Ξ^-原子X線分光で探るΞN相互作用

実験、反応・構造計算、格子QCDで解き明かすハドロン分光 @ ELPH

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2023/11/8-9

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    - with “kinematical” selection
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❖Summary

ΞN interaction

❖(K^-, K^+) reaction spectroscopy

- KEK E224, BNL E885, (J-PARC E05/E70)

→ the depth of the ΞN potential is **10 - 20 MeV**

❖Nuclear Emulsion experiment

- KEK E176, KEK E373

Observation of N- Xi bound system (KISO)
→ ΞN interaction is **attractive**

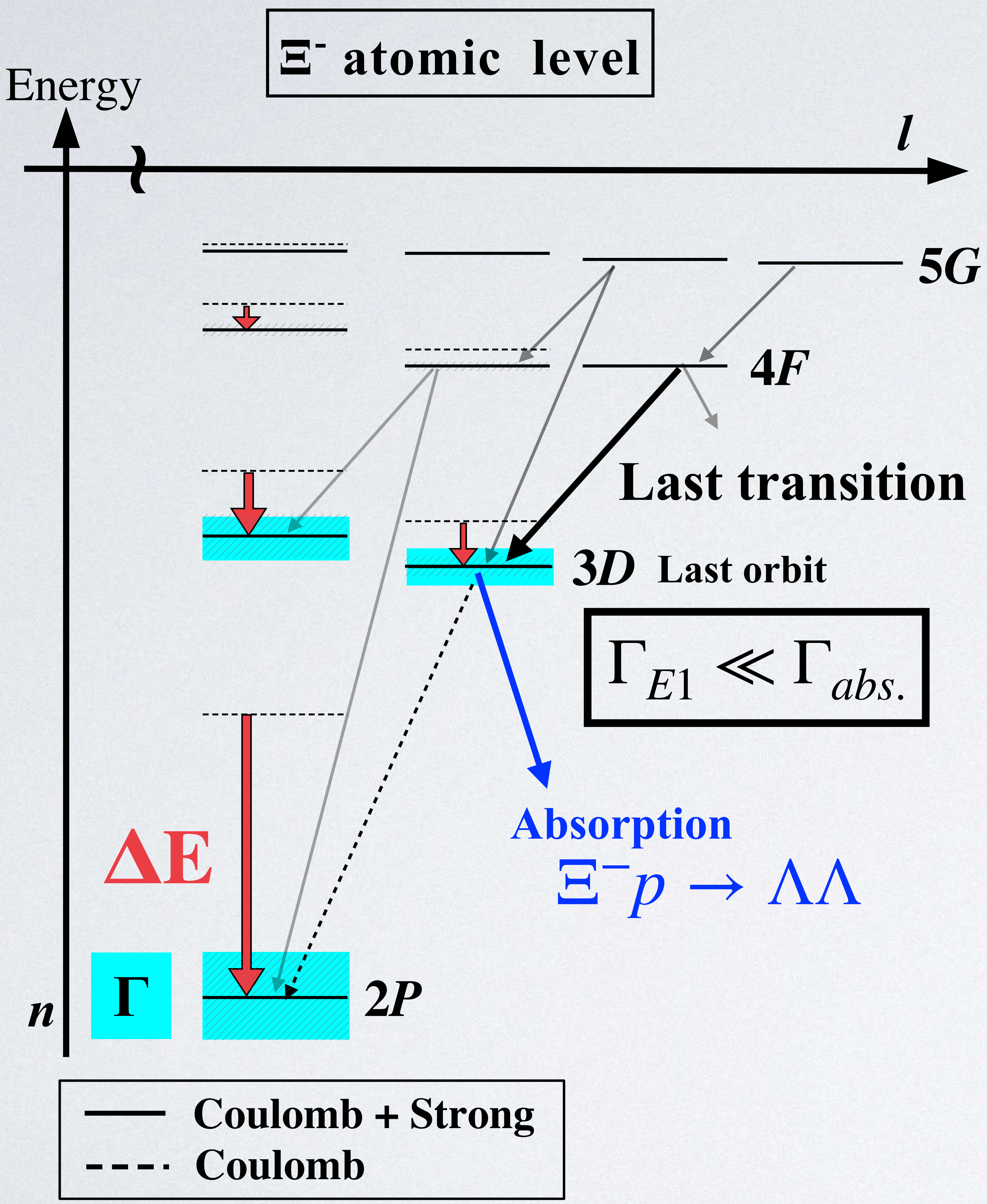
- J-PARC E07 (2016-2017)

Observation of **Ξ /ΛΛ hypernuclei**

❖Ξ atomic X-ray spectroscopy

- The world-first challenge at J-PARC

Principle

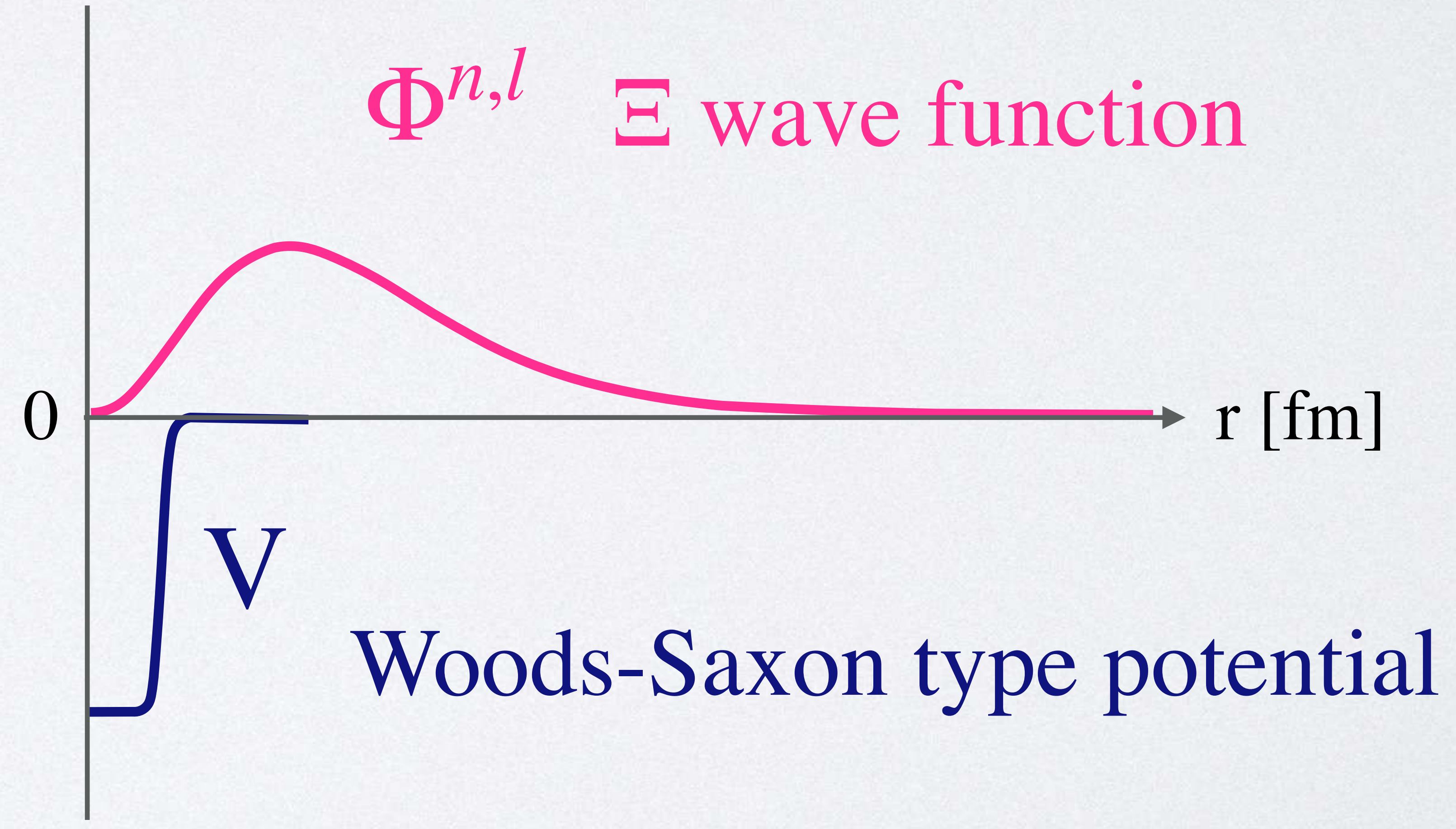


Ξ-nucleus potential : $U = V + iW$

Energy shift (ΔE) ⟺ $\langle \Phi^{n,l} | V | \Phi^{n,l} \rangle$

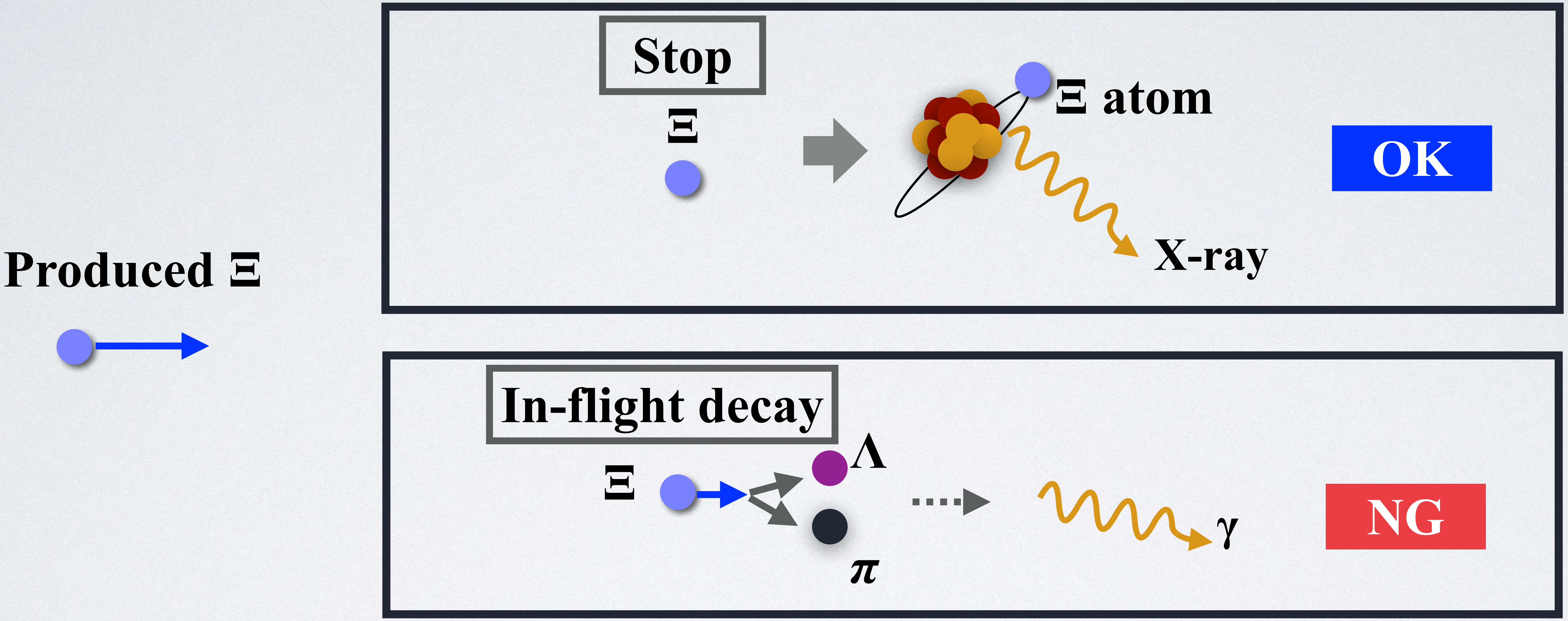
$\langle \Phi^{n,l} | H_{kin} + U_{Coul} + V | \Phi^{n,l} \rangle - \langle \Phi'^{n,l} | H_{kin} + U_{Coul} | \Phi'^{n,l} \rangle$

Width (Γ)
Branching ratio (BR_{abs}) ⟺ $\langle \Phi^{n,l} | W | \Phi^{n,l} \rangle$



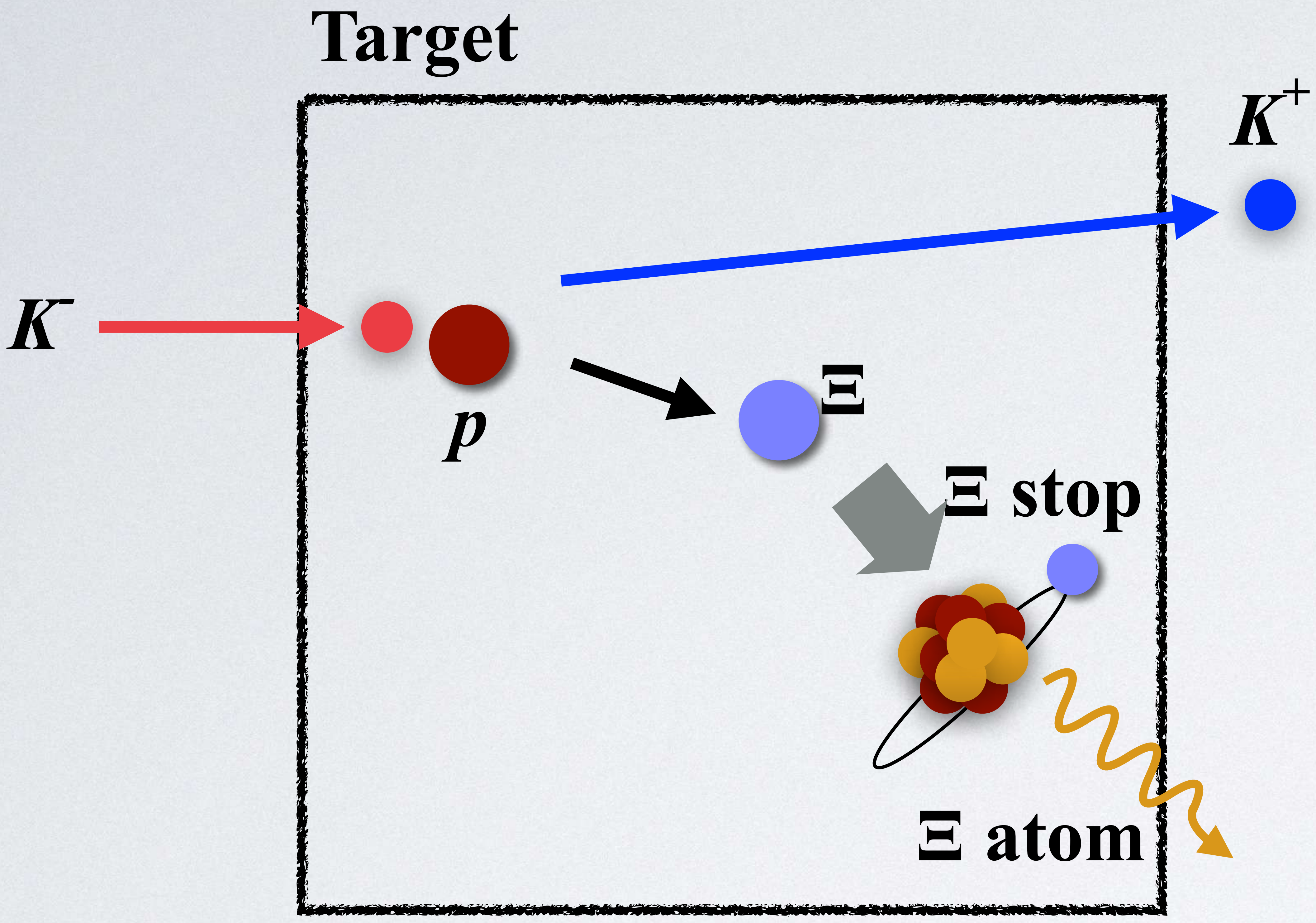
Experimental difficulty

- Huge background from in-flight decay



"key" : selecting stopped Ξ^- events cleanly

Experimental method



1 Ξ production via the (K^-, K^+) reaction

➡ **Magnetic spectrometers**

2 Stop Ξs in material and form Ξ atoms

➡ **stopped Ξ^- selecting methods**

3 Measure Ξ atomic X-rays

➡ **Ge array [Hyperball-X]**

in coincidence

Overview

done

1st experiment (J-PARC E07)

Data taking status : done [2017]
Stop Ξ selection : **counter(Ge)-emulsion coincidence method**
Target : Ag, Br, C
Result : M. Fujita et al., PTEP. **2022,** 123D01 (2022)

2nd experiment (J-PARC E03)

Data taking status : done (10% stat.) [2021]
Stop Ξ selection : **“kinematical” method**
Target : Fe
Result : Analysis is ongoing

Coming

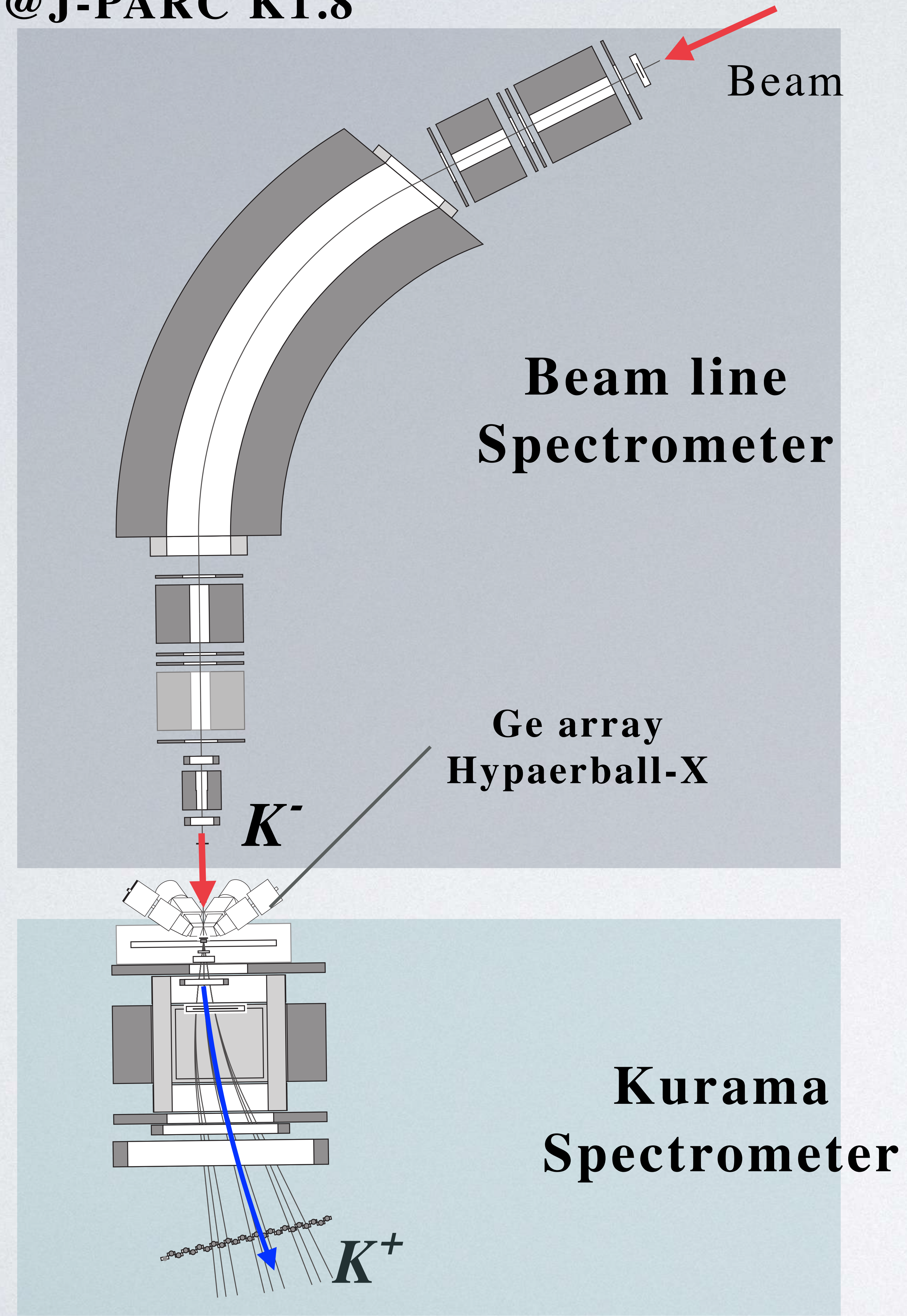
3rd experiment (J-PARC E96)

Data taking status : soon [2023]
Stop Ξ selection : **Ge-AFT coincidence method**
Target : C

