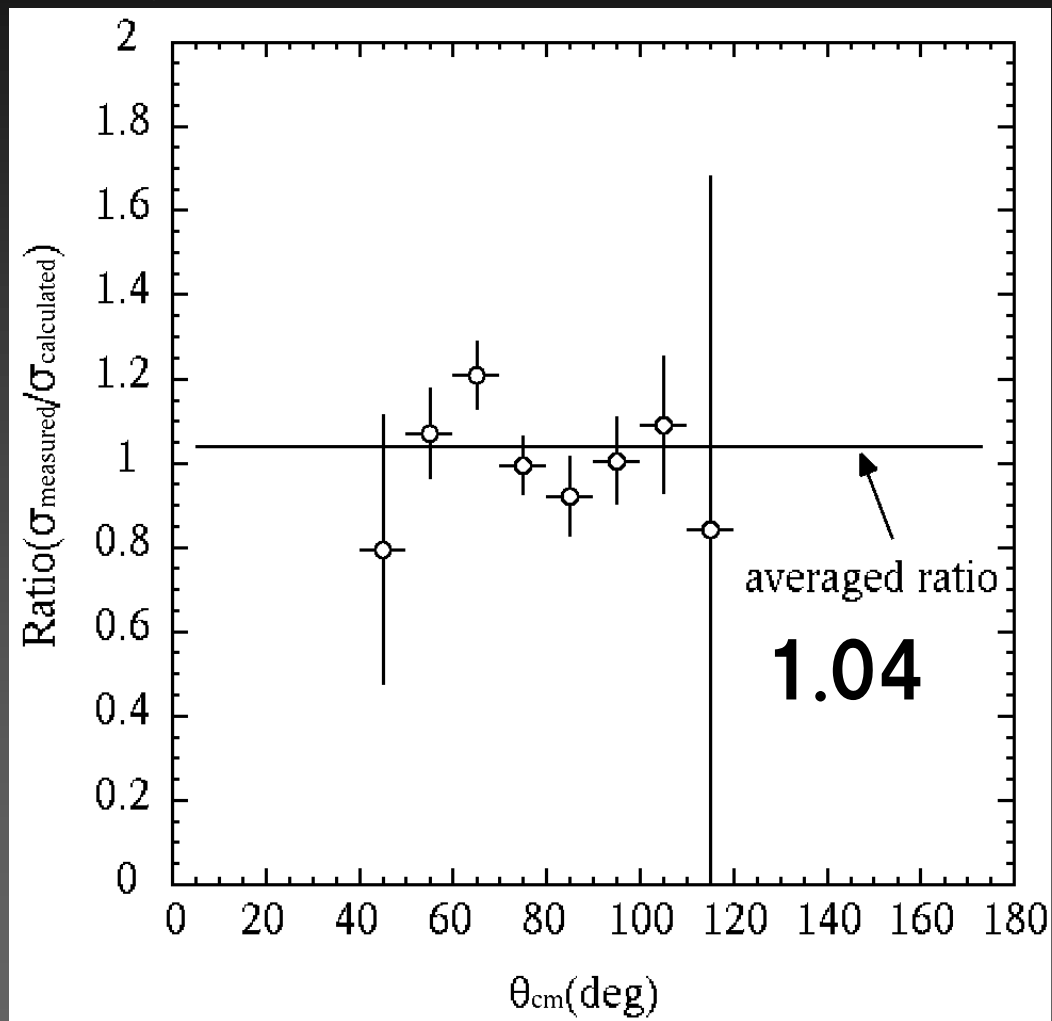
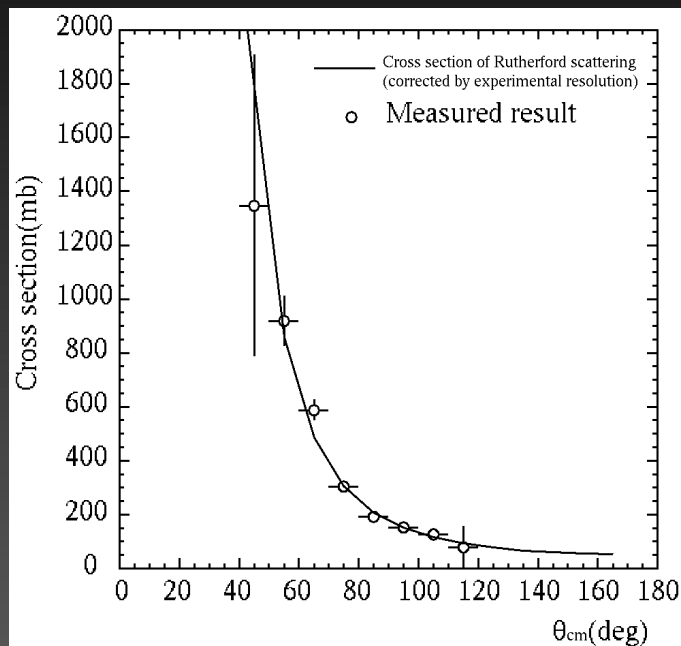


parallel



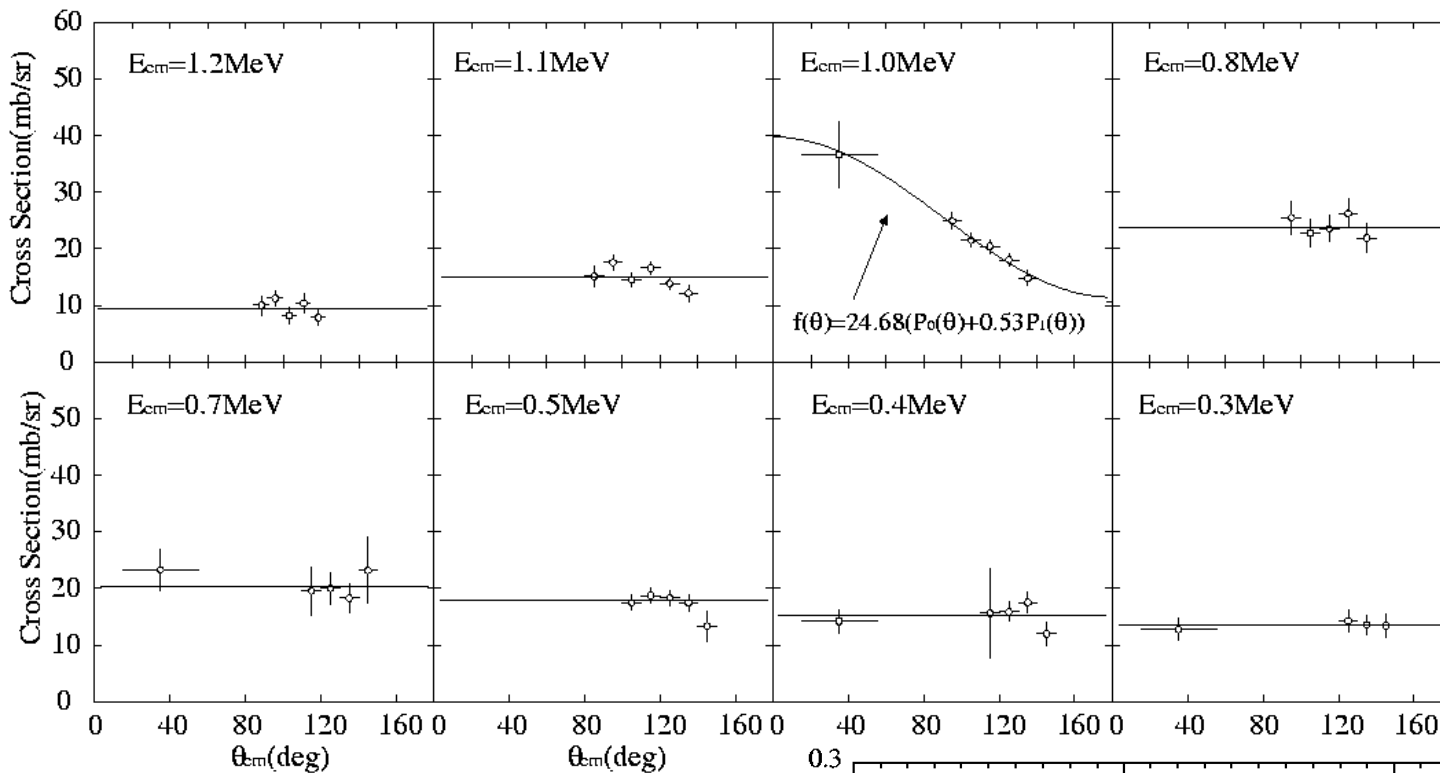
Verification of the present experiment procedure

