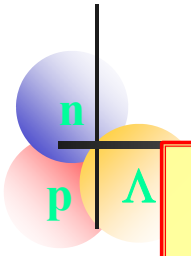


HYP2022

# Information on double hypernuclei with nuclear emulsion detector

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**Phys. Dept., Gifu Univ., JAPAN**
**27th June, 2022**

**On behalf of E07(J-PARC) collaborations**

## Outline

- Experiments using nuclear emulsion for Double hypernuclei
- Results of Double Hypernuclei from those experiments
  - double-Λ hypernuclei
  - Ξ hypernuclei
- Event analysis with X-ray microscopy
- Overall scanning (Scanning whole volume of the emulsion)
- Summary and perspective



# Topics with Double Hypernuclei

**1) s-shell DBL. hypernuclei : ${}^{4}_{\Lambda\Lambda}$H, ${}^{5}_{\Lambda\Lambda}$He and ${}^{5}_{\Lambda\Lambda}$H**

**ΛΛ-ΞN-H** coupling interaction affects mass, since s-shell nucleons are not fully occupied. Thus, it can be determined.

**2) A = 6~17 ΛΛ hypernuclei (spectroscopy)**

Confirmation of ΛΛ interaction strength and nuclear structure effects such as shrinkage due to Λ, independent information of NAGARA event, ${}^{6}_{\Lambda\Lambda}$He.

**3) Ξ-hypernuclei : $\Xi^{-}{}^{16}$O, $\Xi^{-}{}^{14}$N, $\Xi^{-}{}^{12}$C**

From multiple events of Ξ-hypernucleus, we can determine the (natural) width of Ξ-hypernucleus, which is related to ΛΛ-ΞN coupling interaction.

**4) ΞN interaction with X-ray from Ξ-atoms**

Expected yields for X-rays from Br and Ag are so small. To observe the shifts, it is necessary for detecting peak shapes with 10 times statistics.

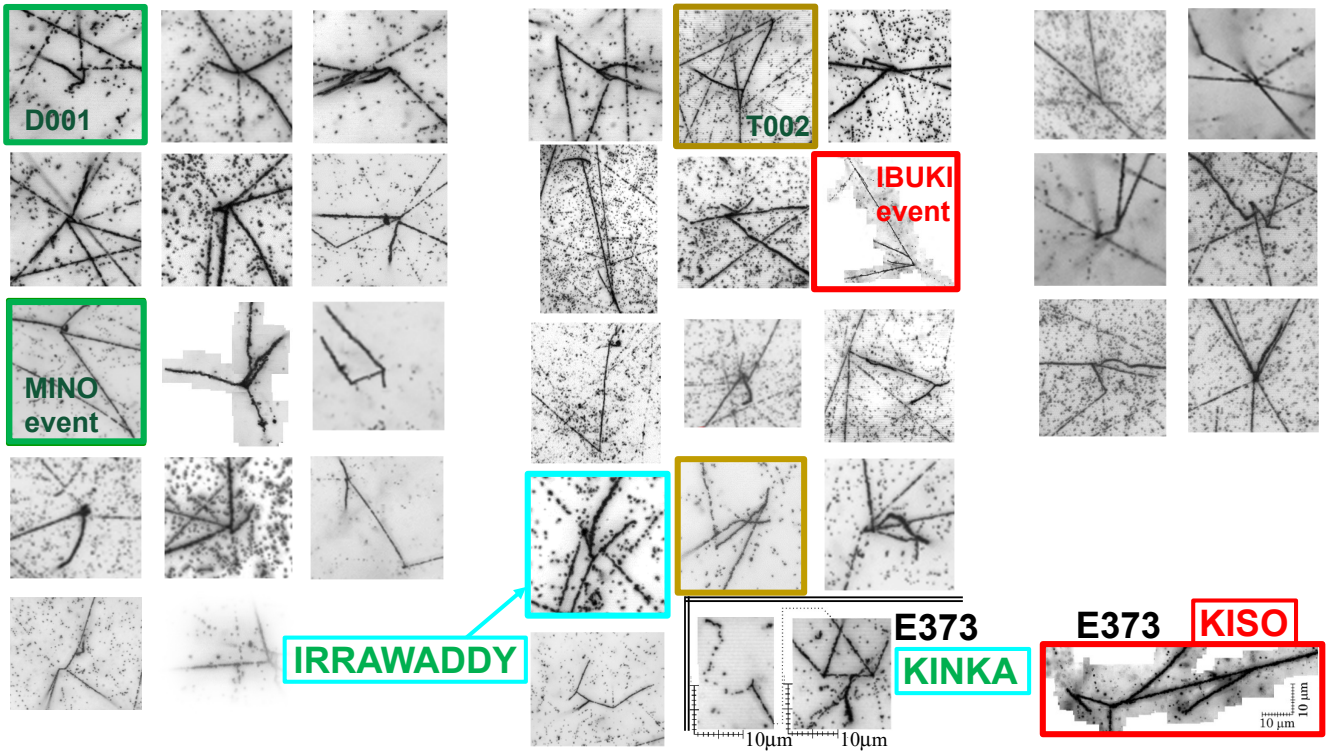
**5) Λ-Λ P-wave interaction (?)**

If ΛΛ hypernuclei can be detected in excited states with **one Λ-hyperon in p-orbit**, it may present information on ΛΛ p-wave interaction, where that will be recognized via the spectroscopy of ΛΛ hypernuclei. The interaction might change max. mass of n-star.