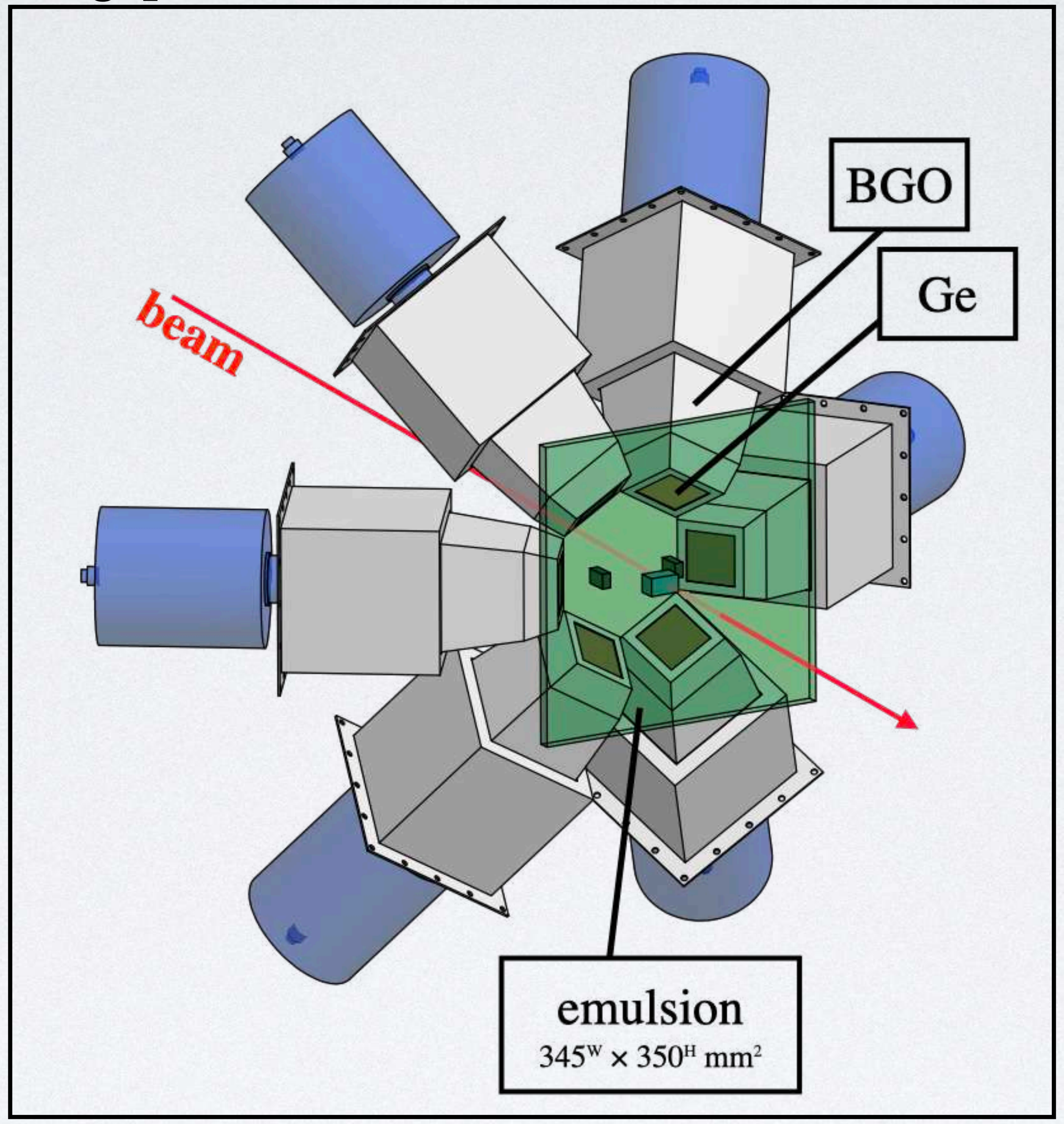
1st experiment (J-PARC E07)

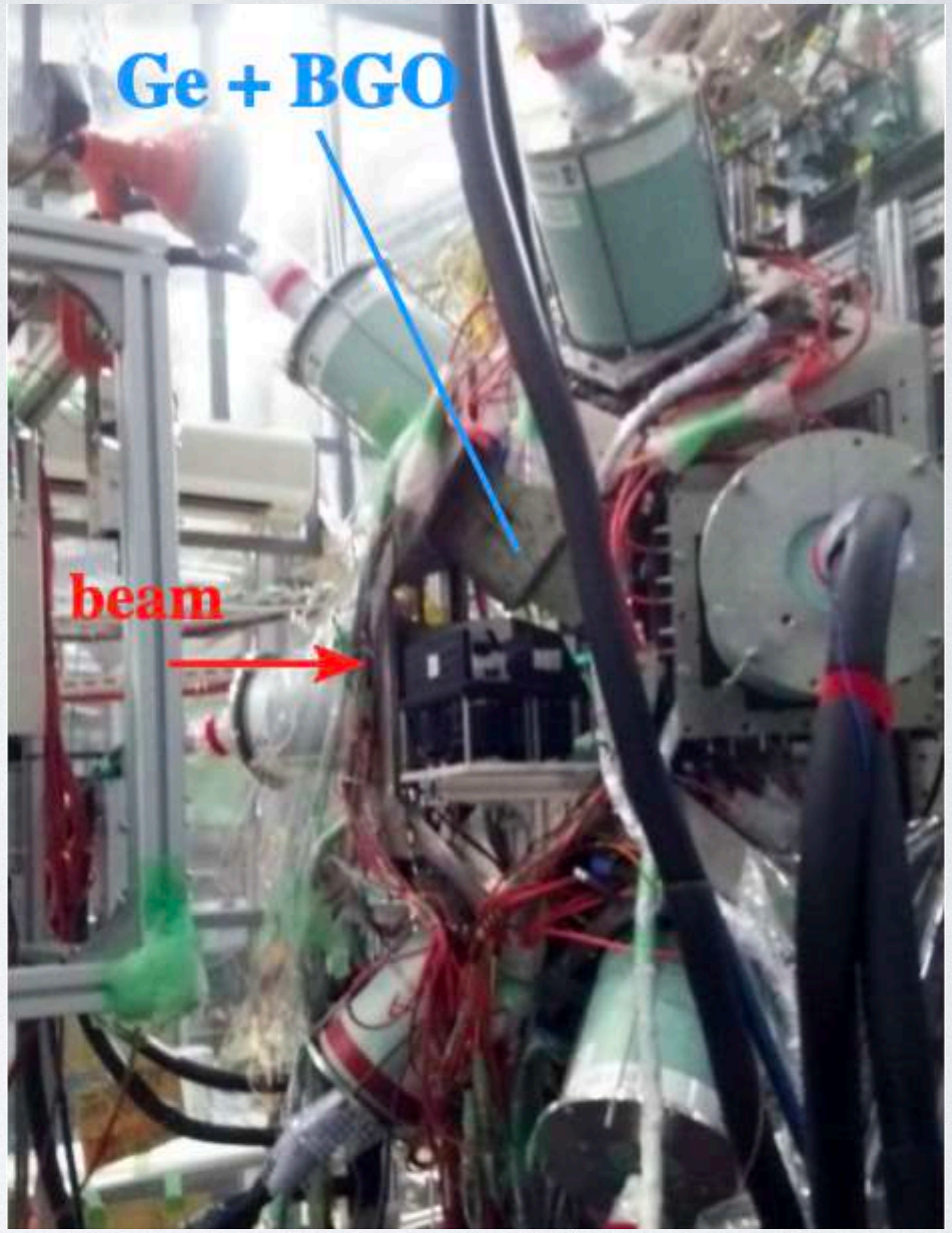
proposed by H. Tamura, K. Nakazawa, K. Imai

@J-PARC K1.8



Hyperball-X (for E07)



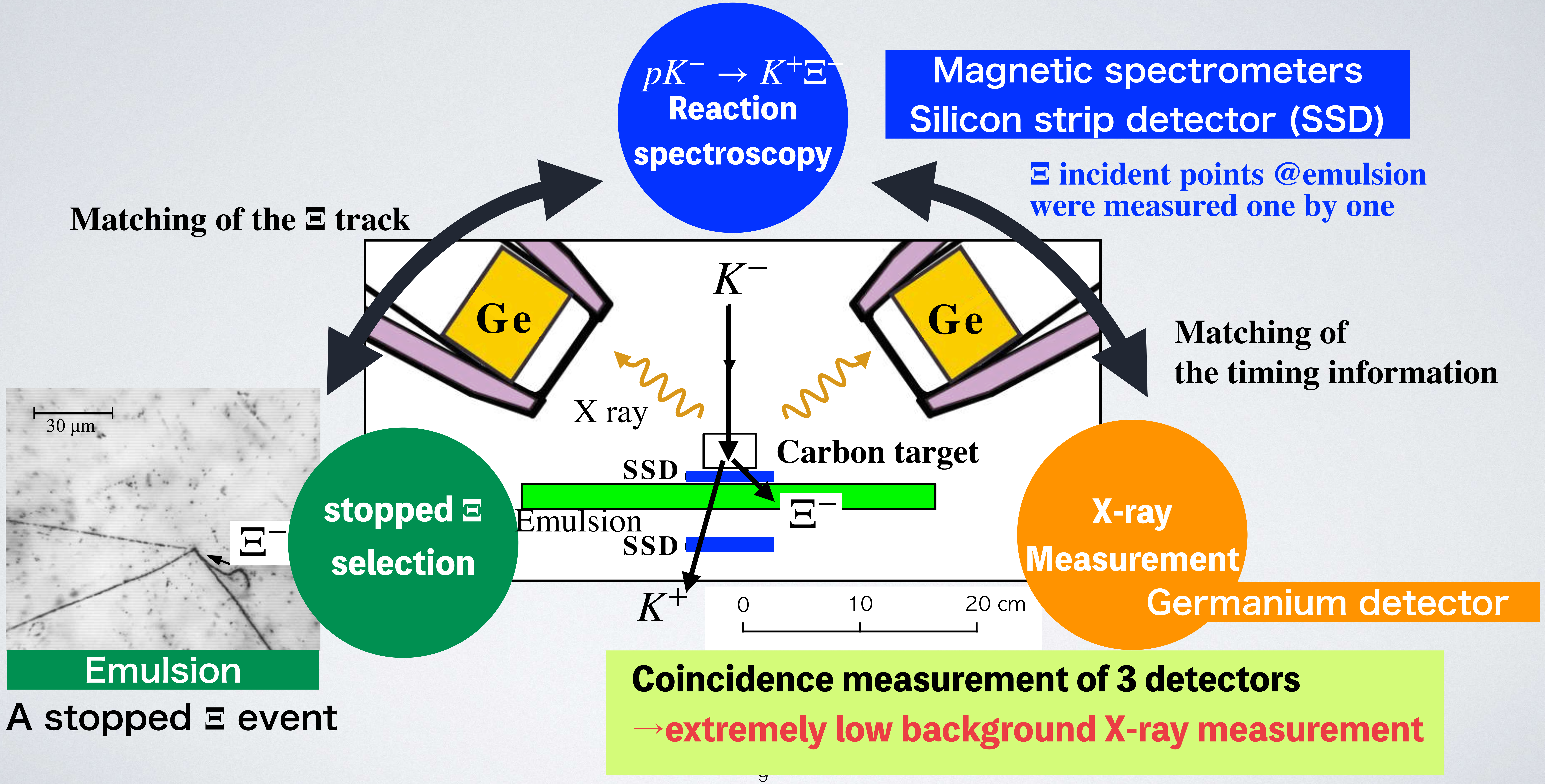


Development of Hyperball-X

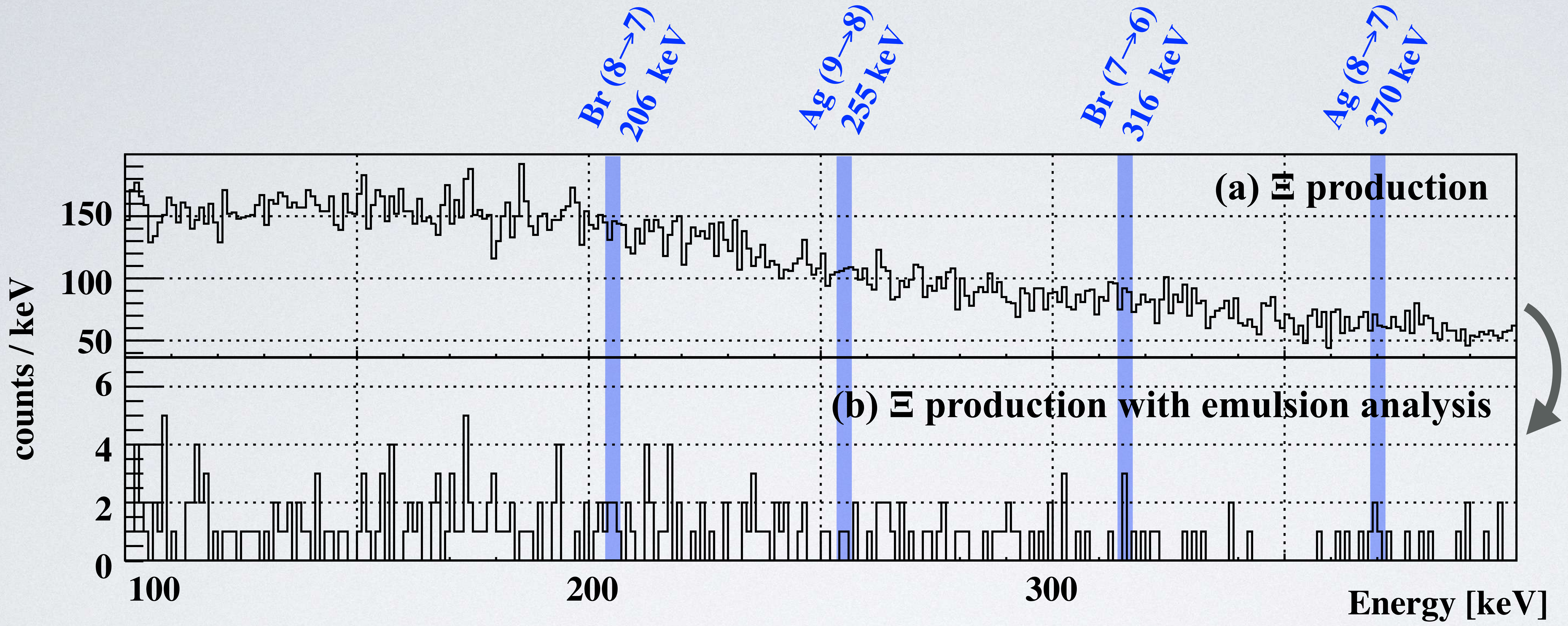
In-beam energy calibration method using LSO

Nucl. Instr. and Meth. A**1042**, 167439 (2022)

Counter-emulsion coincidence method



Results of J-PARC E07



Background level ~1/170

Established the coincidence method using the emulsion, the Ge detectors, and magnetic spectrometers

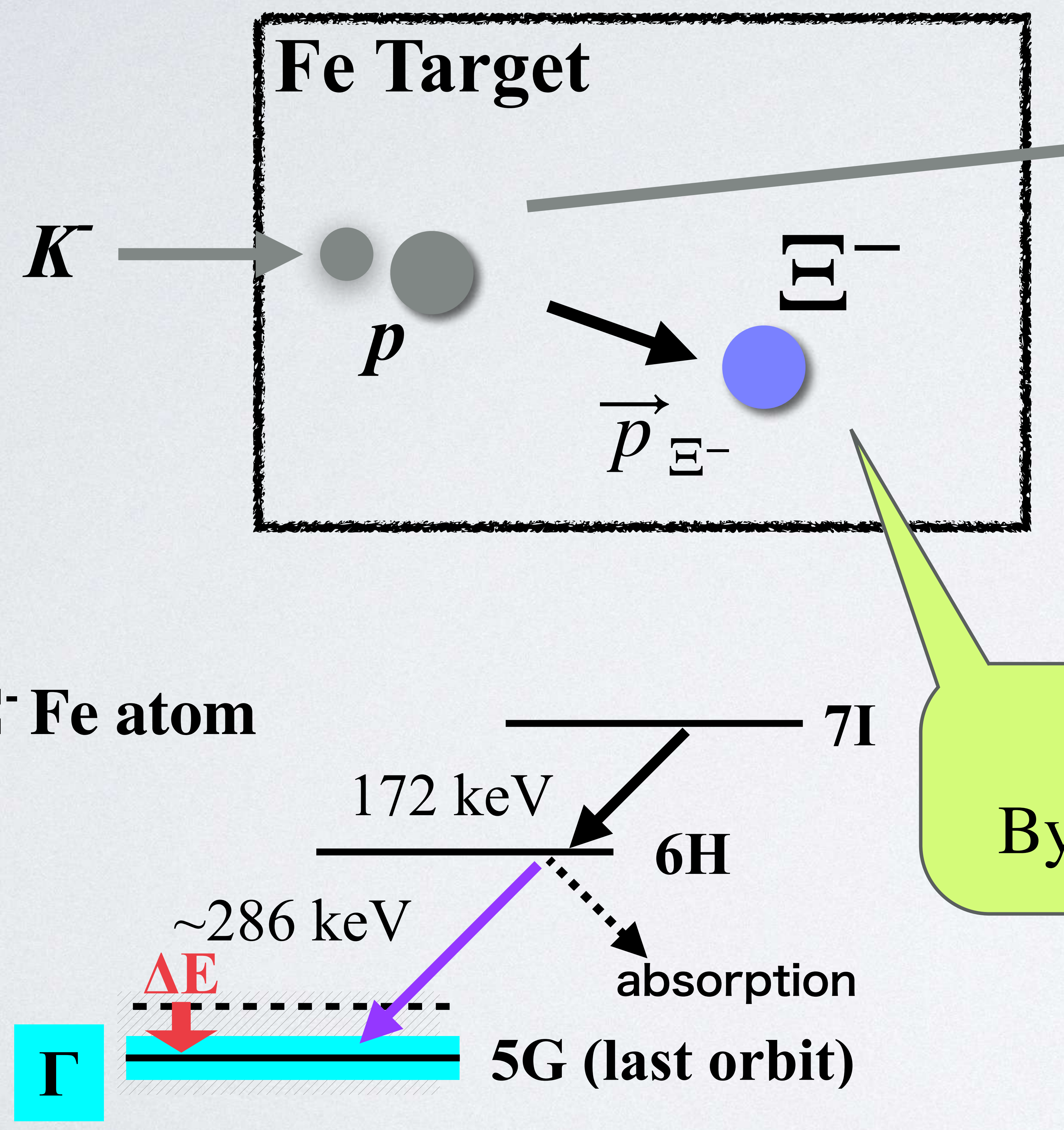
→ It was found that X-ray measurement would be achieved by increasing the statistical value by five times.

M. Fujita et al., PTEP. **2022**, 123D01 (2022)

2nd experiment (J-PARC E03)

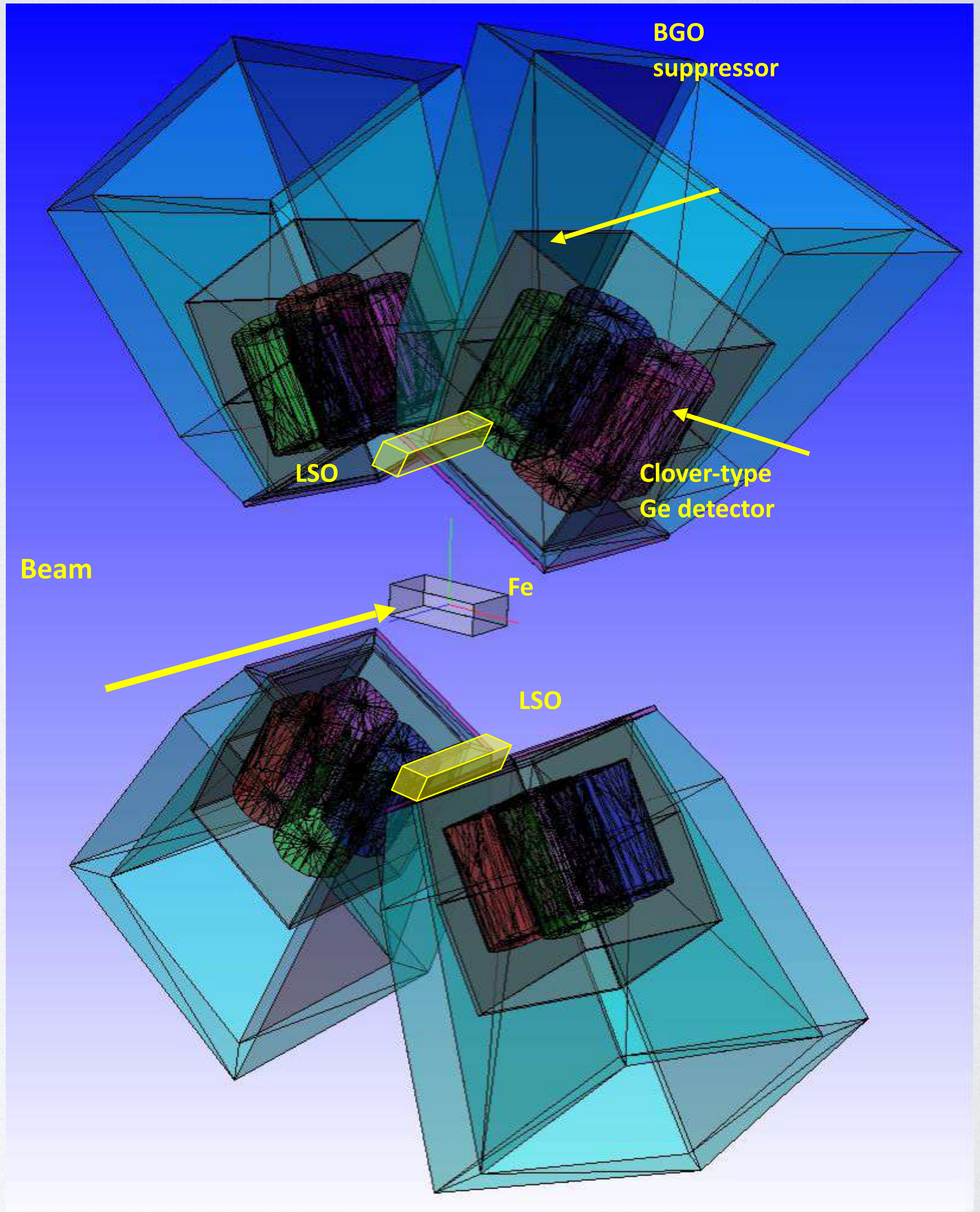
proposed by K. Tanida

- Physics data taking : 2020-2021
- Kaon beam 1st period : 95G Kaon (10% statistics run)