Elastic scattering of ${}^8\text{Li}+{}^{12}\text{C}$

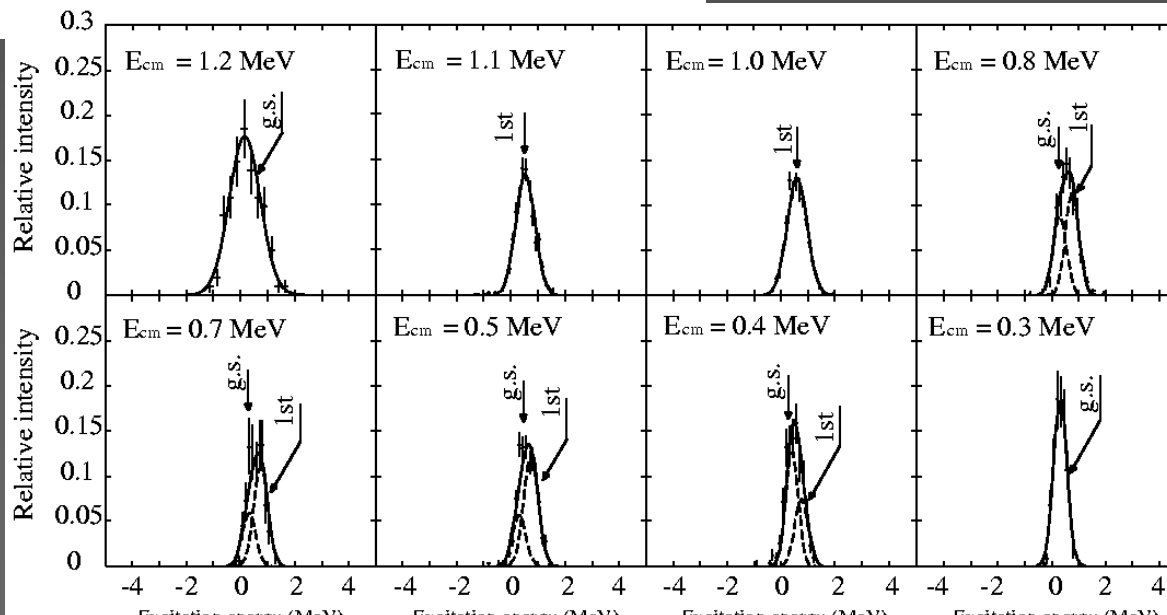


The present results include $\pm 4\%$ systematic error

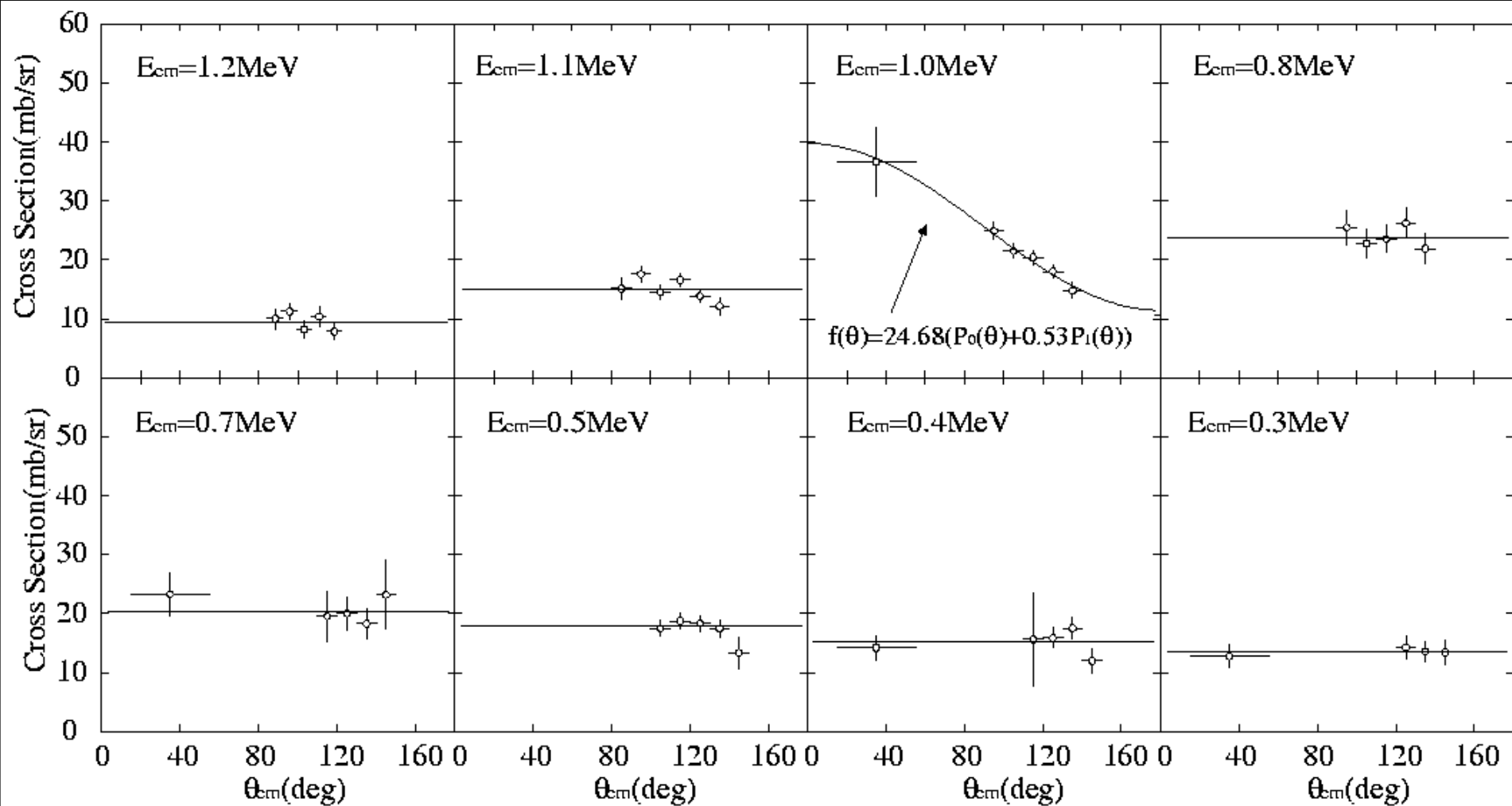
Angular distributions



Excitation energy spectra of ${}^7\text{Li}$

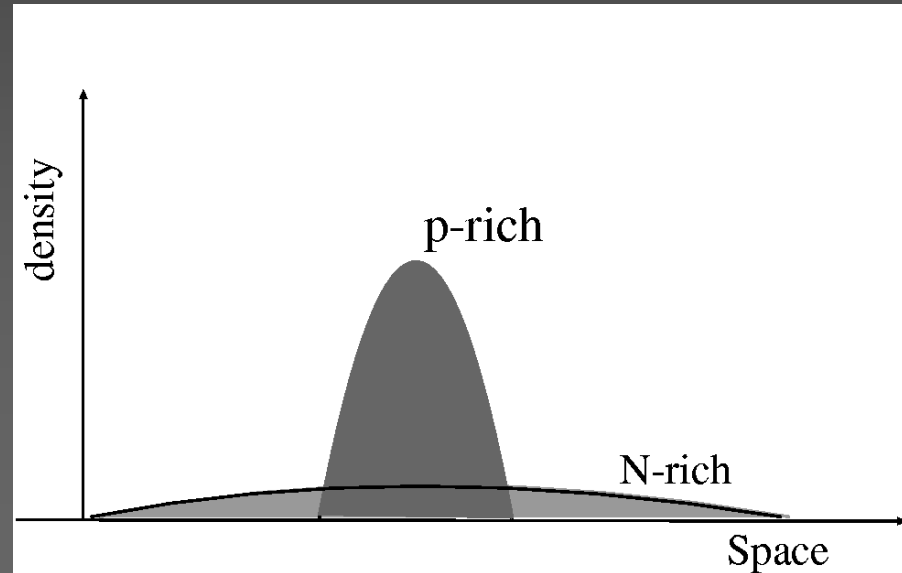
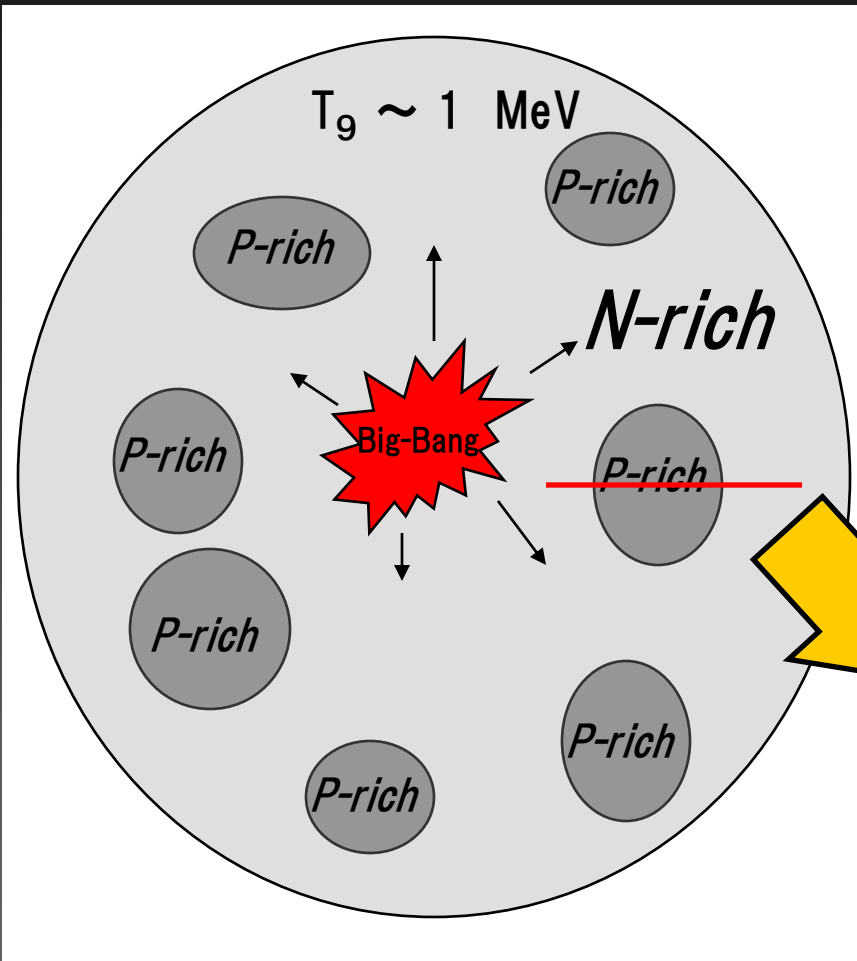


Angular distributions



Inhomogeneous Big-Bang Model (IBBM)

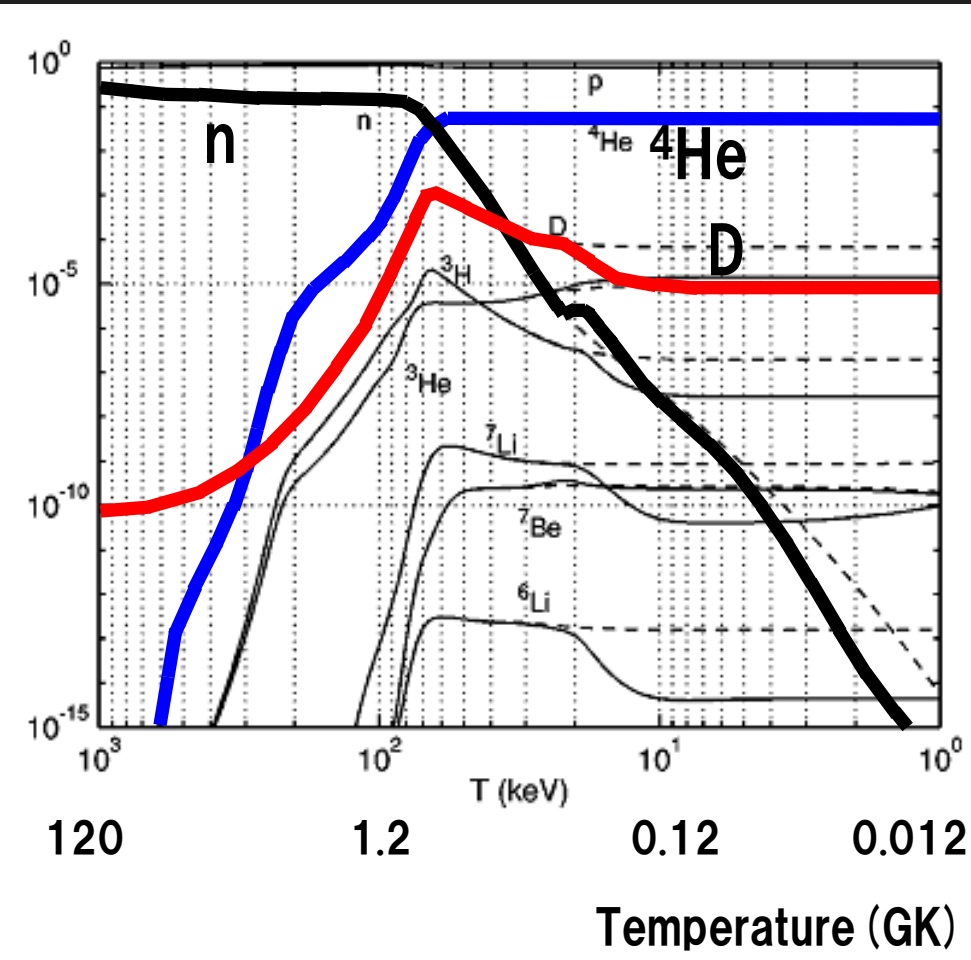
The density of proton and neutron becomes inhomogeneous