# List of detected events in E07 (Jun., 2022)

| | KEK-PS | E176 | E373 | J-PARC E07 |
|---|---|---|---|---|
| ΛSearching period | | ~10 years | ~7 years | 2 years (Apr., 2018 ~ ) |
| S=-2 system | | **4** (1+2+[1]) | **10** (4+3+[3]) | **33** (14+13+[6]) => **47** |

14 double-Λ events | 13 twin-hyper events | 6 others






# List of detected events ever published

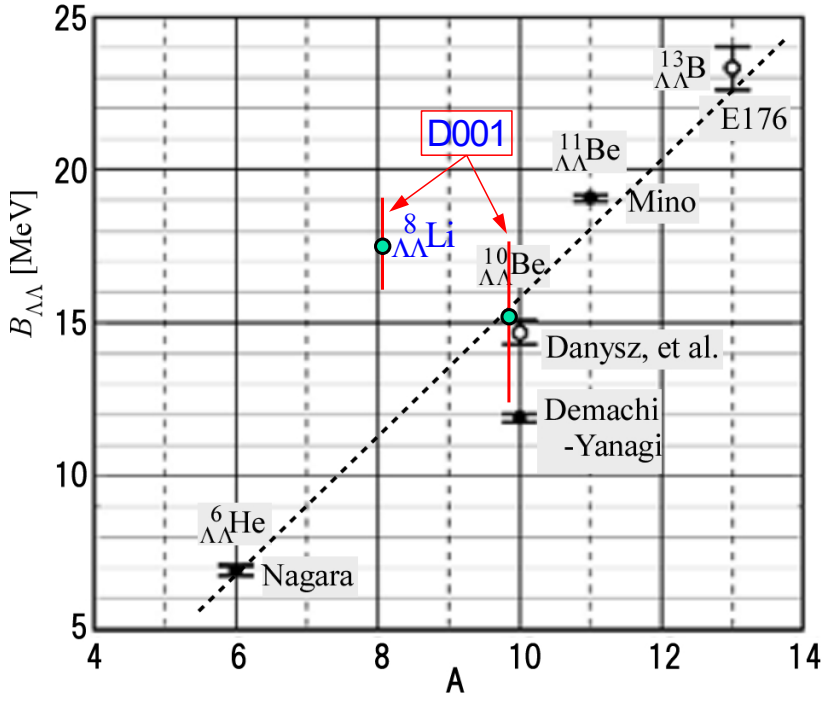
## Double-Λ hypernuclei

**Table 13** Published data for $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$. The atomic 3D absorption of $\Xi^-$ was assumed for all cases. Those data from Danysz et al. and Hida are nominated by consistent interpretations with Nagara event. The daughter single-Λ hypernucleus for E176 and Danysz et al. will be excited state. The difference of $B_{\Lambda\Lambda}$ ( $\Delta B_{\Lambda\Lambda}$) values between Demachi-Yanagi and Danysz et al. would be the excitation energy being 2.8 MeV of ${}^{10}_{\Lambda\Lambda}$Be. In the Sec. 5 – 1 – 6, the error was separated into statistical and systematic ones for the Mino event.