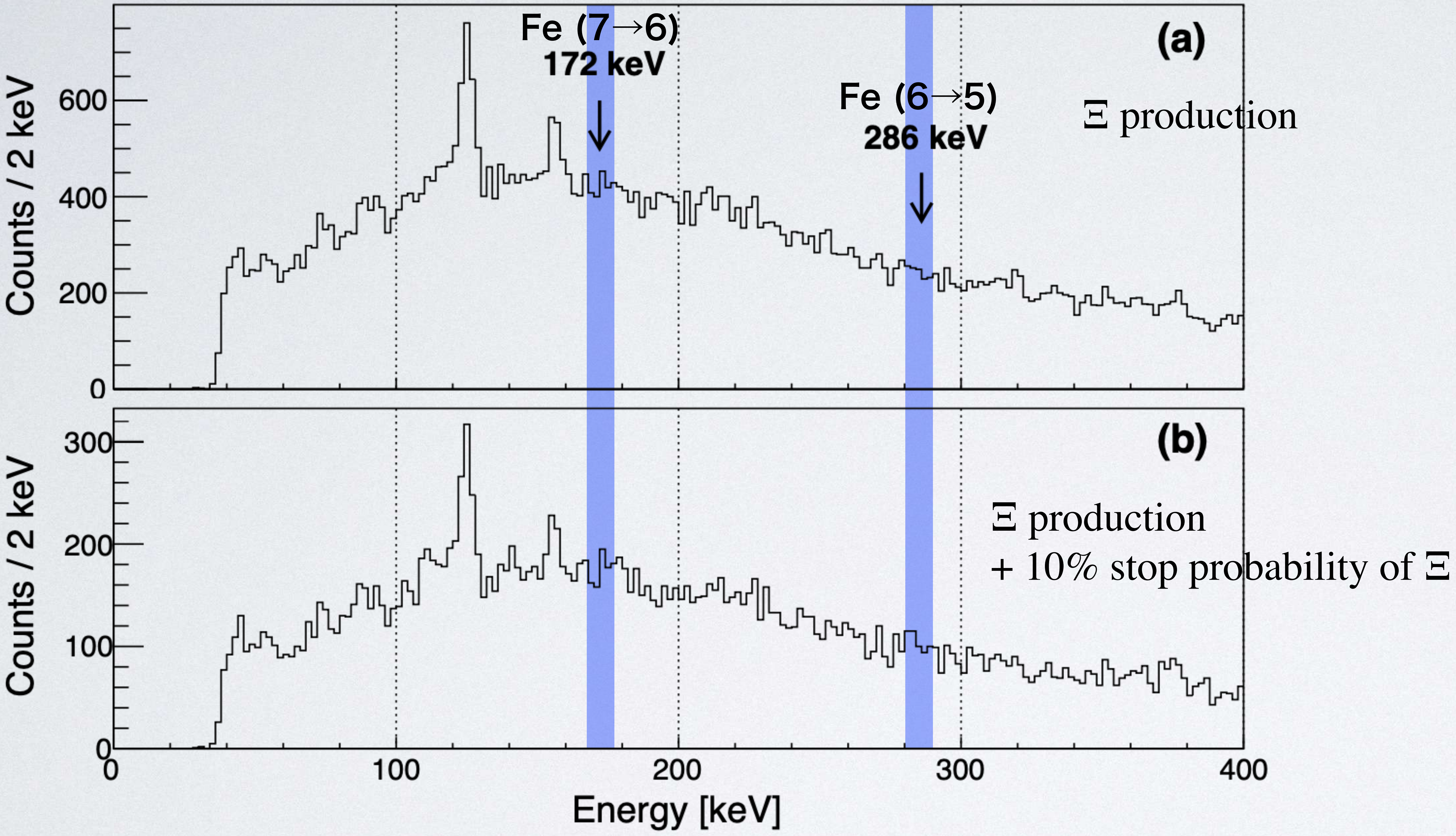
- Ξ stop selection : "kinematical" method

Stop or Not
By Monte Carlo Simulation



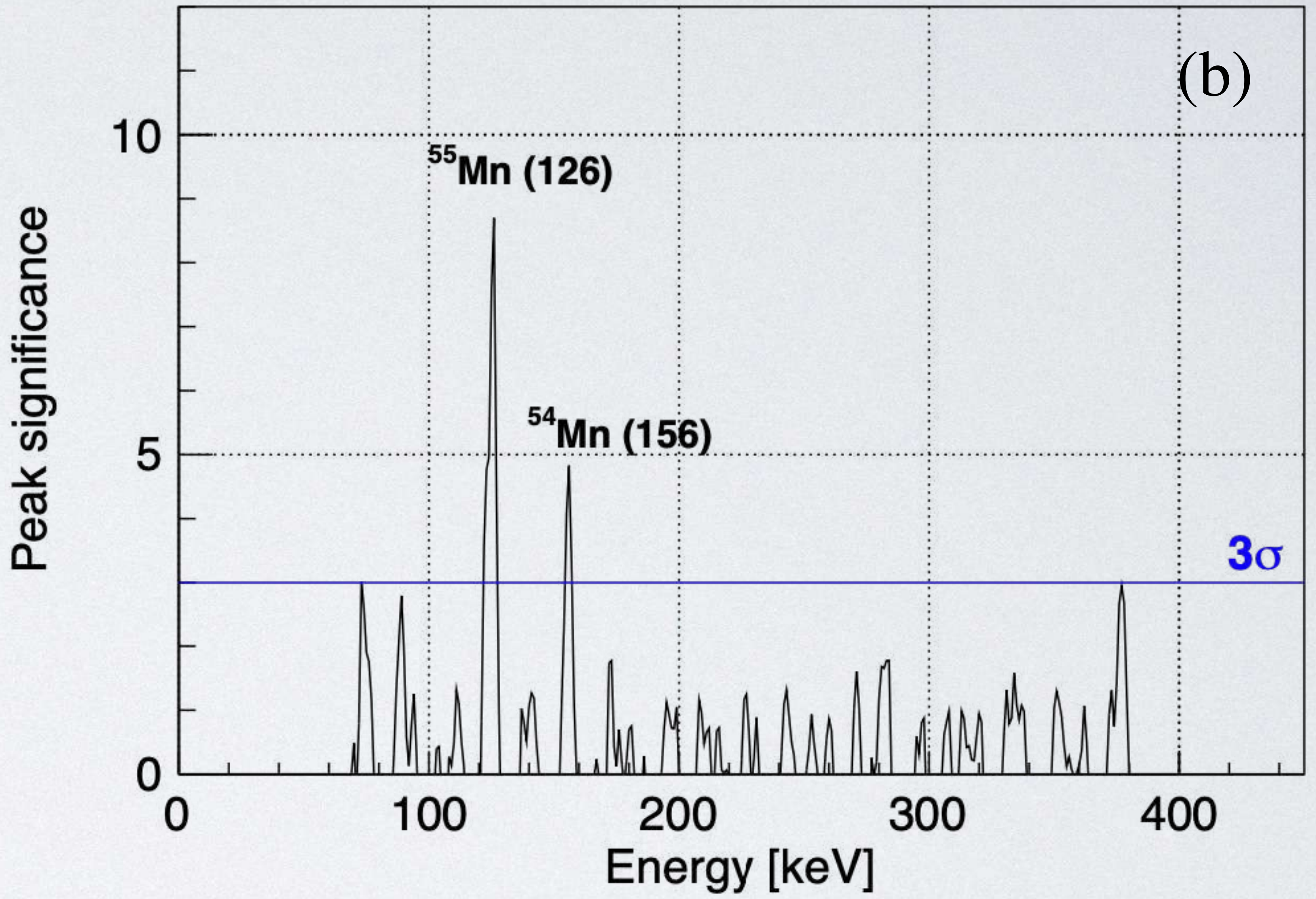
Hyperball-X (for E03)

Ξ^- Fe atom X-ray spectrum



Y. Ishikawa, Doctoral thesis 2022 Tohoku Univ.

Peak Search



✓ No clear peak was observed.

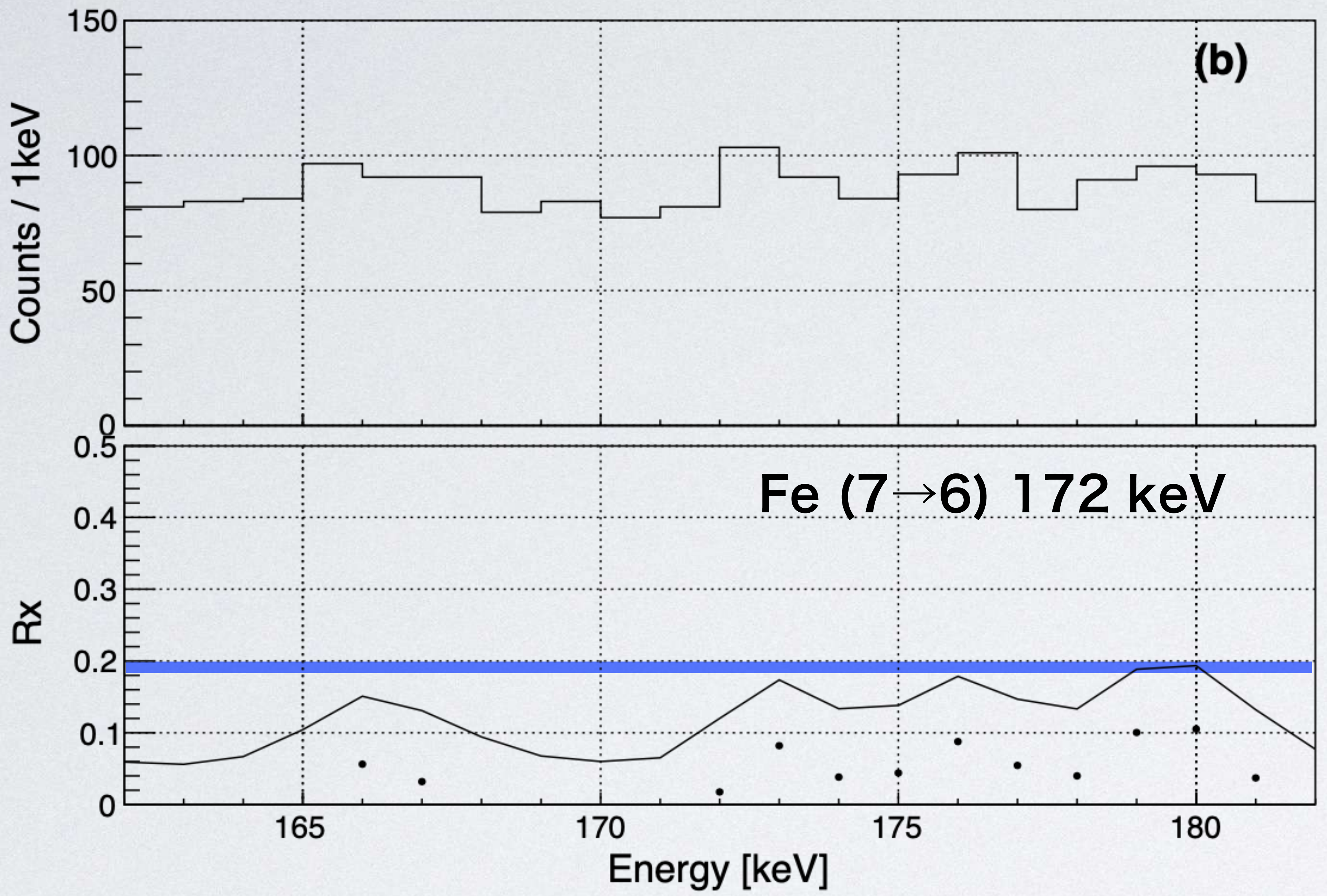
✓ As result of fitting @ 172 keV (±2σ)

S (Peak area) = 35 ± 29

N (BG area) = 754

→ $S/\sqrt{S+N} = 1.24$

Results of J-PARC E03



Y. Ishikawa, Doctoral thesis 2022 Tohoku Univ.

$$N_{Xray} = N_{stopped\ \Xi^-} \times R_X \times \epsilon_{HBX}$$

Intensity of Xray per stopped Ξ

→ Rx < 0.19 90%C.L.

Cf. Rx ~ 0.3 (estimation)

Analysis Upgrade is on-going by Yamamoto-san

$S/\sqrt{(S+N)}$ of Fe Ξ X-rays via the Fe(KK) reaction was evaluated.

Rx < 0.19 @90%C.L. smaller than the estimation.

→ It was found that 3σ peaks would be observed by reducing the BG level to 1/8 or less.

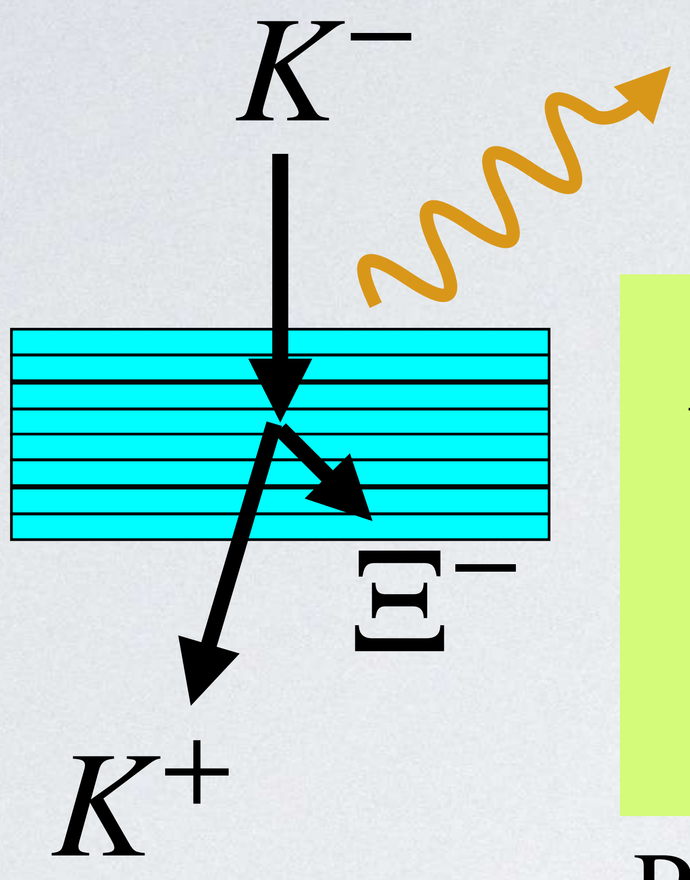
Current status

	1st try (E07)	2nd try (E03)
Stop Ξ selection	**counter-emulsion coincidence method**	**“kinematical” method**
Result	• PTEP. 2022, 123D01 (2022) • **Succeeded in significantly reducing BG,** but X-ray was not observed. • Necessary to improve the issue where the Ξ track between SSD and emulsion is **not connected** due to distortion of emulsion.	• Y. Ishikawa, Doctoral thesis, Tohoku Univ. (2022) • Analysis is **ongoing.** • Room for improvement in SN by brushing up event selection. • Should be used with some detectors which can identify stopped Ξ.

→ **Need a counter detector to select stopped Ξ !**

3rd experiment (J-PARC E96) proposed by T. O. Yamamoto

❖ Ge-AFT coincidence method



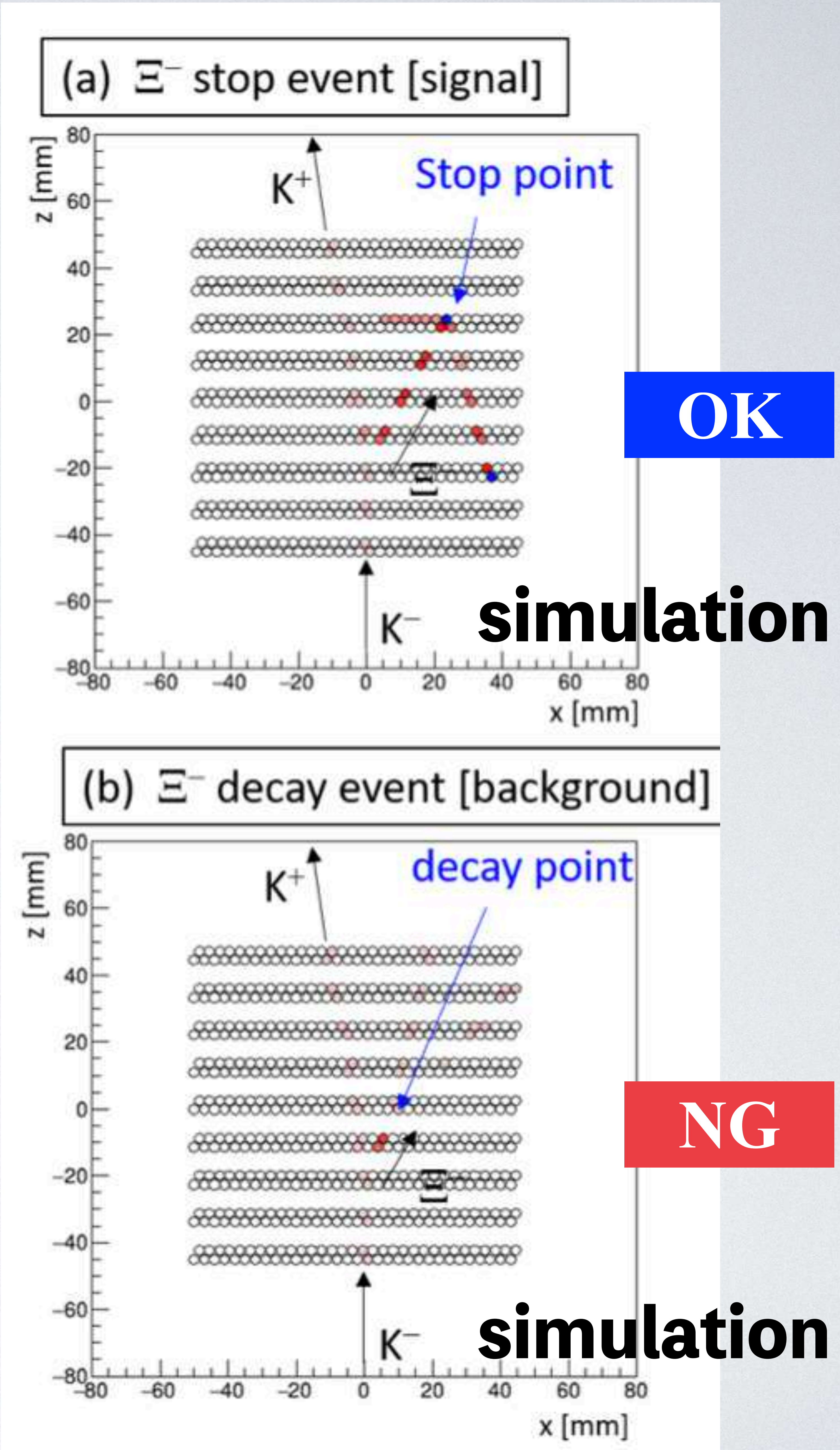
Active Fiber Target (AFT)

➡ **Target & Ξ tracking detector**

Problems :
E07 : Ξ track disconnection
E03 : stopped Ξ cannot be tagged explicitly

Solved!

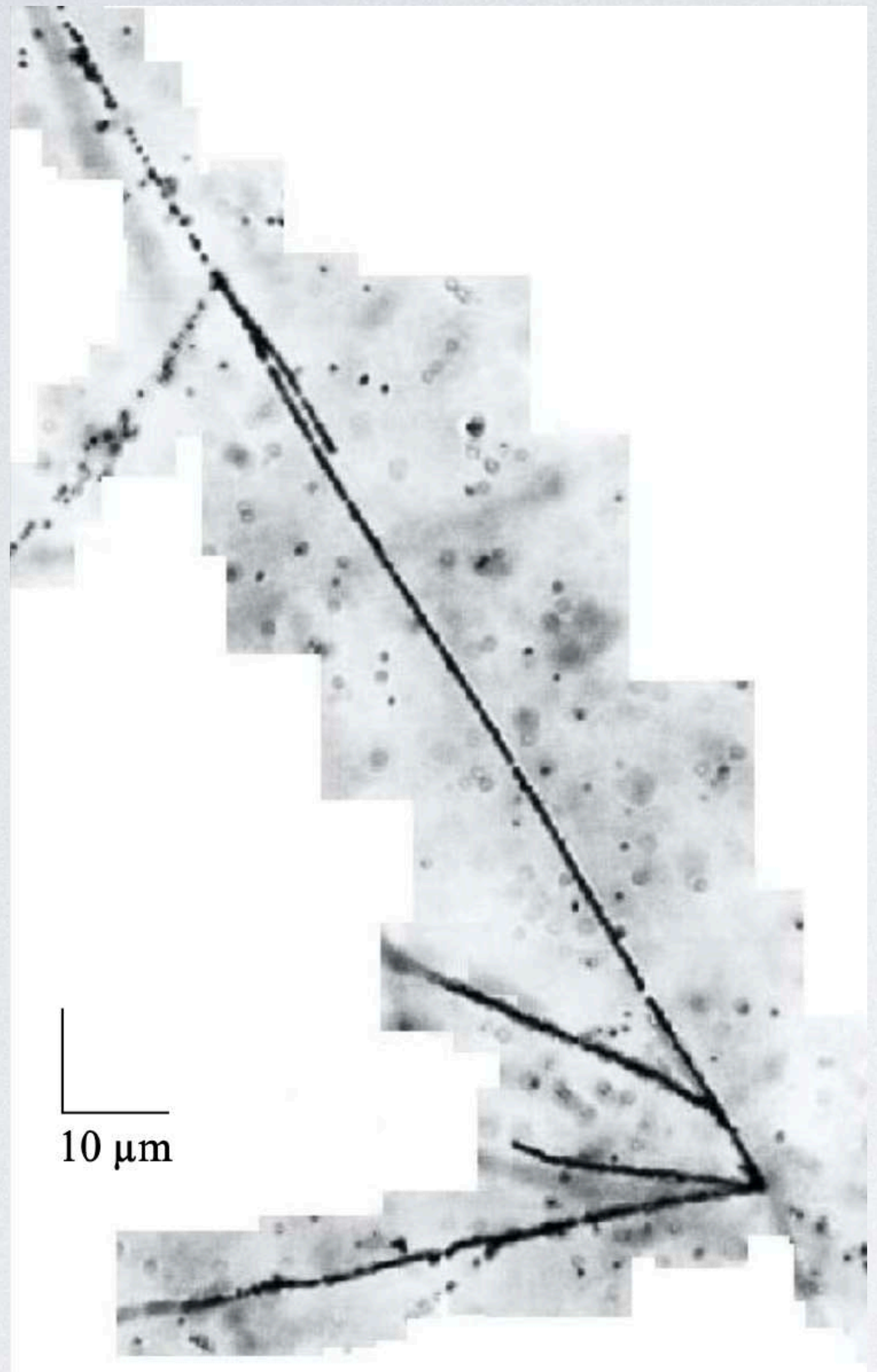
Target Xray : C Ξ atomic Xrays
The E70 AFT is not optimized to stop Ξ.
This measurement is important from a physical point of view.



