Knowledge on doubly-strange hypernuclei and experimental prospect

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MESON2023
22nd -27th June, 2023 KRAKÓW, POLAND

Outline

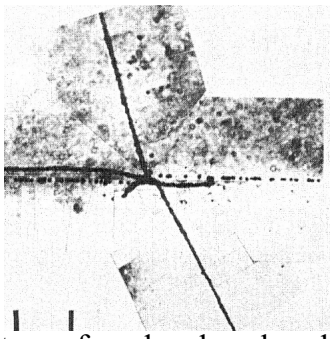
* To understand Bryon-Baryon interaction under $SU(3)_f$ symmetry
  Advancement of knowledge with *Hybrid-emulsion method*
  for doubly-strange Hypernuclei (s = -2 nuclei)
  (double-Λ hypernucleus, Xi hypernucleus)
* New questions are arising and discuss how to solve them?
  Overall-scanning method (without information by real-time detectors)
* Summary and experimental prospects

Double-Λ Hypernucleus

■ Experimental status in ~1985

Only **2** candidate events

M.Danysz et al., PRL.11(**1963**)29;



The event was found and analysed in Warsaw
【the European K⁻ Collaboration】

$^{10}_{\Lambda\Lambda}$**Be**
$\Delta B_{\Lambda\Lambda}$ = **4.5**±0.4 MeV

or $^{11}_{\Lambda\Lambda}$**Be**
$\Delta B_{\Lambda\Lambda}$ = **3.2**±0.6 MeV

D.J.Prowse, PRL.17(**1966**)782

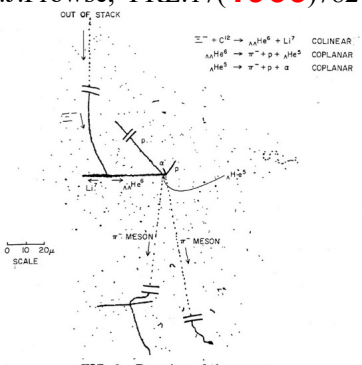


FIG. 1. Drawing of the event.

$^{6}_{\Lambda\Lambda}$**He**
$\Delta B_{\Lambda\Lambda}$ = **4.6**±0.5 MeV

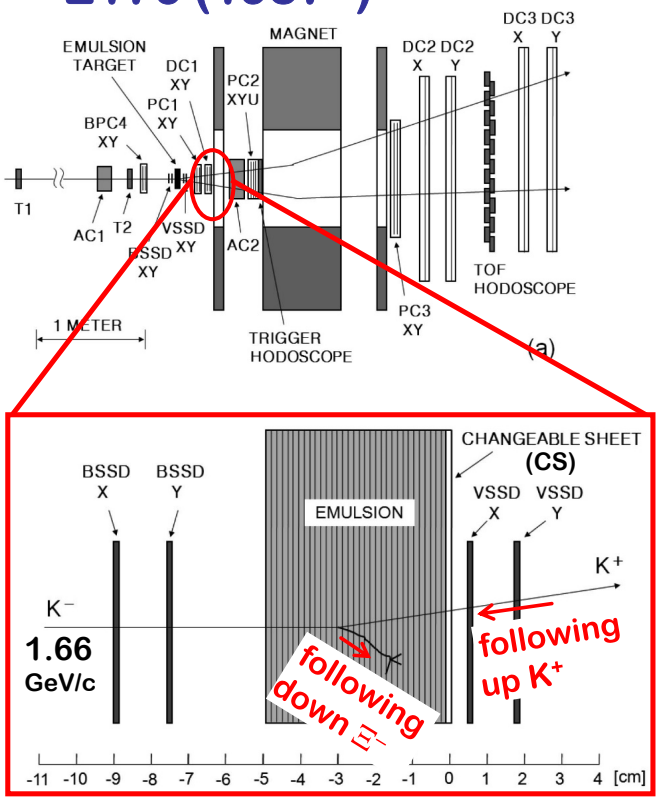
There was a sound of alert:
No independent study or analysis nor indeed observation, of the event is known,,,,,
R.H.Dalitz et al., Proc. R.S.Lond.A436(**1989**)1

Λ-Λ interaction energy
$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2B_{\Lambda}$
where binding energy of
two Λ hyperons : $B_{\Lambda\Lambda}$
single Λ hyperon : B_{Λ}

E176 : Hybrid emulsion method

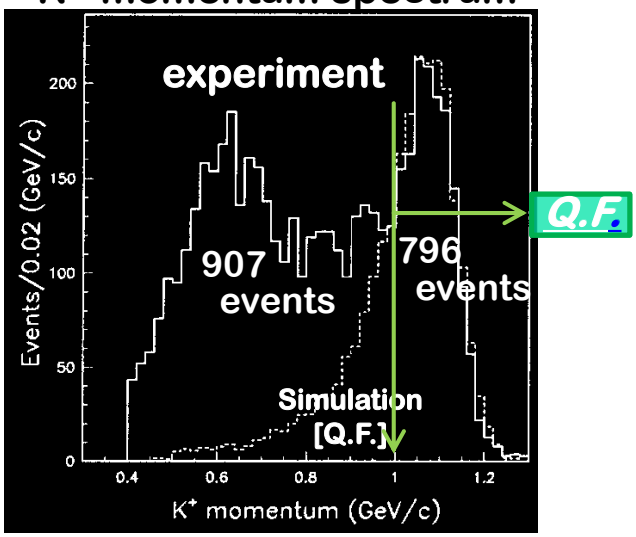
E176 (1987~)

effective tagging '*p*' (K−,K+)Ξ⁻ reaction



The emulsion was used for the target and detector.

K+ momentum spectrum



S.Aoki et al., NPA644 (1998) 365-385

Ξ⁻ stops : 77.6 +/- 5.1 events

captured by

light elem. (C,N,O) : 43%

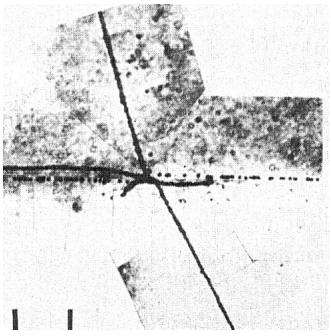
heavy elem. (Ag, Br): 58%

S.Aoki et al., NPA828 (2009) 191

Double-Λ Hypernucleus

n p Λ

M.Danysz et al., PRL.11(1963)29;



Re-analysis

Expected Ξ stops ~ 4

$^{10}_{\Lambda\Lambda}$Be → $^{9}_{\Lambda}$Be + p + π-

$B_{\Lambda\Lambda}$ = 17.7 ± 0.4 MeV

$\Delta B_{\Lambda\Lambda}$ = 4.3 ± 0.4 MeV

R.H.Dalitz et al., Proc. R.S.Lond.A436(1989)1

D.J.Prowse, PRL.17(1966)782

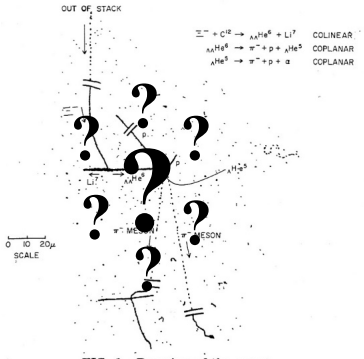


FIG. 1. Drawing of the event.