| Ev. name | nuclide | Target | $B_{\Lambda\Lambda}$ (MeV) | $\Delta B_{\Lambda\Lambda}$ (MeV) | Comments |
|---|---|---|---|---|---|
| Nagara | ${}^{6}_{\Lambda\Lambda}$He | ${}^{12}$C | $6.91 \pm 0.16$ | $0.67 \pm 0.17$ | Uniquely identified |
| Danysz | ${}^{10}_{\Lambda\Lambda}$Be | ${}^{12}$C | $14.7 \pm 0.4$ | $1.3 \pm 0.4$ | ${}^{10}_{\Lambda\Lambda}$Be $\rightarrow {}^{9}_{\Lambda}$Be* ($Ex.$ = 3.0 MeV) |
| E176 | ${}^{13}_{\Lambda\Lambda}$B | ${}^{14}$N | $23.3 \pm 0.7$ | $0.6 \pm 0.8$ | ${}^{13}_{\Lambda\Lambda}$B $\rightarrow {}^{13}_{\Lambda}$C* ($Ex.$ = 4.9 MeV) |
| Demachi-Yanagi | ${}^{10}_{\Lambda\Lambda}$Be* | ${}^{12}$C | $11.90 \pm 0.13$ | $-1.52 \pm 0.15$ | most probable (topology)<br>$Ex.$ ~ 2.8 MeV for ${}^{10}_{\Lambda\Lambda}$Be* |
| Mikage | ${}^{6}_{\Lambda\Lambda}$He | ${}^{12}$C | $10.01 \pm 1.71$ | $3.77 \pm 1.71$ | most probable (mesonic decay) |
| | ${}^{11}_{\Lambda\Lambda}$Be | ${}^{12}$C | $22.15 \pm 2.94$ | $3.95 \pm 3.00$ | |
| | ${}^{11}_{\Lambda\Lambda}$Be | ${}^{14}$N | $23.05 \pm 2.59$ | $4.85 \pm 2.63$ | |
| Hida | ${}^{11}_{\Lambda\Lambda}$Be | ${}^{12}$C | $20.83 \pm 1.27$ | $2.61 \pm 1.34$ | |
| | ${}^{12}_{\Lambda\Lambda}$Be | ${}^{14}$N | $20.48 \pm 1.21$ | $(2.00 \pm 1.21)$ | Assumed 10.24 MeV for $B_{\Lambda}({}^{11}_{\Lambda}$Be) |
| Mino | ${}^{10}_{\Lambda\Lambda}$Be | ${}^{16}$O | $15.05 \pm 0.11$ | $1.63 \pm 0.14$ | |
| | ${}^{11}_{\Lambda\Lambda}$Be | ${}^{16}$O | $19.07 \pm 0.11$ | $1.87 \pm 0.37$ | most probable ($\chi^2$ minimum) |
| | ${}^{12}_{\Lambda\Lambda}$Be | ${}^{16}$O | $13.68 \pm 0.11$ | $-2.7 \pm 1.0$ | |
| D001 | ${}^{8}_{\Lambda\Lambda}$Li | ${}^{12}$C | $17.50 \pm 1.46$ | $6.34 \pm 1.46$ | |
| | ${}^{10}_{\Lambda\Lambda}$Be | ${}^{14}$N | $15.05 \pm 2.78$ | $1.63 \pm 2.78$ | likely by $B_{\Lambda\Lambda}$ |

# Double-Λ hypernuclei

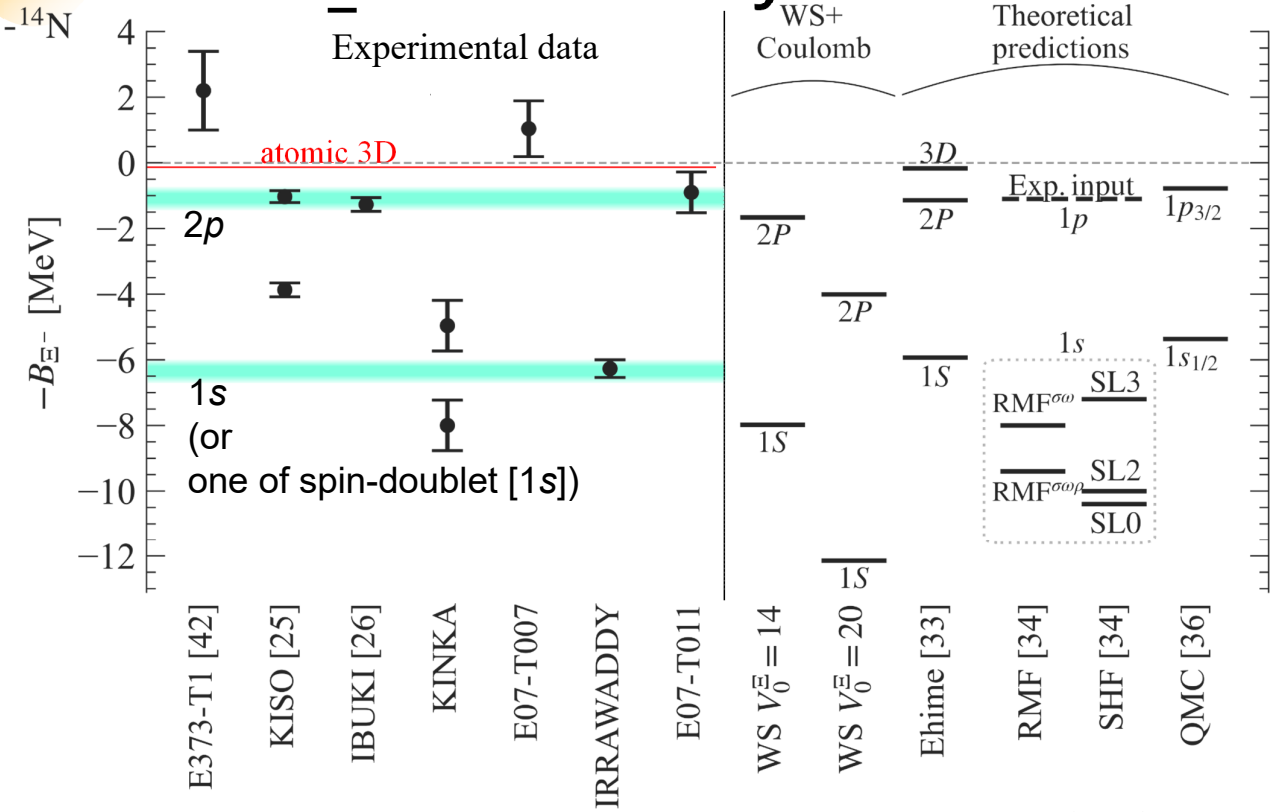
## Mass number (A) dependence of $B_{\Lambda\Lambda}$