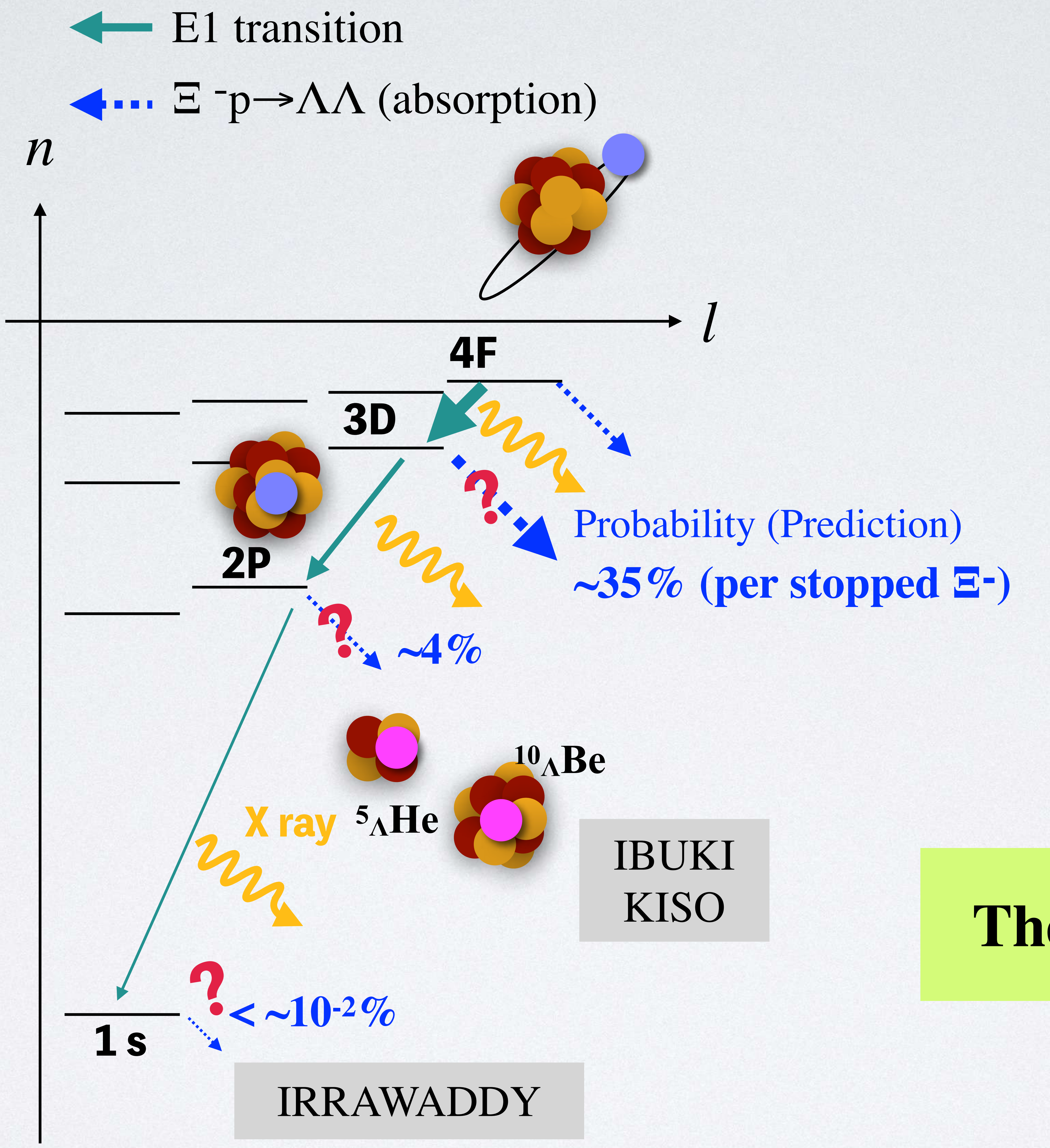
J-PARC E96 proposal, T. O. Yamamoto et al.

Physical motivation

Ξ hyper nuclear event (IBUKI)



S. H. Hayakawa *et al.*, PRL, **126,** 062501(2019).



According to the theoretical prediction, absorption is dominant in the 3D orbit

In the IBUKI event, Absorption occurred in the 2P orbital, which is closer to the nucleus!

The *Ξp-ΛΛ* coupling is weak?

Ξ⁻ C atomic X-rays

- Energy shift (ΔE) and Width (Γ)

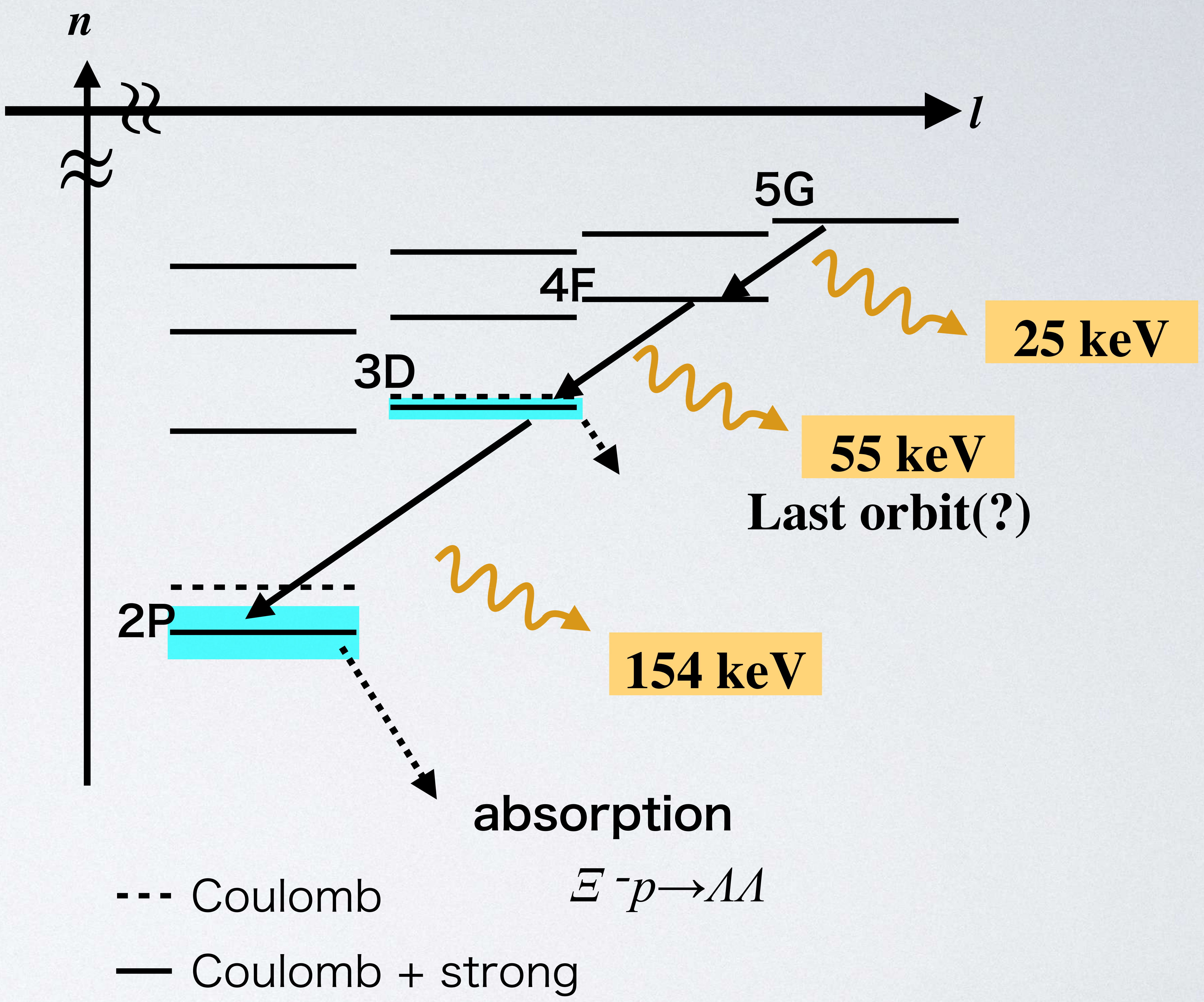
Theoretical predictions are strongly model dependent

	ESC potential	HAL-QCD Potential
ΔE (keV)	~1100	~90
Γ (keV)	~2000	~6

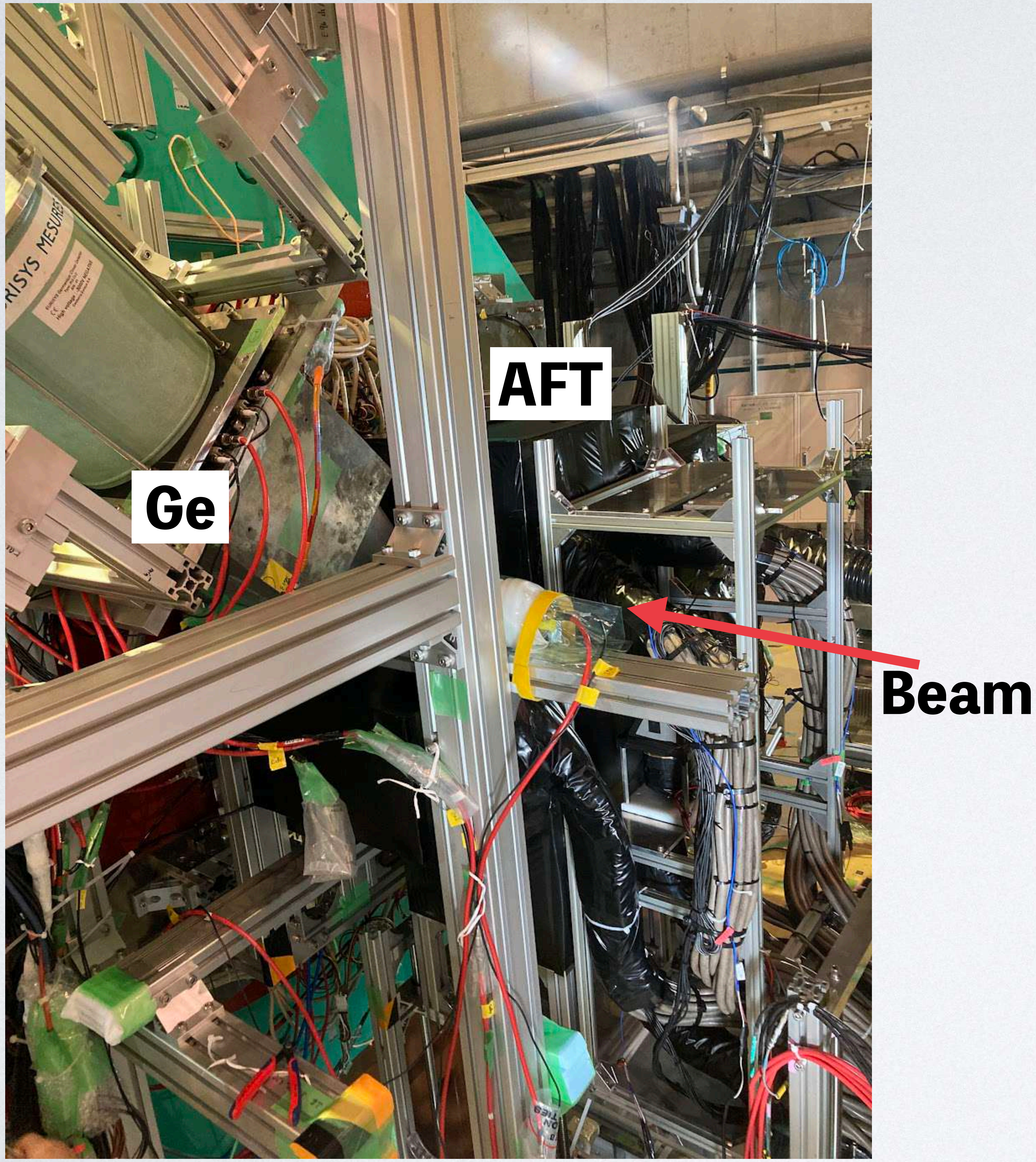
- X-ray Intensity

Series X-ray observation required

Transition	ESC potential	HAL-QCD Potential
4-→3	~40%	
3→2	A few %	~40%



E96 : Commissioning & physics run



- E96 core members :

K. Kamada, F. Oura, C. Son, R. Imamoto,
H. Tamura (Tohoku Univ.)

M. Ukai (KEK)
T.O. Yamamoto, M. Fujita (JAEA)

- Run at the same time with
  J-PARC E70 (Ξ hyper nuclear spectroscopy)

- Commissioning : done @ 2023 June

- Physics run : coming soon

Summary

- The Ξ Atomic X-ray spectroscopy is a powerful method to approach the ΞN interaction.

- The "key" is how to select stopped Ξ .

  - Counter-Emulsion coincidence method (J-PARC E07)

    M. Fujita et al., PTEP. **2022**, 123D01 (2022)

  - "Kinematical" method (J-PARC E03)

    Y. Ishikawa, Doctoral thesis, Tohoku Univ. (2022)

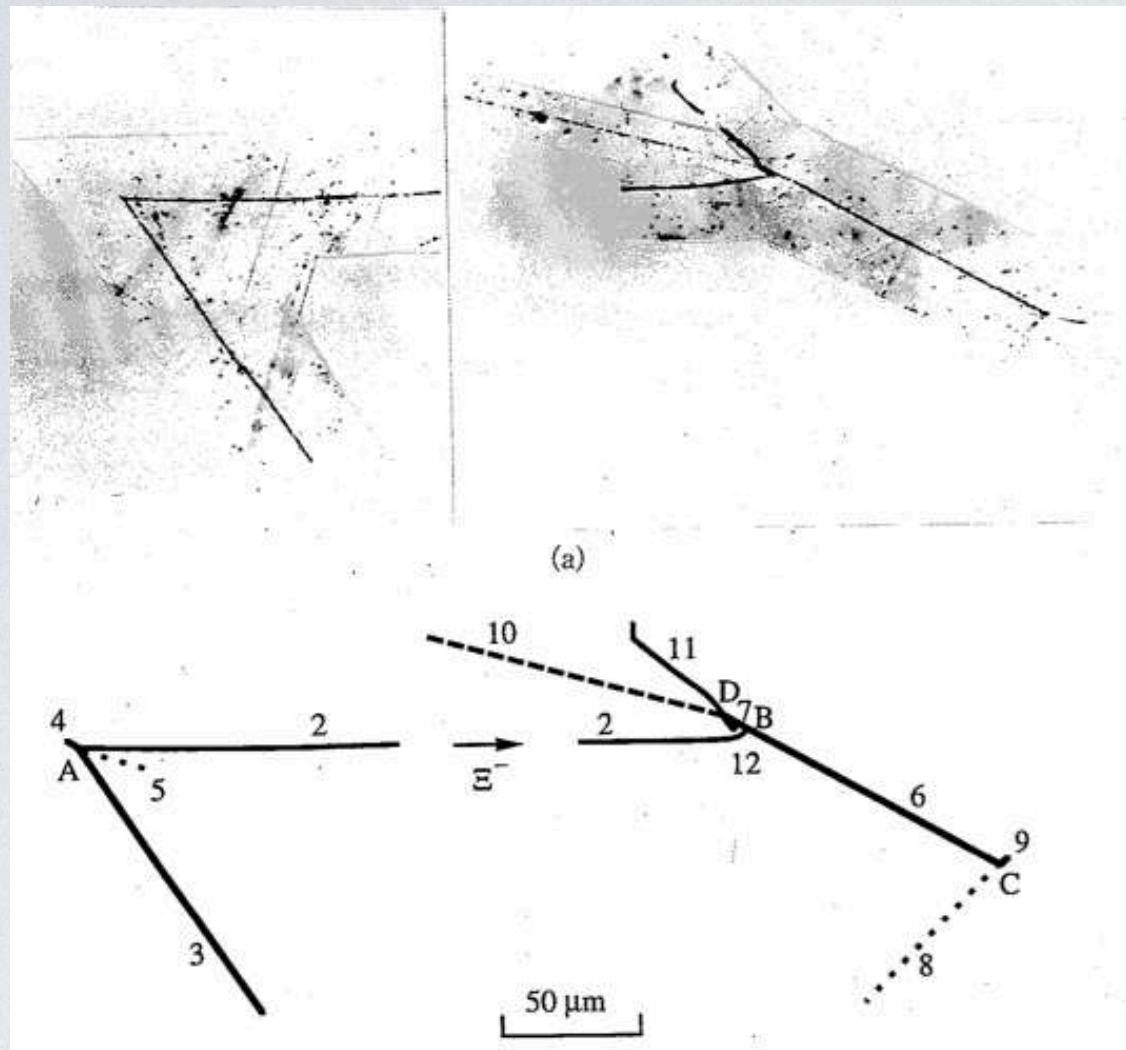
  - Ge-AFT coincidence method (J-PARC E96)