Inhomogeneous Big-Bang model

E. Keihanen, Phys. Rev. D66 (2002) 043512

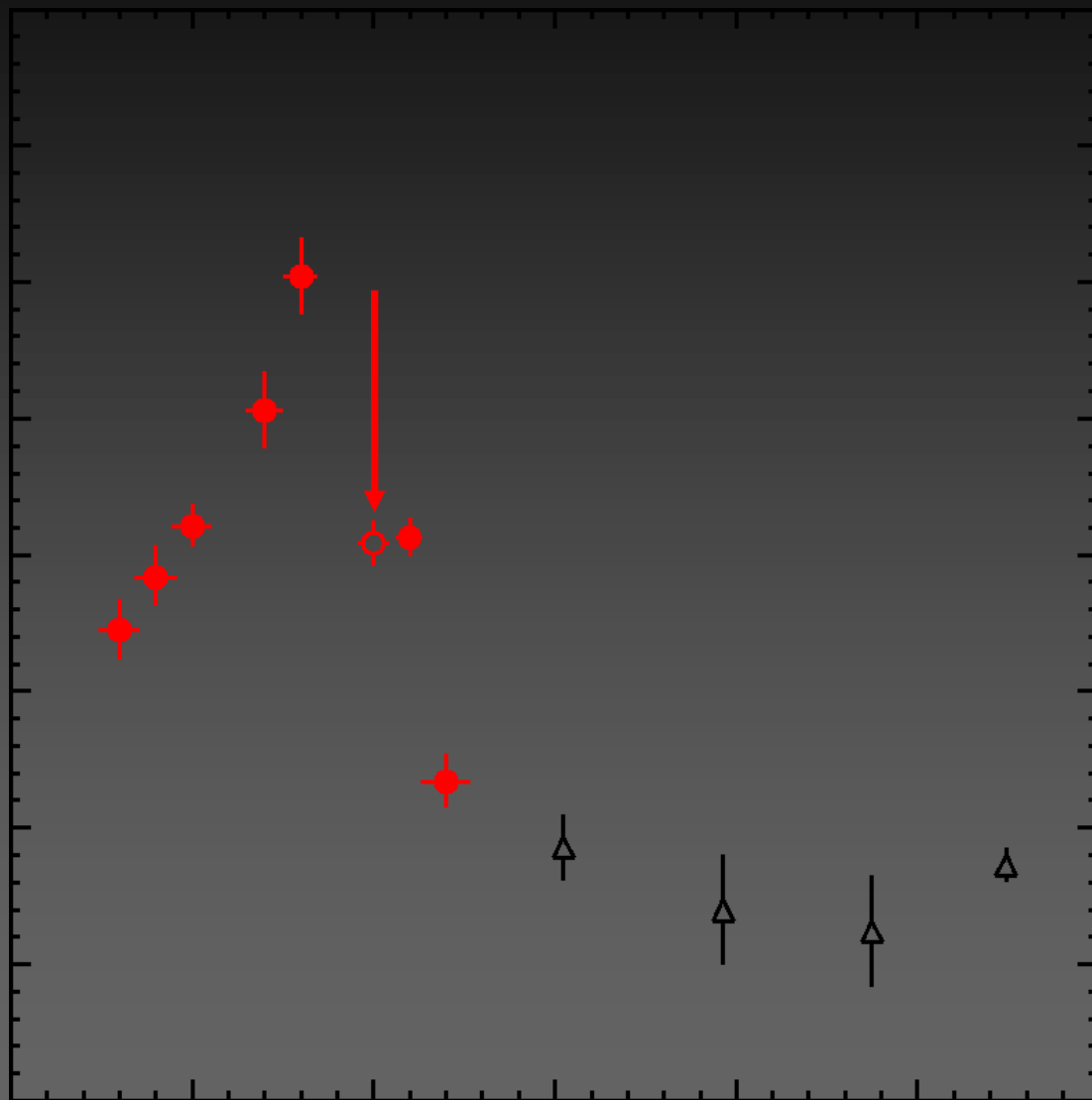
Evolution of the abundance of light isotopes



Inhomogeneous big-bang nucleosynthesis with hydrodynamics.

Calculated condition

- Spherical symmetry space
- The radius of simulation volume $r=10^7\text{m}$ at $T=1.2\times 10^7\text{K}$
- Initial density distribution \rightarrow step like
- $R = \eta_h / \eta_l = 10^6$
- Volume fraction $f_v = 0.01$
- Average density $\eta = f_v \eta_h + (1 - f_v) \eta_l = 6 \times 10^{-10}$
(Result from WMAP : $\eta = 6.13 \pm 0.25 \times 10^{-10}$)



Introduction

Explosive Nucleosynthesis

stable
 unstable

Proton ↑

p

D

T

³He

⁴He

⁶He

⁸He

⁶Li

⁷Li

⁸Li

⁹Li

¹¹Li

⁷B

⁹Be

¹⁰Be

¹¹Be

¹²Be

⁸B

¹⁰B

¹¹B

¹²B

¹³B

¹⁴B

¹⁵B

¹⁷B

¹⁹B

¹¹C

¹²C

¹³C

¹⁴C

¹⁵C

¹⁶C

¹⁷C

¹⁸C

¹⁹C

²⁰C

¹³N

¹⁴N

¹⁵N

¹⁶N

¹⁷N

¹⁸N

¹⁹N

²⁰N

²¹N

¹⁵O

¹⁶O

¹⁷O

¹⁸O

¹⁹O

²⁰O

²¹O

²²O

¹⁹F

²⁰F

²¹F

²²F

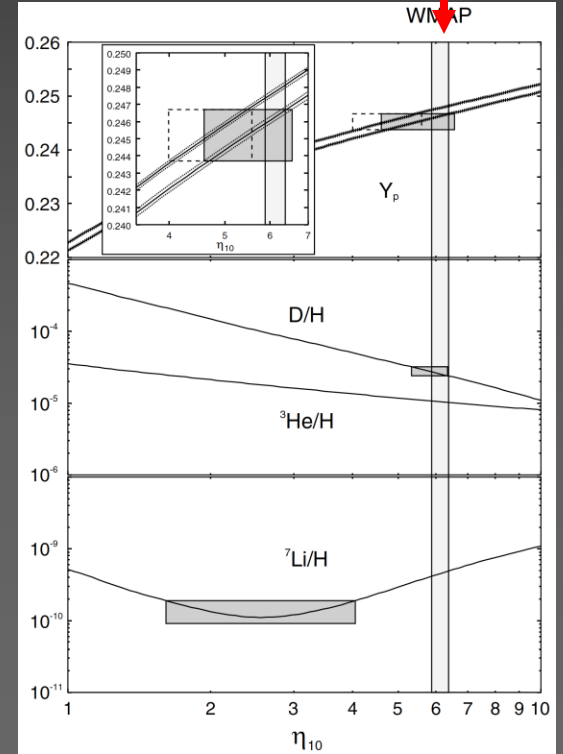
²³F

²⁴F

Neutron →

n

WMAP: $\Omega_b h^2 = 0.024 \pm 0.001$

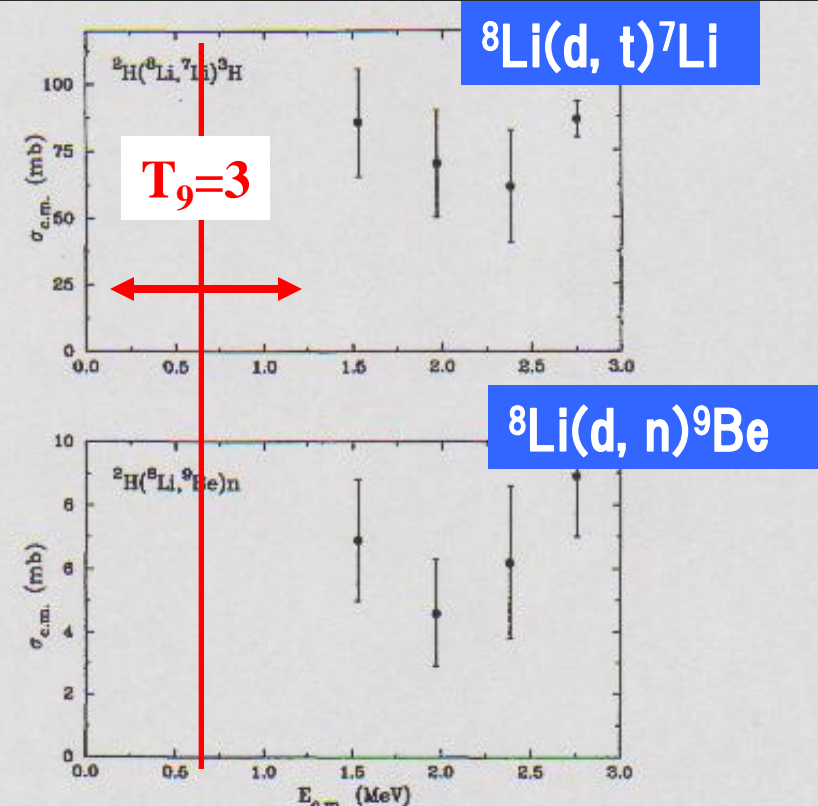
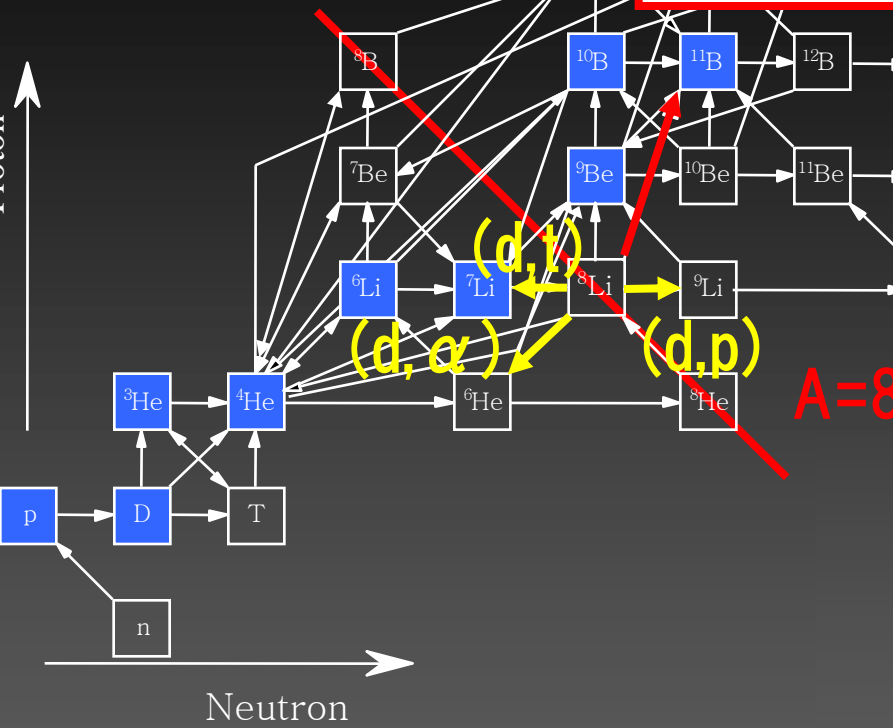


Supernova Explosion & Big-bang nucleosynthesis

$$T_9 = 1 \sim 3 \quad (T_9 = 10^9 \text{ K})$$

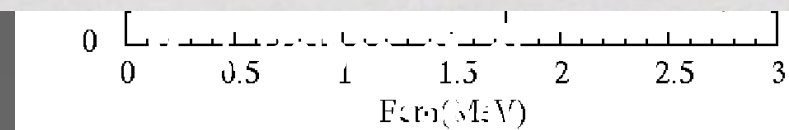
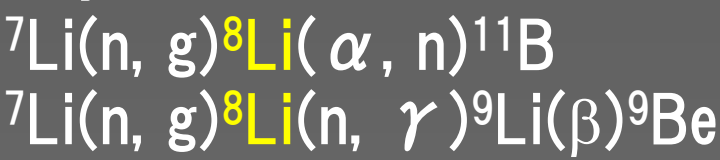
stable
 unstable