# Ξ hypernuclei

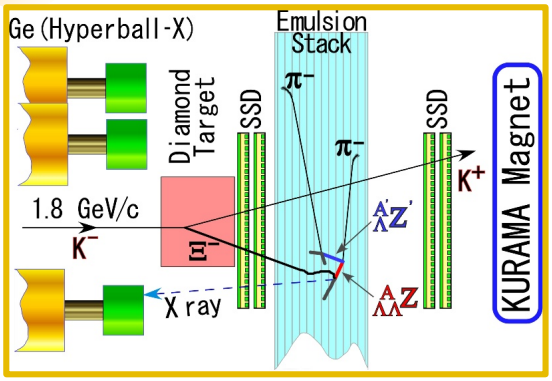
## $B_{\Xi^-}$ of $\Xi^-$-$^{14}$N system




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

# The E07 experiment @ J-PARC [2016-]
# (K-,K+) reaction

## 1.New Hybrid method




1. Pure K-beam
   ( better 3.5 times than KEK-PS)
2. More emulsion volume ( x 3 )

$10^3$ (E373) ➔ $10^4$ Ξ⁻ stop events
1. X ray measurement from Ξ **atom**
   with **Hyperball-X**
   ➔ study of **Ξ-N interaction**
2. ~$10^2$ double hypernuclei

***Automated track-following***

## 2. *Overall-scanning*

**VP : Vertex Picker**

Fully automatic detection of
3 vtx. event
like NAGARA event, KISO event

10 times statistics of that
with the hybrid method

(1/0.3) : free from
X acceptance & tracking
4 : ・'$p$'$(K^-, K^+)\Xi^-$ in the emulsion
・'$n$'$(K^-, K^0)\Xi^-$ reaction

➔ $10^5$ Ξ⁻ stop events
Measurement of the mass of
~$10^3$ double hypernuclei
with A<16