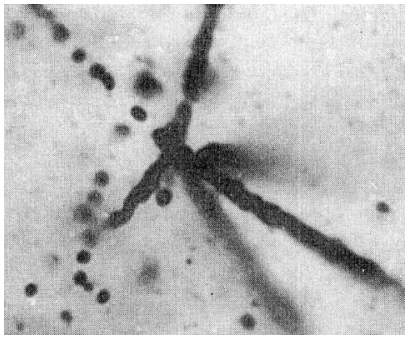
$^{6}_{\Lambda\Lambda}$He → $^{5}_{\Lambda}$He + p + π-

$B_{\Lambda\Lambda}$ = no discussion(?)

$\Delta B_{\Lambda\Lambda}$ = 4.6 ± 0.5 MeV

KEK-E176

S.Aoki et al, PTP.85(1991)1287



in ~80 Ξstops

$^{13}_{\Lambda\Lambda}$B

$B_{\Lambda\Lambda}$ = 27.6 ± 0.7 MeV

or $\Delta B_{\Lambda\Lambda}$ = 4.9 ± 0.7 MeV

$^{10}_{\Lambda\Lambda}$Be

$B_{\Lambda\Lambda}$ = 8.5 ± 0.7 MeV

$\Delta B_{\Lambda\Lambda}$ = −4.8 ± 0.7 MeV

Why $V_{\Lambda\Lambda}$ so strong?

"interesting theoretical problem"

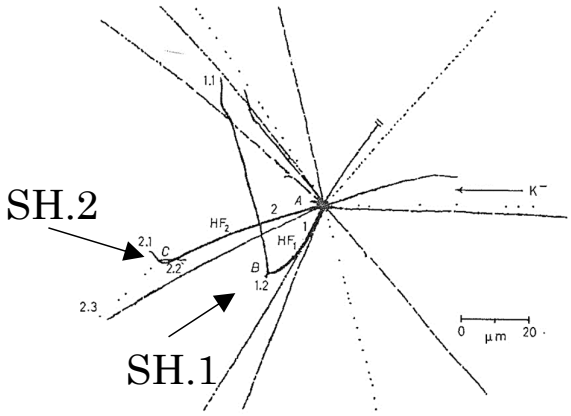
C.B.Dover, Proc. HYP91, NP.A547(1992)27c

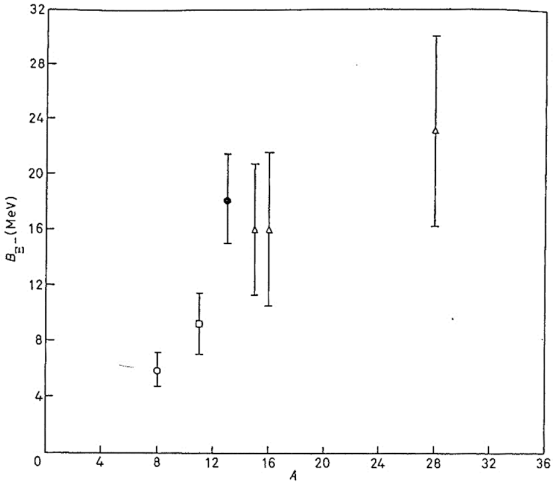
Ξ Hypernucleus

■ Experimental status in ~1985

Only ? candidate events

K^- interaction => Twin Hyperfragment => Mass reconstruction





A.S.Mondal, et al., IL NUOVO CIMENTO, 54 (1979) 333

1983 $U_\Xi = -(21\sim24)$ MeV

C.B.Dover and A.Gal, Ann. Phys., 146 (1983) 309

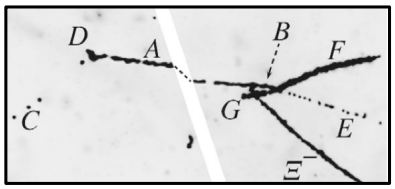
Are two Λ hyperons surely produced via ΞN interaction? (or two-step process?)

Ξ Hypernucleus

E176 results

Ξ⁻ (S = -2) is clearly absorbed by a nucleus

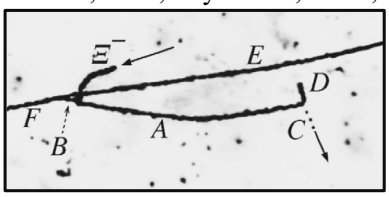
S. Aoki, et al., PTP 89 (**1993**) 493



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

$B_{\Xi^-} = 0.54 \pm 0.20$ MeV

S. Aoki, et al., Phys. Lett., **B355**, 45 (**1995**)



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

$B_{\Xi^-} = 0.62\ ^{+0.18}_{-0.19}$ MeV

Theoretical prediction of B_{Ξ^-} values for the Ξ^--^{12}C and Ξ^--^{14}N systems using **Coulomb and Ehime potentials**.

State	$B_{\Xi^-}[\Xi^- - {}^{12}C]$ (MeV)	$B_{\Xi^-}[\Xi^- - {}^{14}N]$ (MeV)
1s	4.77	5.93
2p	0.58	1.14
3D	0.126	0.174
2s	0.40	0.54
3p	0.19	0.28

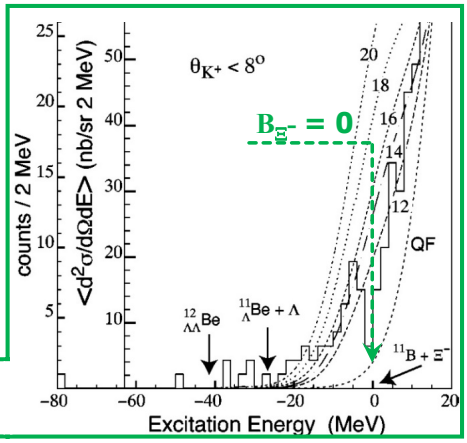
M.Yamaguchi, K. Tominaga, Y. Yamamoto, and T. Ueda, PTP **105**, 627 (**2001**)

Updated data

S.Aoki et al., NPA828 (**2009**) 191

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

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

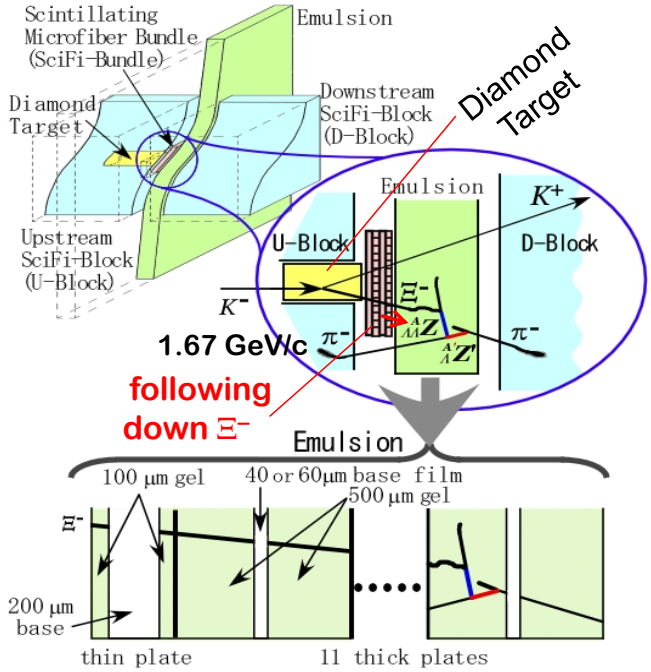


1998 $U_\Xi > -20$ MeV **Missing mass spectrum** (KEK-E224)
T.Fukuda, et al., Phys. Rev. C58 (1998)

2000 $U_\Xi \sim -14$ MeV **Missing mass spectrum** (AGS-E885)
P.Khaustov, et al., Phys. Rev. C61 (2000) 054603

