New results on Xi hypernuclei

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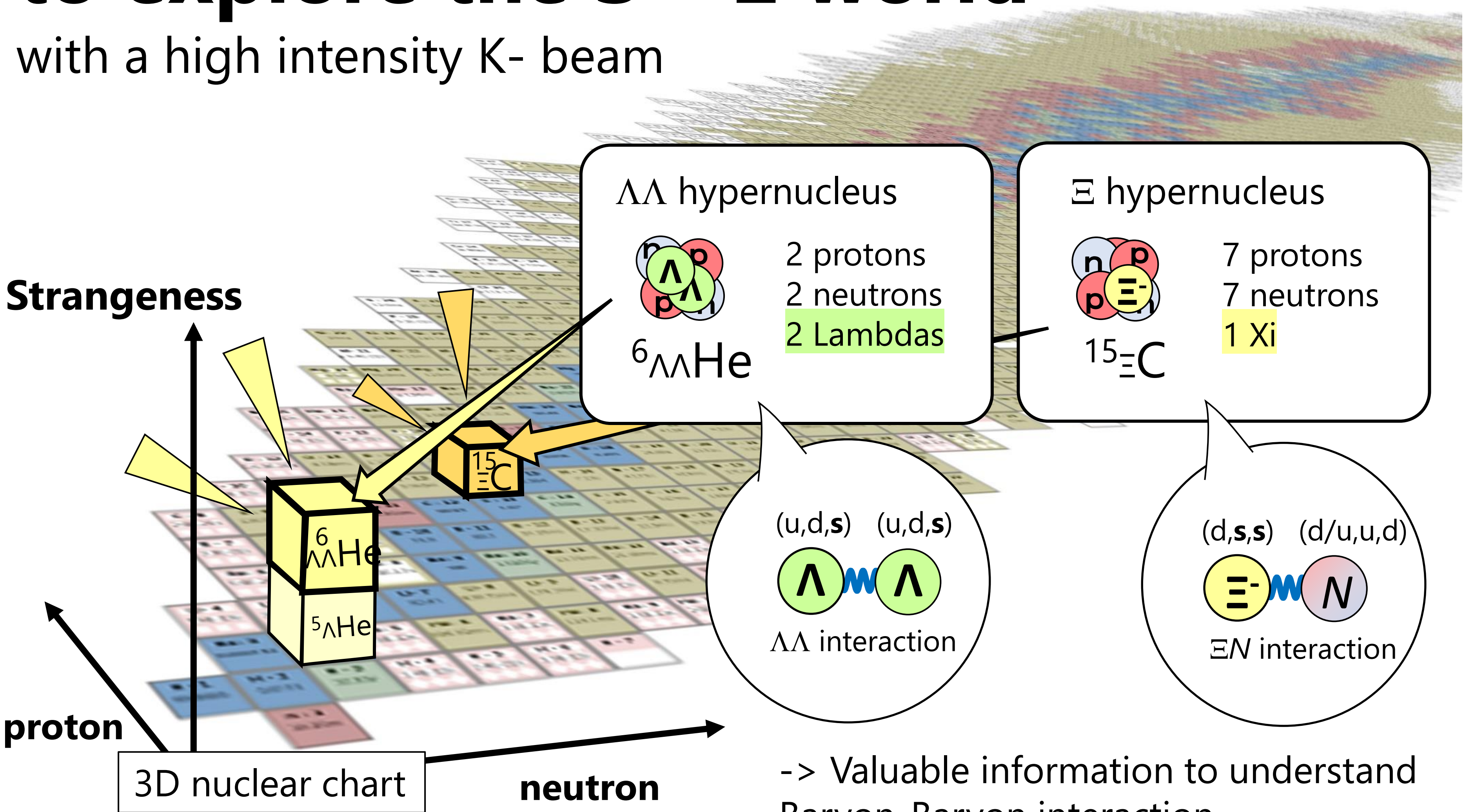
on behalf of the E07 collaboration at J-PARC

M. Yoshimoto, *et al.* *PTEP* **2021**, 073D02 (2021).
https://doi.org/10.1093/ptep/ptab073
S. H. Hayakawa, *et al.* *Phys. Rev. Lett.* **126**, 062501 (2021).
https://doi.org/10.1103/PhysRevLett.126.062501 https://arxiv.org/abs/2010.14317