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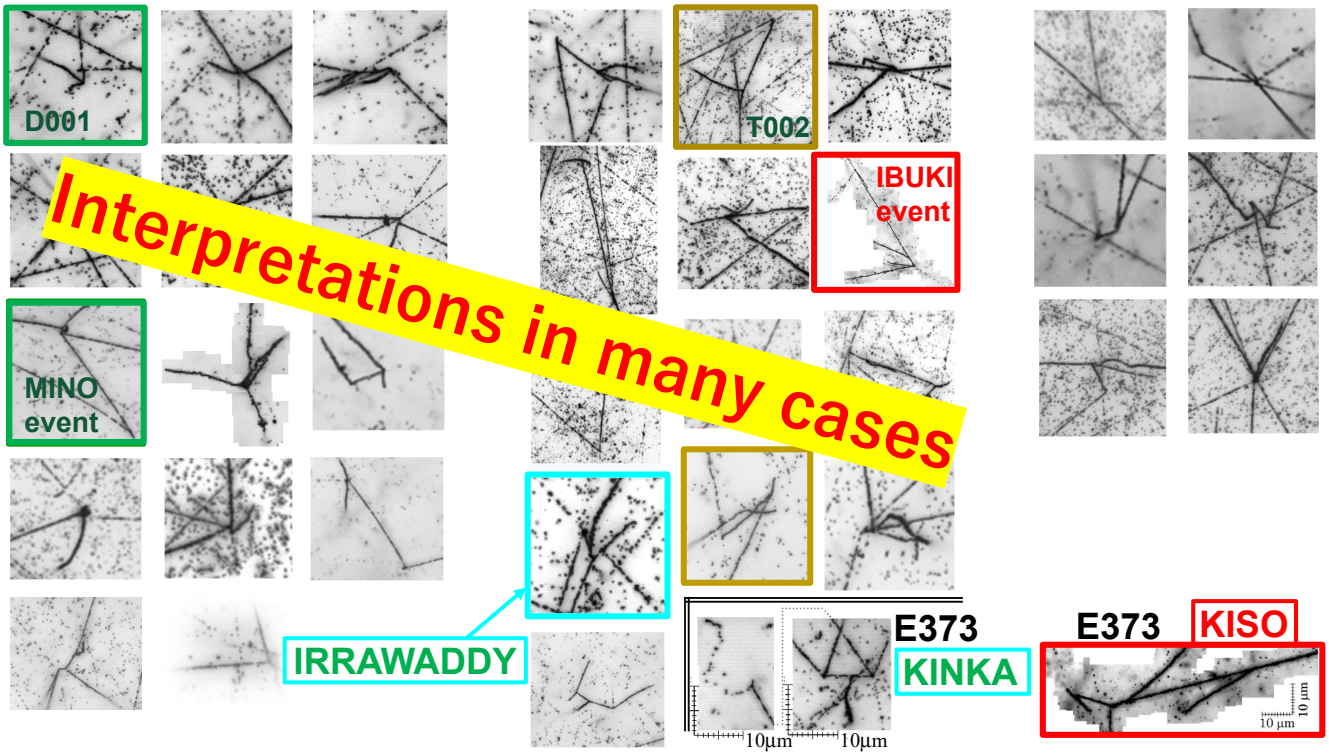
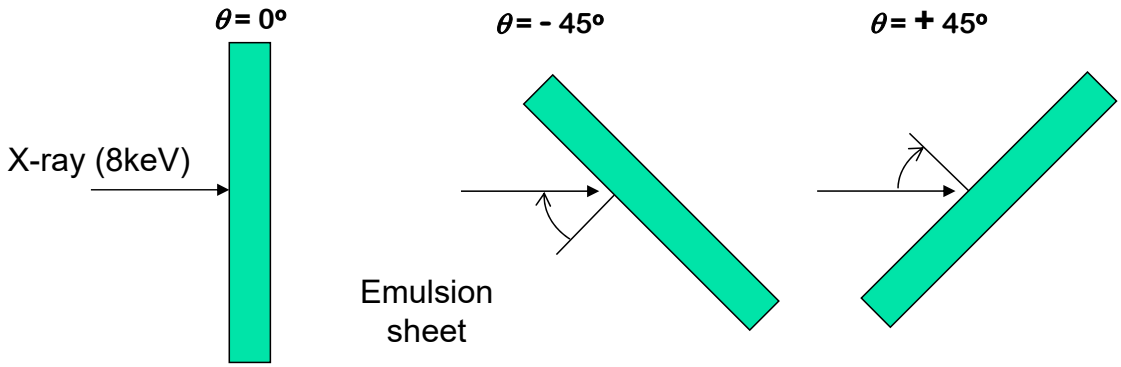