Inhomogeneous Big-Bang Model (IM) a theoretical candidate to solve this problem

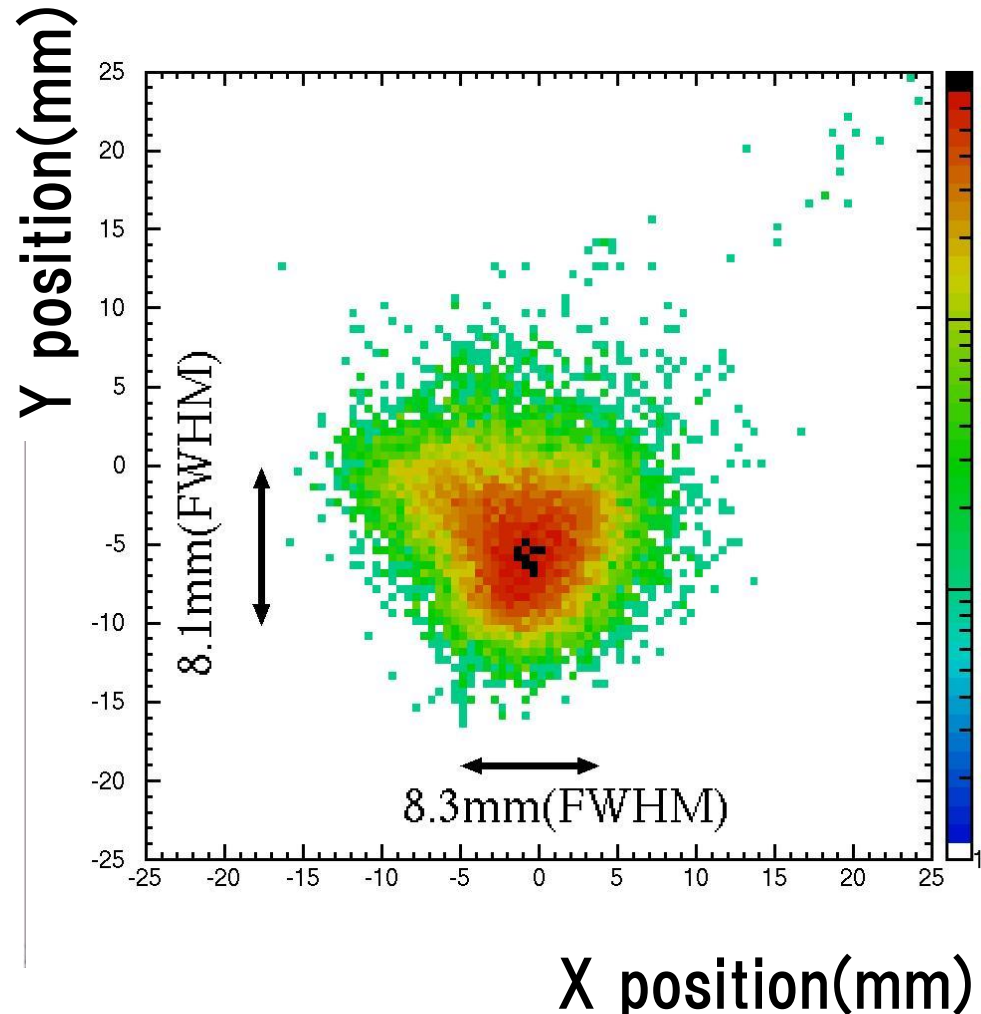
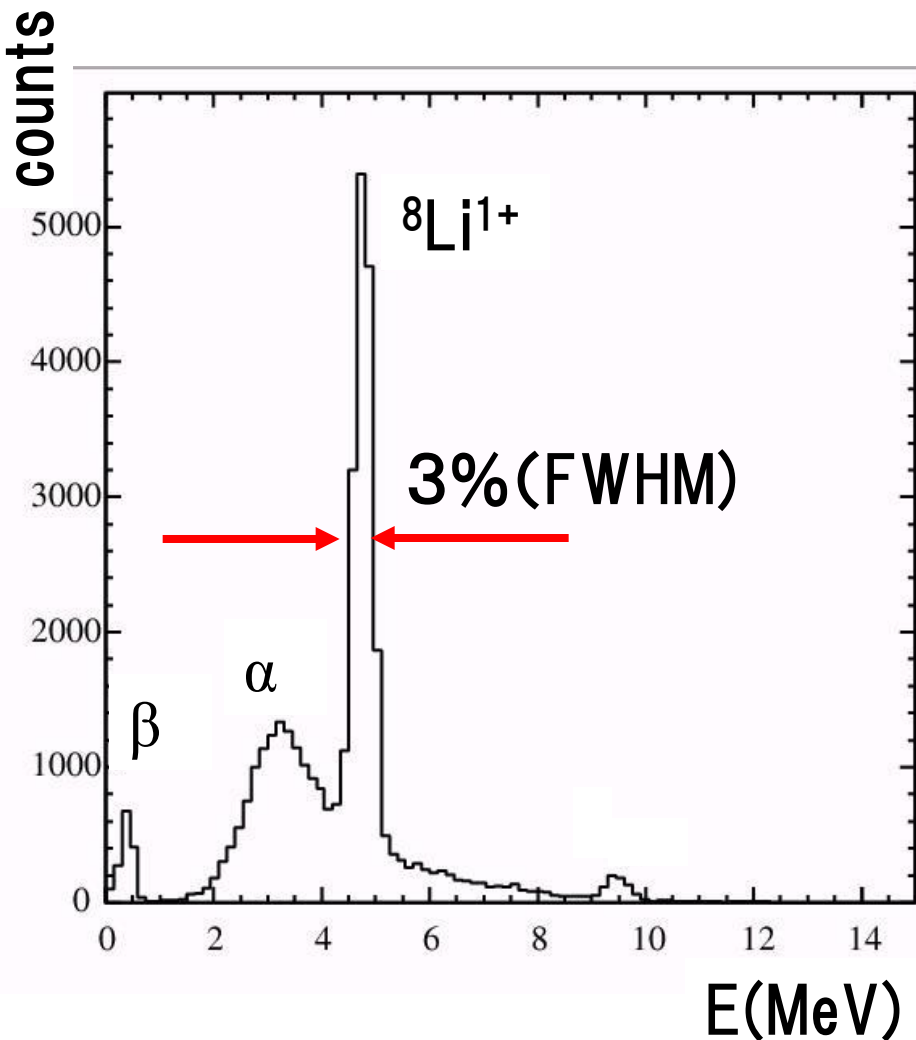


Measured result at Notre Dame Univ.

Key Reaction



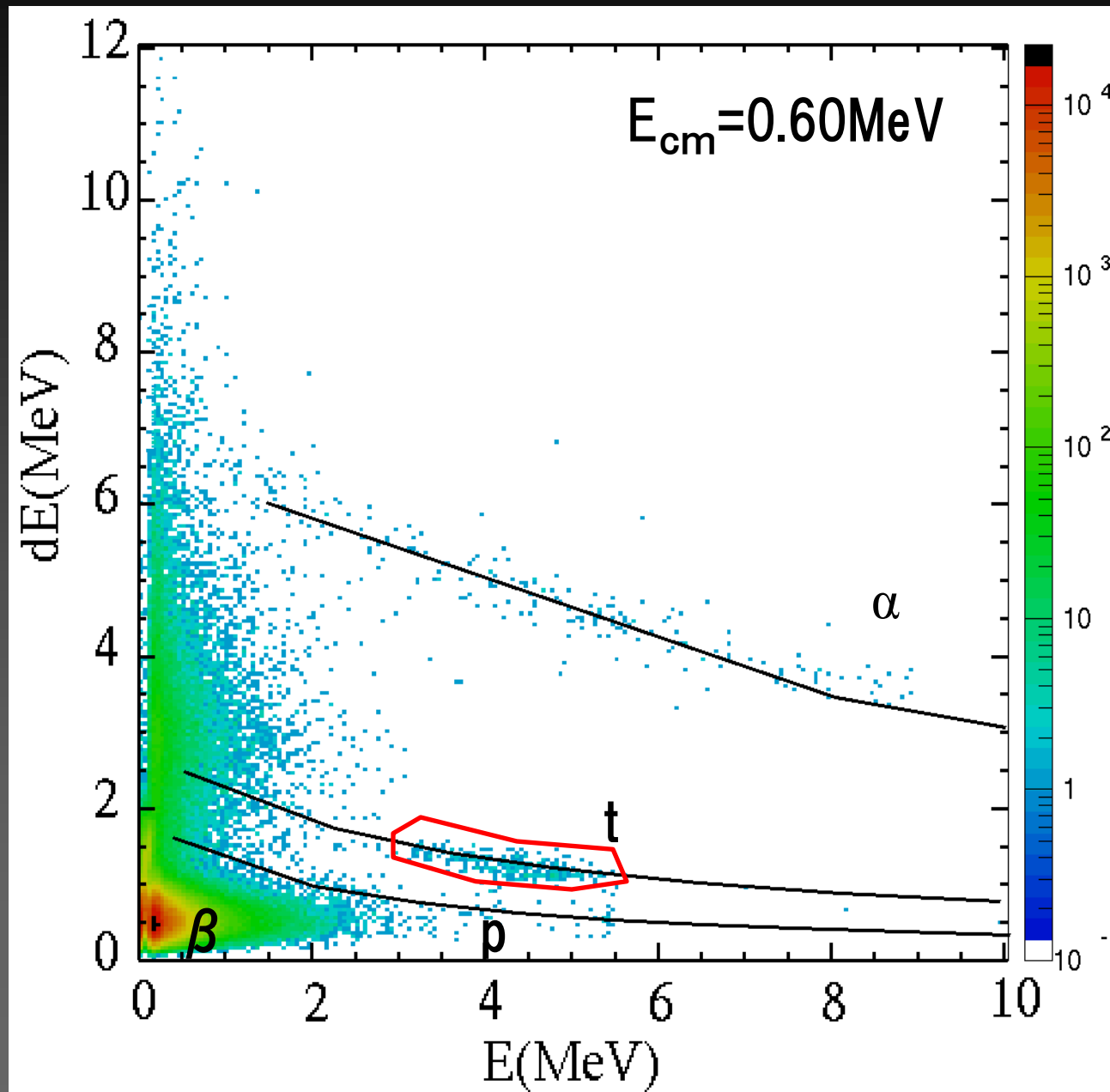
Beam profile



$E=0.6\text{MeV/u}$ 、 $I=8.1 \times 10^4\text{pps}$ 、purity $\sim 100\%$

Those profiles were same value in all beam energies

Analysis(Downstream side)