Our main goal is

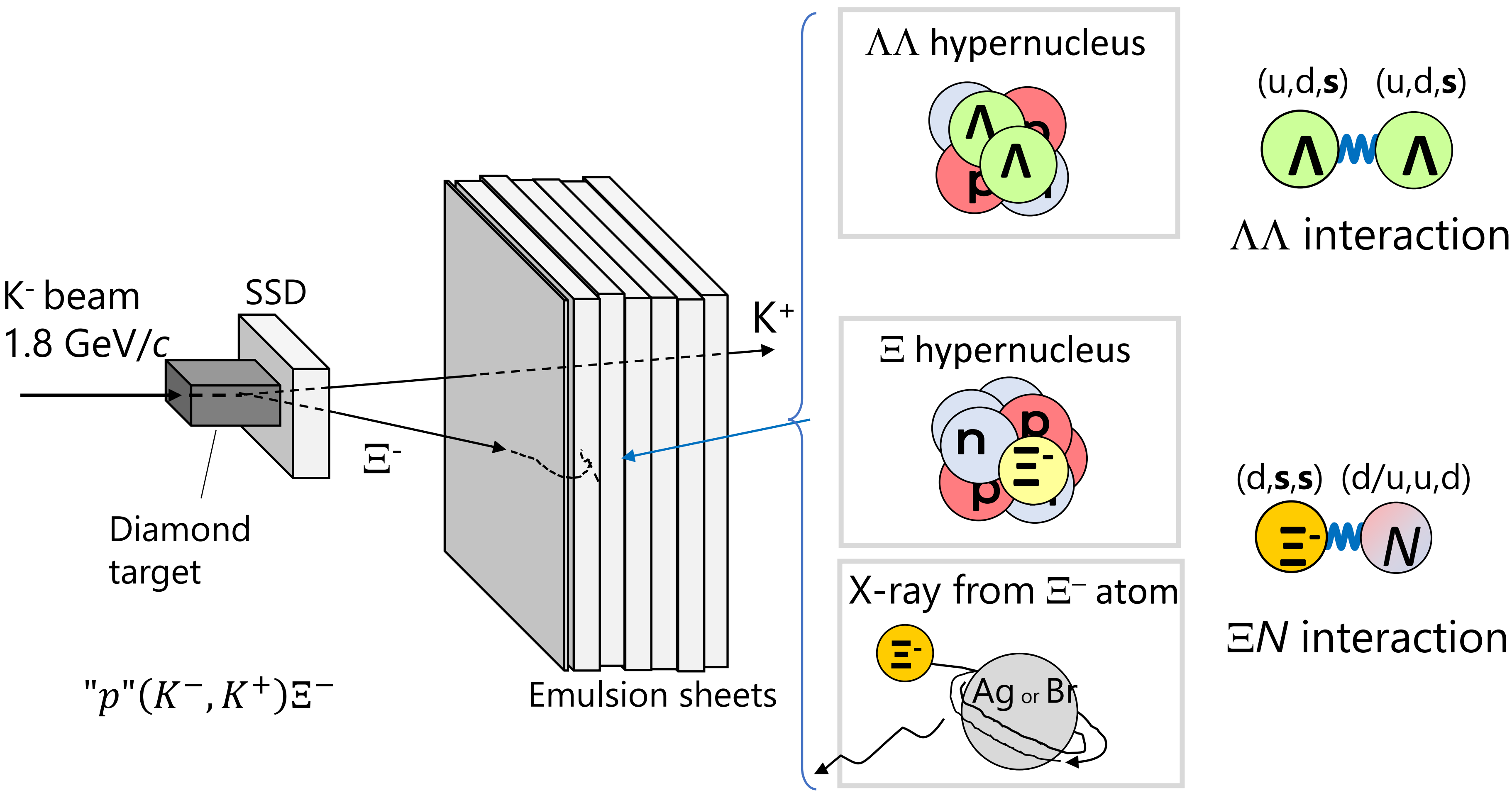
to explore the S=-2 world

with a high intensity K- beam



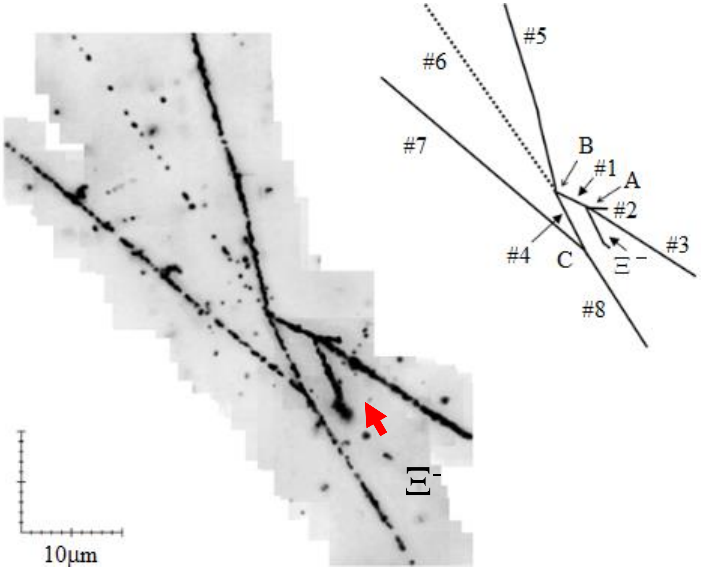
-> Valuable information to understand Baryon-Baryon interaction

Study of ΛΛ & Ξ hypernucleus



$"p"(K^-, K^+)\Xi^-$

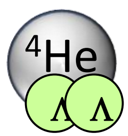
NAGARA event, ΛΛ hypernuclei (2001)

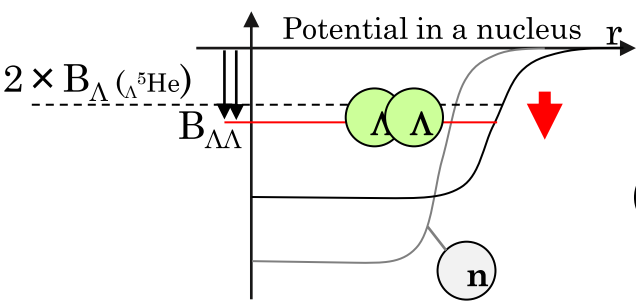


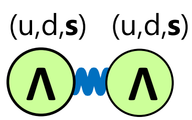
J. K. Ahn, *et al. Phys. Rev. C* **88**, (2013).

$$\Xi^- + {}^{12}C \rightarrow {}_{\Lambda\Lambda}{}^{6}He + He + t$$
$${}_{\Lambda\Lambda}{}^{6}He \rightarrow {}_{\Lambda}{}^{5}He + p + \pi^-$$

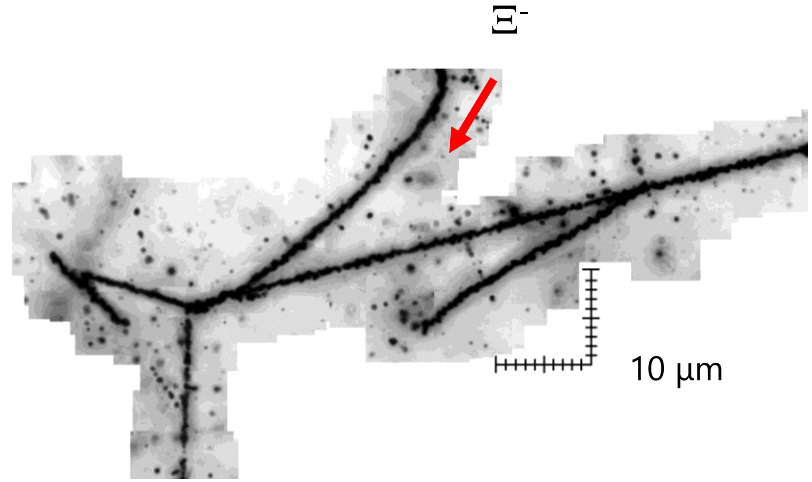
$$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17 \text{ MeV}$$







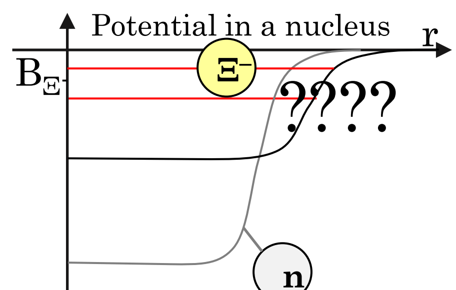
KISO event, Ξ hypernucleus(2013)

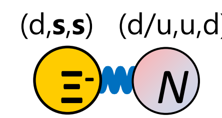


K. Nakazawa *et al. PTEP* **2015**, 33D02-0 (2015).
E. Hiyama, *et al. Annu. Rev. Nucl. Part. Sci.* **68**, 131–159 (2018).

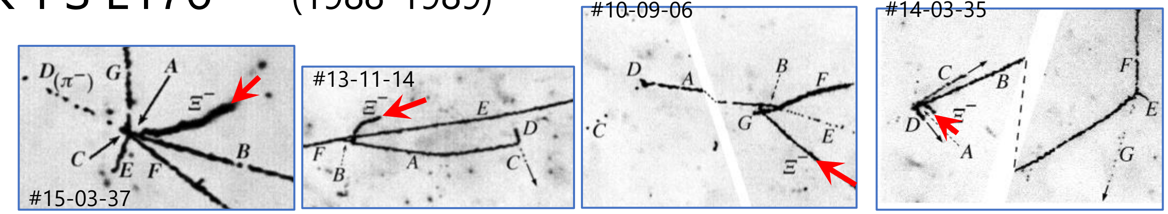
$$\Xi^- + {}^{14}N \rightarrow {}^{10}_{\Lambda}Be + {}^{5}_{\Lambda}He$$
$$\text{or} \rightarrow {}^{10}_{\Lambda}Be^* + {}^{5}_{\Lambda}He$$

$$B_{\Xi^-} = 1.03 \pm 0.18 \text{ or } 3.87 \pm 0.21 \text{ MeV}$$





KEK-PS E176 (1988-1989)

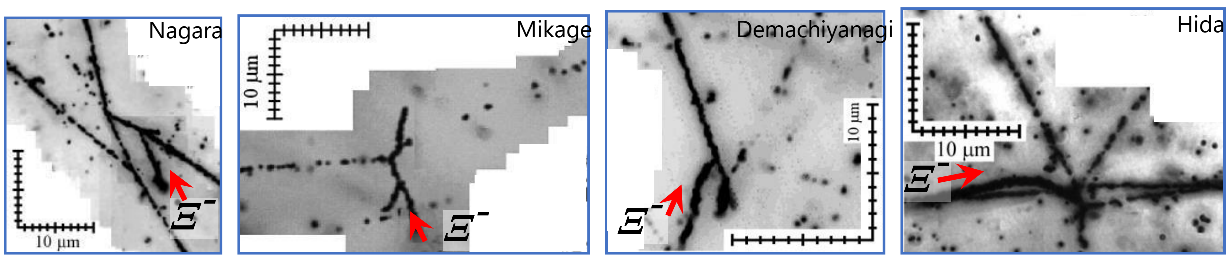


Nuclear Physics A 828 (2009) 191–232

* ~80 Ξ⁻ stop events
* Confirmed the existence of double Λ hypernucleus

X10 statistics

KEK-PS E373 (1998-2000)



PHYSICAL REVIEW C 88, 014003 (2013)

* ~650 Ξ⁻ stop events
* NAGARA event, KISO event

X10 statistics

J-PARC E07 (2016-2017)