→expect the world's first carbon Ξ atomic X-ray observation

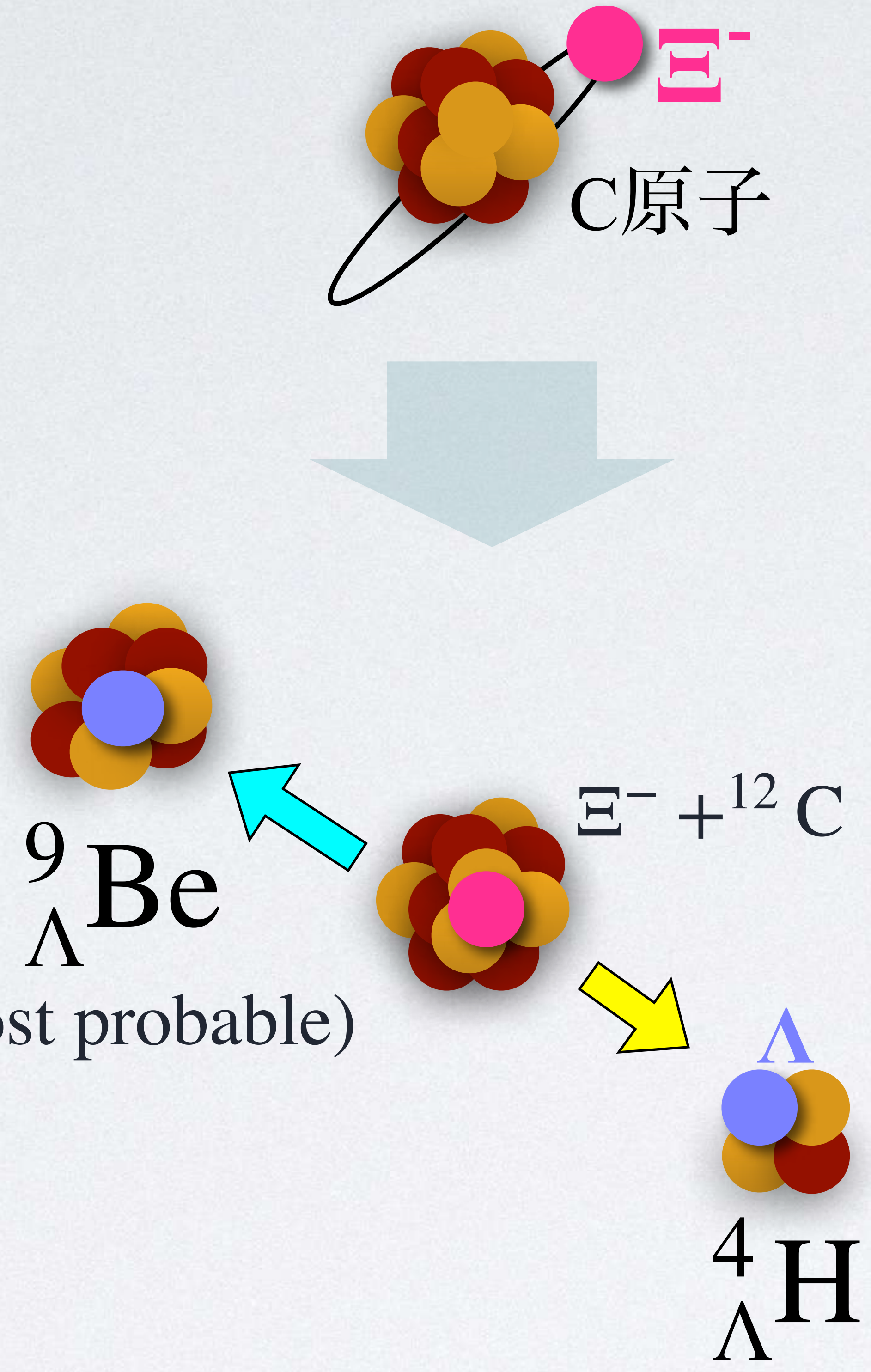
Back up

Twin Λ hypernucleus events @KEK E176

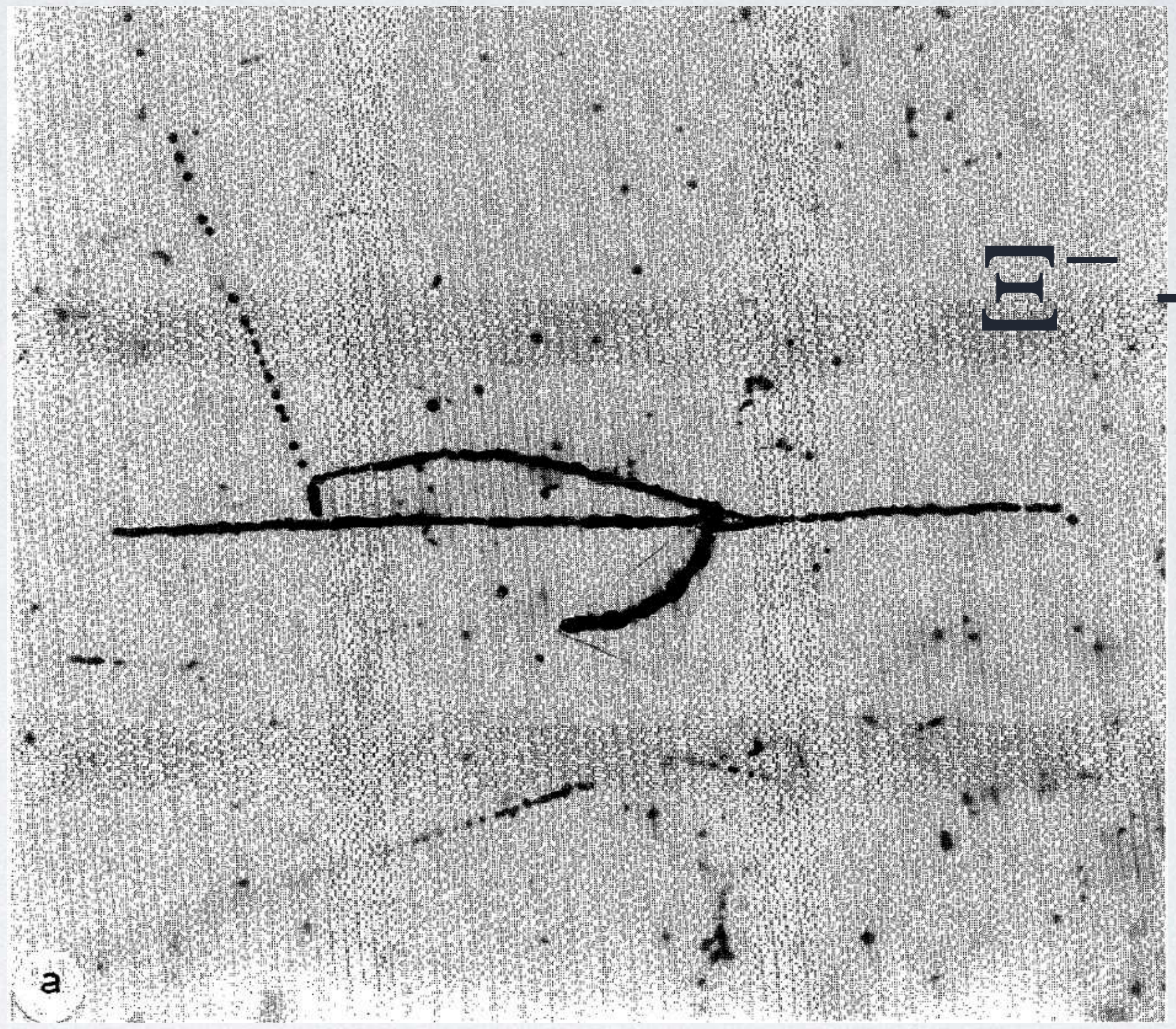
#10-09-06（Yokohama）



S. Aoki *et al*.
Prog. Theor. Phys. 89, 493 (1993)



#13-11-14



$\Xi^- + ^{12}\mathrm{C} \rightarrow ^{4}_{\Lambda}\mathrm{H} + ^{9}_{\Lambda}\mathrm{Be}$

(most probable)

S. Aoki *et al*.
Phys. Lett. B 355, 45 (1995)

- ✓ Cによるcapture
- ✓ $^{4}_{\Lambda}$H(確定)と$^{9}_{\Lambda}$Be(most probable)が生成

  $\rightarrow B_{\Xi^-} = 0.82 \pm 0.17$ MeV

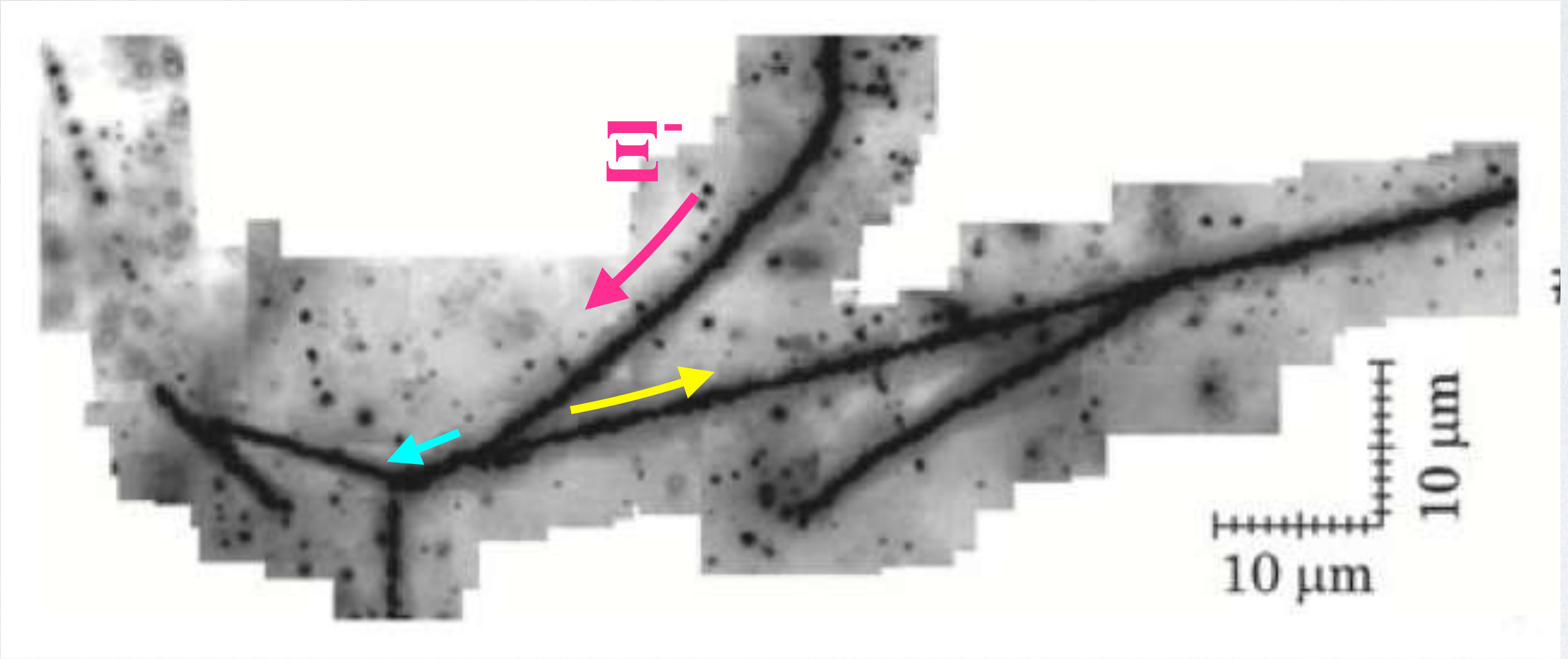
- ✓ most probableはCによるcapture
- ✓ 生成Λ核の基底or励起状態は決定できず
- ✓ $^{4}_{\Lambda}$H(基底)と$^{9}_{\Lambda}$Be(励起)と仮定すると

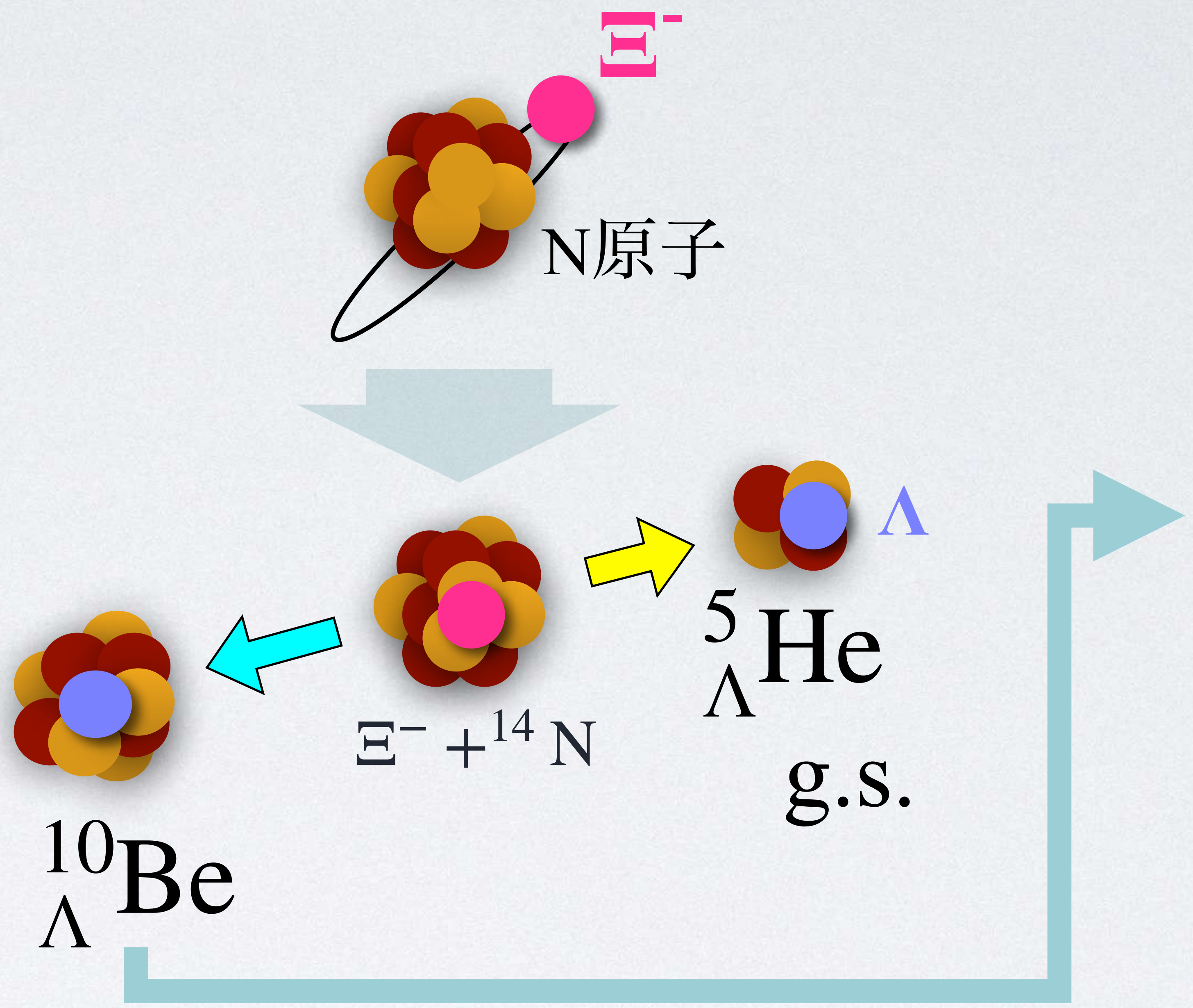
  $\rightarrow \quad B_{\Xi^-} = 0.82 \pm 0.14$ MeV

反応を一意に特定できなかった

KISO @KEK E373

K. Nakazawa *et al.*,
PTEP 2015, 033D02 (2015)





- ground stateなら

B_{Ξ^-} = 3.87 ± 0.21 MeV

- excited stateなら

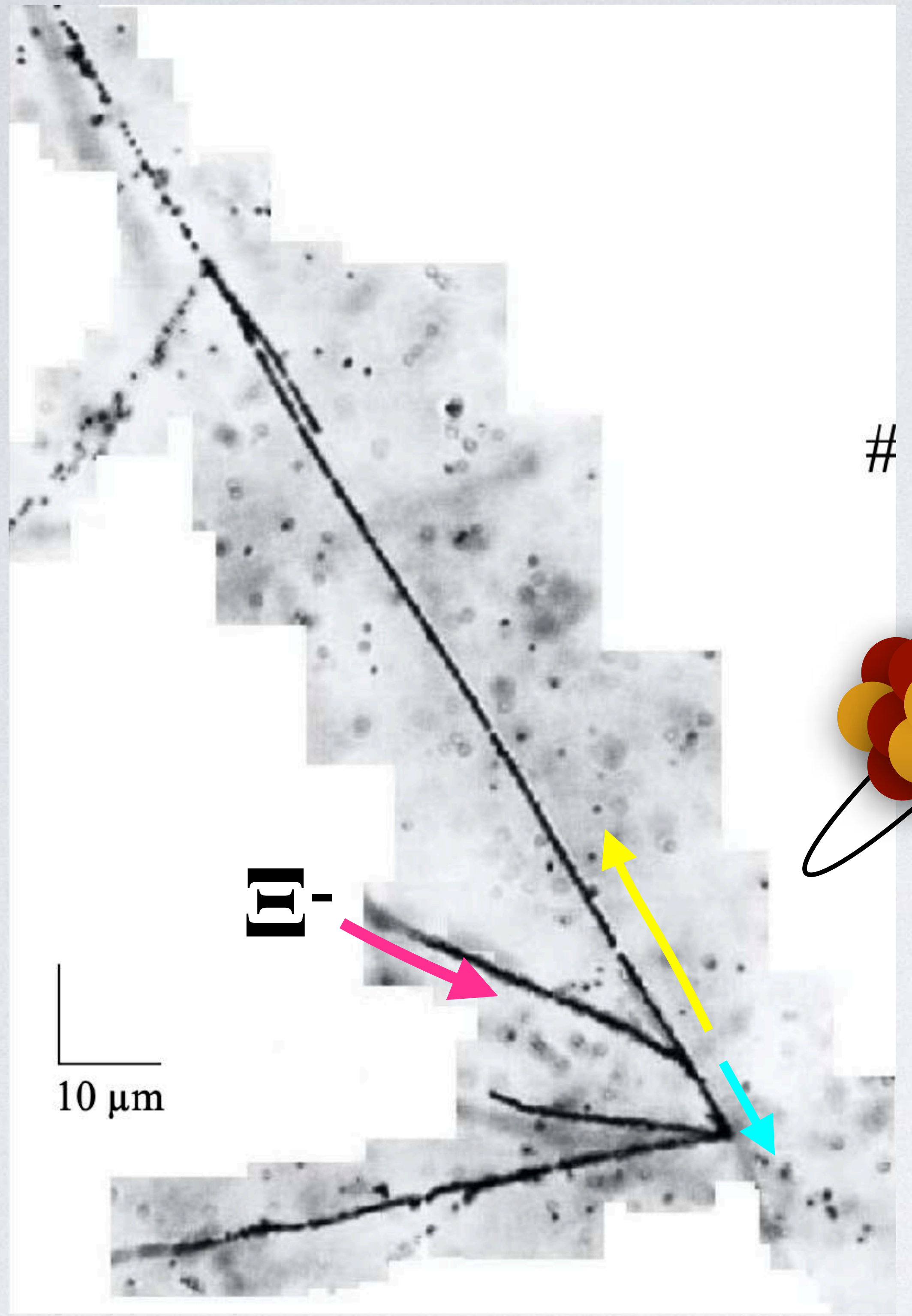
B_{Ξ^-} = 1.03 ± 0.18 MeV

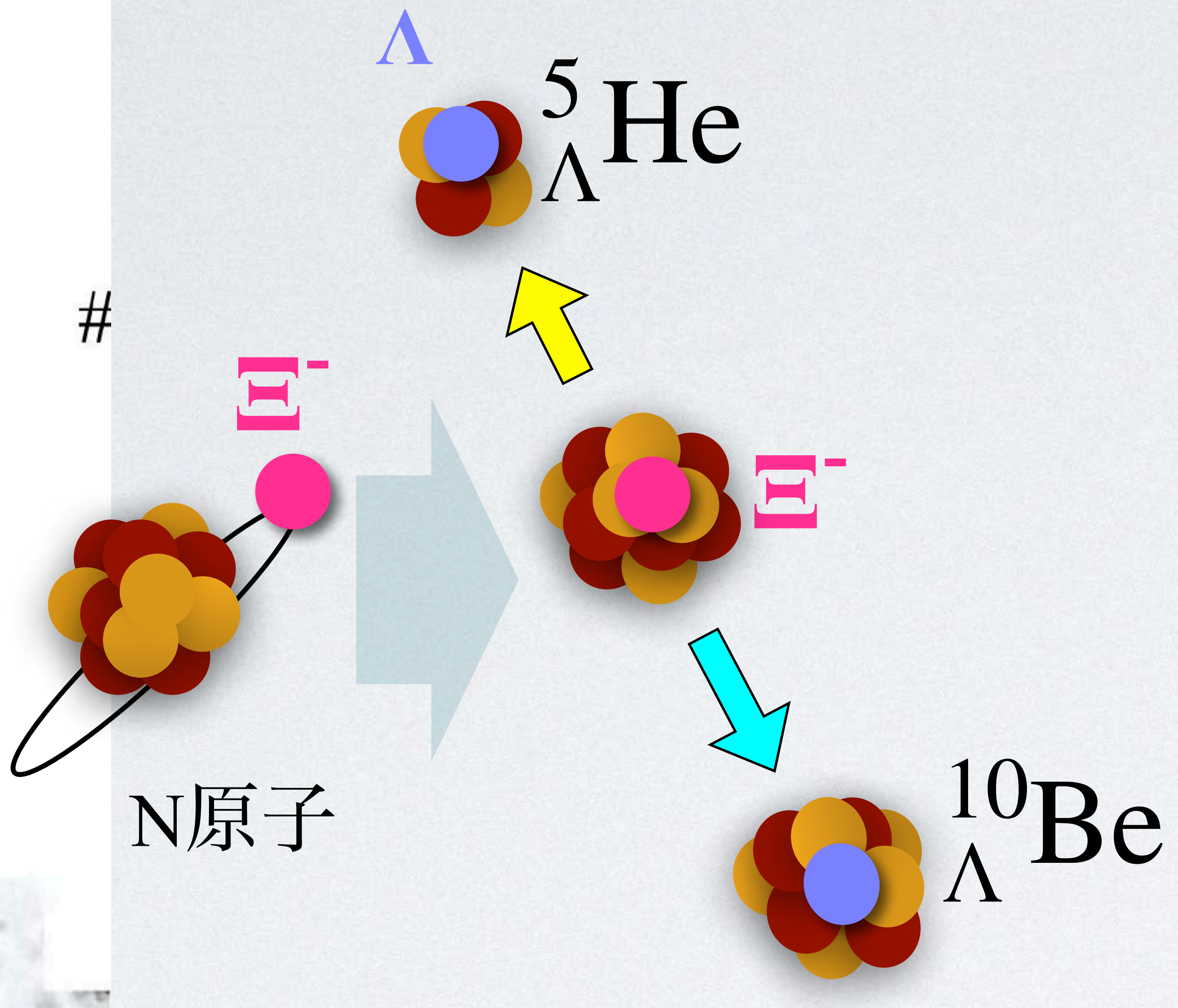
"The first evidence of a deeply bound state of Ξ-^{14}N system,"