Interpretations in many cases

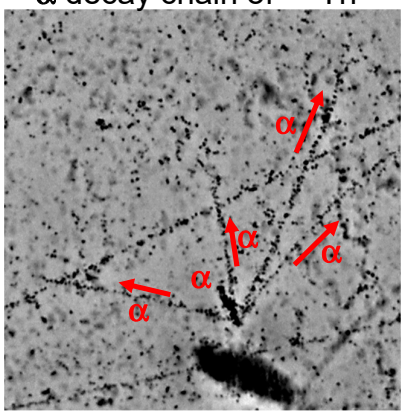
# Event analysis with X-ray microscopy

A. Kasagi et al., submitted to EPJ A **at SPring8**

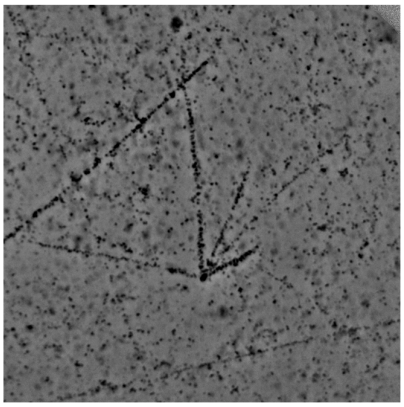
## 1. 3D imaging




α decay chain of $^{228}$Th




θ= - 45° ~ + 45° / 5° step



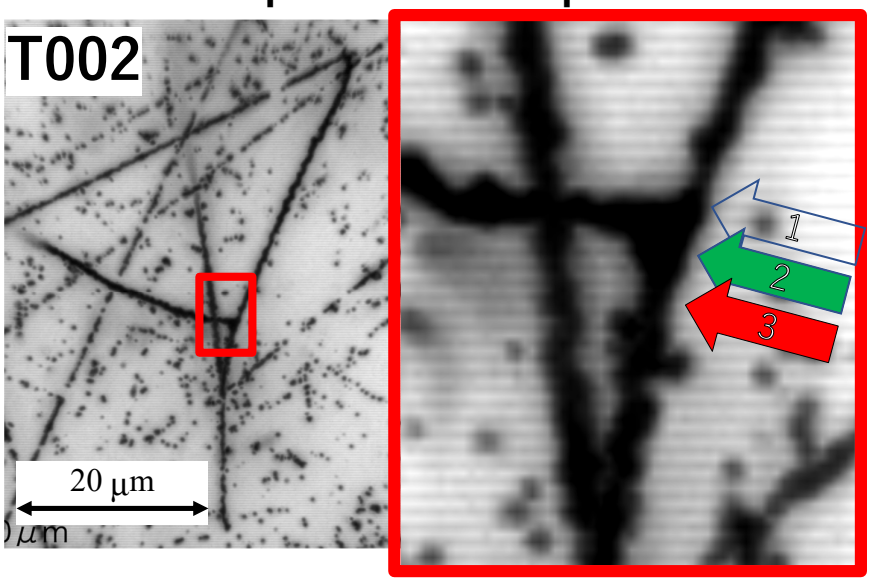


# Event analysis with X-ray microscopy

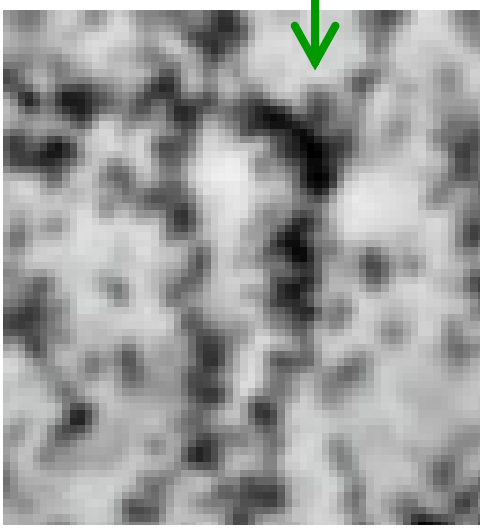
A. Kasagi et al., submitted to EPJ A **at SPring8**

## 2. Precise measurement

**Optical microscope**




**X-ray microscope**
a Ag grain



$^{14}N + \Xi^- \rightarrow {}^{9}_{\Lambda}Be + {}^{5}_{\Lambda}He + n$, $B_{\Xi^-} =$ - 4 ~ 1 MeV @ vtx1~3