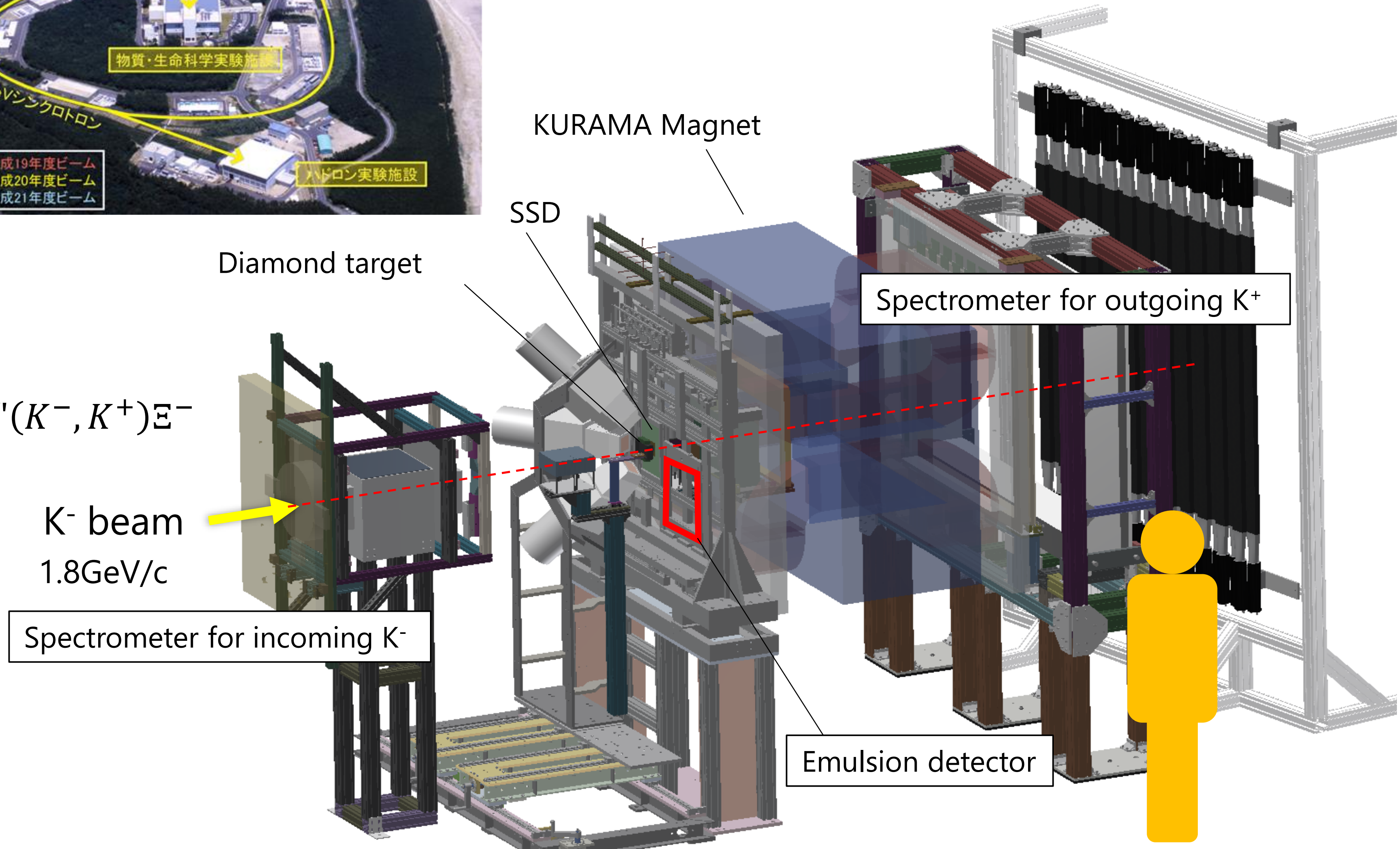
* ~10^4 Ξ⁻ stop events
* Systematic study of S=-2 system

	Emulsion gel	K^- purity	Number of K^-
E373	0.8 tons	25%	14×10^9
E07	2.1 tons	82%	113×10^9