来年度予定

${}^8\text{Li}(d, t)$ 、 (d, p) 、 (d, α) 反応の解析と測定

- ・ ${}^8\text{Li}(d, t)$ は解析はほぼ終了
バックグラウンドの見積もり

系統誤差の見積もり

を行った上で論文投稿

- ・ ${}^8\text{Li}(d, p)$ 、 (d, α) の解析

その他

${}^8\text{B}(\alpha, p)$ 反応測定@RMS

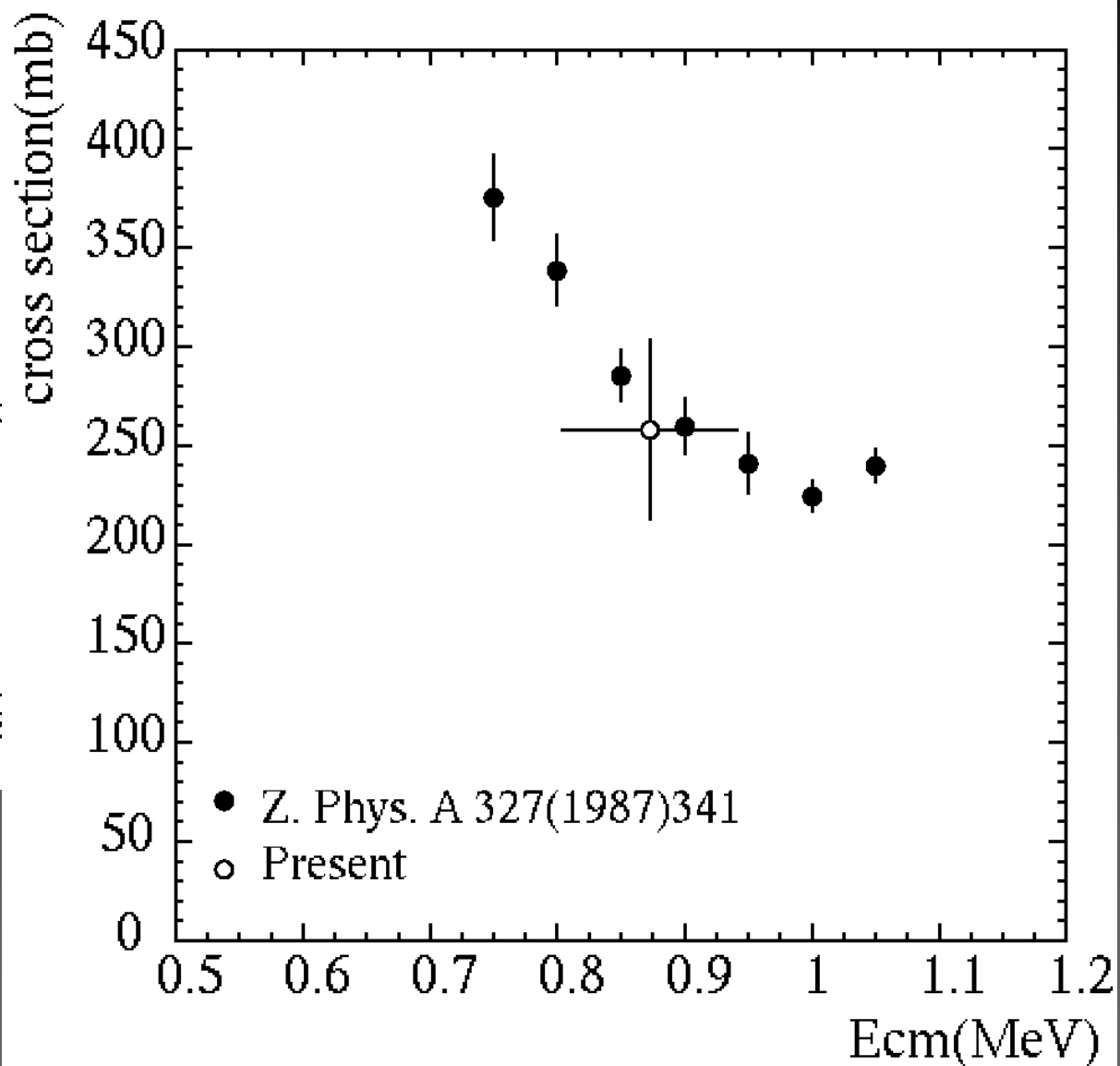
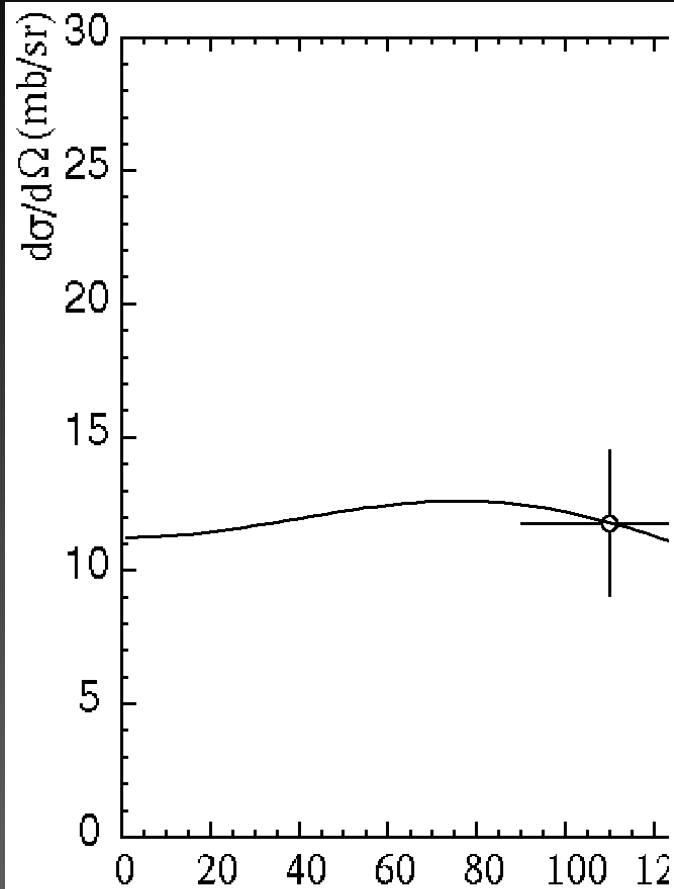
Hot pp-chainから爆発的水素燃焼過程へ抜け出す反応の一つ
本年度3月にRMSにおいてビーム生成実験を予定

${}^8\text{Li}(\alpha, n)$ 反応測定@TRIAC

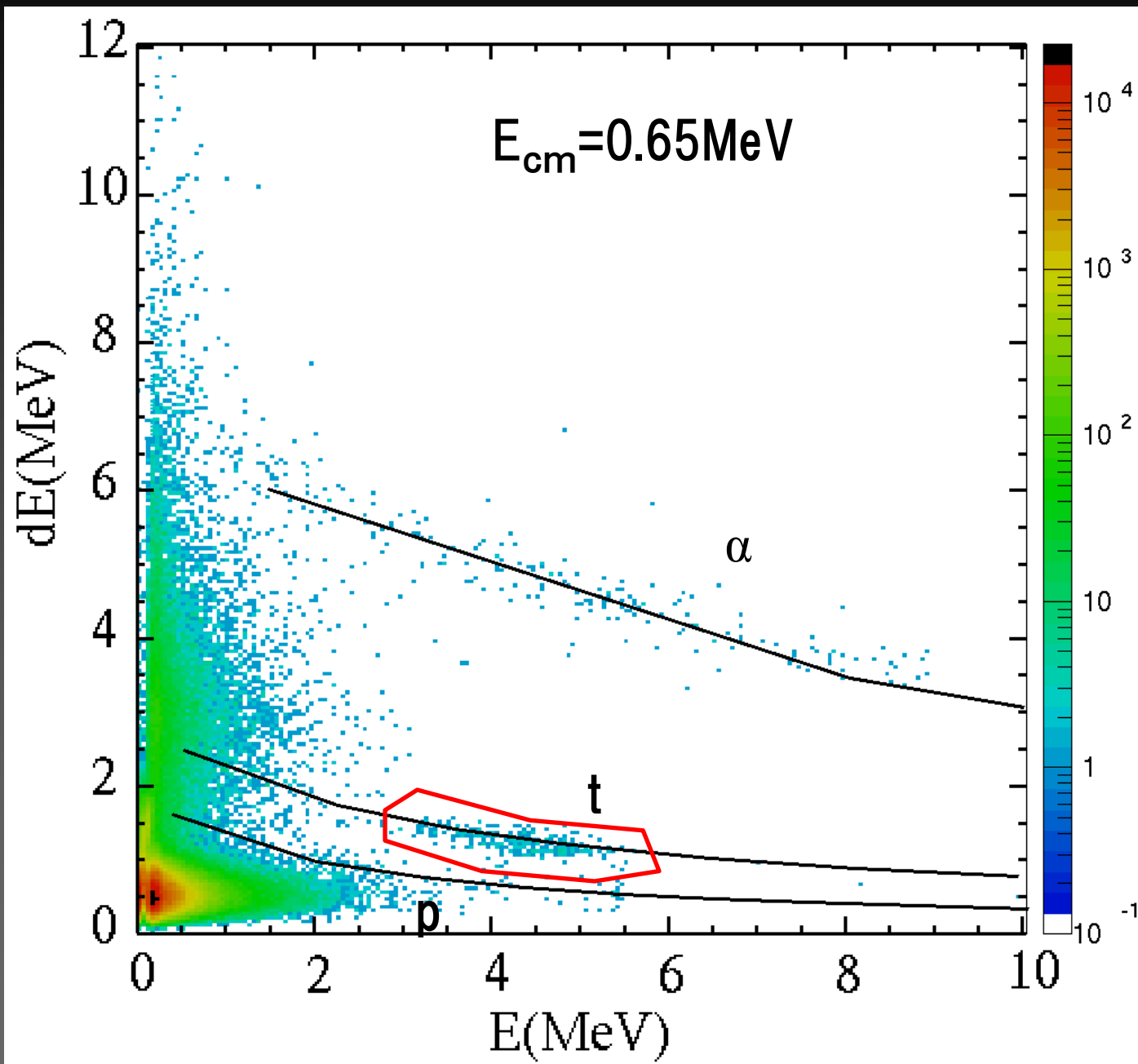
以前の測定で見られた $E_{cm}=0.8\text{MeV}$ 付近の共鳴の
位置、幅、全断面積の高精度測定

来年度夏に ${}^{13}\text{C}(\alpha, n)$ 反応を用いた較正実験を予定

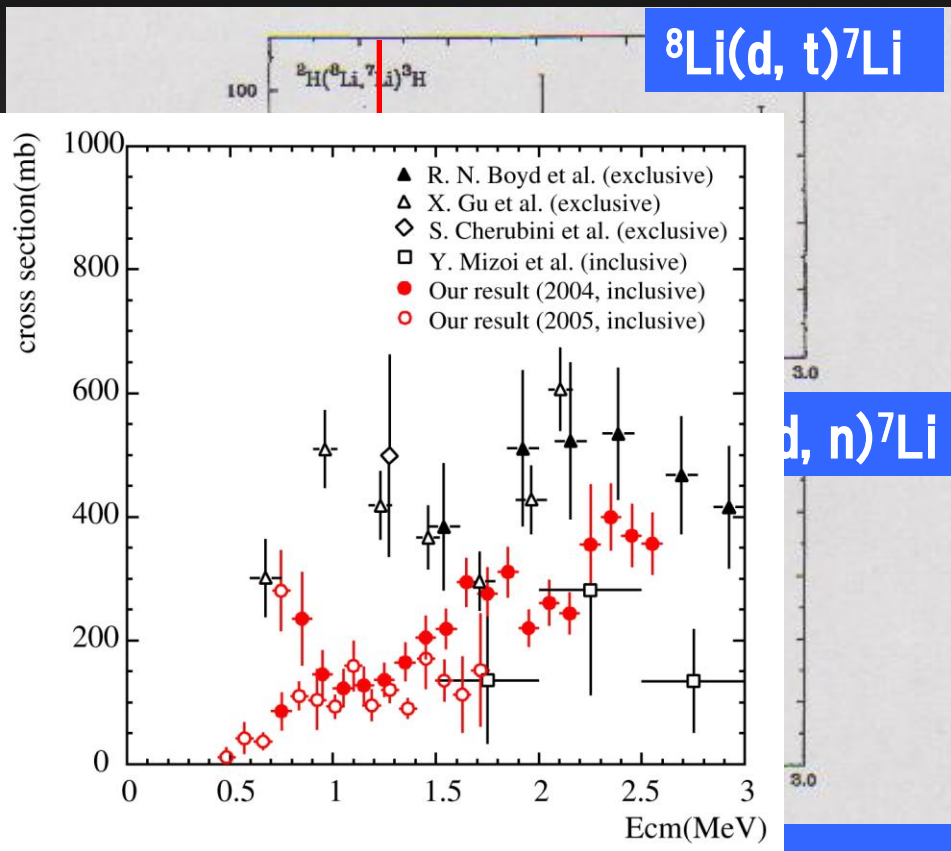
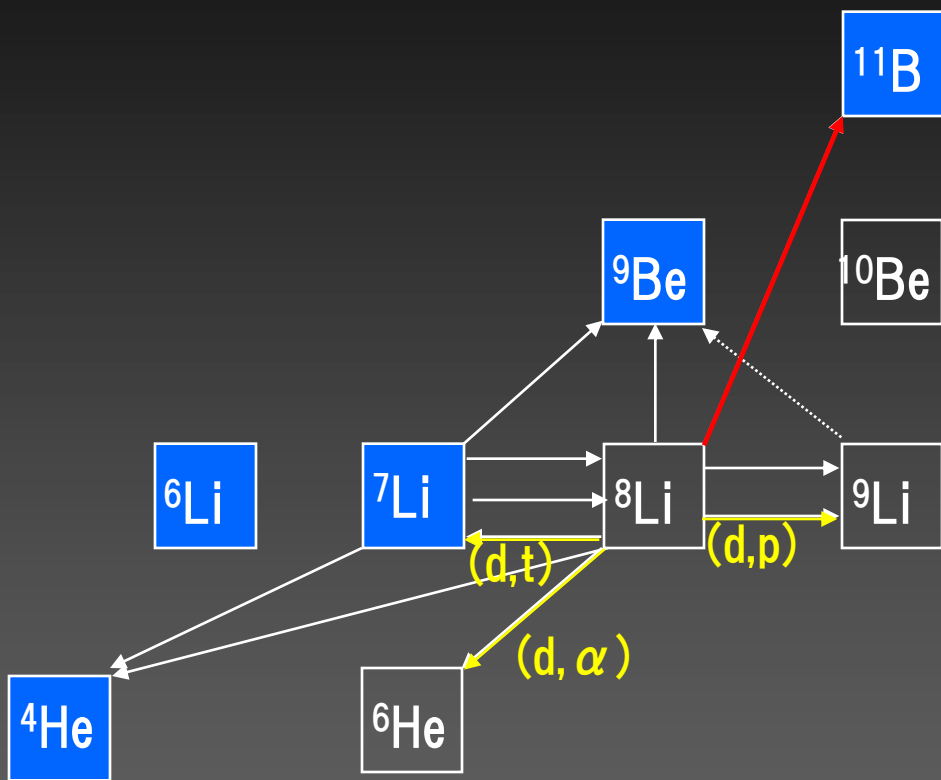
$^{11}\text{B}(p, \alpha)$ reaction cross section