ΞN is attractive

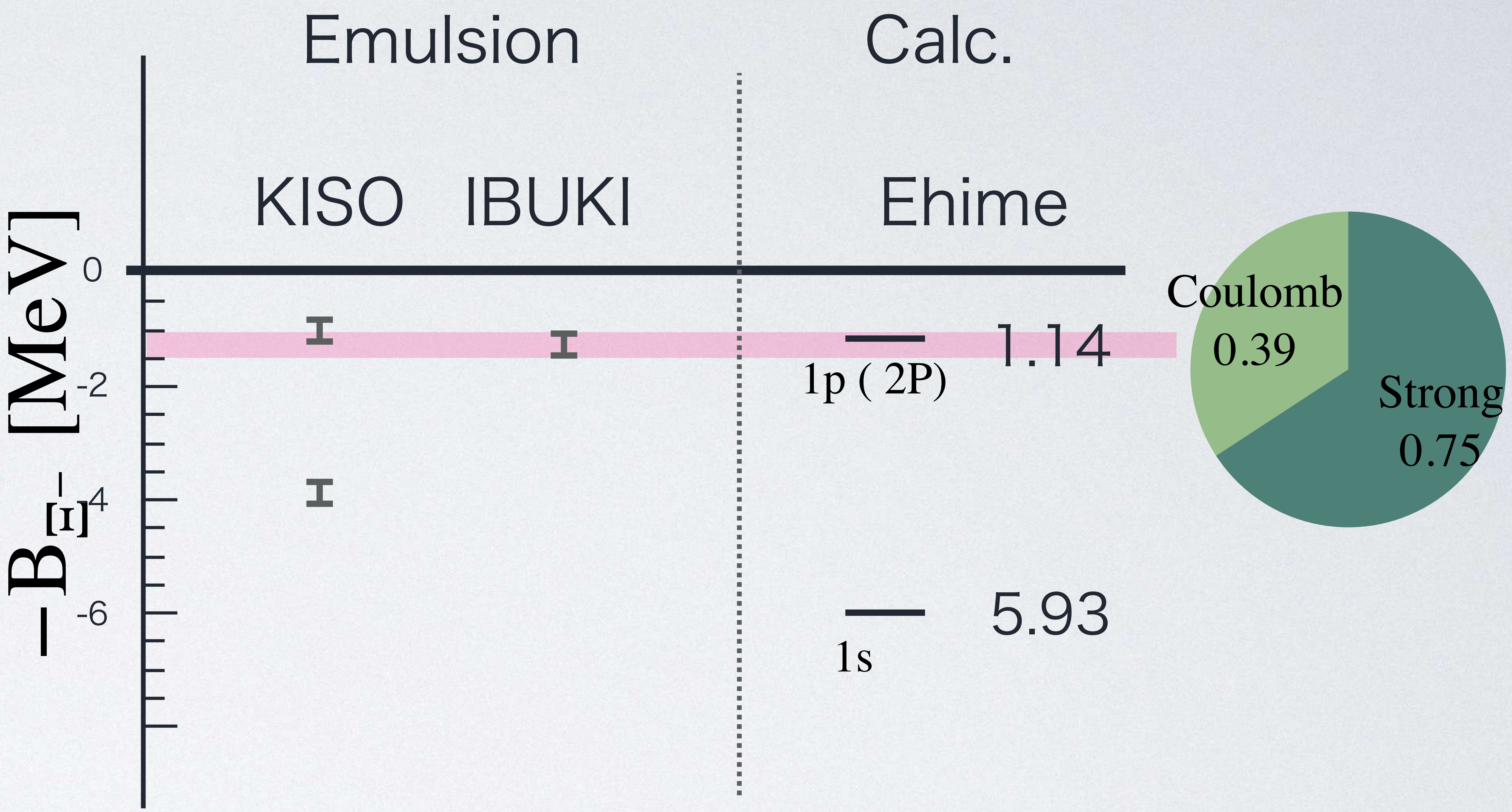
IBUKI @J-PARC E07

<u>S. H. Hayakawa</u> *et al.*,
Phys. Rev. Lett. **105**, 627 (2021)





$B_{\Xi^-} = 1.27 \pm 0.21$ MeV

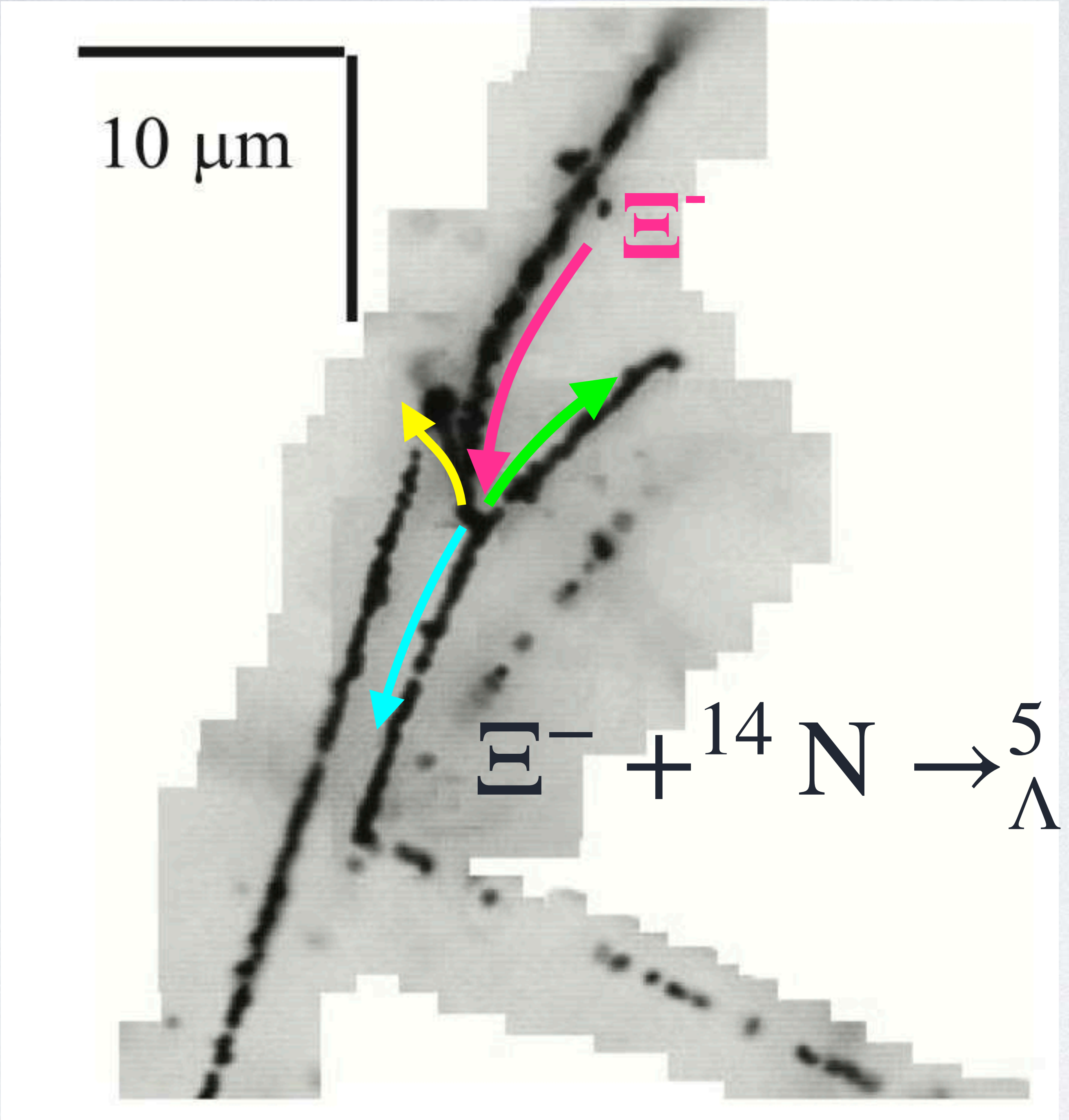


IBUKI : a Coulomb-assisted $1p_{\Xi^-}$ state

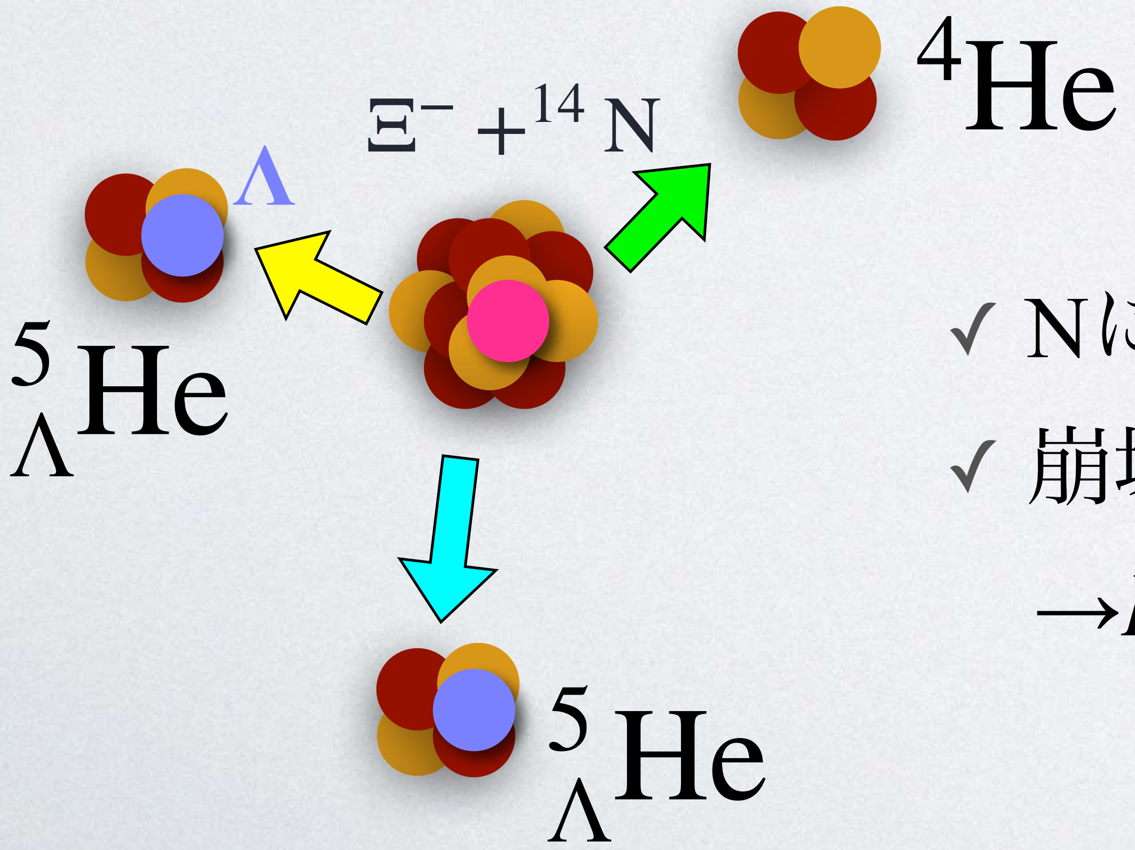
IRRAWADDY/ KINKA @E07/E373

M. Yoshimoto *et al.*,
Prog. Theor. Exp. Phys 2021, 073D02 (2021)

#IRRAWADDY



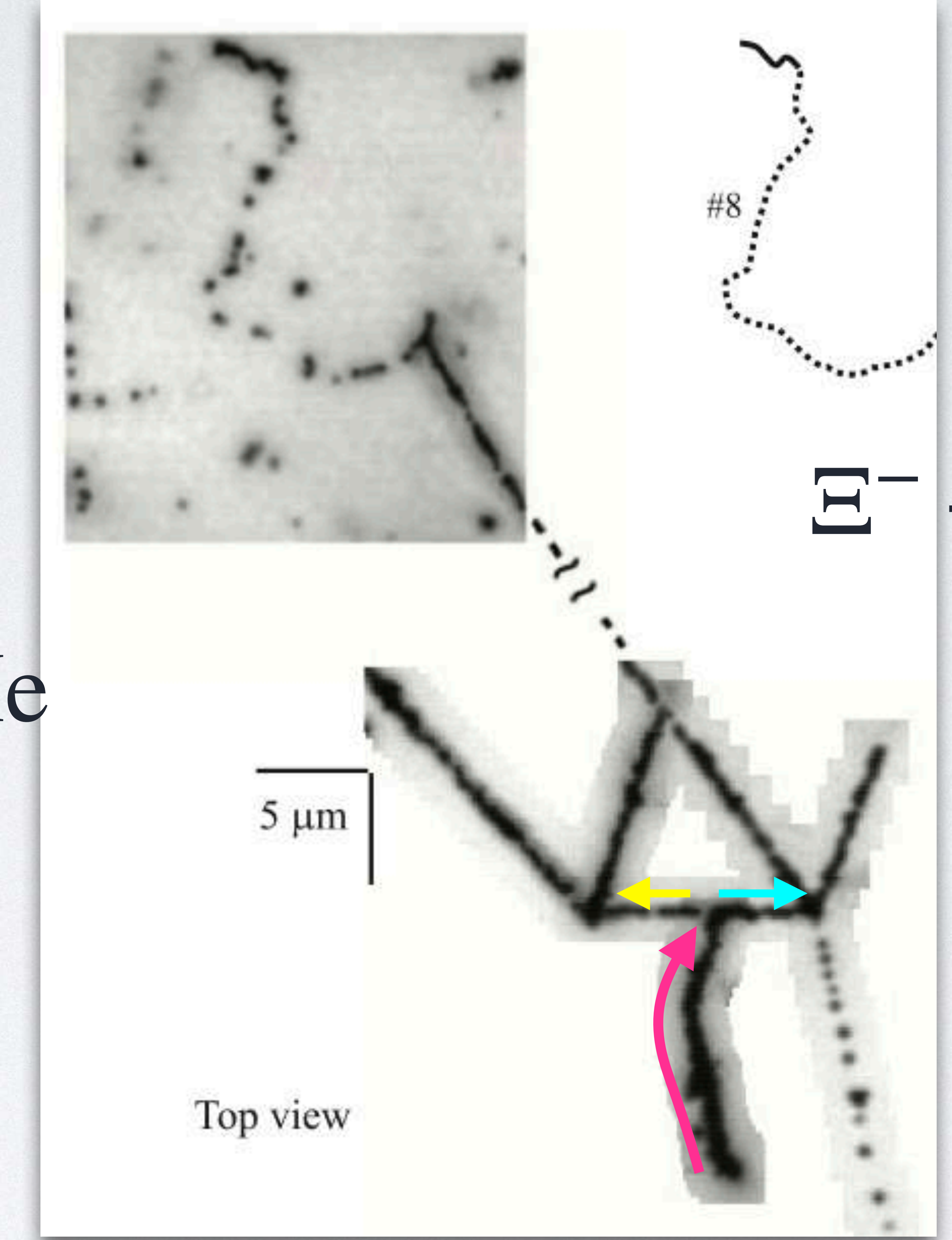
$$\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + {}^{5}_{\Lambda}\mathrm{He} + {}^{4}\mathrm{He}$$



- ✓ Nによるcapture
- ✓ 崩壊モードは一意に決定

  $\rightarrow B_{\Xi^-} = 6.27 \pm 0.27$ MeV

#KINKA



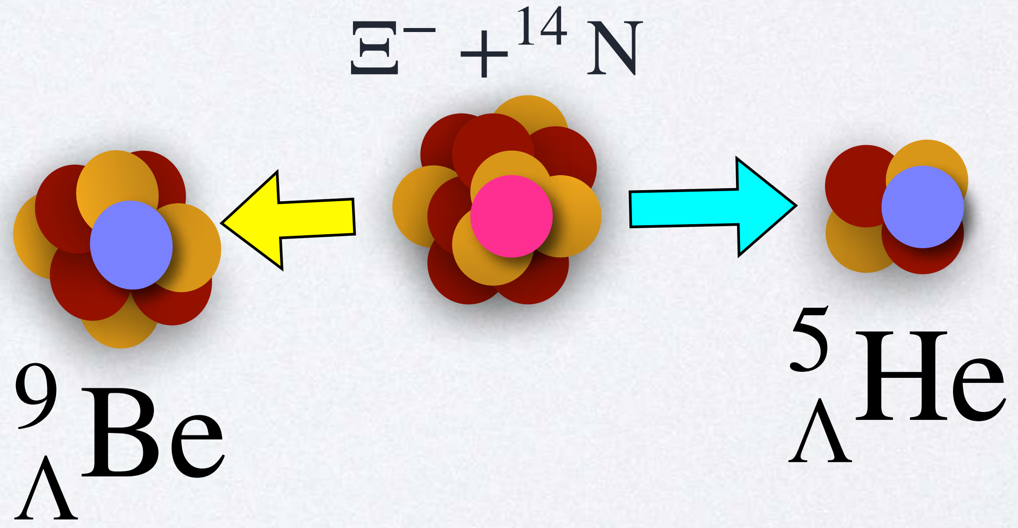
$$\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{9}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He} + \mathrm{n}$$

- ${}^{9}_{\Lambda}$Beがground stateなら

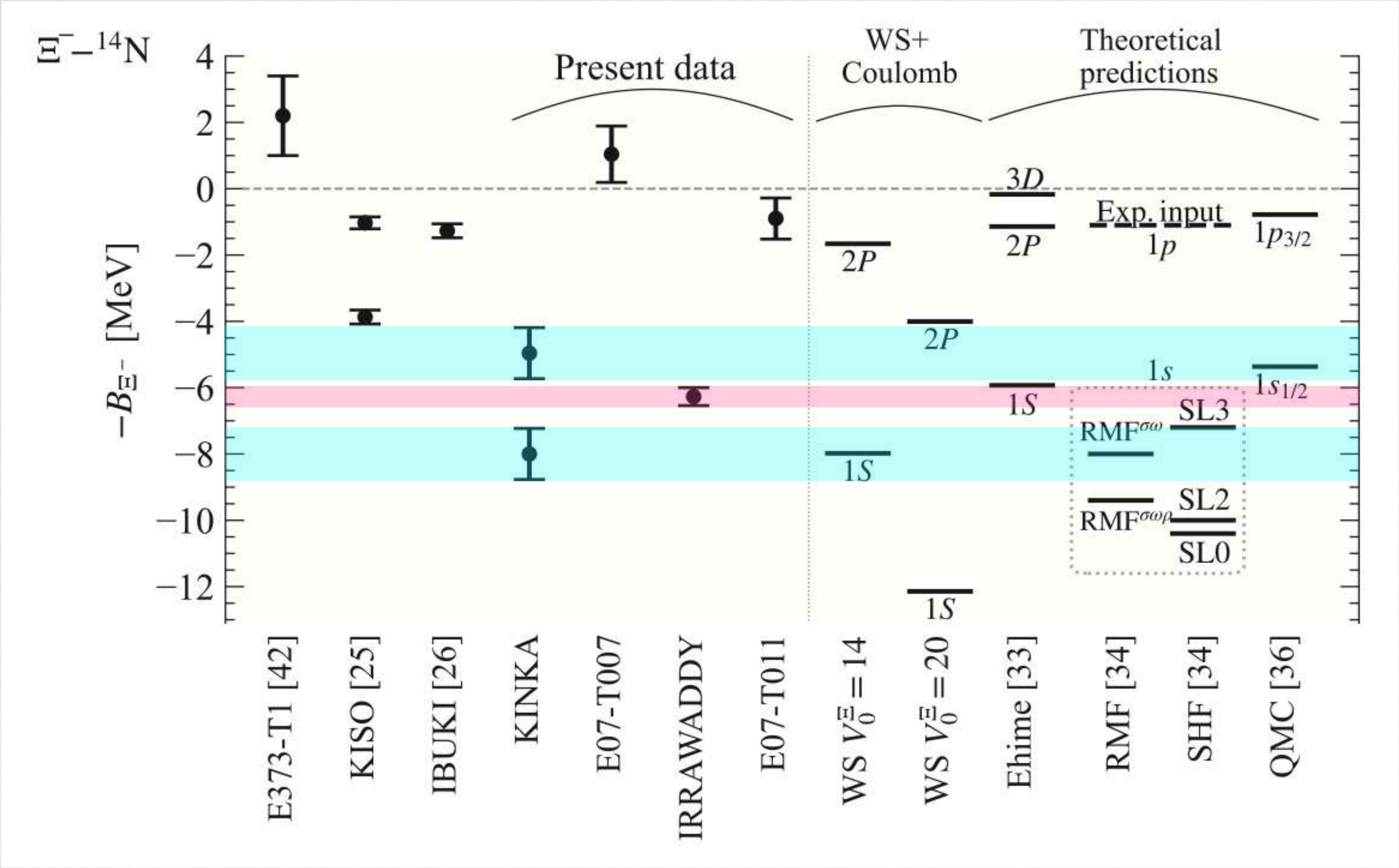
  $B_{\Xi^-} = 8.00 \pm 0.77$ MeV

- ${}^{9}_{\Lambda}$Beがexcited stateなら

  $B_{\Xi^-} = 4.96 \pm 0.77$ MeV



IRRAWADDY, KINKAに関する議論



M. Yoshimoto et al.,
Prog. Theor. Exp. Phys 2021, 073D02 (2021)

"the first observation of a nuclear 1*s* state of the hypernucleus, ^{15}C"

$\sim 10^{-2}$

E1(2P→1S) rate << E1(3D→2P) rate

"Assigning a $\Xi_{1s} - {}^{14}N$ bound state to IRRAWADDY is therefore questionable. "

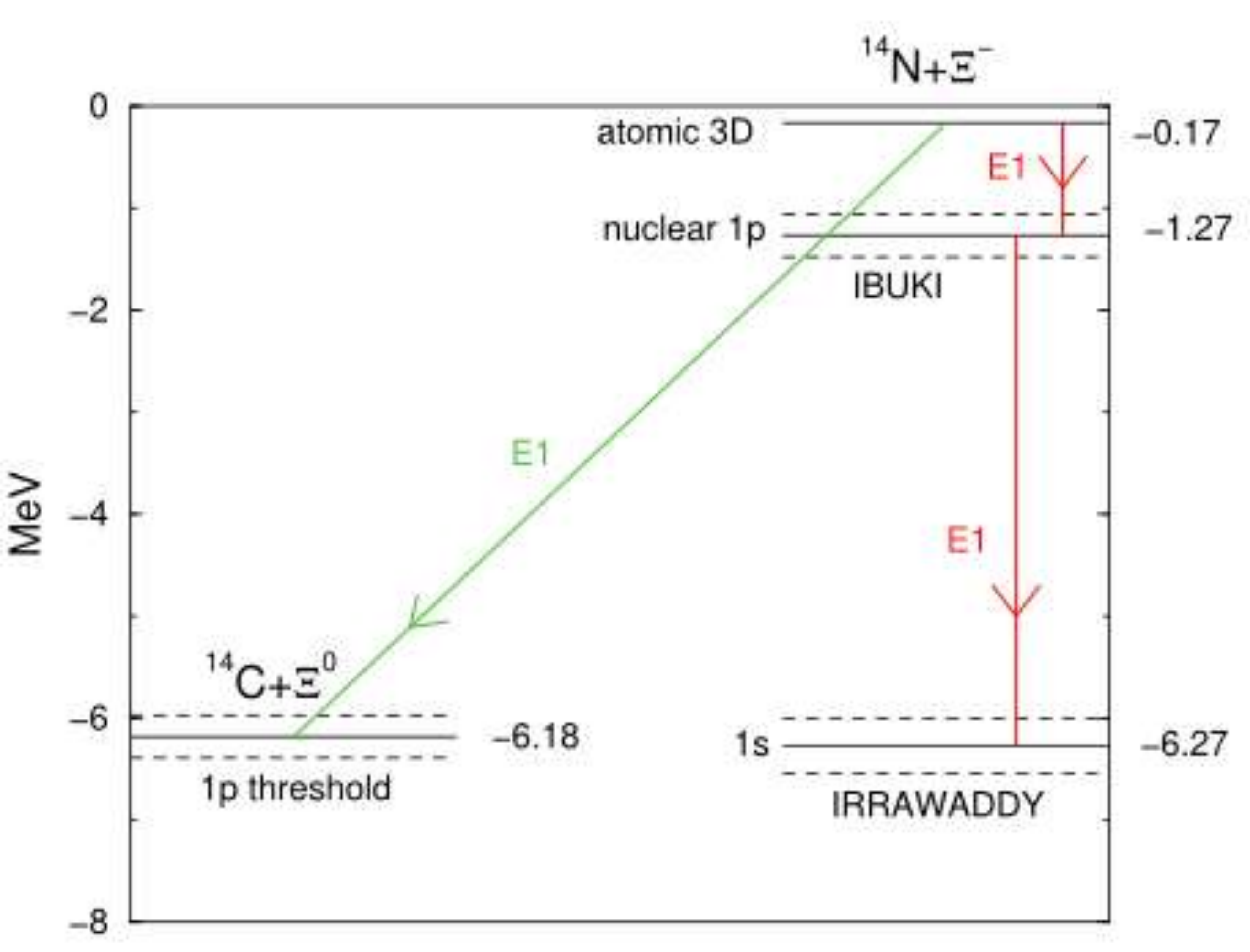
A.Gal et al. PLB 837

?