E07 Experiment setup

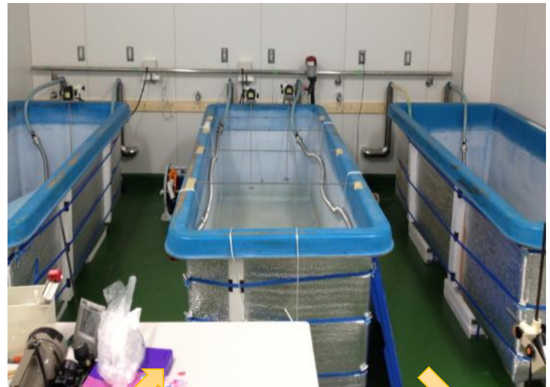
J-PARC Hadron hall K1.8 beamline

$"p"(K^{-}, K^{+})\Xi^{-}$



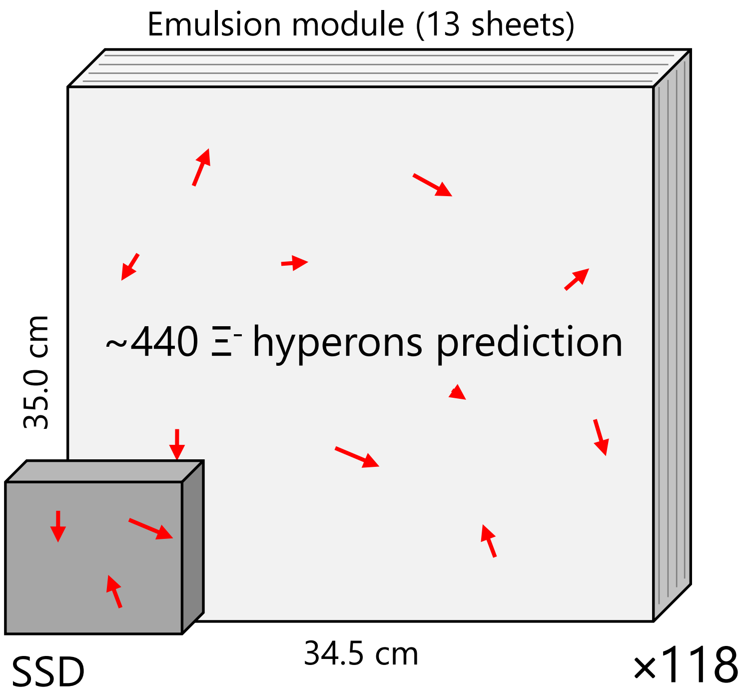
2013-2014
Emulsion production

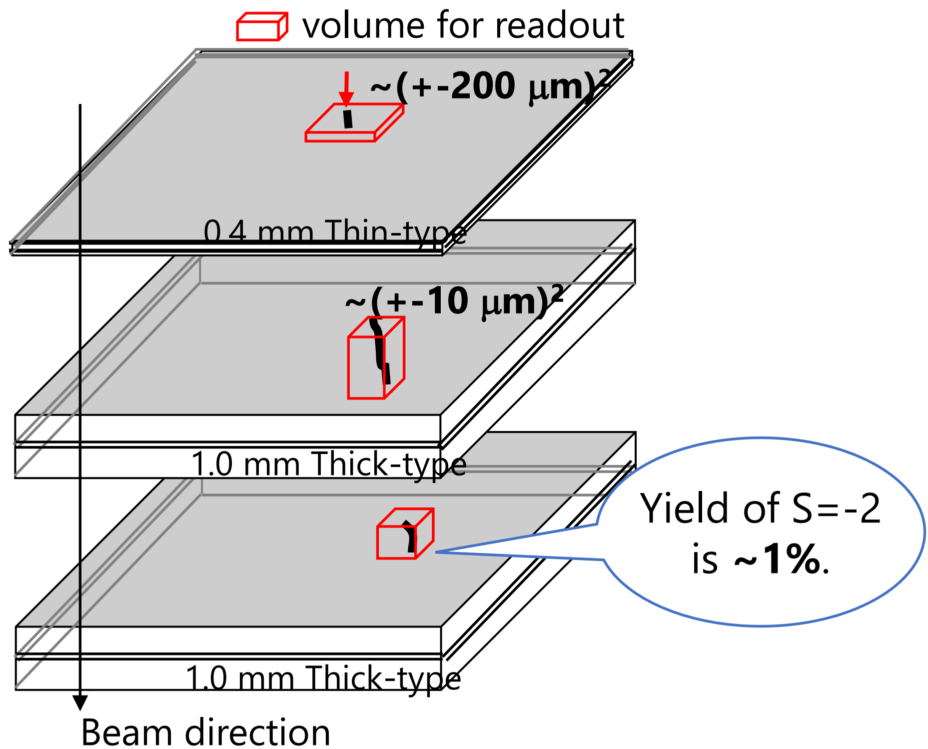
2016-2018
Photographic development



2018-2020
Ξ^- track following

2016-2017 Beam exposure





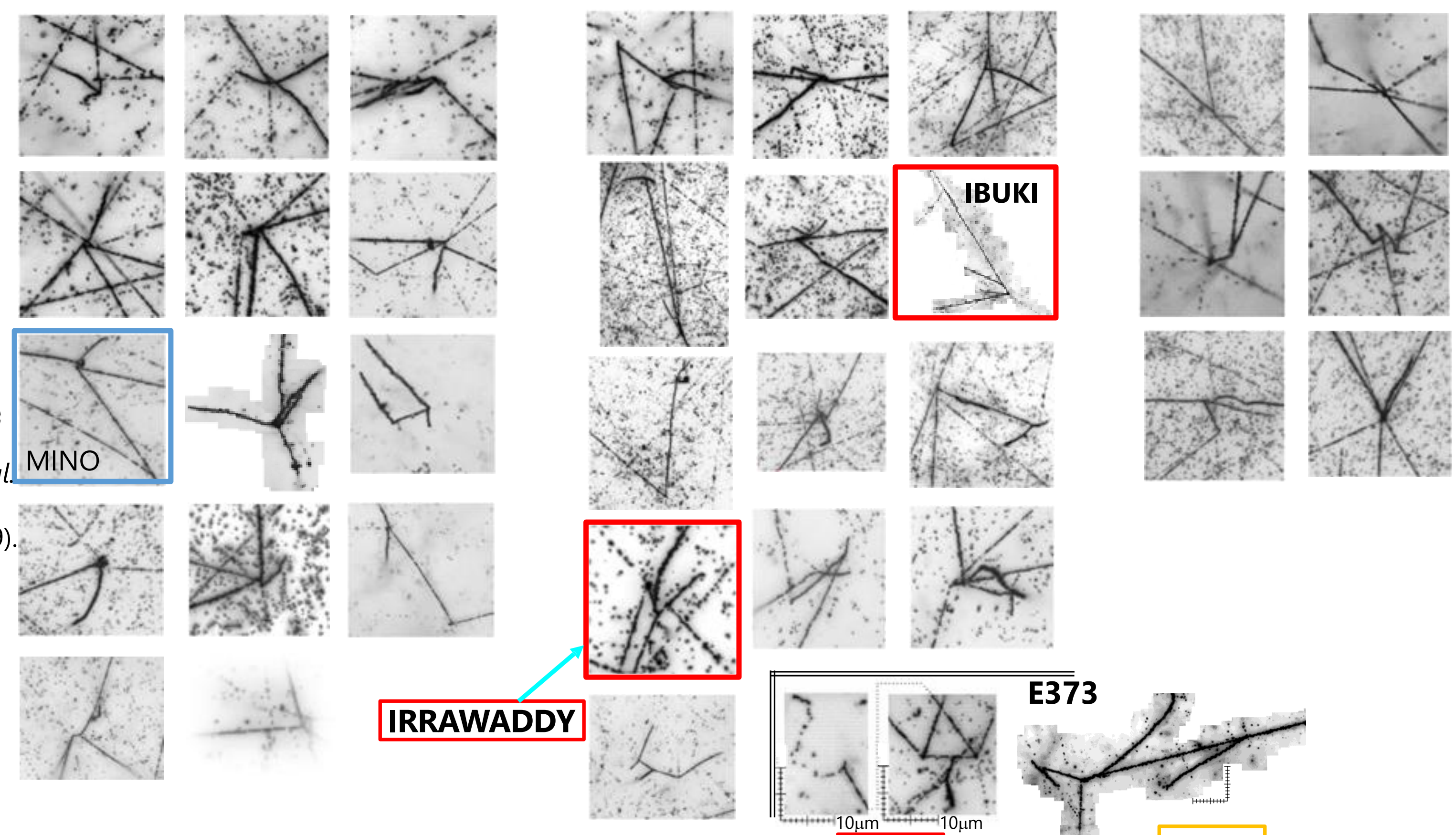
S=-2 system candidates

	KEK-PS E373	J-PARC E07
Event search	~7 years	**2.5 years** (April 2018 to Sep. 2020)
S=-2 sytem	9	**33**

14 ΛΛ hypernuclei **13 twin hypernuclei** 6 either

$^{11}_{\Lambda\Lambda}\mathrm{Be}$

Ekawa, H. *et al.* *PTEP* **2019**, 021D02 (2019).