Hybrid emulsion experiment

E373 (KEK:1995~) tagging 'p' (K−,K+)Ξ⁻ reaction



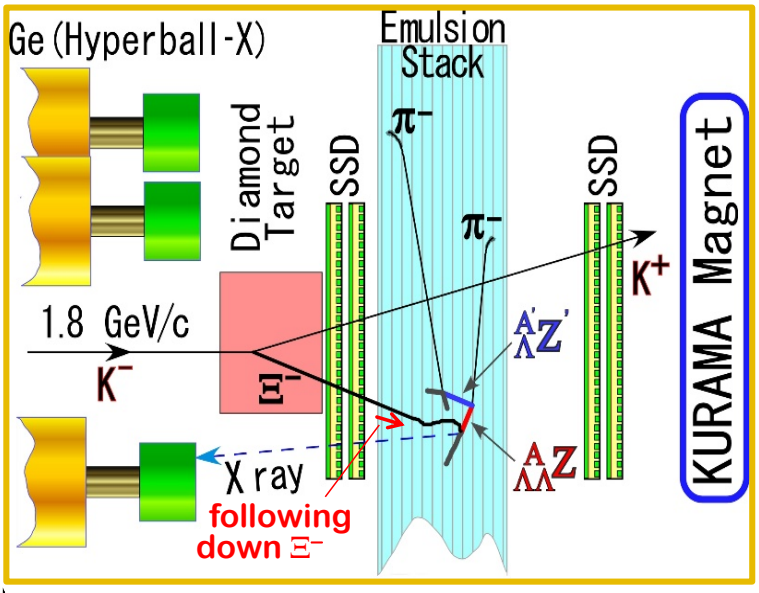
24.5 x 25.0 cm² : 1.0 x 10³ sheets

followed Ξ⁻ cand. track : ~2.0 x 10⁴,

➔ ~ 650 Ξ⁻ stops.

Aye Moh Moh Theint, et al., PTEP, 021D01 (2019)

E07 (J-PARC :2007~)



34.5 x 35.0 cm² : 1.2 x 10³ sheets

followed Ξ⁻ cand. track : 3.5 x 10⁴,

➔ ~3 x 10³ Ξ⁻ stops (?).

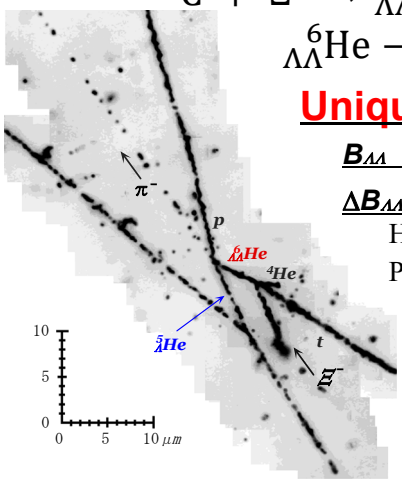
Double-Λ Hypernucleus

NAGARA event (E373)

The event was named after Nagara, a clear stream in Gifu, Japan

$$^{12}\mathrm{C} + \Xi^- \rightarrow {}_{\Lambda\Lambda}^{6}\mathrm{He} + {}^{4}\mathrm{He} + t$$

$${}_{\Lambda\Lambda}^{6}\mathrm{He} \rightarrow {}_{\Lambda}^{5}\mathrm{He} + p + \pi^-$$

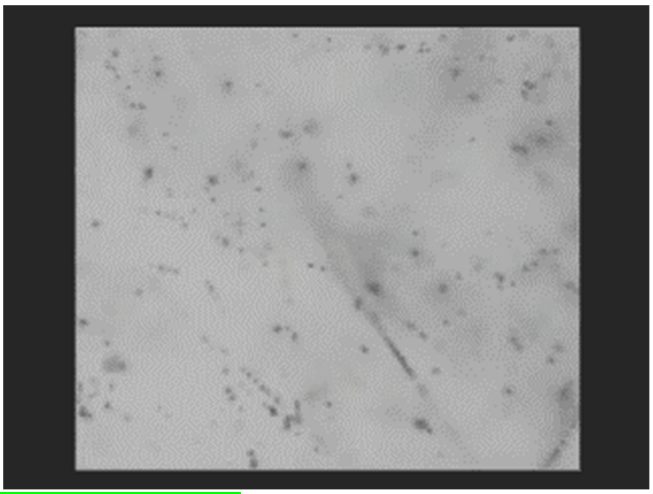


Unique assignment

$B_{\Lambda\Lambda}$ = 7.25 +/- 0.19 MeV,

$\Delta B_{\Lambda\Lambda}$ = 1.01 +/- 0.20 MeV

H. Takahashi, et al., PRL 87 (2001) 212502



Confirmed

Λ-Λ int.

➔ ***weakly attractive***

Updated data

J.K Ahn et al., PRC88 (2013) 014003

1. From Consistency at production & decay : B_{Ξ^-} < 1.86 MeV
2. By kinematical fitting : $B_{\Lambda\Lambda}$ = 6.79 + 0.91B_{Ξ^-} (+/- 0.16) MeV

   $\Delta B_{\Lambda\Lambda}$ = 0.55 + 0.91B_{Ξ^-} (+/- 0.17) MeV

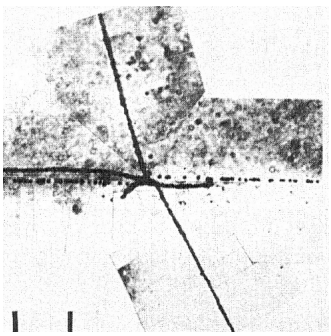
We take into account B_{Ξ^-} = 0.13 MeV [atomic 3*D* : ¹²C- Ξ⁻]

$B_{\Lambda\Lambda}$ = 6.91 +/- 0.16 MeV, $\Delta B_{\Lambda\Lambda}$ = 0.67 +/- 0.17 MeV

Double-Λ Hypernucleus

Λ by NAGARA data : $\Delta B_{\Lambda\Lambda}$ ~ 1 MeV

M.Danysz et al., PRL.11(1963)29;



Re-analysis

Expected Ξ stops ~ 4

$^{10}_{\Lambda\Lambda}$Be → $^{9}_{\Lambda}$Be + p + π-

~~$B_{\Lambda\Lambda}$ = 17.7 ± 0.4 MeV~~

~~$\Delta B_{\Lambda\Lambda}$ = 4.8 ± 0.4 MeV~~

R.H.Dalitz et al., Proc. R.S.Lond.A436(1989)1

$^{10}_{\Lambda\Lambda}$Be -> $^{9}_{\Lambda}$Be*

$B_{\Lambda\Lambda}$ = 14.7 ± 0. 4 MeV

$\Delta B_{\Lambda\Lambda}$ = 1.3 ± 0. 4 MeV

J.K. Ahn et al., PR C88 (2013) 014003

D.J.Prowse, PRL.17(1966)782

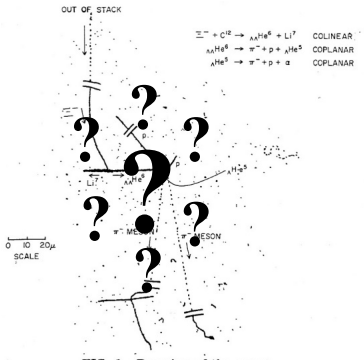


FIG. 1. Drawing of the event.