$\Xi^{-}p \leftrightarrow \Xi^{0}n$ mixing

A. Gal et al. PLB 837

$\Xi^{-}p \rightarrow \Xi^{0}n$ 反応の影響を指摘



3D atomic stateからのE1遷移により

$\Xi^{-}_{1p} - ^{14}\mathrm{N}$ / $\Xi^{0}_{1p} - ^{14}\mathrm{C}$

Nの場合は、２つの状態へ同程度の割合で遷移

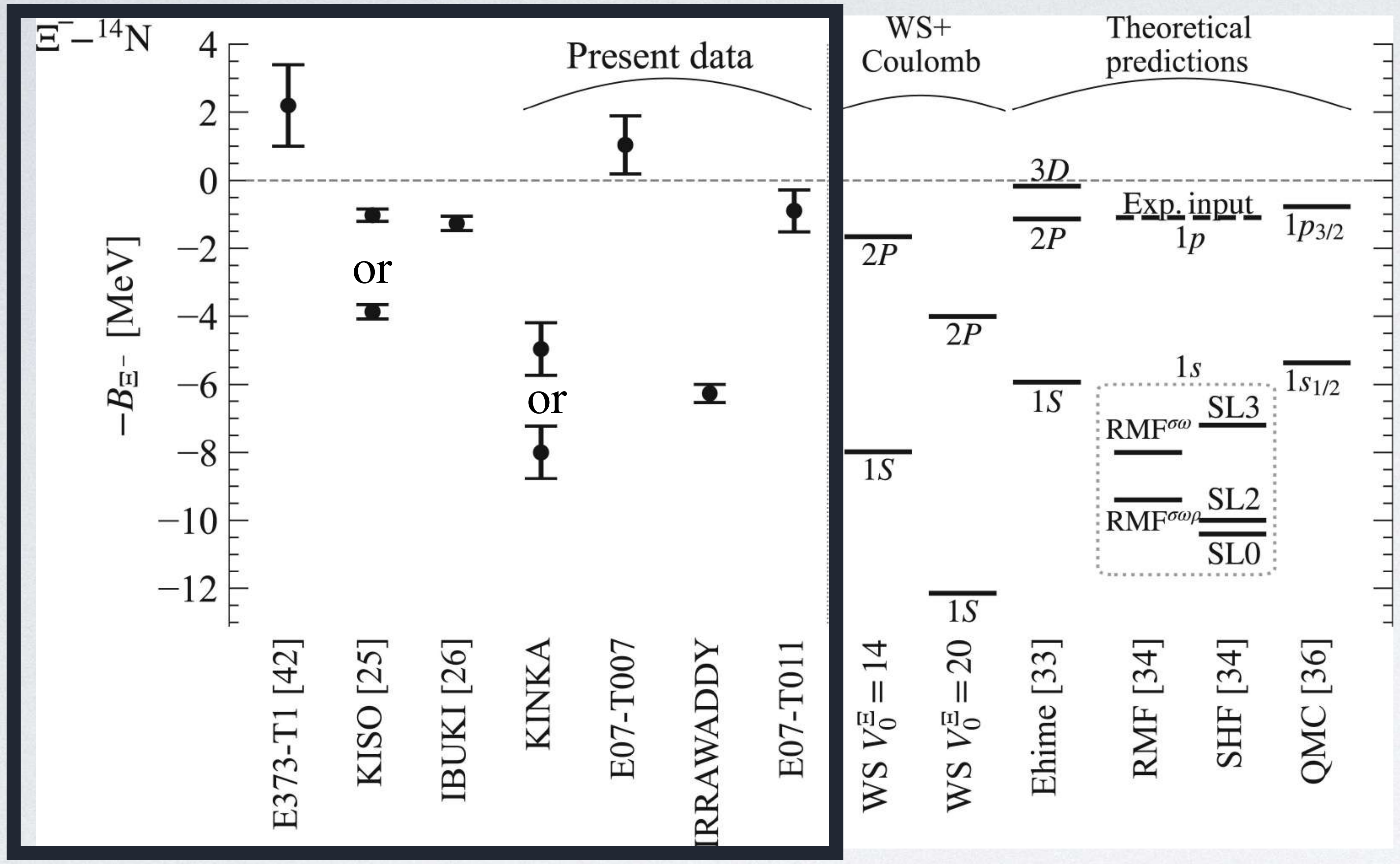
→ IRRAWADDYは$\Xi^{0}_{1p} - ^{14}\mathrm{C}$の状態だと解釈できる

$m_{\Xi^-} - m_{\Xi^0}$	M(^{12}B)-M(^{12}C)	M(^{14}C)-M(^{14}N)	M(^{16}N)-M(^{16}O)
6.85 MeV	13.9 MeV	0.67 MeV	10.93 MeV

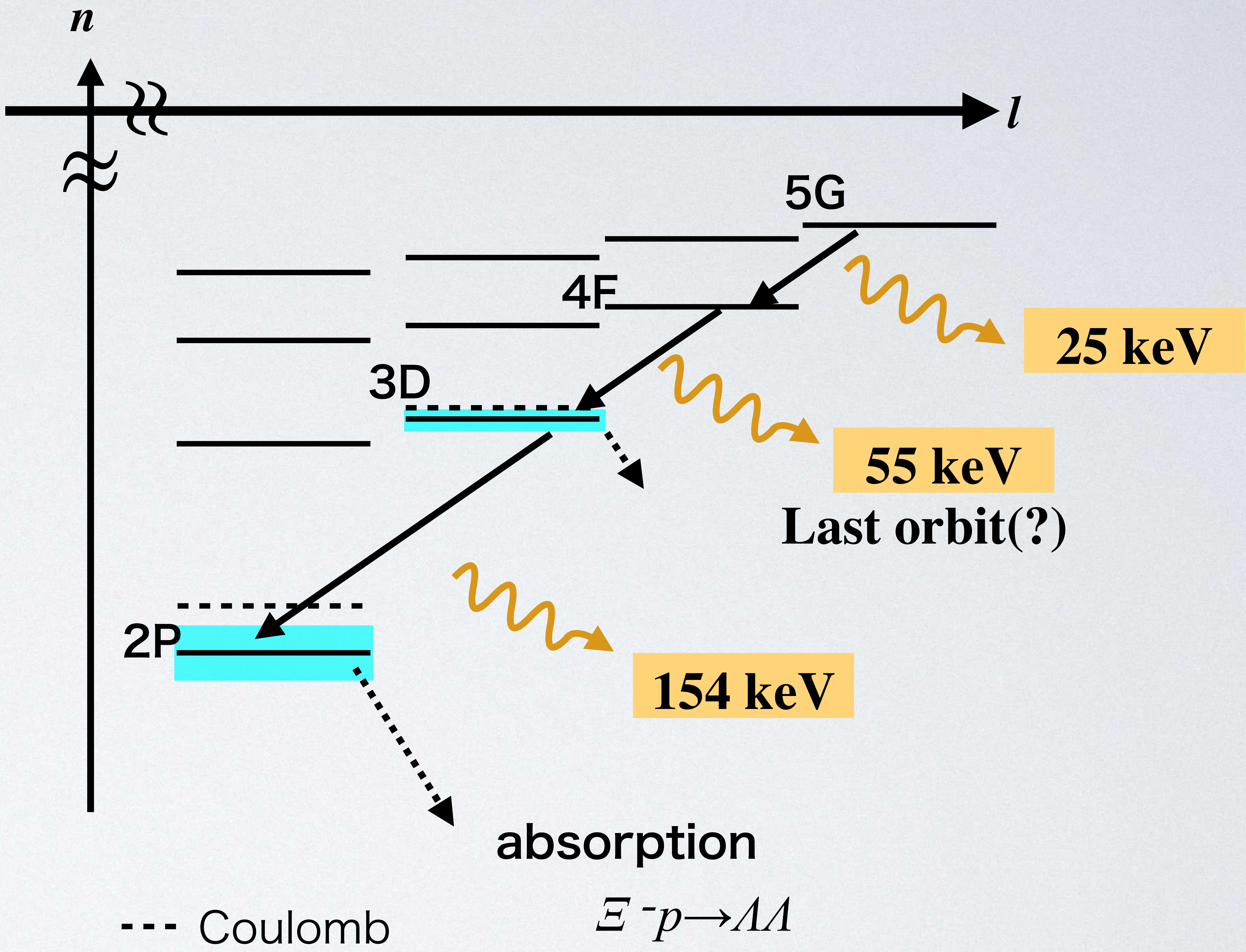
Ξ^{-}_{1s}の原子核状態の存在を明らかにするためには、$\Xi^{-}p \leftrightarrow \Xi^{0}n$が大きく抑制されるC, Oにおいて、E1遷移の分岐比の測定が必要

炭素Ξ原子X線測定

▼E373,E07で観測された窒素Ξ束縛系のΞ束縛エネルギー



M. Yoshimoto *et al.*, PTEP 2021, 073D02 (2021)



[実験] P, S軌道からの吸収と見られる事象が多数観測された

⇕ ?

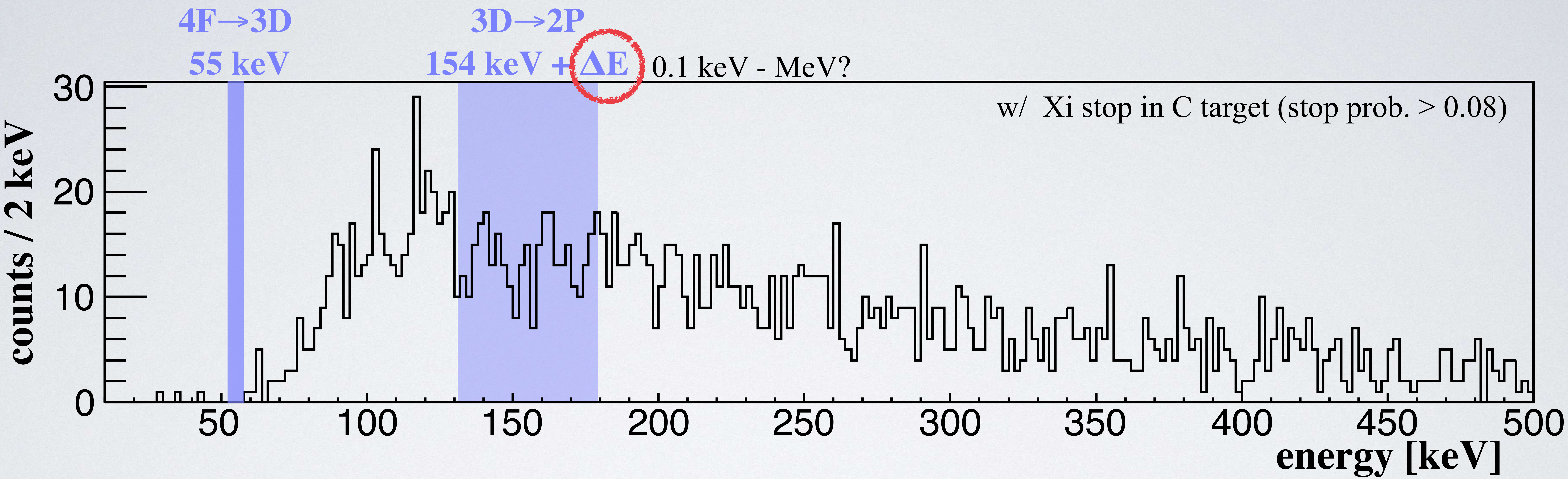
[理論計算] *T. Koike, J. Phys. Soc. Jpn. Conf. Proc. 17, 033011 (2017).

Pからの吸収 : 0.5 - 2%

Dからの吸収 : 47.9 - 75.7%

X線観測による分岐比の直接測定が有力

C Ξ atomic X-ray measurement @ E07



0.1 - 1 MeV領域で幅を仮定してピーク探索

→ No evident peak

$\Xi^- p \to \Lambda\Lambda$ に関する議論

- X線yield (N_{Xray})のupper limitによってE1遷移の分岐比BRのupper limitが評価できる

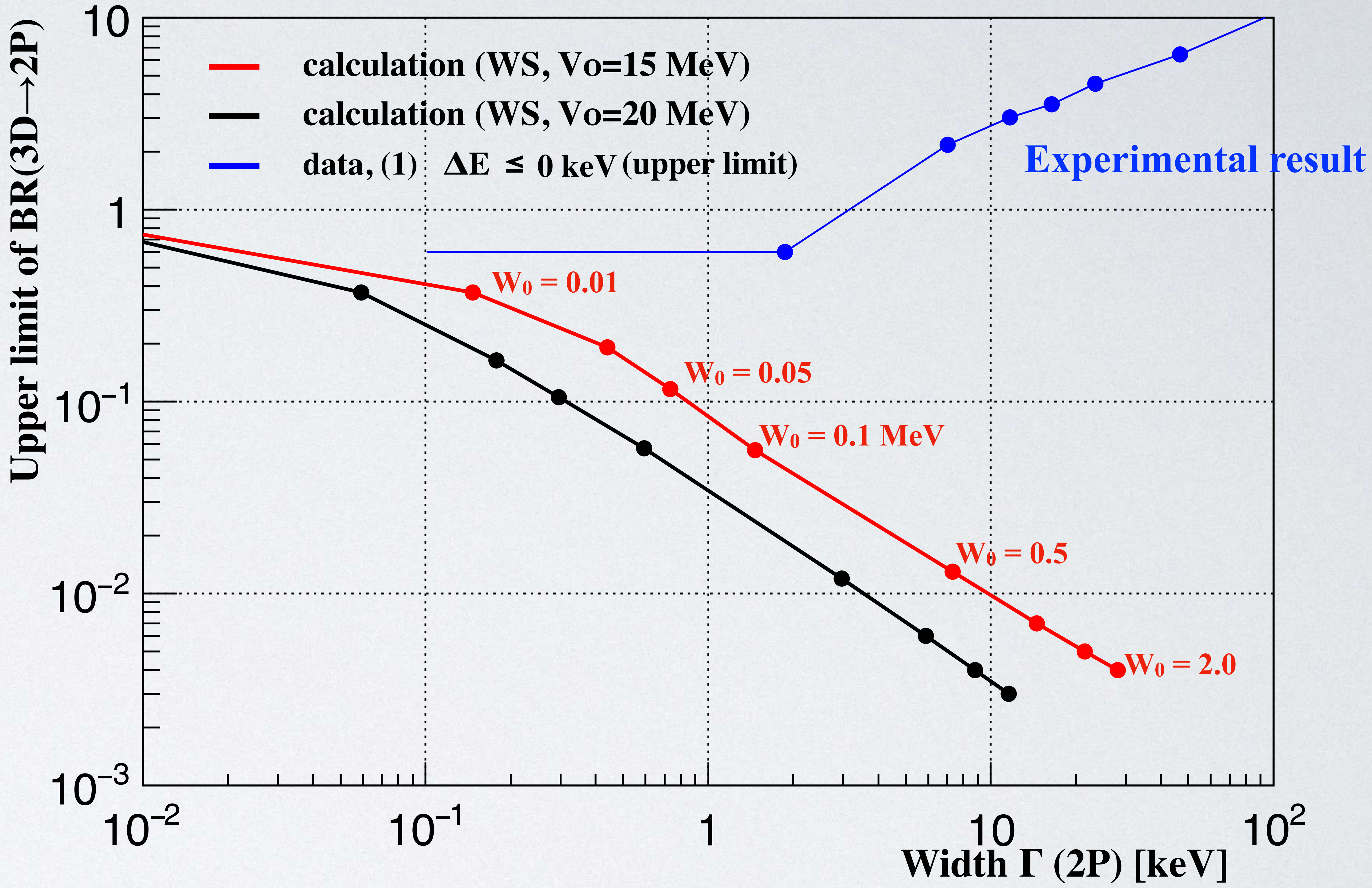
$$BR(E1, 3D \to 2P) = \frac{N_{Xrays}}{N_{\Xi capture} \times P_{\Xi}(3D) \times \epsilon_{Ge}}$$

- BRによって吸収の幅 $\Gamma^{3D}_{abs.}$ ($\sim W_0$)のlower limitが評価できる

$$BR(E1, 3D \to 2P) = \frac{\Gamma^{3D \to 2P}_{E1}}{\Gamma^{3D \to 2P}_{E1} + \Gamma^{3D}_{abs.}}$$

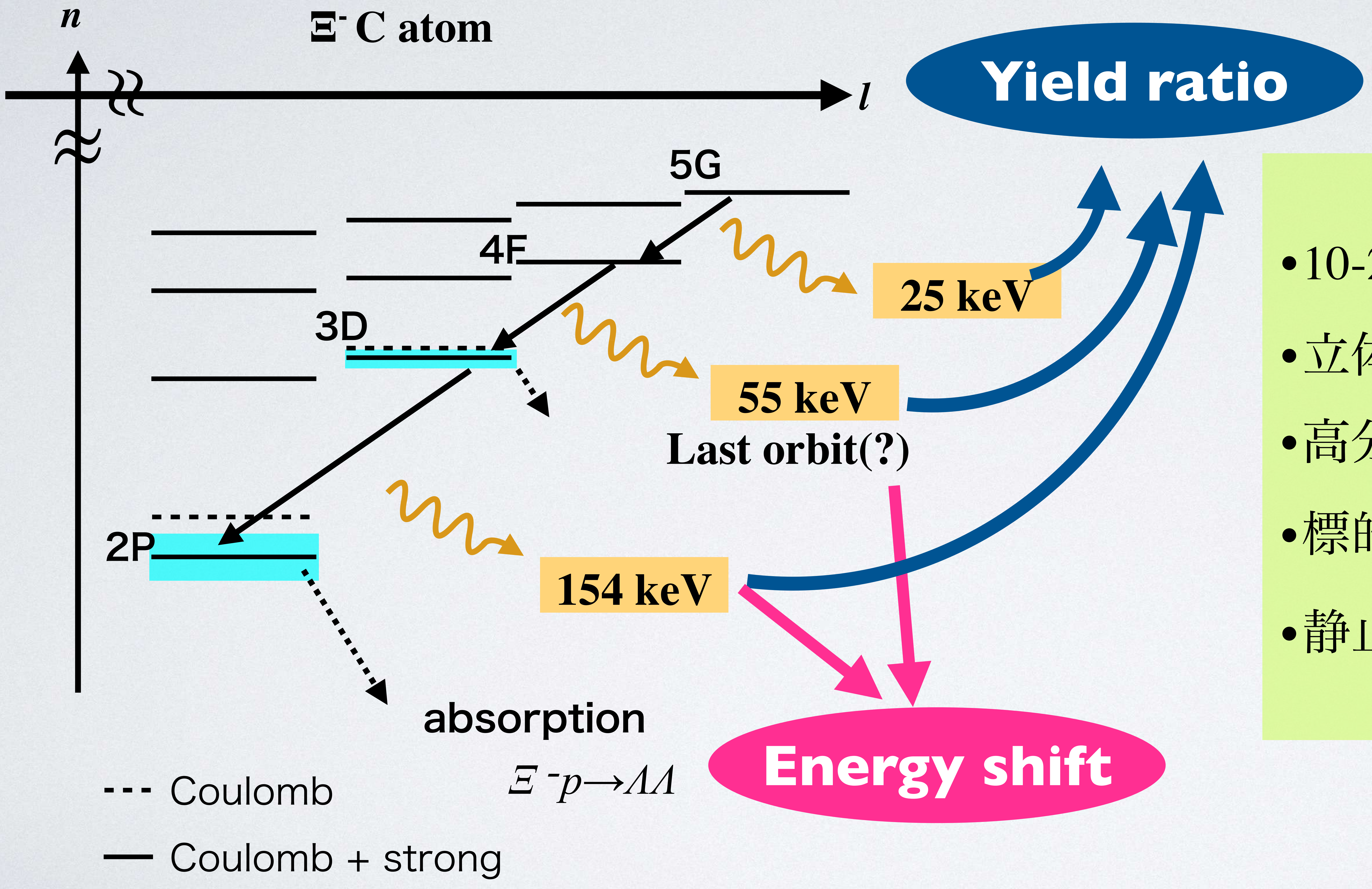
Calc. (WS type)