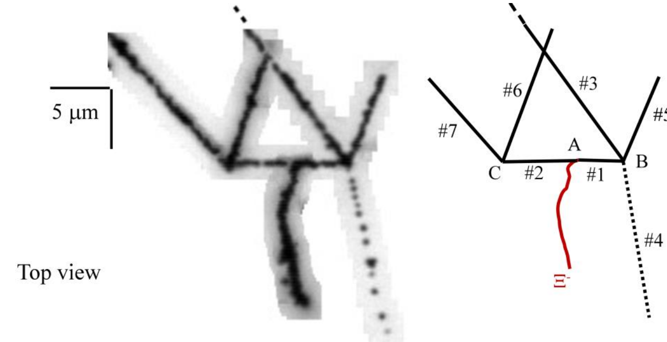


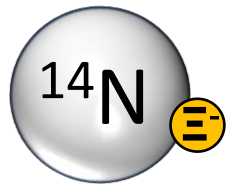
New Ξ hypernuclei

KINKA event

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

$B_{\Xi^-} = 8.00 \pm 0.77$ or 4.96 ± 0.77 MeV

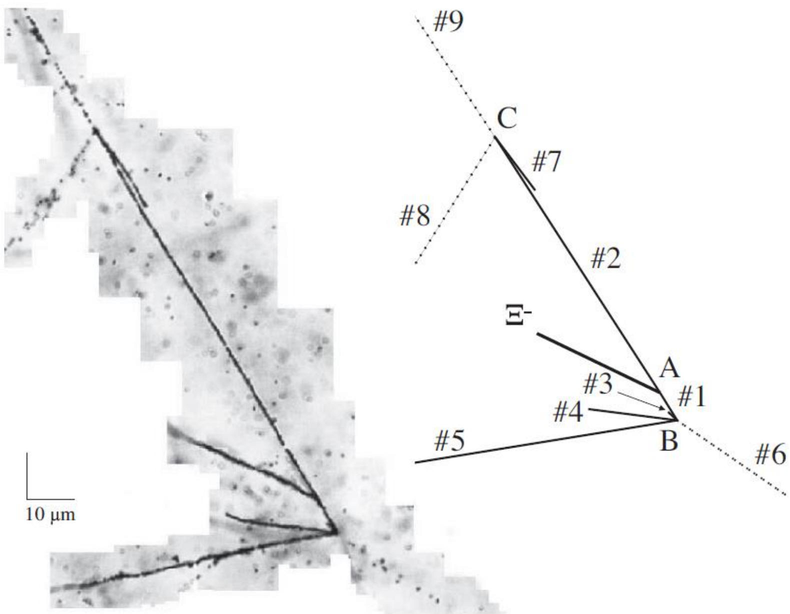




IBUKI event

$\Xi^- + {}^{14}N \rightarrow {}_{\Lambda}{}^{10}Be + {}_{\Lambda}{}^{5}He$

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

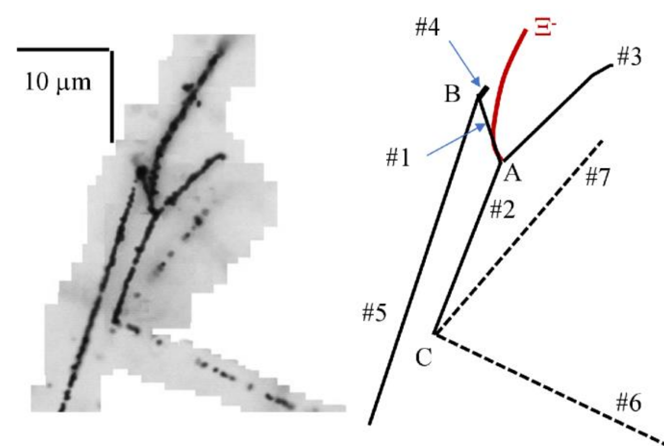


S. H. Hayakawa, *et al.*
Phys. Rev. Lett. **126**, 062501 (2021).

IRRAWADDY event

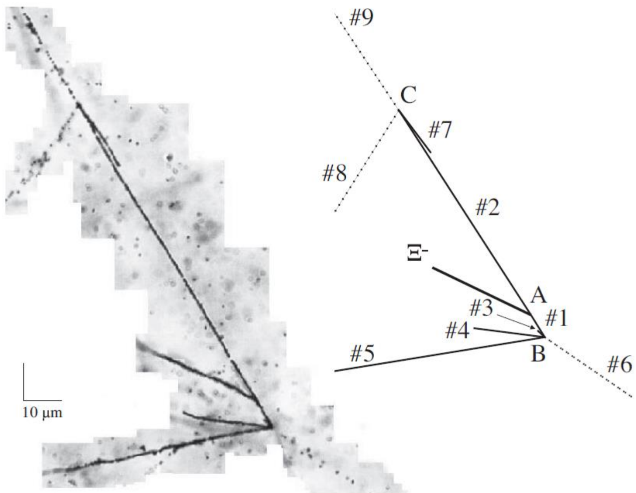
$\Xi^- + {}^{14}N \rightarrow {}_{\Lambda}{}^{5}He + {}_{\Lambda}{}^{5}He + {}^{4}He + n$

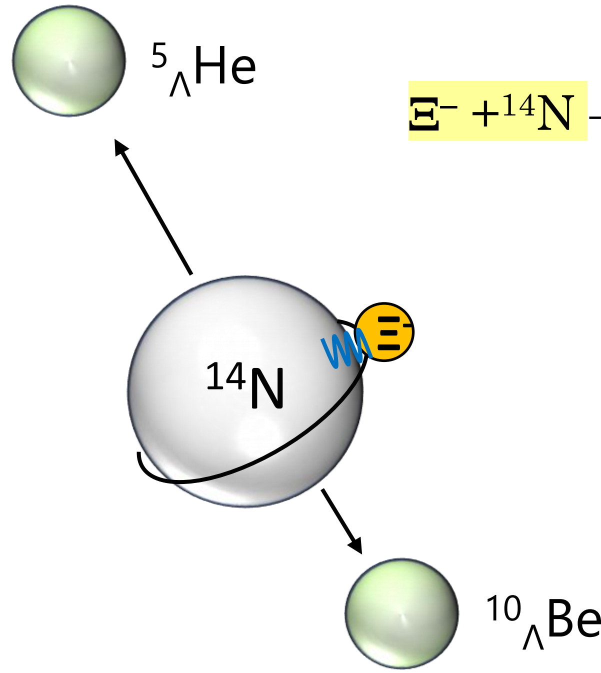
$B_{\Xi^-} = 6.27 \pm 0.27$ MeV



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

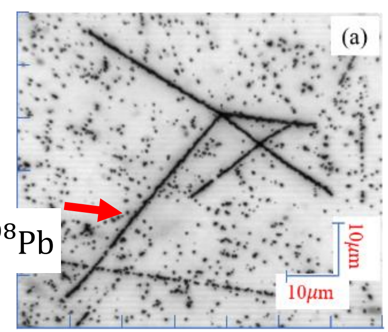
IBUKI event





$\Xi^- + {}^{14}\mathrm{N} \rightarrow {}_{\Lambda}^{10}\mathrm{Be} + {}_{\Lambda}^{5}\mathrm{He}$

Track	Nuclide	Range [μm]	Kinetic energy [MeV]
#1	$^{10}_{\Lambda}$Be	9.4	7.03
#2	$^{5}_{\Lambda}$He	87.7	13.79
Calib.	α particle (132 events)	50.25 ± 0.11	8.785



$^{212}\mathrm{Po} \rightarrow {}^{208}\mathrm{Pb}$

Range-Energy relation was calibrated by α particle = ^{4}He

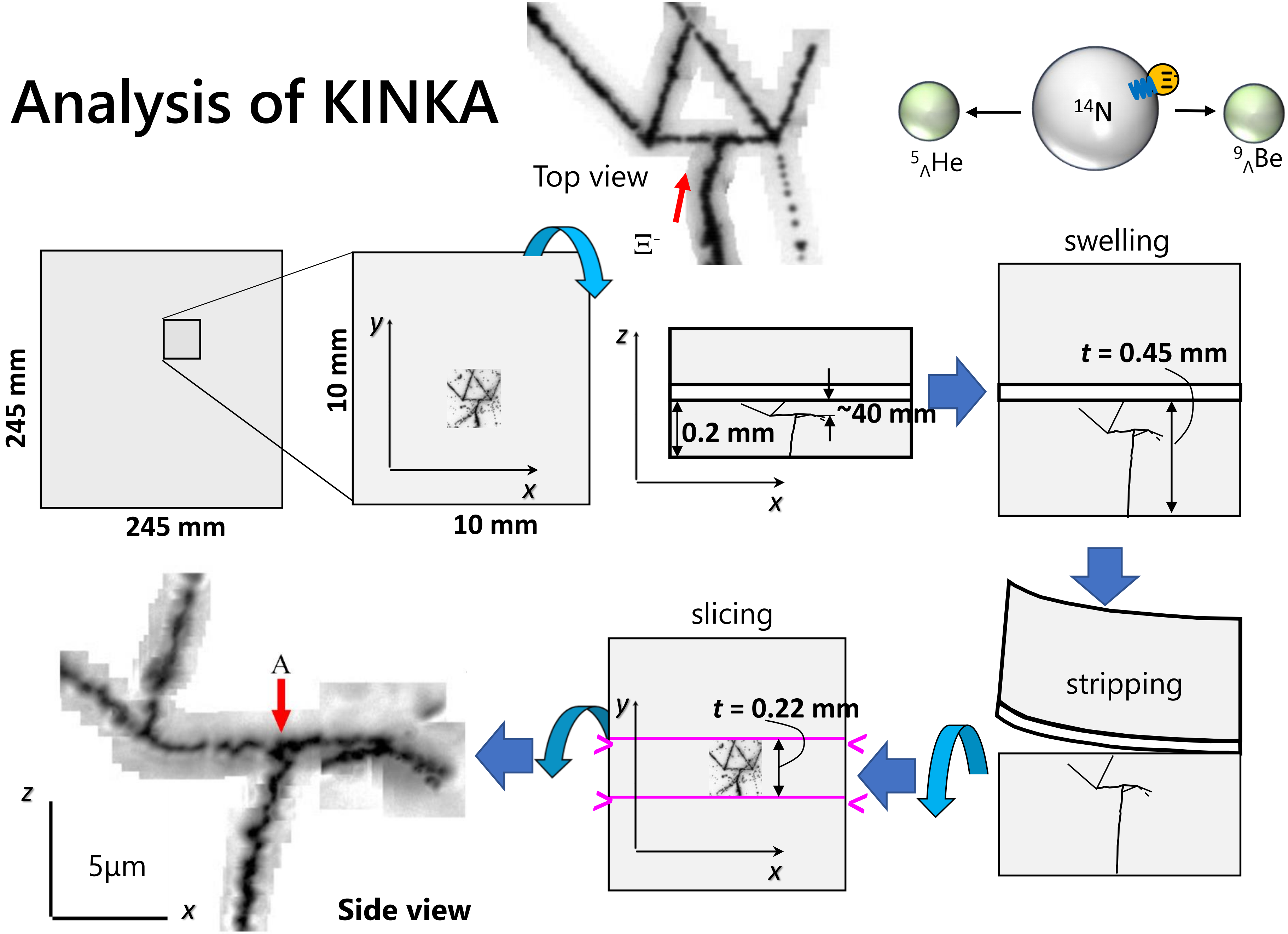
$$B_{\Xi^-} = Q\ value - KE$$
$$= 22.09 \quad - (20.82 \pm \underline{\underline{0.08}})$$
$$= 1.27\ \mathrm{MeV}$$