dE-E plot



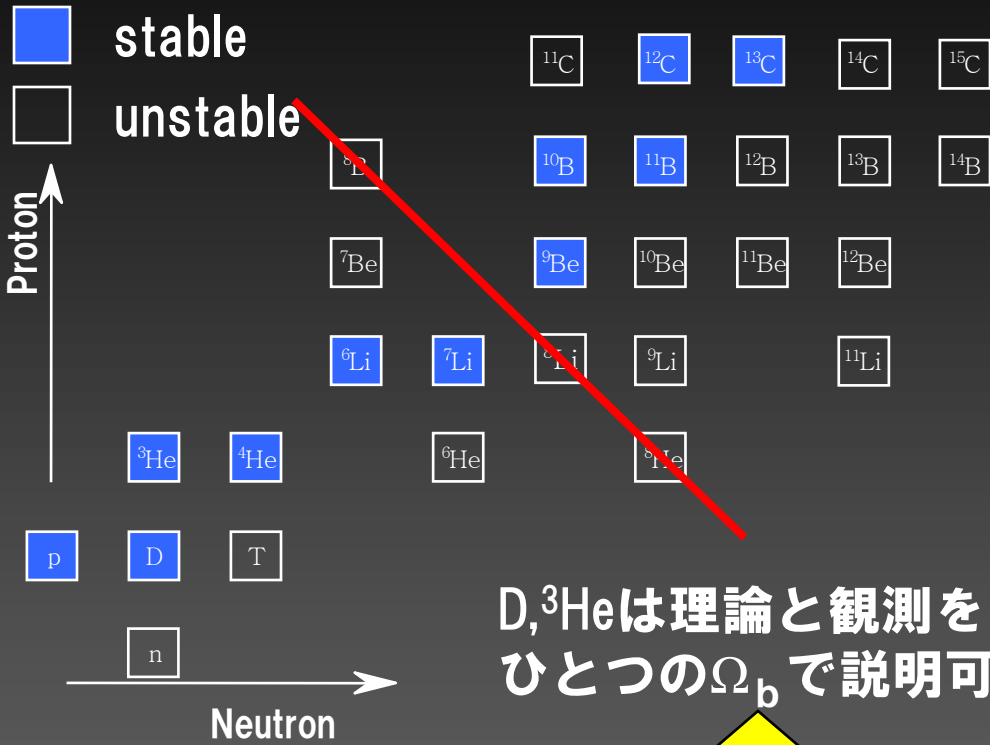
^8Li ・安定核の存在しない質量数8の領域を越える鍵核



ノートルダム大学での測定

M. J. Balbes, et. al.,
Nucl. Phys. A584(1995)315

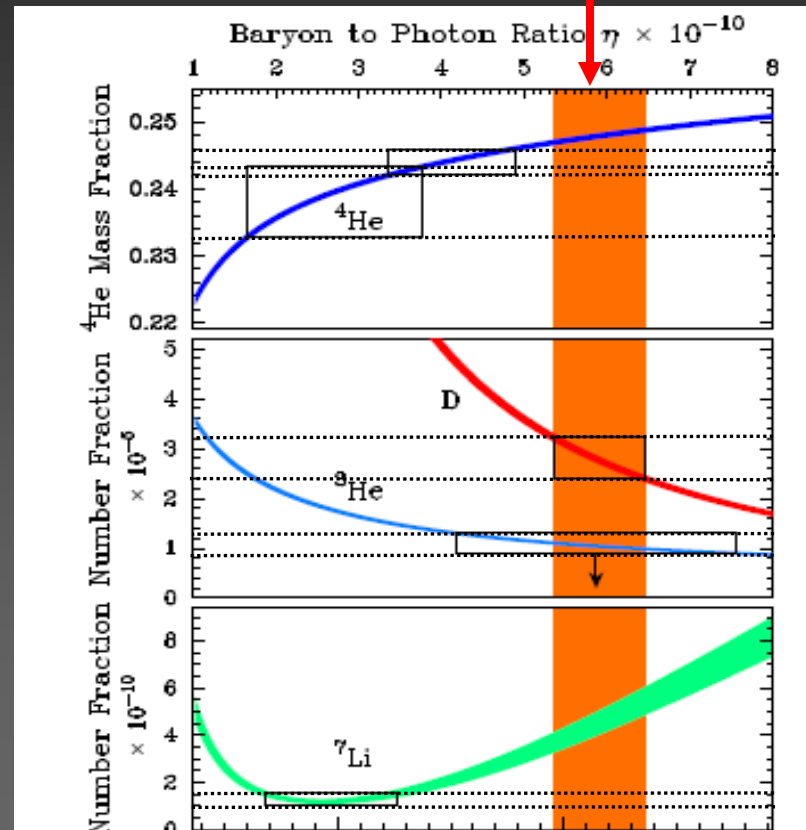
Big-bang nucleosynthesis



WMAP: $\Omega_b h^2 = 0.024 \pm 0.001$

D, ^3He は理論と観測を
ひとつの Ω_b で説明可能

^4He , ^7Li の組は説明不可



観測で得られたバリオン密度を説明しきれない

Collaborators

JAEA 光岡真一、西尾勝久、池添博、市川進一、佐藤哲也、
長明彦、松田誠

KEK 石山博恒、渡辺裕、平山賀一、今井伸明、宮武宇也、
鄭淳讚、田中雅彦、吉川宣治

東京理科大 石川智子、中井浩二

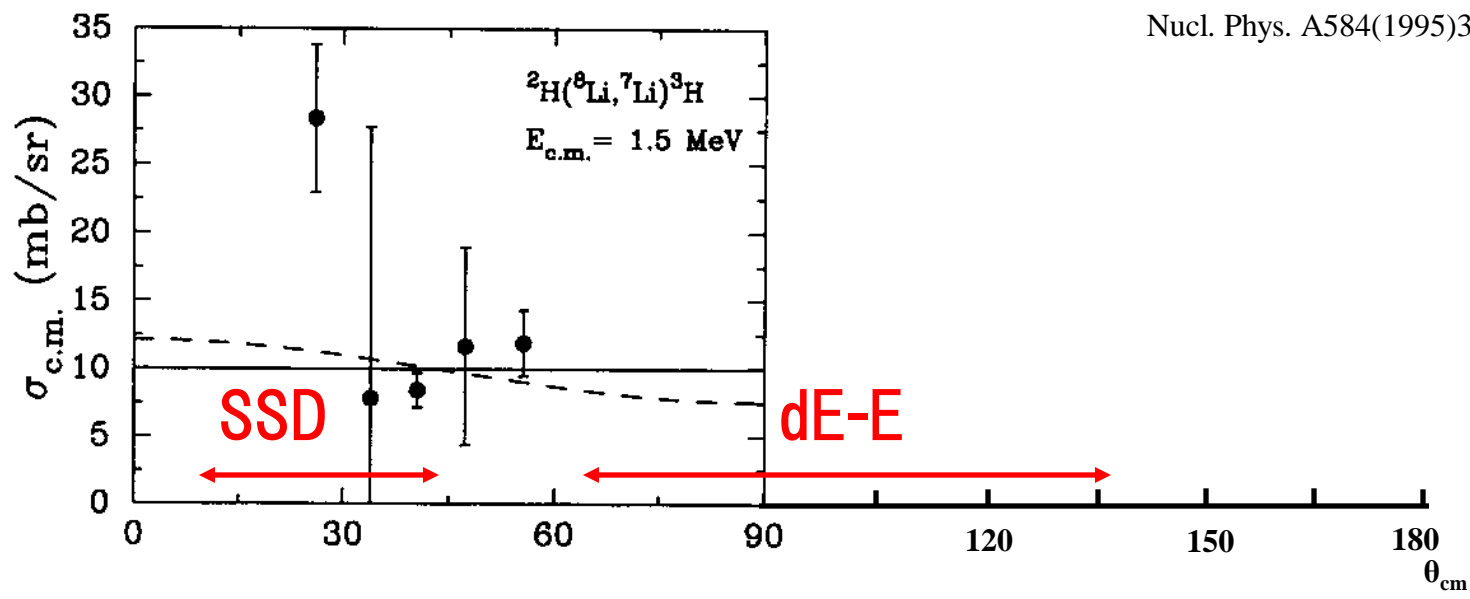
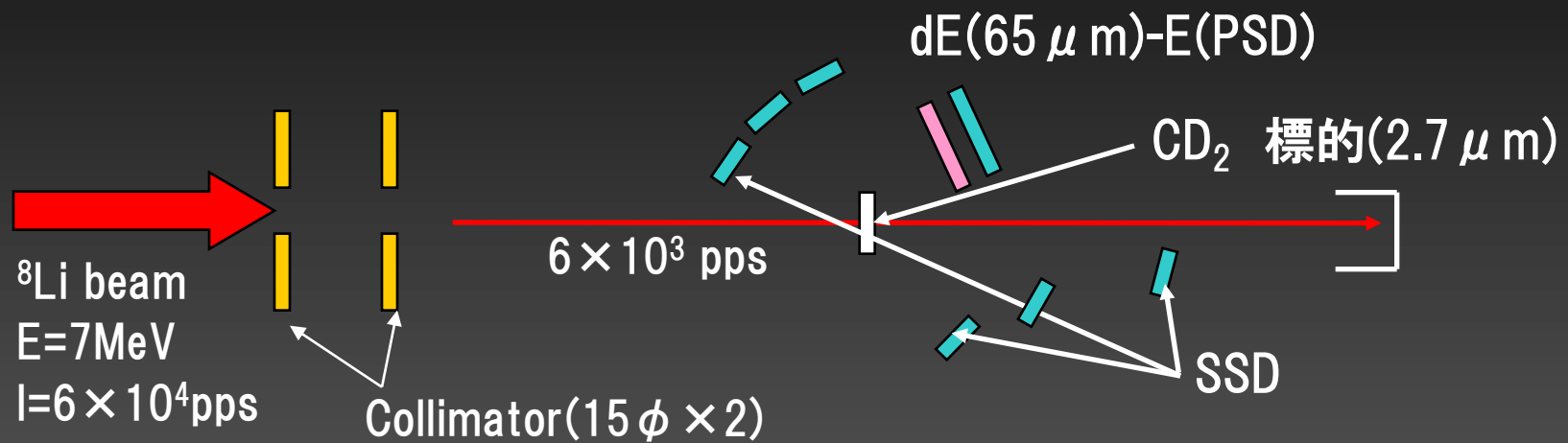
大阪電気通信大学 Suranjan. K. DAS、溝井浩、福田共和