➔ With X-ray microscope, $B_{\Xi^-} = -1.5 \pm 1.0$ MeV

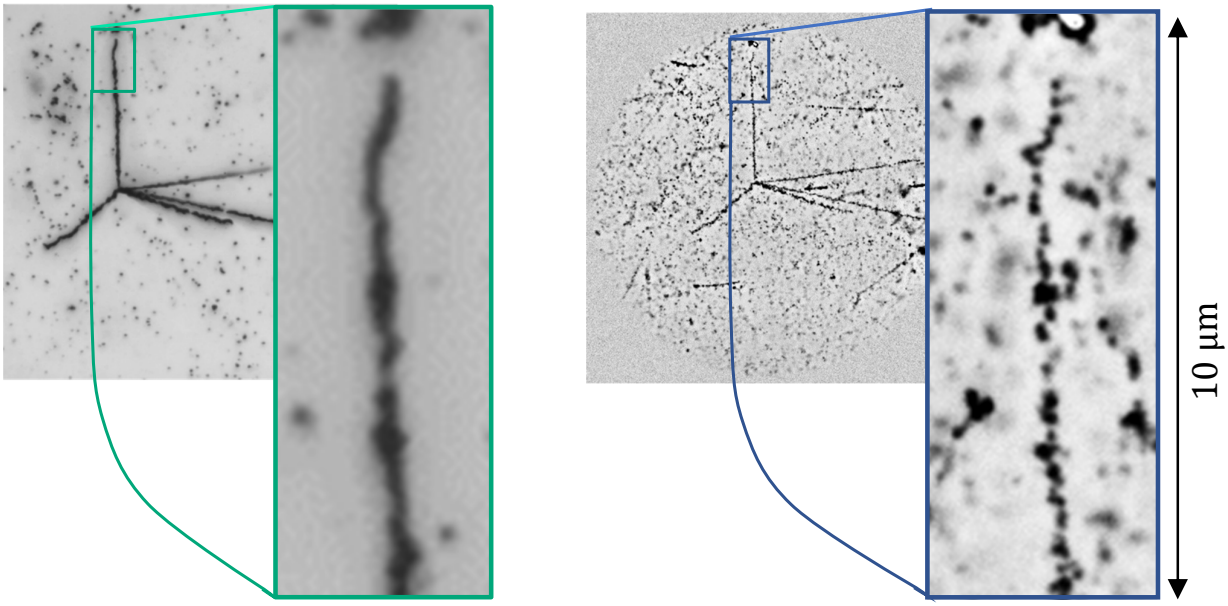
# Event analysis with X-ray microscopy

at SPring8

## 3. Charge Identification

Optical microscope

X-ray microscope




**Recognizing Ag grains constructing the track *!!***

**Grain Density ∝ d*E*/d*x* (energy loss)**



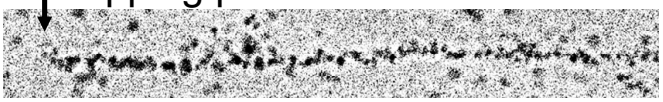
# Event analysis with X-ray microscopy

at SPring8

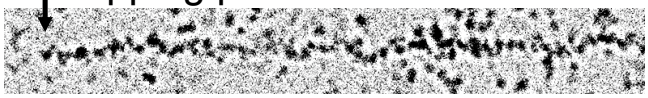
## 3. Charge Identification

X-ray microscope

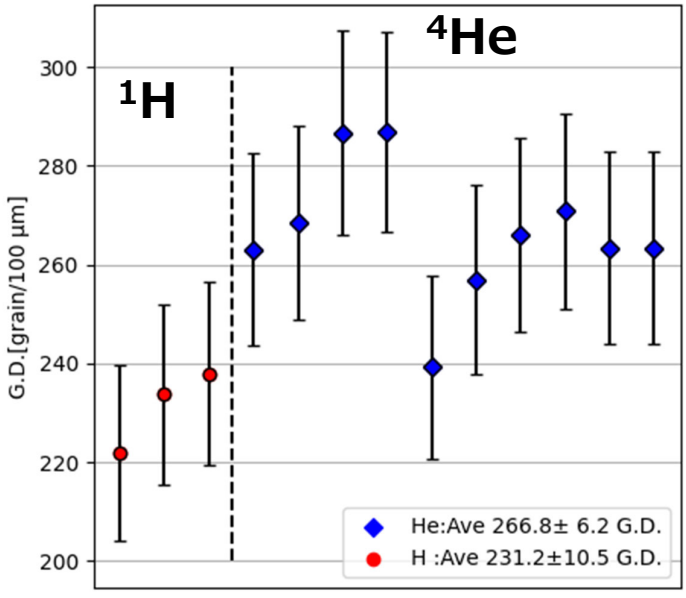
stopping point $^{1}$H



stopping point $^{4}$He



Grain densities (G.D.)
10 ~ 80 μm
from stopping point.

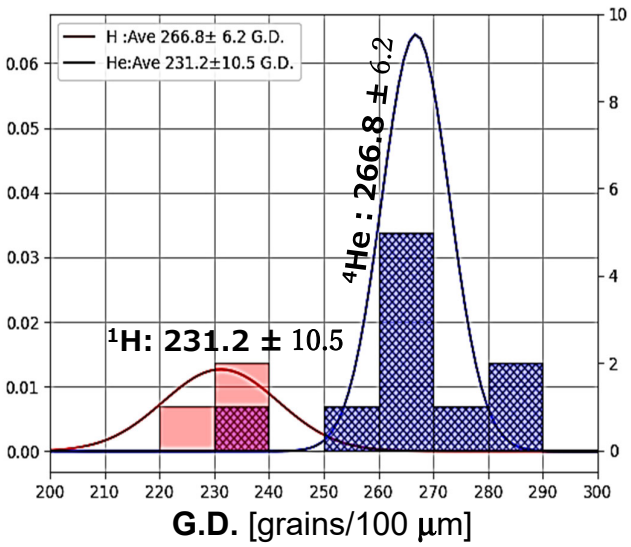


# Event analysis with X-ray microscopy

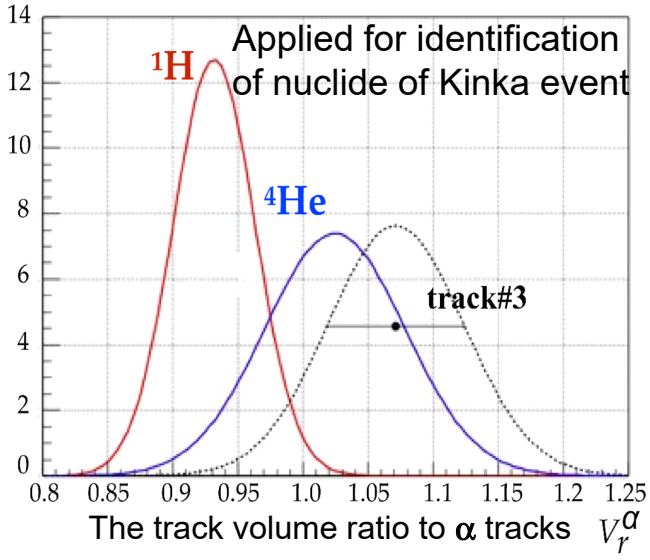
at SPring8

## 3. Charge Identification

**X-ray microscope**




**Optical microscope**




**Proposal Submitted to SPring8 on 14th June, 2022**

Near future

**Charge ID : ¹H, ⁴He => Li, Be, B**

Calibrated by 200 α tracks with measurement of track thickness

S. Kinbara, et al., Prog. Theor. Exp. Phys. **2019**, 011H01 (2019).



## Overall-scanning

Gifu U. : Speeding up for scanning of E07 emulsion)