Emulsion intrinsic error

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

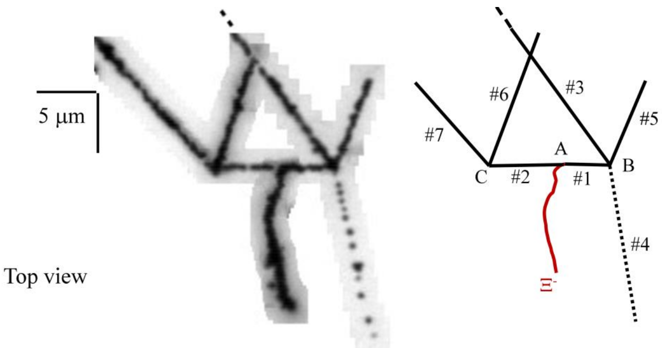
Emulsion intrinsic error
&
mass error (Ξ^-, ${}_{\Lambda}^{10}\mathrm{Be}$, ${}_{\Lambda}^{5}\mathrm{He}$)

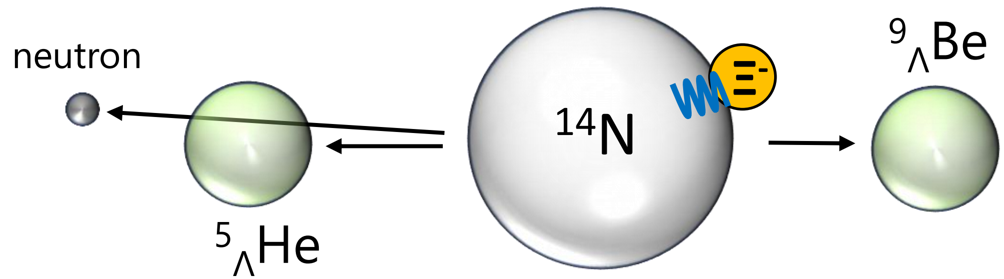
Analysis of KINKA



KINKA event

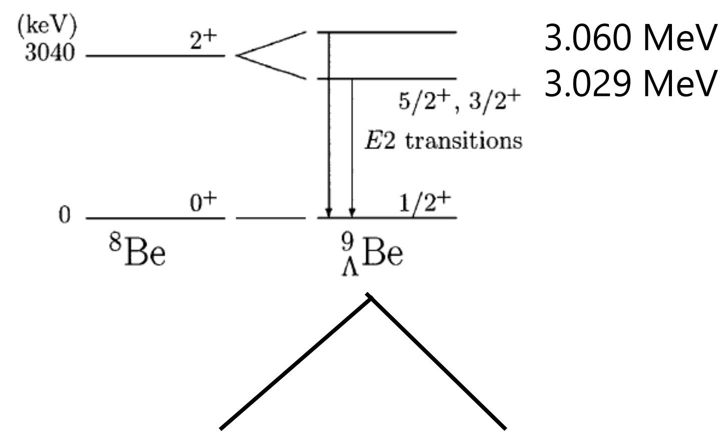
$\Xi^- + {}^{14}N \rightarrow {}_{\Lambda}^{9}Be + {}_{\Lambda}^{5}He + n$





Track	Nuclide	Range [μm]	Kinetic energy [MeV]
#1	${}^{9}_{\Lambda}Be$	4.34	3.14 ± 0.17
#2	${}^{5}_{\Lambda}He$	5.74	1.72 ± 0.07
--	neutron	--	5.71 ± 0.75

BNL E930
H. Akikawa, *et al. Phys. Rev. Lett.* **88**, (2002).

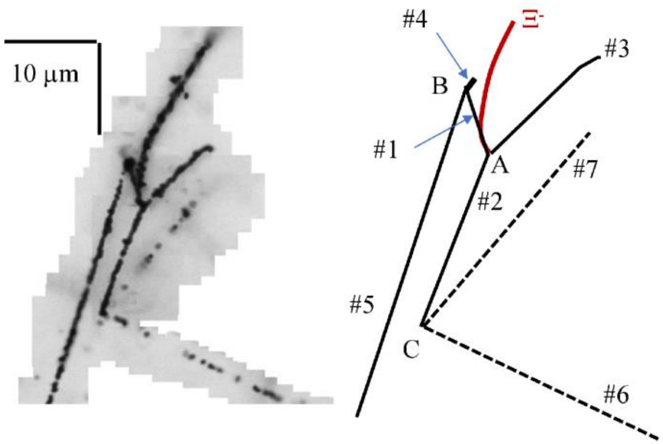


$$B_{\Xi^-} = Q\ value - KE$$
$$= 18.58 \quad - (10.58 \pm \underline{0.77})$$
$$= 8.00\ \mathrm{MeV}$$

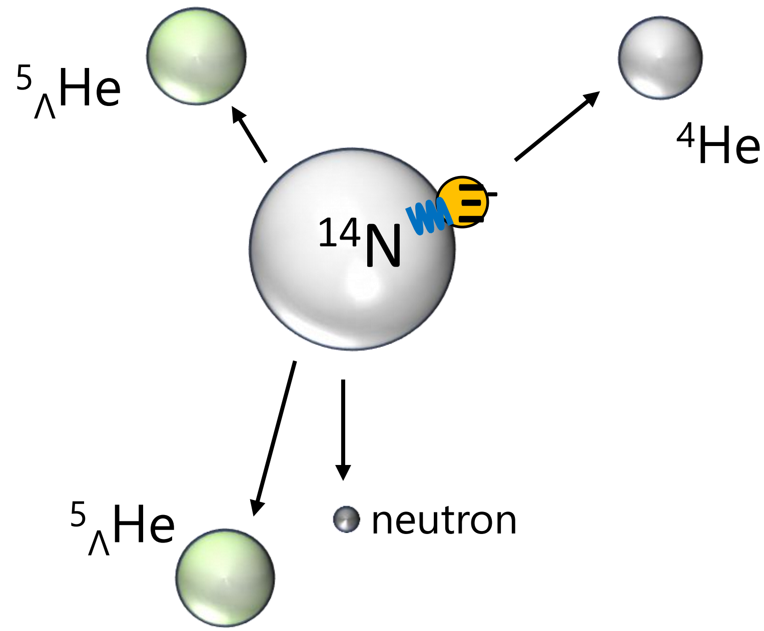
Kinematical error

$$B_{\Xi^-} = 8.00 \pm 0.77 \text{ or } 4.96 \pm 0.77\ \mathrm{MeV}$$

IRRAWADDY event



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



Track	Nuclide	Range [μm]	Kinetic energy [MeV]
#1	${}^{5}_{\Lambda}He$	4.99	1.48 ± 0.07
#2	${}^{5}_{\Lambda}He$	12.31	3.53 ± 0.06
#3	${}^{4}He$	10.12	2.87 ± 0.06
--	neutron	--	0.95 ± 0.24

$$B_{\Xi^-} = Q\ value - KE$$
$$= 15.09 \quad - (8.82 \pm \underline{\underline{0.26}})$$
$$= 6.27\ \mathrm{MeV}$$