~~$^{6}_{\Lambda\Lambda}$He → $^{5}_{\Lambda}$He + p + π-~~

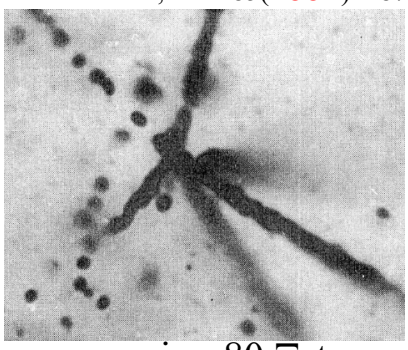
~~$B_{\Lambda\Lambda}$ = no discussion~~(?)

~~$\Delta B_{\Lambda\Lambda}$ = 4.6 ± 0.5 MeV~~

Doubtful !!

KEK-E176

S.Aoki et al, PTP.85(1991)1287



in ~80 Ξstops

$^{13}_{\Lambda\Lambda}$B → $^{13}_{\Lambda}$C + π-

~~$B_{\Lambda\Lambda}$ = 27.6 ± 0.7 MeV~~

~~$\Delta B_{\Lambda\Lambda}$ = 4.9 ± 0.7 MeV~~

$^{13}_{\Lambda\Lambda}$B -> $^{13}_{\Lambda}$C*

$B_{\Lambda\Lambda}$ = 23.3 ± 0. 7 MeV

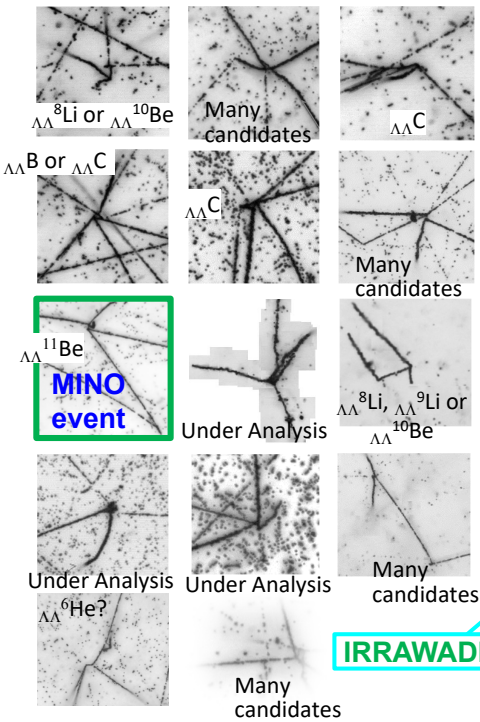
$\Delta B_{\Lambda\Lambda}$ = 0.6 ± 0. 8 MeV

S.Aoki et al., NP. A828 (2009) 191

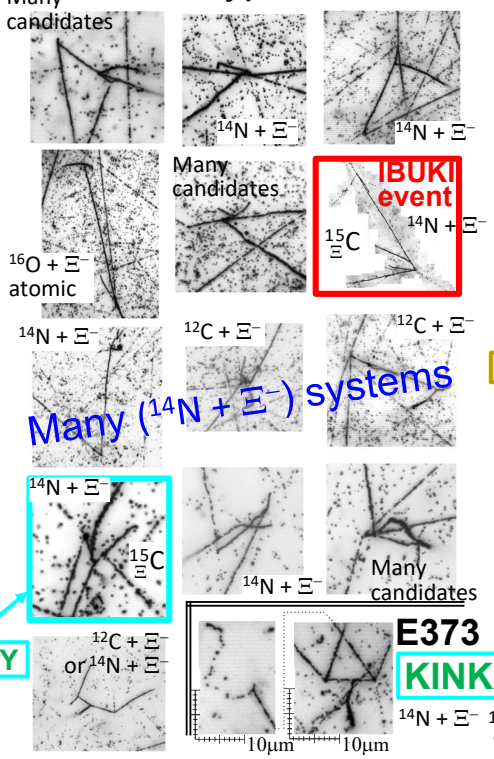
List of detected events in E07

	KEK-PS	E176	E373	J-PARC E07	
Searching period		~10 years	~10 years	2 years (hybrid Meth.)	
S=-2 system		4	10	33	Tot.47

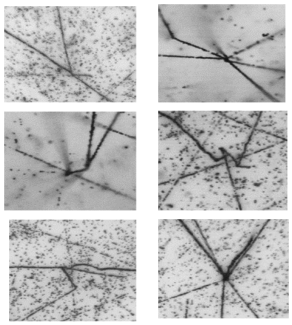
14 double-Λ events



13 twin-hyper events



6 confused ➔ X-ray



Outstanding Paper Award (JPS)

22nd : KISO event (2017)

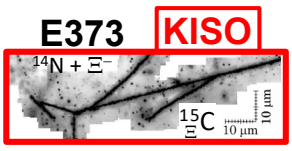
K. Nakazawa, et al. PTEP, 2015, 033D0

Confirming the existence of Xi Hypernucleus

26th : MINO event (2021)

H. Ekawa, et al., PTEP, 2019, 021D02

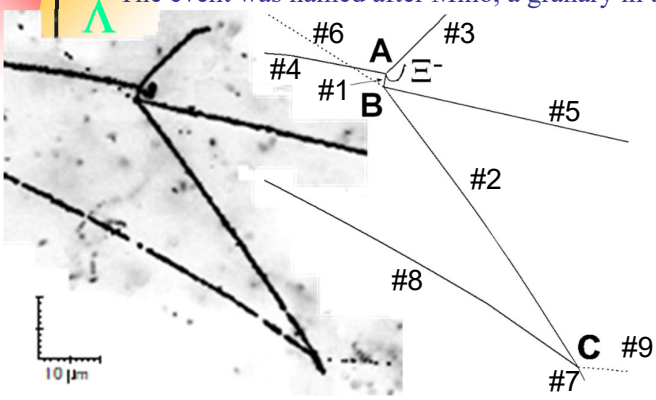
Detecting nuclear medium effect on double-Λ Hypernuclei



Double-Λ Hypernucleus (E07)

MINO event (nuclide : uniquely identified)

The event was named after Mino, a granary in the southern part of Gifu, Japan



Checking consistencies for **VTX. C, B and A,** the nuclide was uniquely identified as $_{\Lambda\Lambda}$**Be.**

$$^{16}\mathrm{O} + \Xi^- \to (^{10}_{\Lambda\Lambda}\mathrm{Be},\ ^{11}_{\Lambda\Lambda}\mathrm{Be},\ ^{12}_{\Lambda\Lambda}\mathrm{Be}) + {}^4\mathrm{He} + (t,\ d,\ p),$$
$$\hookrightarrow {}^{5}_{\Lambda}\mathrm{He} + (p, d, t) + p + xn,$$
$$\hookrightarrow {}^4\mathrm{He} + p + \pi^-.$$

Table 6 χ^2 and p-value of the kinematic fitting at vertex A.