| SPEC | E373 | 4MCamera | Piezo(x20)Old | Ultra-High Speed (x20) |
|---|---|---|---|---|
| Visual field size (μm × μm) | 140×120 | 270×270 | 560×280 | 560×560 |
| Effective field size | 110×90 | 240×240 | 530×250 | 530×530 |
| Pixel size (μm) | 0.28 | 0.11 | 0.275 | 0.275 |
| Frame rate (Hz) | 60 | 160 | 300 | 160 |
| Depth of field (μm) | 3 | 3 | 6 | 6 |
| # of picture in half side | 80 | 80 | 40 | 40 |
| Dead time (s) | (0.2) | (0.2) | 0.2 | 0.2 |
| Scanning area(cm²/day) | 5.5 | 71 | 380 | 540 |
| For all E07 Emulsions (yr) | 1500 | 110 | 21 | 16 |

Condition
area : 1000 cm²/Em_sheet
working : 250 days/year

×10
×100

~ 4 years/ 4 Mic.
near future 10

# Overall-scanning

## RIKEN : Machine learning to detect 3 vertices of double hypernuclei

## Strategy (due to very little samples for HY)

Many Images of Hypernuclei simulated by Geant4

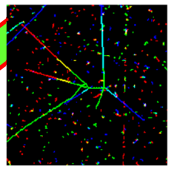
Simulated image

Image-to-Image translation

[Pix2Pix]

条件付き敵対的生成ネットワーク(CGAN)

Conditional Generative Adversarial Net.

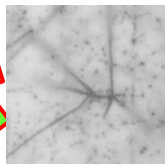


Double HY

Simulated Image

(test)

Translated Emulsion Images of Hypernuclei



Translated Image

(test)

Mask R-CNN

Machine Learning

Convolutional Neural Network

Best selection eff.

application to

Overall Scanning

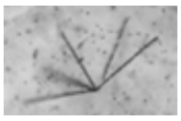
~$10^3$ Double HY

~$10^6$ light single HY

Application for detection (α decay / ${}^{3}_{\Lambda}$H)

${}^{3}_{\Lambda}$H ($pn\Lambda$) production and decay

α decay



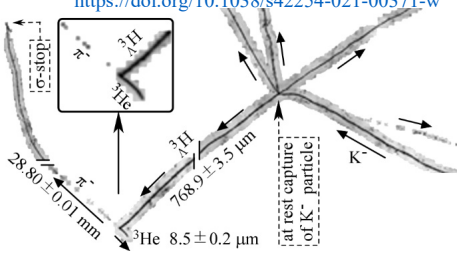
50 μm

Efficiency : 80%

Purity : 20%

T.R Saito et.al. Nature Reviews Physics

https://doi.org/10.1038/s42254-021-00371-w






# ＊Summary and Prospect

1. Under the few results for DBL hypernuclei by previous experiments, we have challenged E07 experiment. Detection with Hybrid-emulsion method has been finished in this April, and then we got 33 samples of DBL HY.

2. At present, $B_{\Lambda\Lambda}$ for DBL-Λ HY may linearly depends on mass number (A). ΞN interaction is **attractive** and level scheme in ${}^{15}_{\Xi}$C hypernucleus could be seen without any theoretical aspects.

3. To realize Overall Scanning for expected **~ 1×10³ DBL HY** and **~ 1×10⁶ SGL HY**, developments have been started for

   Speeding up for scanning, Machine learning

   ➔ 3.1 A dependence of $B_{\Lambda\Lambda}$ in DBL-Λ HY.
   ➔ 3.2 $B_{\Xi^-}$ at the production of DBL-Λ HY.
   ➔ 3.3 Level scheme in ${}^{15}_{\Xi}$C hypernucleus.
   ➔ 3.4 Systems for $\Xi^-$-${}^{12}$C and $\Xi^-$- ${}^{16}$O.
   ➔ 3.5 Challenge for $\Xi^-$- ${}^{10}$B(${}^{11}_{\Xi}$Be : ${}^{10}$B doping emulsion [new exp.]).

4. Σ- stop events, (K-, $\pi^+$), are expected in **~ 1×10³** for E07.
   ➔ precise measurement of $B_{\Sigma^-}$ on C, N and O.

   Physics with Bi-products

5. ➔ $S = -3$ physics