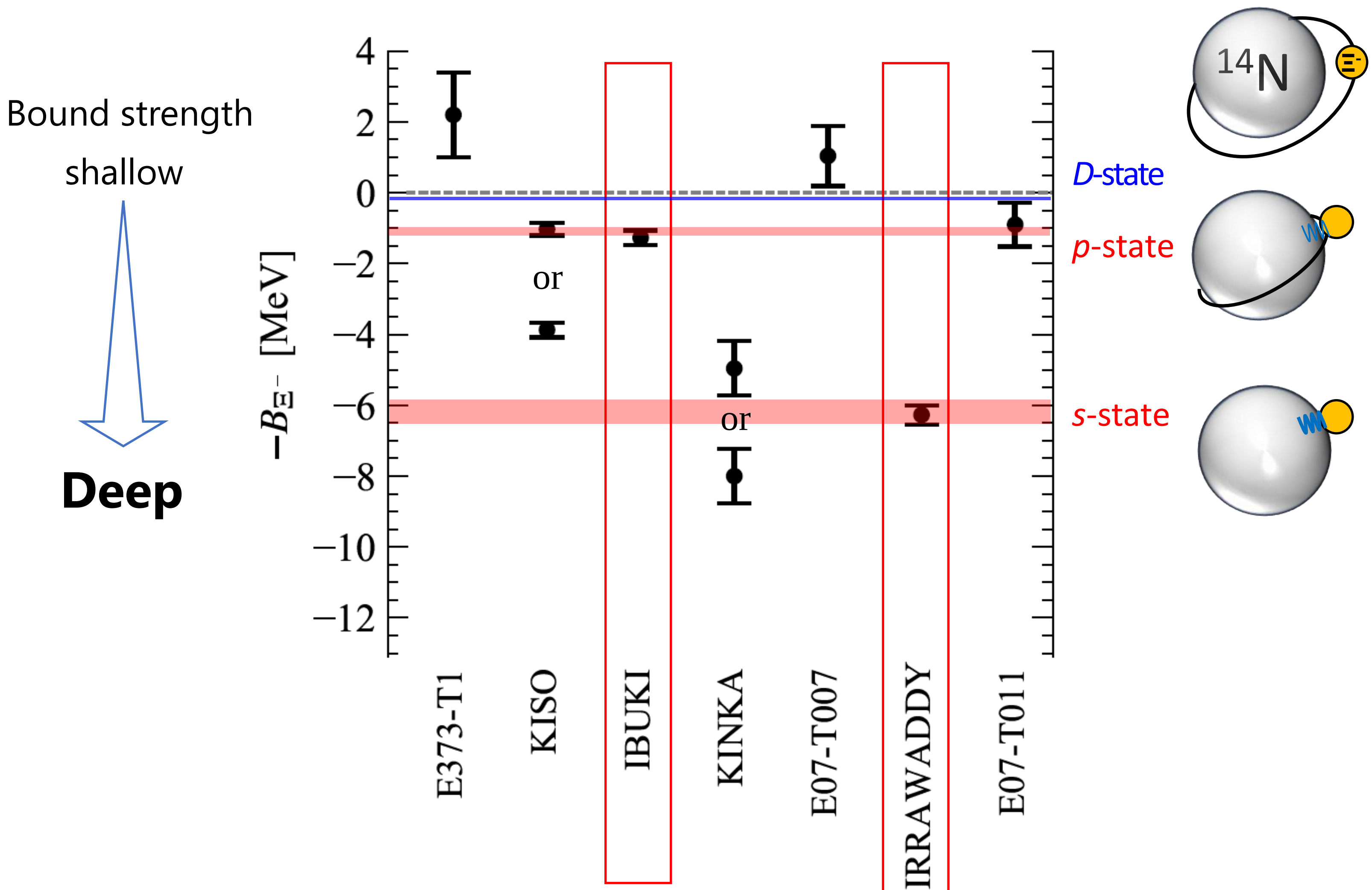
Kinematical error

${}_{\Lambda}^{5}He$ and ${}^{4}He$ has no excited state.

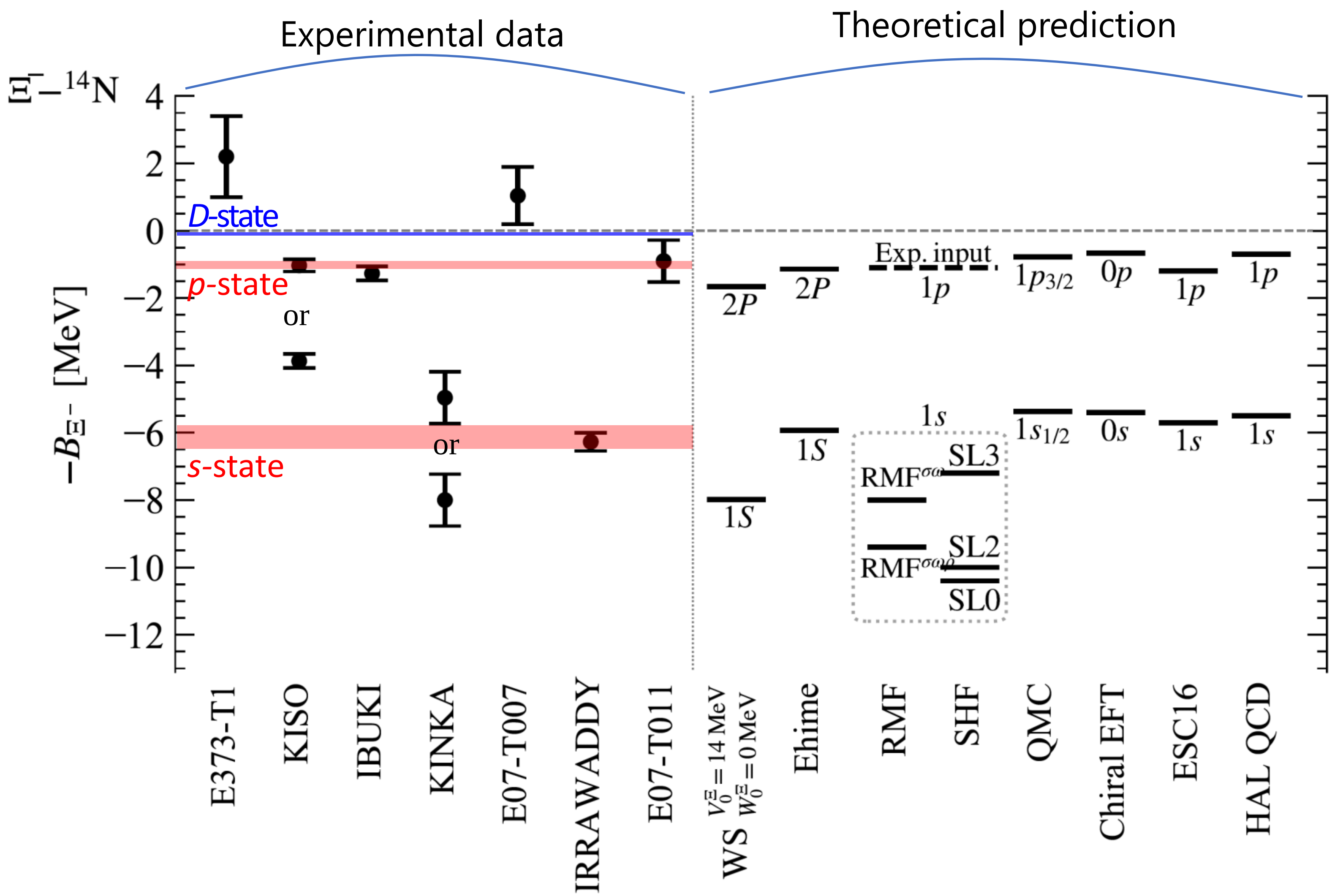
$$B_{\Xi^-} = 6.27 \pm \underline{\underline{0.27}}\ \mathrm{MeV}$$

Kinematical error
&
mass error (Ξ^-, ${}_{\Lambda}^{5}He$)

Summary of twin hypernuclei from Ξ^- + ^{14}N



vs Theoretical prediction



Absorption probability in s-state

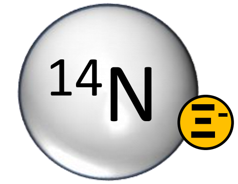


TABLE I. Calculated Ξ^- capture probabilities (in %) from s, p, d, and f atomic orbits,[a] for various choices of Ξ^--nucleus real and imaginary potential-well depths[b] V_0 and W_0.