Decay mode	χ^2	p-value [%]
$^{16}\mathrm{O} + \Xi^- \to {}^{10}_{\Lambda\Lambda}\mathrm{Be} + {}^4\mathrm{He} + t$	11.5	0.93
$^{16}\mathrm{O} + \Xi^- \to {}^{11}_{\Lambda\Lambda}\mathrm{Be} + {}^4\mathrm{He} + d$	7.28	6.35
$^{16}\mathrm{O} + \Xi^- \to {}^{12}_{\Lambda\Lambda}\mathrm{Be} + {}^4\mathrm{He} + p$	11.3	1.02

$_{\Lambda\Lambda}^{11}$**Be** is the most probable (in the assumption of Ξ- capture on atomic 3D state)

➔ $B_{\Lambda\Lambda}(\Delta B_{\Lambda\Lambda}) =$ **19.07** $\pm$ 0.11 (1.87 $\pm$ 0.37) MeV

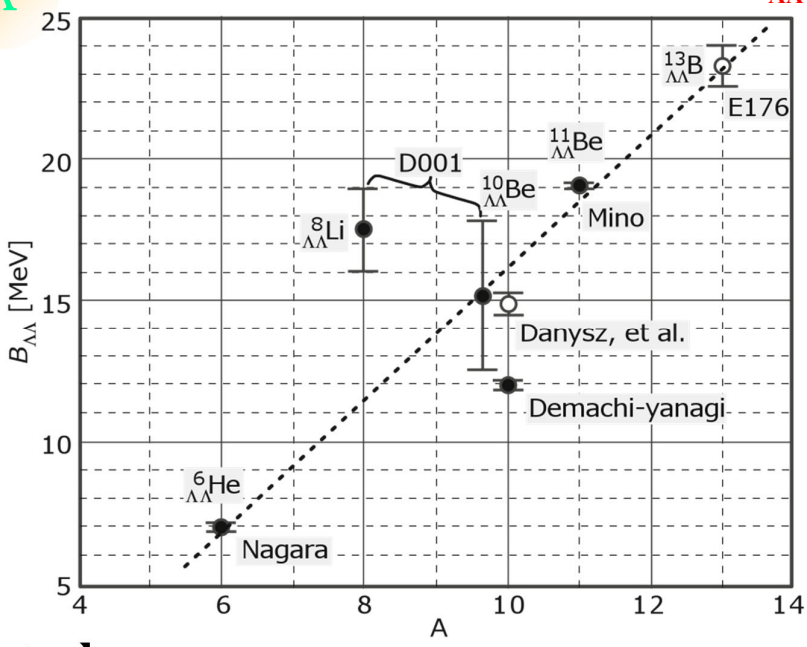
H. Ekawa et al., PTEP, 2019, 021D02 (2019)

The Value of $\Delta B_{\Lambda\Lambda}$ seems to be not consistent with that of the NAGARA event.

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

Double-Λ Hypernucleus

Linear relation between mass numbers **A** and $B_{\Lambda\Lambda}$ for double-Λ hypernuclei.



Nakazawa, K. (2023).
"Experimental Aspect of $S = -2$ Hypernuclei"
In: Tanihata, I., Toki, H., Kajino, T. (eds)
Handbook of Nuclear Physics . Springer, Singapore.
https://doi.org/10.1007/978-981-15-8818-1_33-1

【Questions】 1. What is the lightest double-Λ hypernucleus?

2. When one of two Λ hyperons enters the excited state, is there still attractive between them?

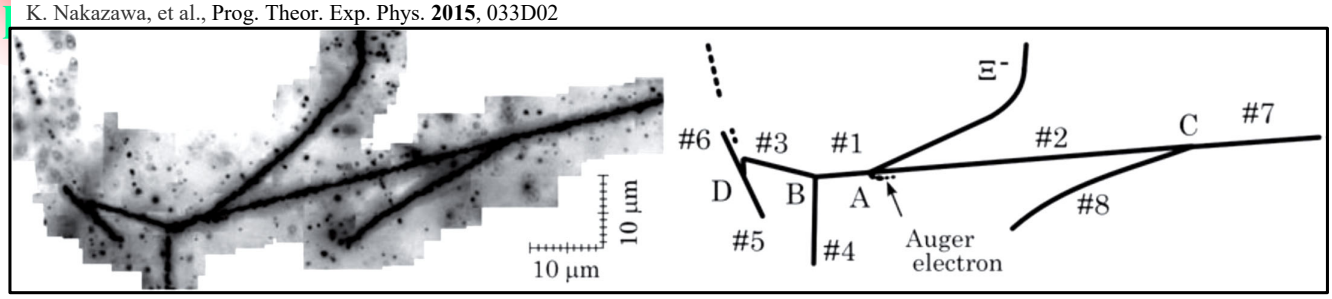
Systematic understanding is still lacking!!

Ξ Hypernucleus

Kiso event (E373) in the development Overall-scanning

The event was named the Kiso after the majestic Kiso River, Japan.

K. Nakazawa, et al., Prog. Theor. Exp. Phys. **2015**, 033D02



$^{14}\mathrm{N} + \Xi^- \rightarrow (^{15}_{\Xi}\mathrm{C}) \rightarrow {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$: $B_{\Xi^-} = 3.87 \pm 0.21$ MeV

$(^{15}_{\Xi}\mathrm{C}) \rightarrow {}^{10}_{\Lambda}\mathrm{Be}^* + {}^{5}_{\Lambda}\mathrm{He}$: $B_{\Xi^-} = 1.03 \pm 0.18$ MeV

Sufficiently larger than atomic orbital (0.17 MeV @ 3D level)

First evidence of the existence of Ξ hypernucleus

➔ Ξ-Nucleus potential : ***attractive!!***

- E. Hiyama and K. Nakazawa, Annu. Rev. Nucl. Part. Sci. 2018. 68:131–59, https://doi.org/10.1146/annurev-nucl-101917-021108
- Nakazawa, K. (2023). "Experimental Aspect of $S = -2$ Hypernuclei" In: Tanihata, I., Toki, H., Kajino, T. (eds) Handbook of Nuclear Physics . Springer, Singapore. https://doi.org/10.1007/978-981-15-8818-1_33-1

Ibuki : $^{14}\mathrm{N} + \Xi^- \rightarrow {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$: $B_{\Xi^-} = 1.21 \pm 0.21$ MeV

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

Kinka : $^{14}\mathrm{N} + \Xi^- \rightarrow {}^{9}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He} + n$: $B_{\Xi^-} = 8.00 \pm 0.77$ MeV

$\rightarrow {}^{9}_{\Lambda}\mathrm{Be}^* + {}^{5}_{\Lambda}\mathrm{He} + n$: $B_{\Xi^-} = 4.96 \pm 0.77$ MeV

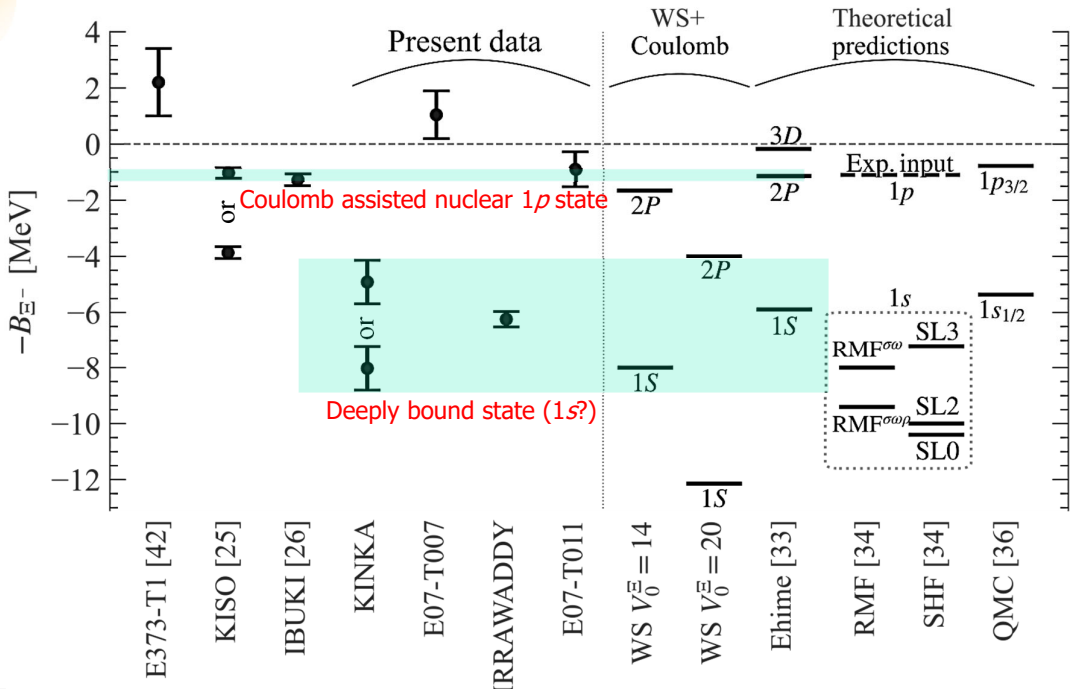
Irrawaddy : $^{14}\mathrm{N} + \Xi^- \rightarrow {}^{5}_{\Lambda}\mathrm{He} + {}^{5}_{\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + n$: $B_{\Xi^-} = 6.27 \pm 0.27$ MeV