大阪大学 佐藤昭彦、下田正

Test experiment@RMS

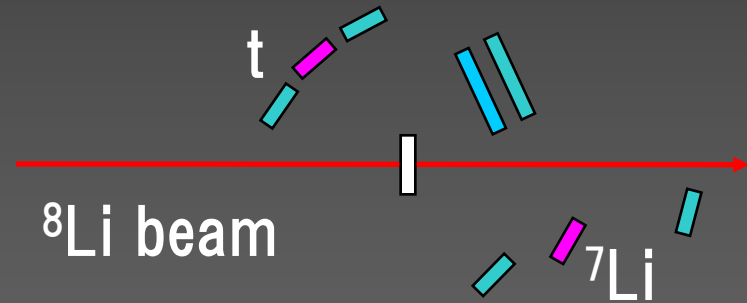
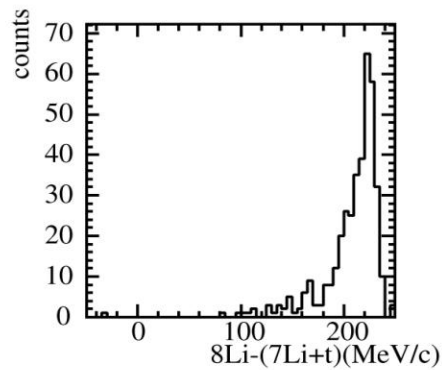
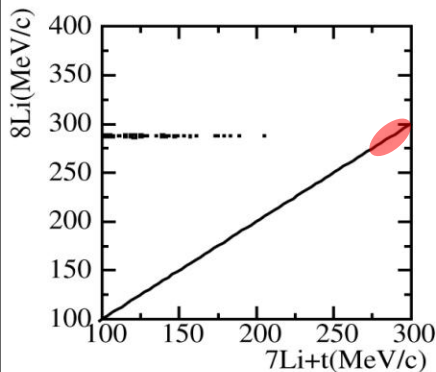
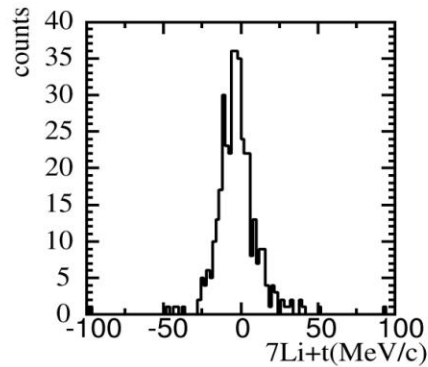
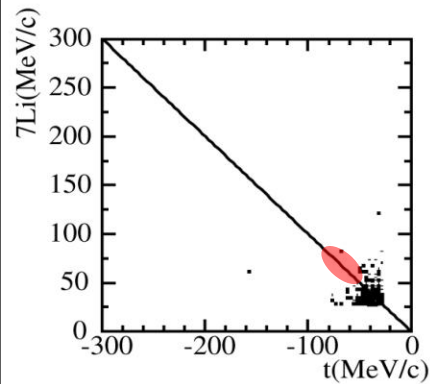
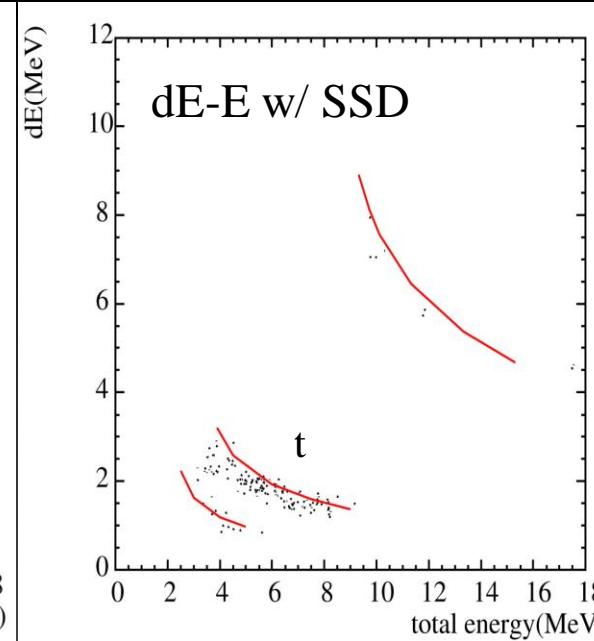
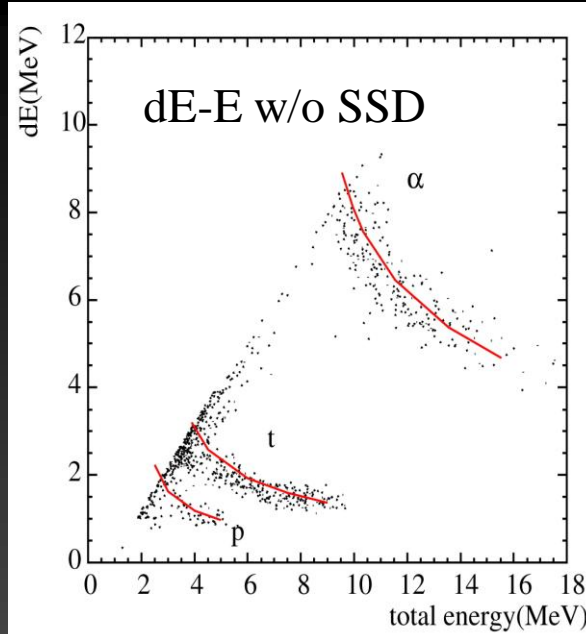
目的: バックグラウンドの寄与

Notre Dameの測定データの検証



Nucl. Phys. A584(1995)315

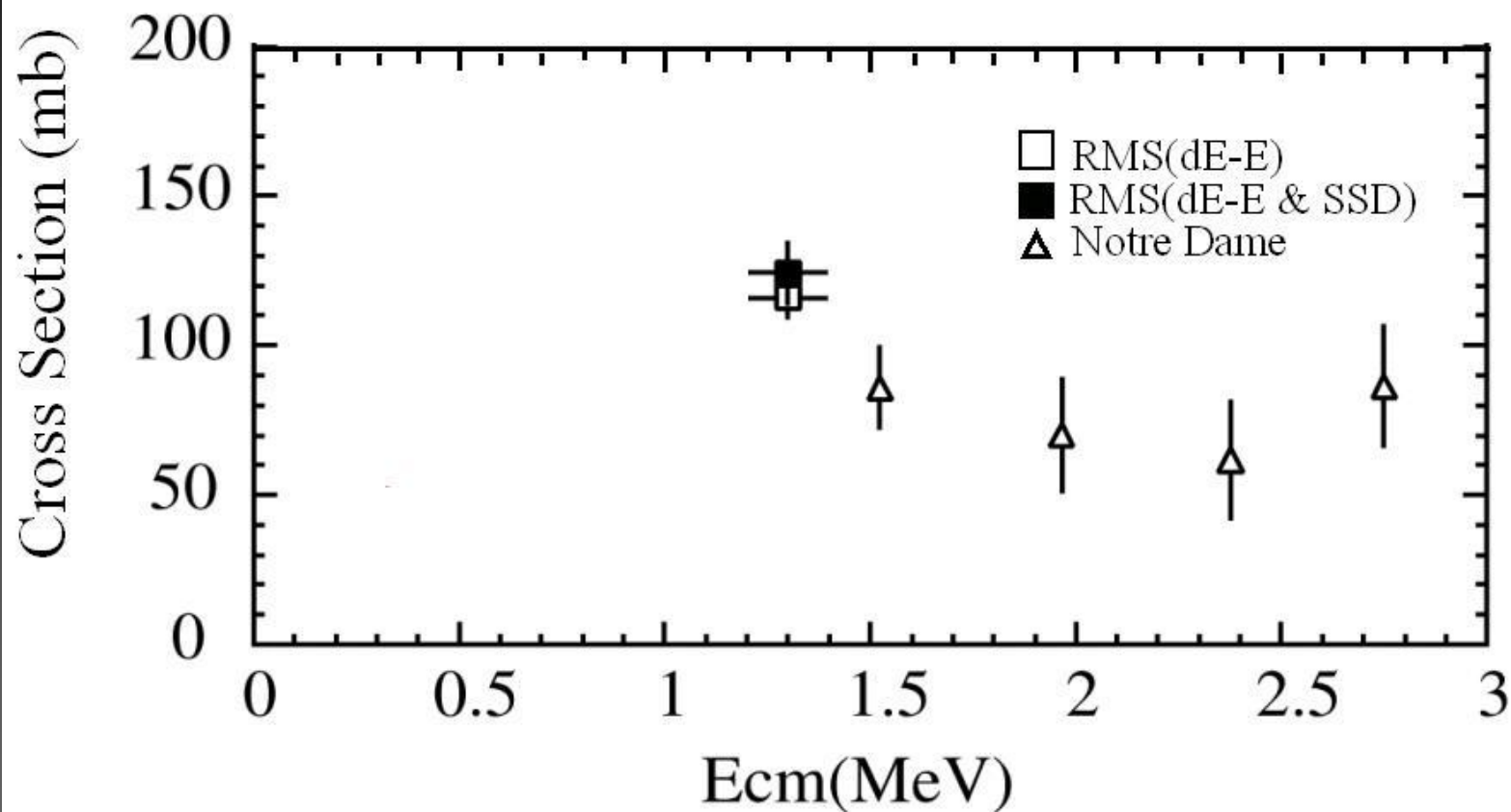
Experimental result



運動量保存則を用いて
全てのイベントが排除される

Notre Dameで測定された
角分布から理解可能

$^8\text{Li}(d, t)^7\text{Li}$ 反応断面積



特異な振る舞いはない

TRIACで行う場合のバックグラウンドレートの見積もり

RMSの場合

Total event rate 13.4cps

True event rate 3.10×10^{-2} cps

コリメータで止まったビーム由来と仮定して第ゼロ近似

└ 下流側に来るβのみ測定

$$60\text{kpps} \times 0.9 \times 0.5 \times 0.0081 \times 0.052 = 11.3\text{cps}$$

ダクトから覗く立体角

└ 閾値による効率

TRIACの場合

ビーム強度 $\sim 100\text{kpps}$

10° に80%のビームを集約可能

$$\text{Estimate } \frac{100\text{kpps} \times 0.2}{60\text{kpps} \times 0.9} \times 11.3\text{cps} = 4.19\text{cps}$$

Beam rate	S/N
6kpps	2.3×10^{-3} (RMS)
80kpps	9.6×10^{-2} (TRIAC)

S/Nは約40倍良くなる→TRIACで実験可能

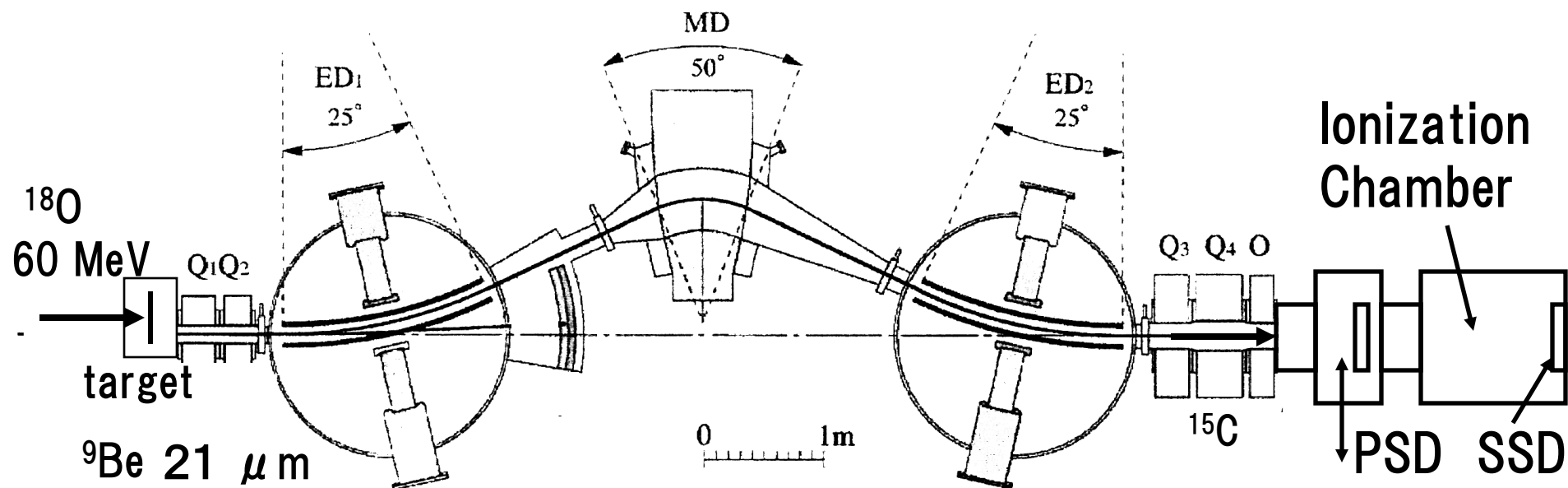
Production of Low Energy Radioactive Nuclear Beam

要求されるビーム条件

エネルギー: 30 MeV ($E_{cm} = \sim 6 \text{ MeV}$)

強度: $\sim 2 \text{ kpps}$

純度: $> 90\%$ (ただし、Cのアイソトープを含まない)



Transfer reaction



($Q=0.692 \text{ MeV}$)

+

JAERI Recoil Mass Separator

Mass acceptance $\pm 4\%$

Energy acceptance $\pm 12\%$

Solid angle 15msr

$\theta_{\text{RMS}} = 5^\circ$

軽い中性子過剰核の寄与: $T_9=2$ 程度 (r 過程が始まる温度)での Y_n/Y_{seed} がどうなるか?