- V_0 = -15 MeV
- V_0 = -20 MeV



BRからW_0の下限値を議論するためには、実験感度を 1 桁向上する必要がある (W_0が0.1 MeV程度と仮定した場合)

解決すべき・要求される事項



- 10-200 keVエネルギー領域での測定
- 立体角の拡大
- 高分解能
- 標的厚/減速材の最適化
- 静止Ξ選択法の改良

測定実現に向けた開発事項

- X線検出器として
  CdTe半導体検出器の導入

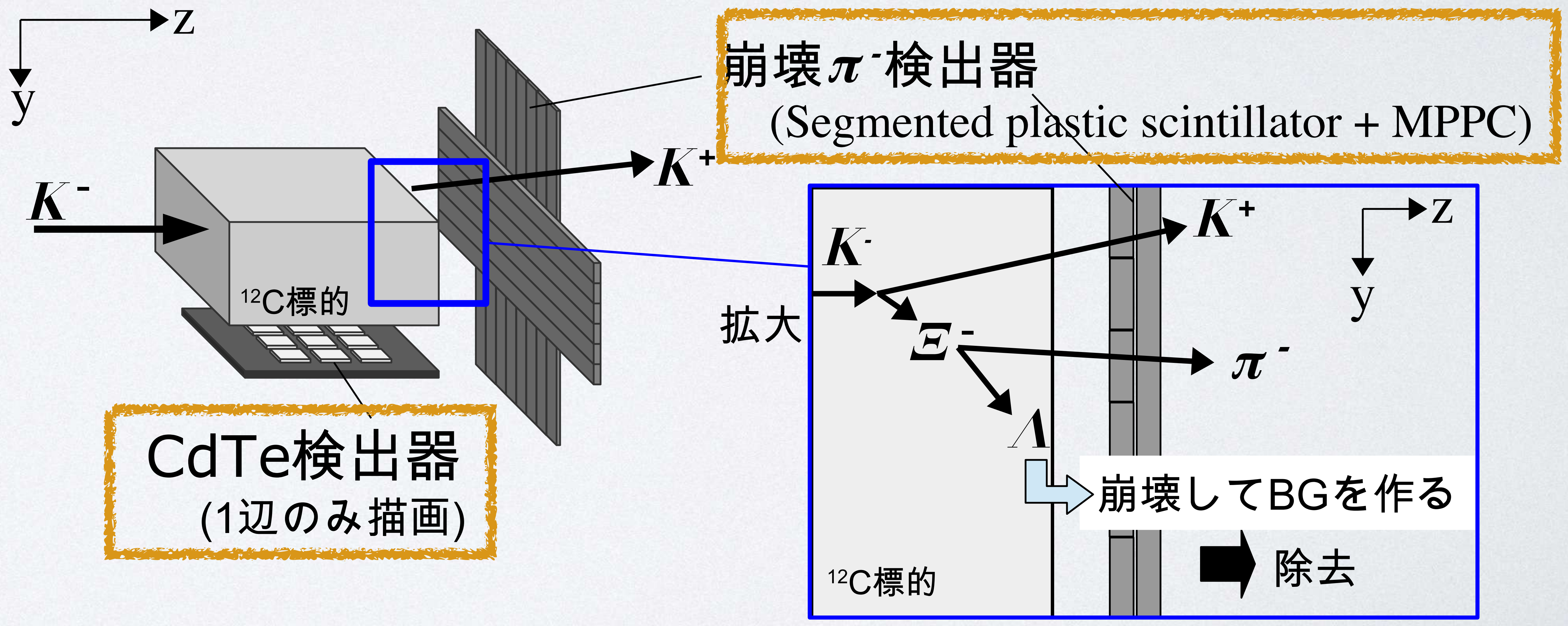
[特徴]

✓ **数 keV - 1 MeV**に感度
✓ **γ吸収効率が高い**
✓ **常温で動作**できる
✓ Ge,Siに比べて**若干E分解能が悪い**
✓ Polarization

	Ge検出器@E07	CdTe(テルル化カドミウム)検出器
エネルギー感度領域	100 - 1400 keV	数 keV - 1 MeV
E分解能	2 keV(FWHM) @ 154 keV	2.7 keV(FWHM)@ 60 keV*
動作	窒素冷却	常温可
立体角	10数%	50 %**

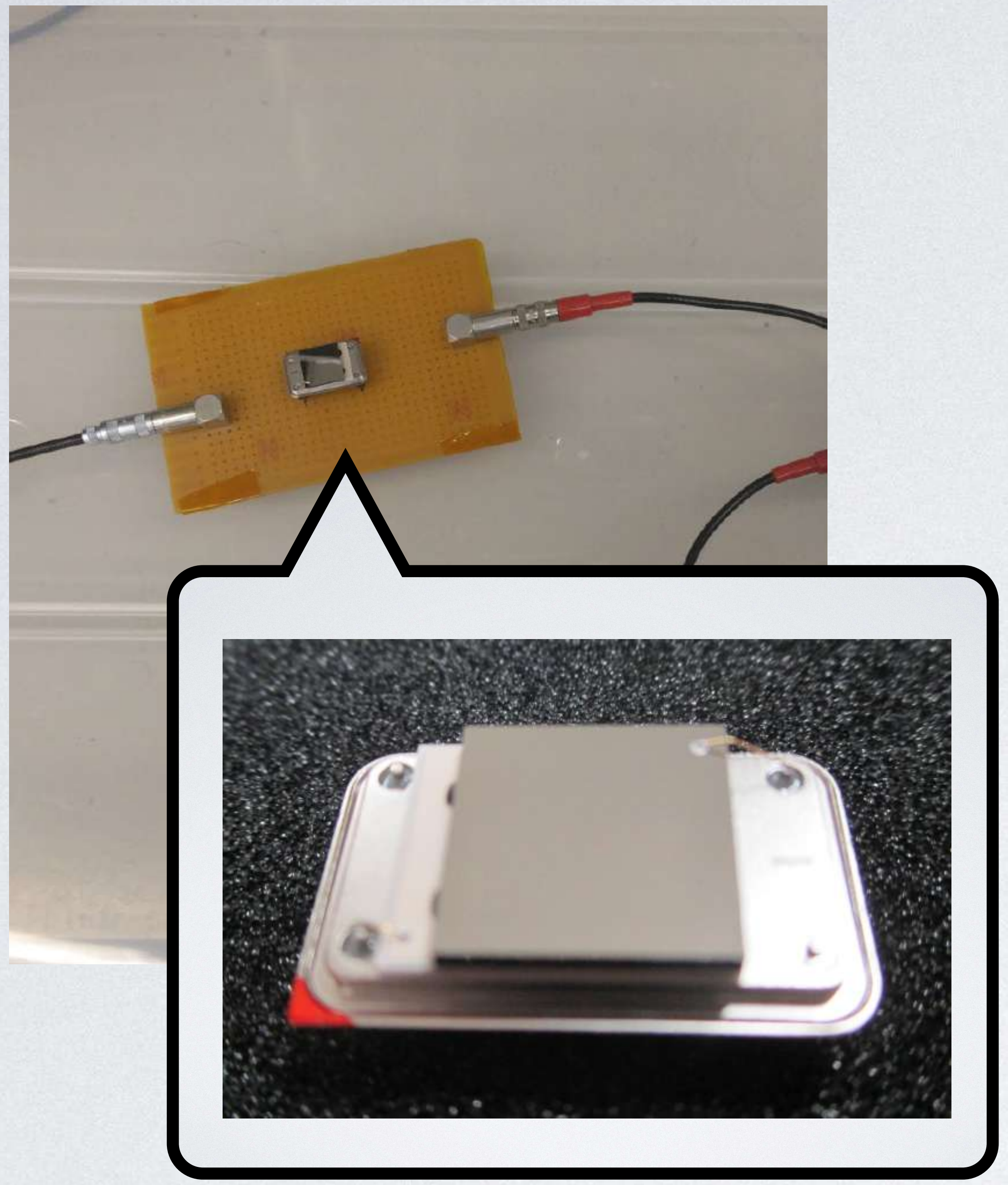
- 新たな静止Ξ事象選択法の検討

✓ 崩壊π検出器
✓ Fiber Tracker (AFT) + degrader

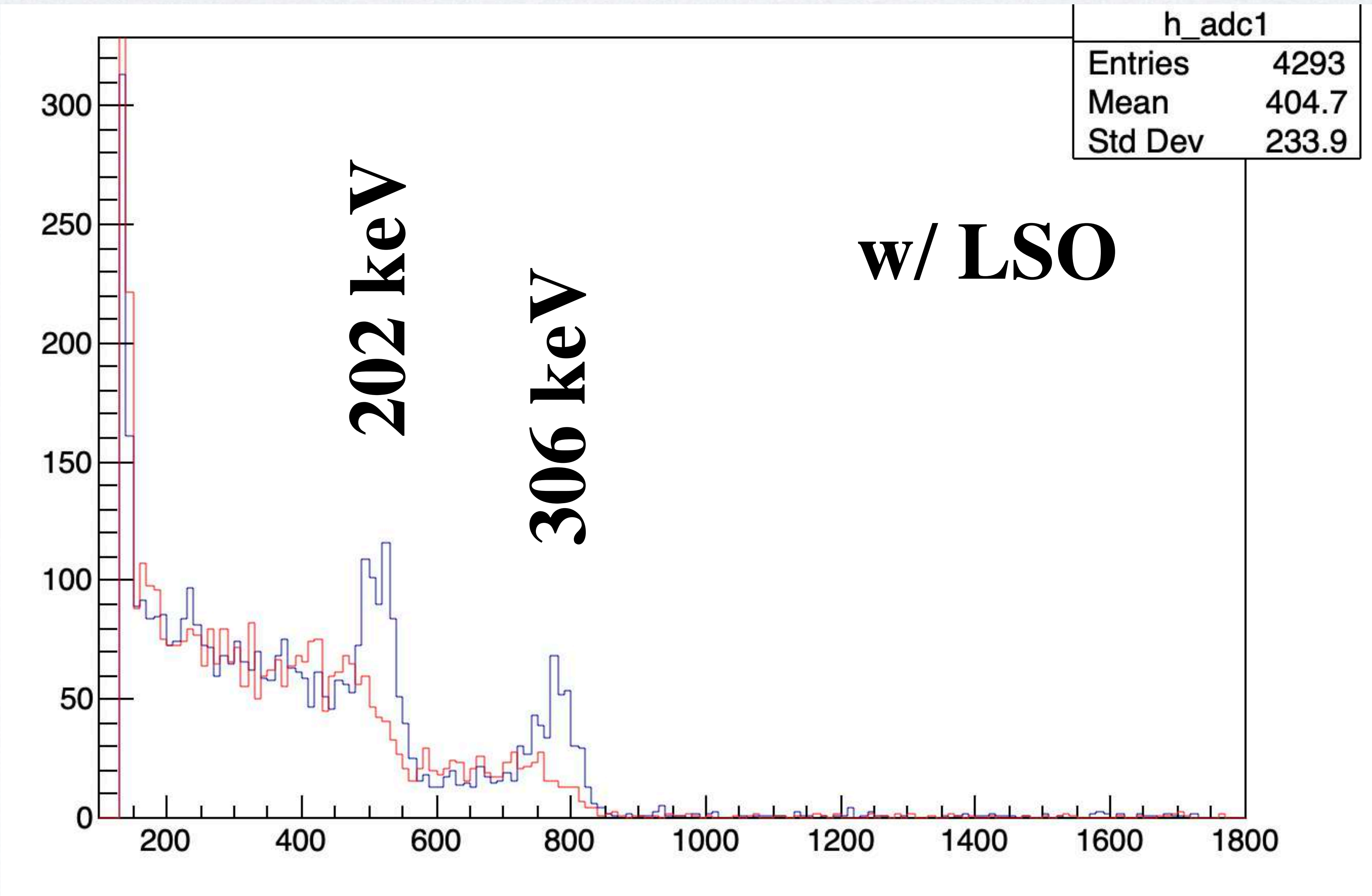


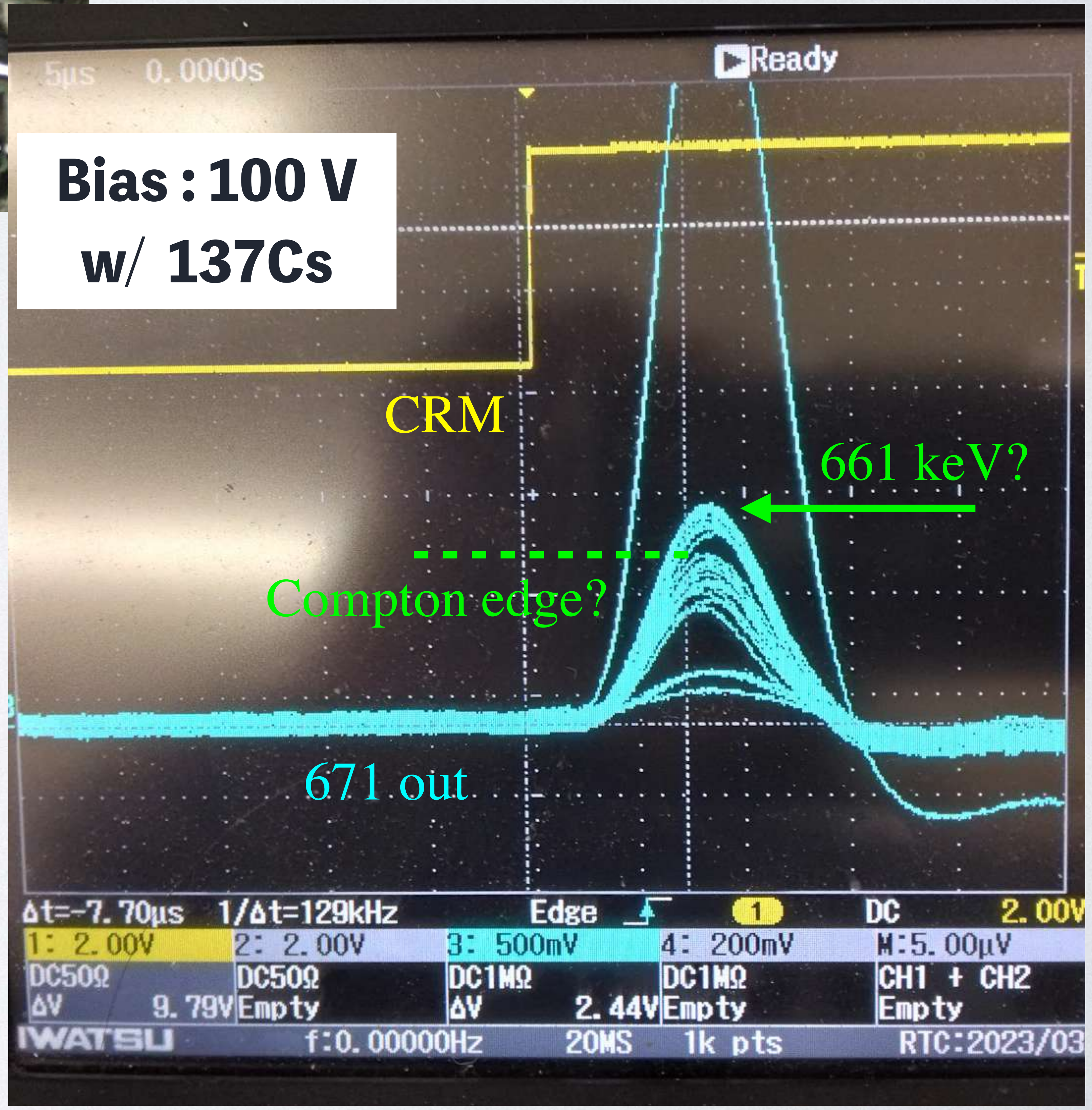
*アクロラド社HPより
**1cm²素子*16個*4基板を標的から3cmの距離に置いた場合

CdTe検出器テスト

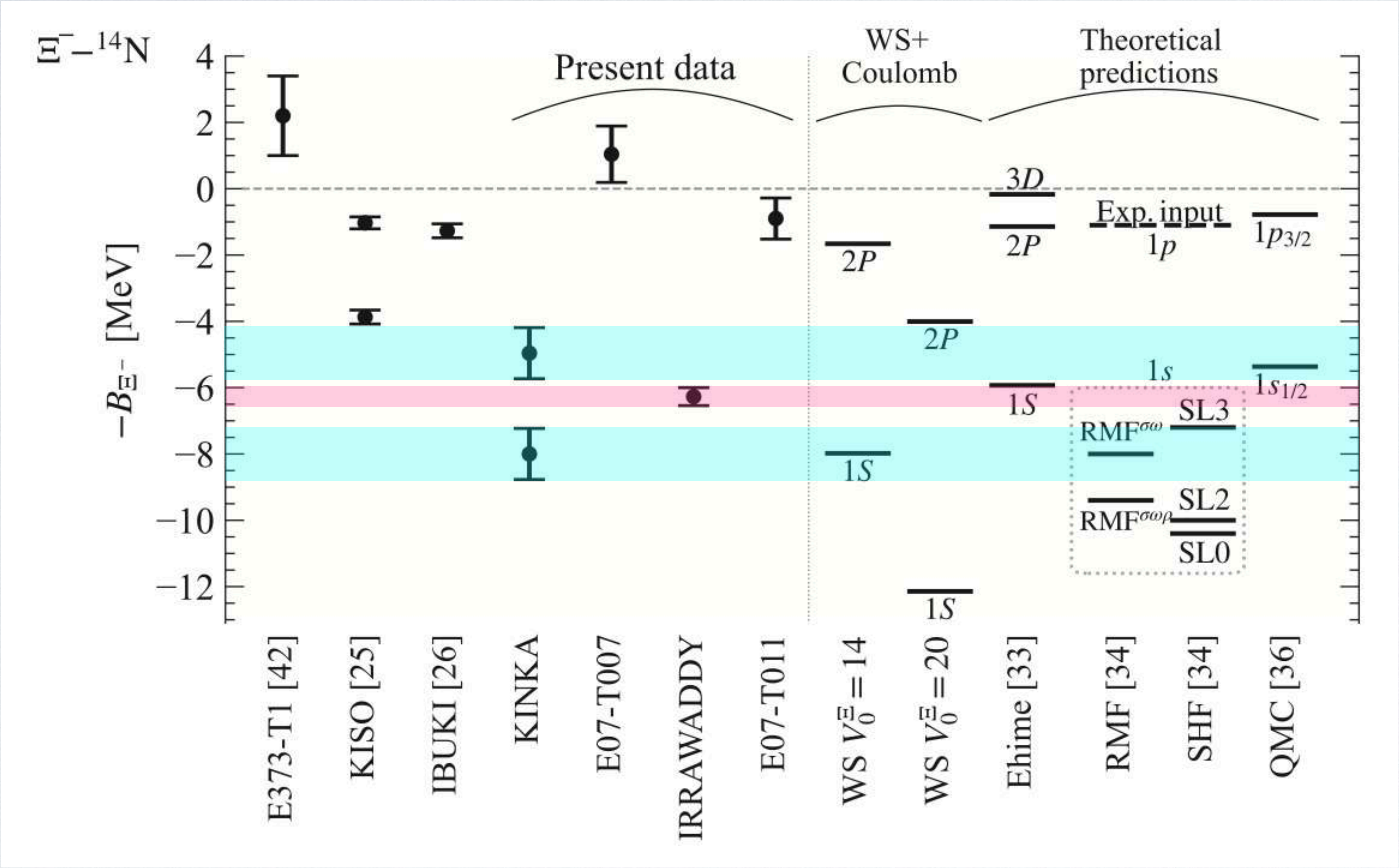


アクロラド社製 1cm*1cm





IRRAWADDY, KINKAに関する議論



M. Yoshimoto et al.,
Prog. Theor. Exp. Phys 2021, 073D02 (2021)

"the first observation of a nuclear 1*s* state of the hypernucleus, ${}^{15}C$"

~10^{-2}

E1(2P→1S) rate << E1(3D→2P) rate

"Assigning a $\Xi_{1s} - {}^{14}N$ bound state to IRRAWADDY is therefore questionable. "

A.Gal et al. PLB 837

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