M. Yoshimoto, et al., Prog. Theor. Exp. Phys. **2015**, 033D02

Ξ Hypernucleus

Ξ Hypernucleus $^{15}_{\Xi}\mathrm{C}$ ($\Xi^- + {}^{14}\mathrm{N}$)

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



【Questions】

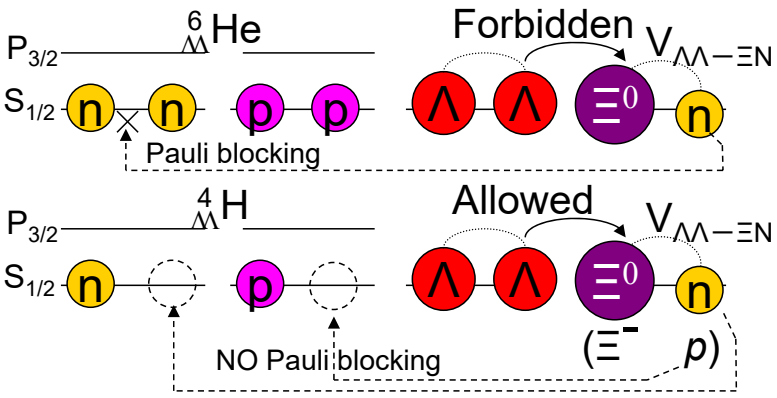
1. Does one of two cases of the Kinka and the Irrawaddy show a different spin state in s-state of $^{15}_{\Xi}\mathrm{C}$?
2. Why so many ($\Xi^- + {}^{14}\mathrm{N}$) systems have been detected?

Systematic understanding is still lacking!!

Summary of questions

[1] The lightest double-Λ HY? ${}^{5}_{\Lambda\Lambda}$He, ${}^{5}_{\Lambda\Lambda}$H, ${}^{4}_{\Lambda\Lambda}$H?

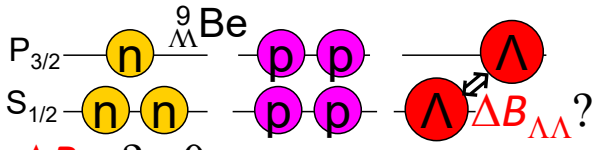
The effect of ΛΛ-Ξ*N* (Ξ⁻*p* ⇔ Ξ⁰*n* ⇔ *H*) coupling



production rate of ${}^{5}_{\Lambda\Lambda}$H ~ 1/10 for ${}^{6}_{\Lambda\Lambda}$He

[just a theoretical prediction]

[2] When one Λ enters an excited state, is ΛΛ interaction still attractive?



$\Delta B_{\Lambda\Lambda}$?< 0 …… if repulsive,

It may be possible that they could support **neutron stars** with heavy mass (≥2$M_{\odot}$).

⇒ increase the number of double-Λ events.

[3] Irrawaddy and one of two cases of KINKA may show different spin state in *s*-state of ${}^{15}_{\Xi}$C ?

[4] Why so many twin-hyper events?

for (Ξ⁻ + ^{14}N) system

Component fraction (mol) of the Emulsion

C : N : O = 0.55 : 0.16 : 0.29

Identified twin-hyper

4 (C) : 7 (N) : 1 (O)

⇒ increase the number of twin-hyper events.

Overall-scanning !!

Leaving from limited information by real-time detectors.

Practical application is essential !!

Collaboration of Gifu and RIKEN was started.

Collaboration of Gifu & RIKEN

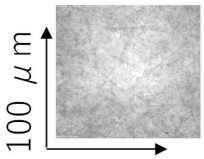
Overall-scanning *trained with machine learning*

Speeding up

for scanning

@ Gifu U.

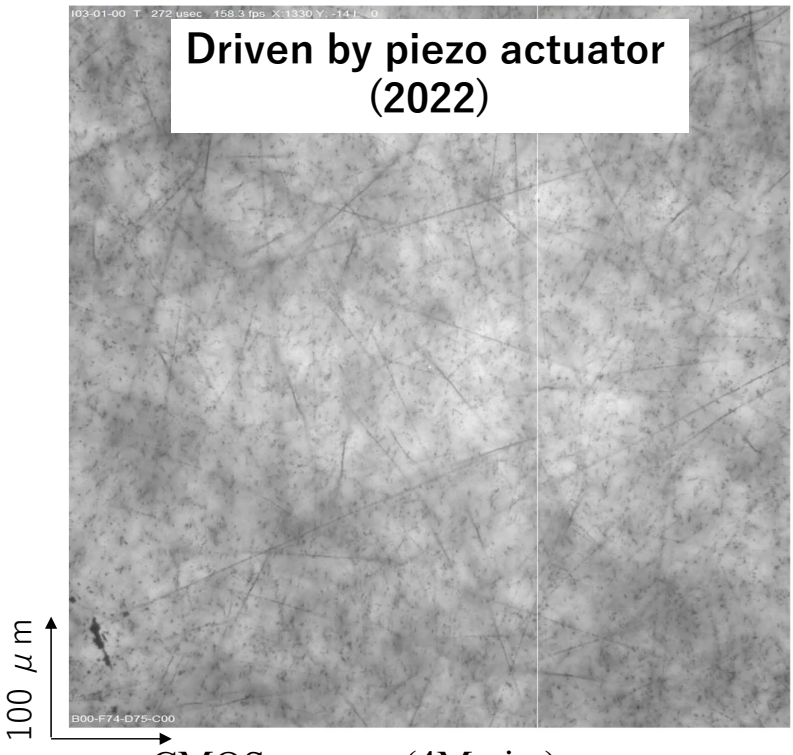
Driven by motor (2013)



CCD camera (512 x 440 pix.)
8 s/view (1000 days/sheet)
60 GB/day

4.5 days x 1,200 sheets /year (300 days) / 5 microscopes
➔ 3.6 years (/all sheets)

Driven by piezo actuator (2022)