定性的には...

Y_n/Y_{seed} 大: 種核が捕まえられる中性子数が多くなり重い核が生成しやすい

Y_n/Y_{seed} 小: 種核が捕まえられる中性子数が少なくなり重い核が生成されにくい

Y_n/Y_{seed} を定量的に評価することで元素生成量の定量的な評価を推し進め r 過程の起こる天体サイト、環境、物理機構等を明らかにする手がかりとなる



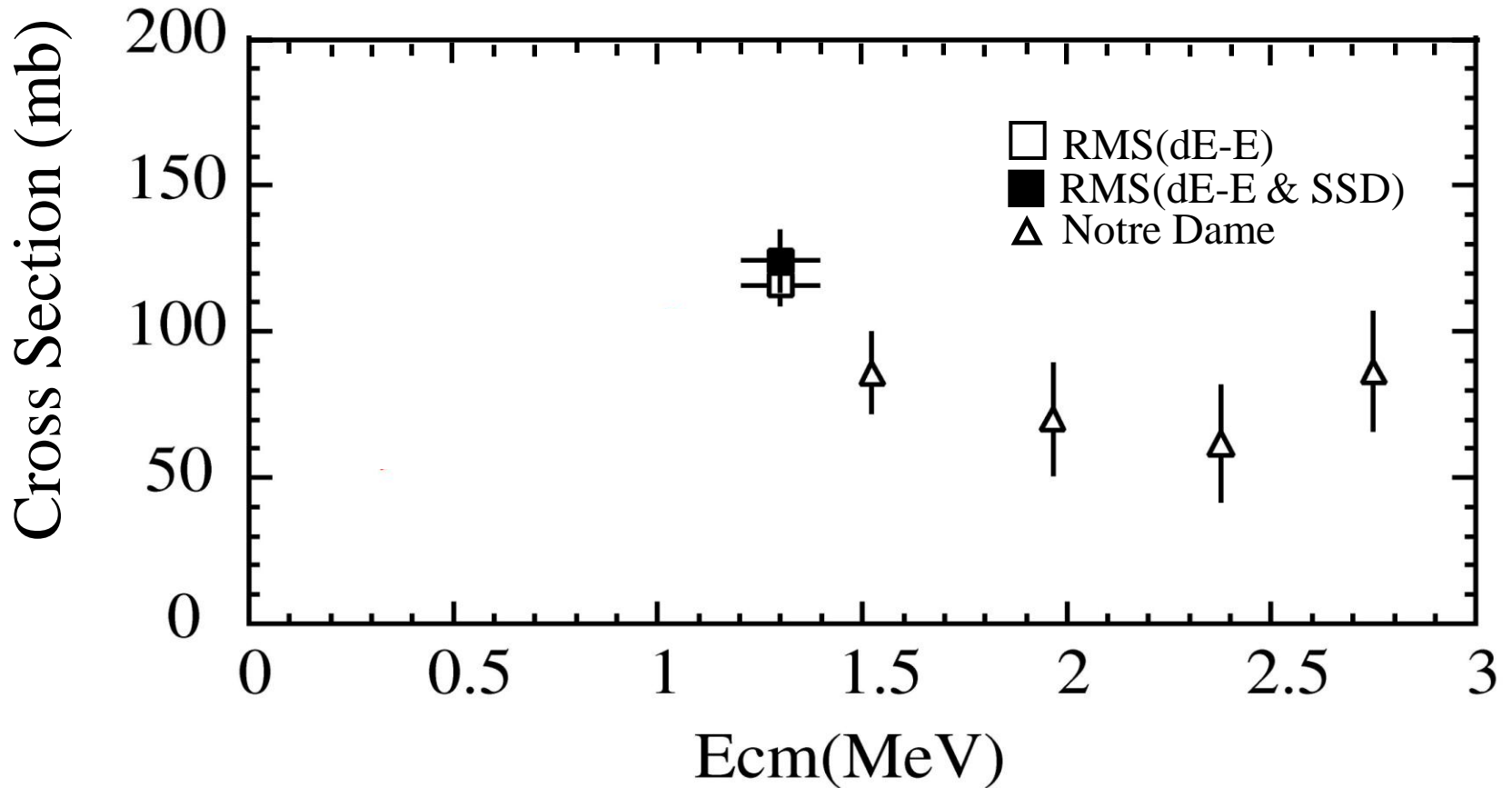
定量的な評価には系統的な測定が必要

軽い核は離散的な共鳴状態の寄与のためは統計モデルによる断面積の予測が困難



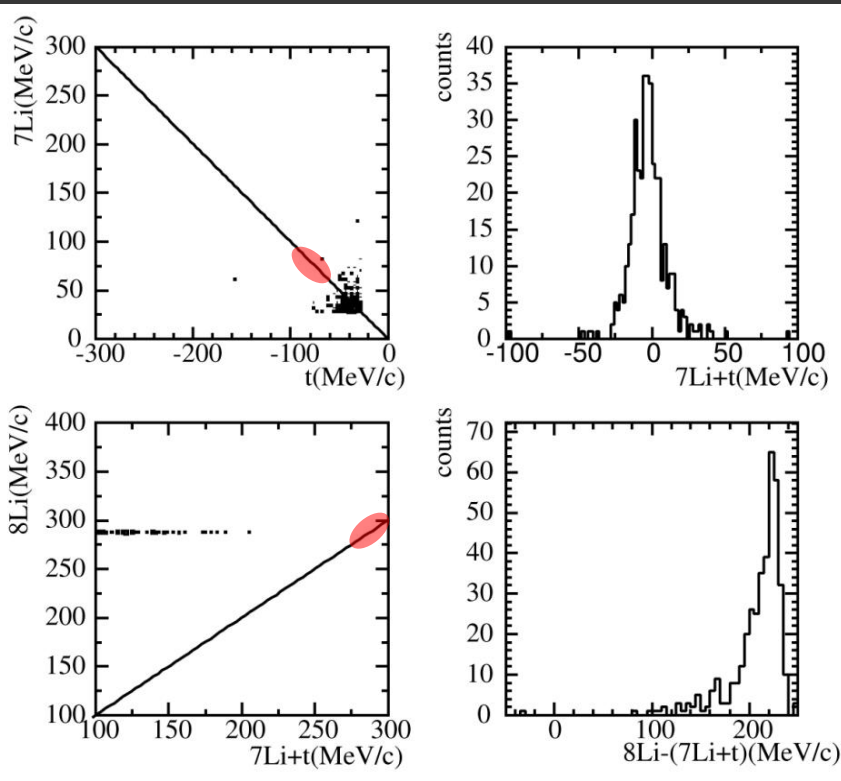
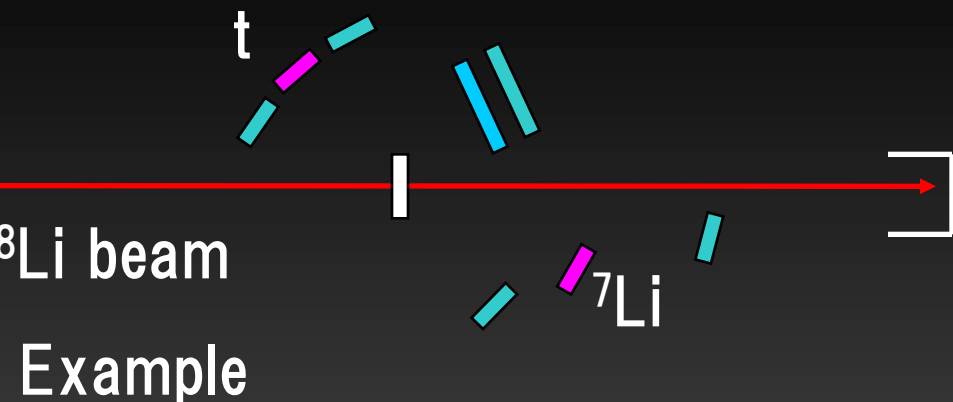
断面積の直接測定が必要

Cross section

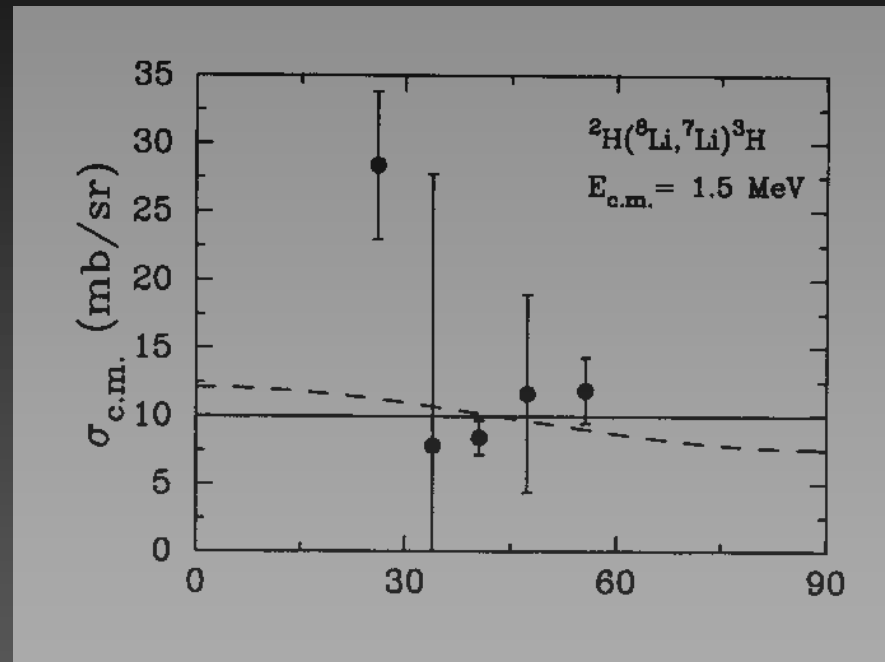


約4倍の統計量を得た上で
Notre Dameの測定結果を支持

SSD(forward) & SSD(backward)



運動量保存則を用いて
全てのイベントが排除される



点線:ルジャンドル関数によるフィット
→角分布無し(Notre Dame)
角分布は本測定でも同様と仮定
→9.2mb/sr

→ イベントが見つからない事と
矛盾しない

対策:ビームを10φ以下に絞る+

ビームダンプは検出器を直接見ないようにする

TRIACでは

ビーム強度 ~100kpps

10φに80%のビームを集約可

$$\text{Estimate } \frac{100\text{kpps} \times 0.2}{60\text{kpps} \times 0.9} \times 13.4\text{cps} = 4.47\text{cps}$$

β線の各所散乱による効果 : 3cps@RMS と仮定

$$\text{Estimate } \frac{100\text{kpps} \times 0.2}{60\text{kpps} \times 0.9} \times 3\text{cps} = 0.9\text{cps}$$

Beam rate 13倍→true event 13倍 と仮定

Beam rate	S/N
6kpps	2.3×10^{-3} (RMS)
80kpps	7.5×10^{-2} (TRIAC)

検出器間の同時計数をとることで更に低減可能