Target	V_0 (MeV)	W_0 (MeV)	s	p	d	f
^{14}N	28.6	7.7	0.00	0.2	54.1	45.6
	28.6	3.9	0.03	0.4	69.9	29.6
	0	3.9	0.03	1.3	75.7	22.9

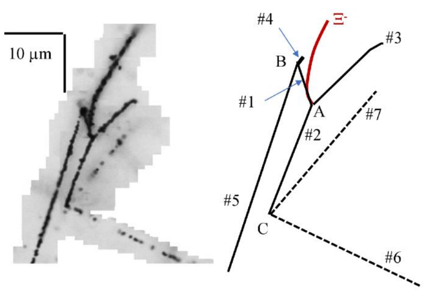
D. Zhu, *et al. Phys. Rev. Lett.* **67**, 2268–2271 (1991).

state	ND	ESC04d	ESC08c	ESC08c-A
1s	0.02	3×10^{-4}	1×10^{-4}	0.01
2p	3.9	0.25	3.8	2.4
3d	35.7	23.5	34.7	34.9
4f	7.8	19.0	8.6	9.4
5g	0.01	0.03	0.01	0.01

(%)

T. Koike, *JPS Conf. Proc.* **17**, 033011 (2017).

IRRAWADDY event



1 s-state event

in 300 Ξ^- stops and captured by Nitrogen in the emulsion

Absorption probability in **s-state** is **>0.035% (90% CL)**.

Imaginary potential depth $W_0^{\Xi} \ll 1$ MeV
& $\Xi N - \Lambda\Lambda$ coupling is likely to be weak.

Probability of twin hypernuclear production

in emulsion-counter hybrid method

Xi –stop at rest ~4000

- Rho-stop w/o NF
- Sigma-stop w/ NF ~2700 events
  - 57% Heavy elements
  - Light elements 43%
    - 45 ΛΛ or twin hypernuclei events
      - Others
      - Unidentified twin
      - Identified twin
        - Ξ^-+C
        - Ξ^-+ N
        - Ξ^-+ O

2 : **8** : 1

Atomic ratio in emulsion

C : N : O = 0.55 : **0.16** : 0.29.

Identified decay modes

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

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

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

$^{14}N + \Xi^- \rightarrow {}^{5}_{\Lambda}He + {}^{10}_{\Lambda}Be$

$^{14}O + \Xi^- \rightarrow {}^{5}_{\Lambda}He + {}^{12}_{\Lambda}B$

$^{5}_{\Lambda}He = \alpha + \Lambda$

$^{9}_{\Lambda}Be = 2\alpha + \Lambda$

$^{10}_{\Lambda}Be = 2\alpha + \Lambda + n$

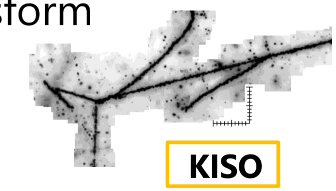
$\Xi^- + {}^{14}N$ is favored.

∵The daughters are based on α-clusters

Machine learning for overall scanning method

Overall scanning method can exceed the limits of the emulsion-counter hybrid method (~10 times events)

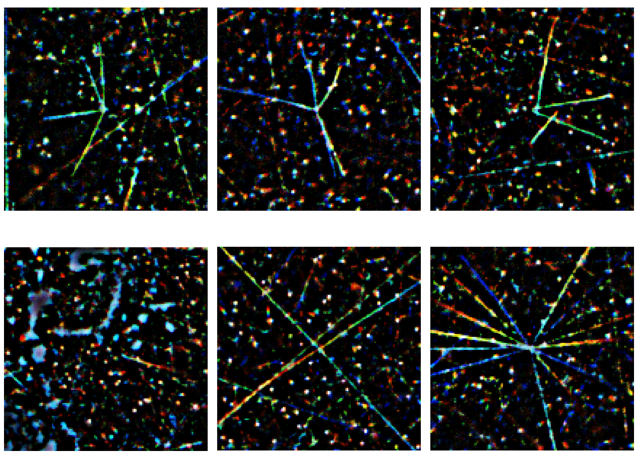
Images with a vertex detected by Hough-transform
J. Yoshida, *et al. NIM A* 847, 86–92 (2017).



~5 years for manual image checking

Alpha decay

Others



Method	Precision	Sensitivity (Recall)	Candidates
w/o CNN	0.081 ± 0.006	0.788 ± 0.056	2489
w/ CNN	0.571 ± 0.017	0.788	350 ± 10

7 times

Convolutional Neural Network (CNN) ResNet50 for alpha decay

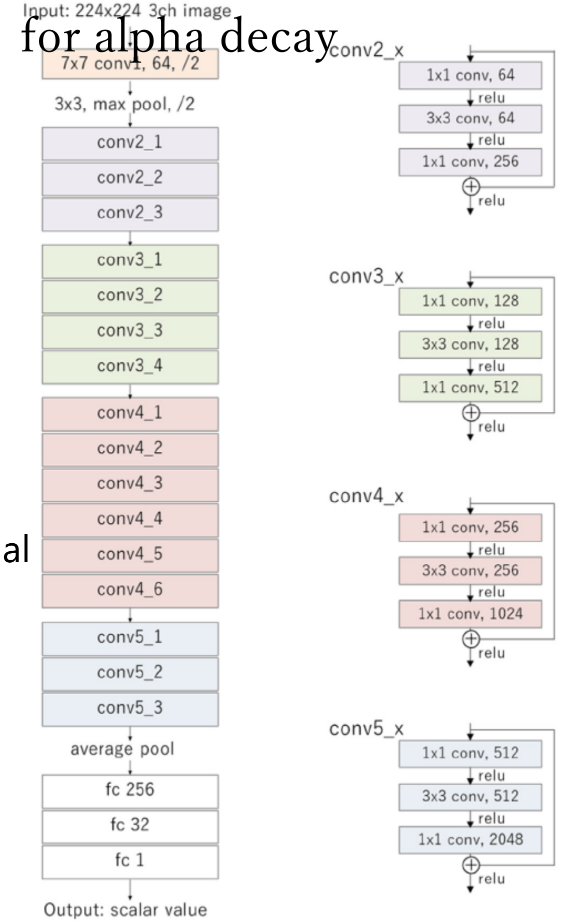


Fig. 2. A graphical sketch of the CNN architecture based on ResNet50. The total number of weight parameters of this CNN was 24.0 million. See the text for details.

J. Yoshida, *et al. NIM A* 164930 (2020).

The method is applying to double hypernucleus

Summary

- By September 2020, **33** new **S=-2 hypernuclei events** were detected in the latest **J-PARC E07** alongside 30 years' technology from E176 experiment.
- **Five twin hypernuclei** events from $\Xi^- + {}^{14}\mathrm{N}$ were published.

- IBUKI and IRRAWADDY events suggested the nuclear ***s*-state near B_{Ξ^-}=6 MeV** and the ***p*-state B_{Ξ^-}=1.1 MeV**. The level structure of the Ξ hypernucleus, ${}^{15}_{\Xi}\mathrm{C}$ were revealed.
- The probability of Ξ^- absorption in ${}^{14}\mathrm{N}$ was higher than the theoretical prediction with large W_0^{Ξ} (imaginary potential depth).
This suggests that **W_0^{Ξ} is small** and **$\Xi N - \Lambda\Lambda$ coupling is likely to be weak**.
- $\Xi^- + {}^{14}\mathrm{N}$ process favors the production of twin hypernuclei with alpha-cluster structure of the daughters.

- Overall scanning method has been initiated. Ten times more twin hypernuclear events will be acquired.