CMOS camera (4M pix.)
1.3 s/view (4.5 days/sheet)
12 TB/day

Collaboration of Gifu & RIKEN

Overall-scanning *trained with machine learning*

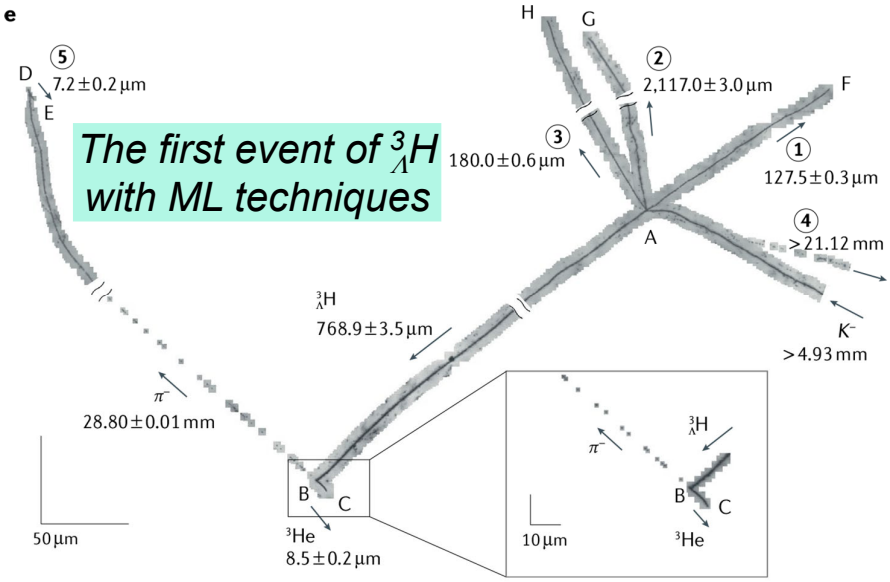
Mchine learning

for detection

@ RIKEN

Previous talk given by Dr. T.R. Saito

"Studies of hypernuclei with the WASA-FRS setup, nuclear emulsion and machine learning"



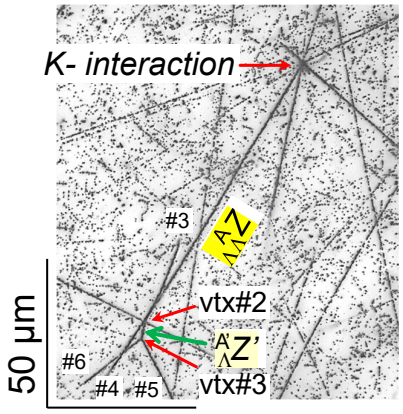
T.R. Saito, et al., Nature Reviews Physics 3, 803 (2021)

Collaboration of Gifu & RIKEN

Overall-scanning *trained with machine learning*

Mchine learning for detection @ RIKEN

Double-Λ hypernucleus via K- interaction



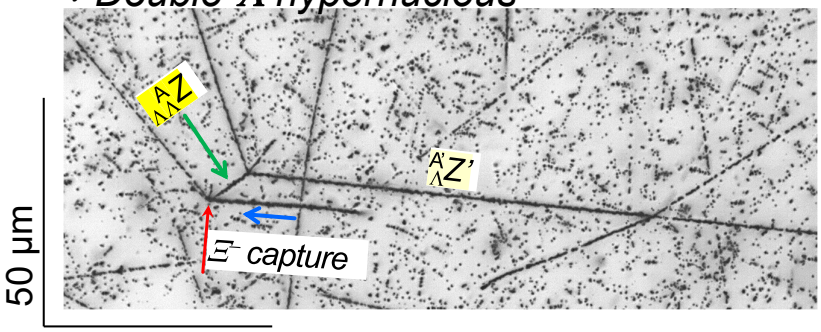
Study of ***ground state*** of Double-Λ hypernuclei

(independent of B_{Ξ^-})

Doubly-strange hypernuclei via Ξ⁻ capture at-rest

(estimated ~ 1 x 10^3 events)

∗Double-Λ hypernucleus



∗Ξ hypernucleus : no candidate at present

Under tuning the ML model

by Overall-scanning

trained with machine learning

Possible to study (Near Future)

[1] lightest double-Λ hypernucleus

[2] double-Λ with one Λ in excited state

[3] precise measurement of level scheme in ${}^{15}_{\Xi}C$

[4] Ξ hypernuclei as systems of (Ξ^--${}^{12}C$) and (Ξ^--${}^{16}O$)

In addition to them,

[5] precise measurement of B_Λ for single-Λ (~1 M events)

[6] Λ-bar nucleus with p-bar beam [1.8 GeV/c] ?

No new beam time is needed.

by Overall-scanning

trained with machine learning

Next-step (New beam time is needed)

[7] Ξ Hypernucleus : ${}^{11}_{\Xi}Be$.

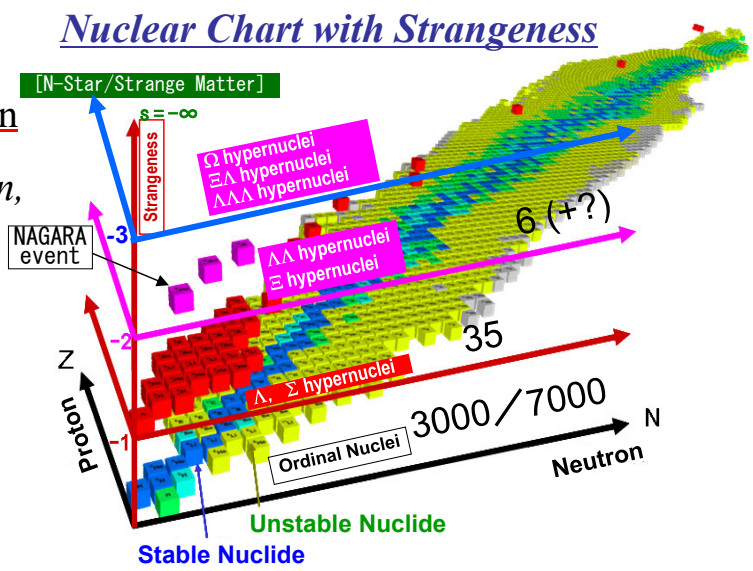
${}^{10}B$ has to be doped into the emulsion

ex. $\Xi^- + {}^{10}B = ({}^{11}_{\Xi}Be) \Rightarrow {}^{5}_{\Lambda}He + {}^{5}_{\Lambda}He + n$,

[8] $S = -3$ nuclear physics

Ω Hypernucleus

(K10@J-PARC)



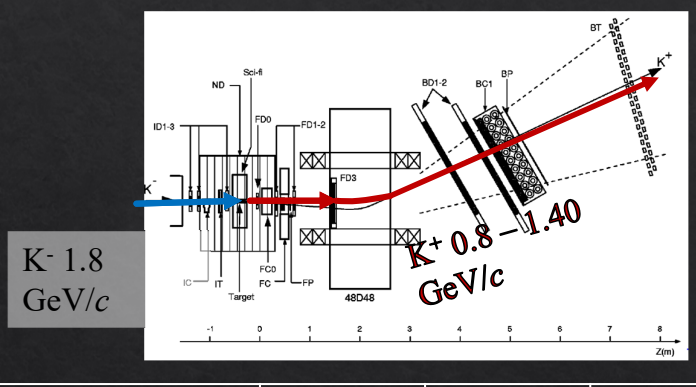
Summary and experimental prospects

1. Under the few results for DBL-Λ hypernuclei by past experiments, we have challenged E176, E373 and E07 experiments. Detection and analysis with Hybrid-emulsion method have been finished by April, 2021, and then we got **47 samples** of Doubly-strange hypernuclei.
2. At present, $B_{\Lambda\Lambda}$ for DBL-Λ hypernuclei may **linearly** depends on mass number (A). Ξ*N* interaction is **attractive** and level scheme in ${}^{15}_{\Xi}C$ hypernucleus could be seen without any theoretical aspects.
3. **Overall-scanning with Machine learning** must make our knowledge rich on not only S=-1 but also S=-2.
4. New experiment (E70) on Xi hypernucleus : ${}^{12}_{\Xi}Be$ shall be started at J-PARC, soon. ➔➔➔

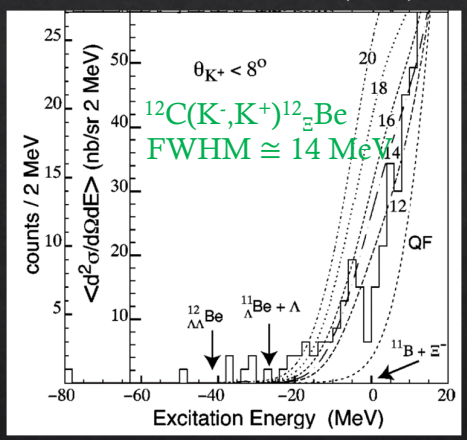
J-PARC E70

start for beam exposure soon

${}^{12}C(K^-,K^+){}^{12}_{\Xi}Be$ ← Missing-mass measurement



P. Khaustov et al., PRC **61** (2000) 054603



Experiment	KEK E224	BNL E885	J-PARC E05
Resolution in FWHM (MeV)	22	14	8

➔ **2 MeV** in J-PARC E70

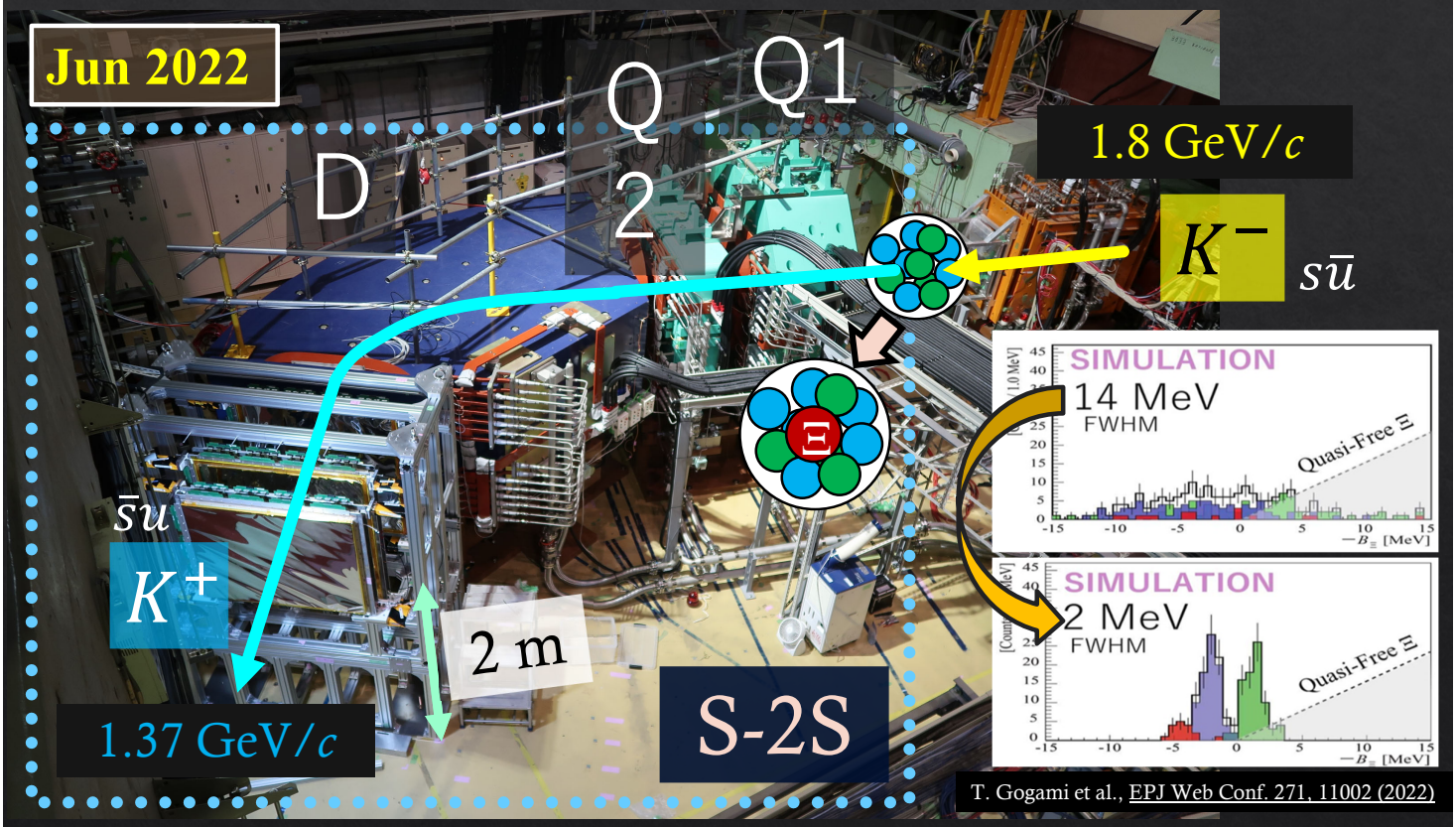
⇨ $V_{0\Xi} \leq 14$ MeV

c.f.)
M. Kohno et al., PTP123, 1 (2010)
M. Kohno, PRC 100, 024313 (2019)

slide by T. Gogami

J-PARC E70

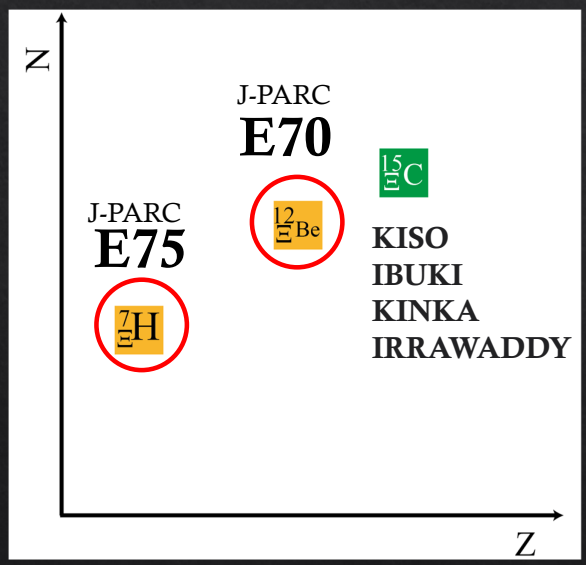
start for beam exposure soon

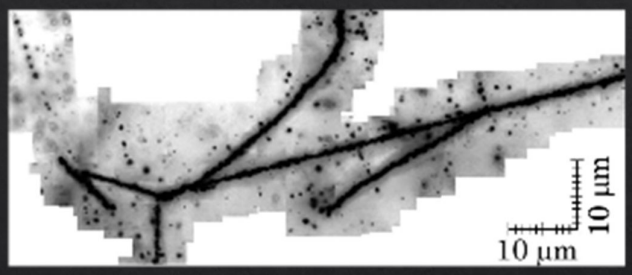


T. Gogami et al., EPJ Web Conf. 271, 11002 (2022)

slide by T. Gogami

Hypernuclear chart ($S = -2$ floor)





- K. Nakazawa et al., PTEP 2015, 033D02 (2015)
- M. Yoshimoto et al., PTEP 2021, 073D02 (2021)
- S. Hayakawa et al., PRL 126, 062501 (2021)

slide by T. Gogami

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4. New experiment (E70) on Xi hypernucleus : ${}^{12}_{\Xi}Be$ shall be started at J-PARC, soon. ➔➔➔
5. Future experiments;
   ➔ 5.1 Challenge for Ξ^-- ${}^{10}B$(${}^{11}_{\Xi}Be$: ${}^{10}B$ doping emulsion)
   ➔ 5.2 $S = -3$ physics. (**K10** beam-line @ J-PARC)

Thank you for your attention