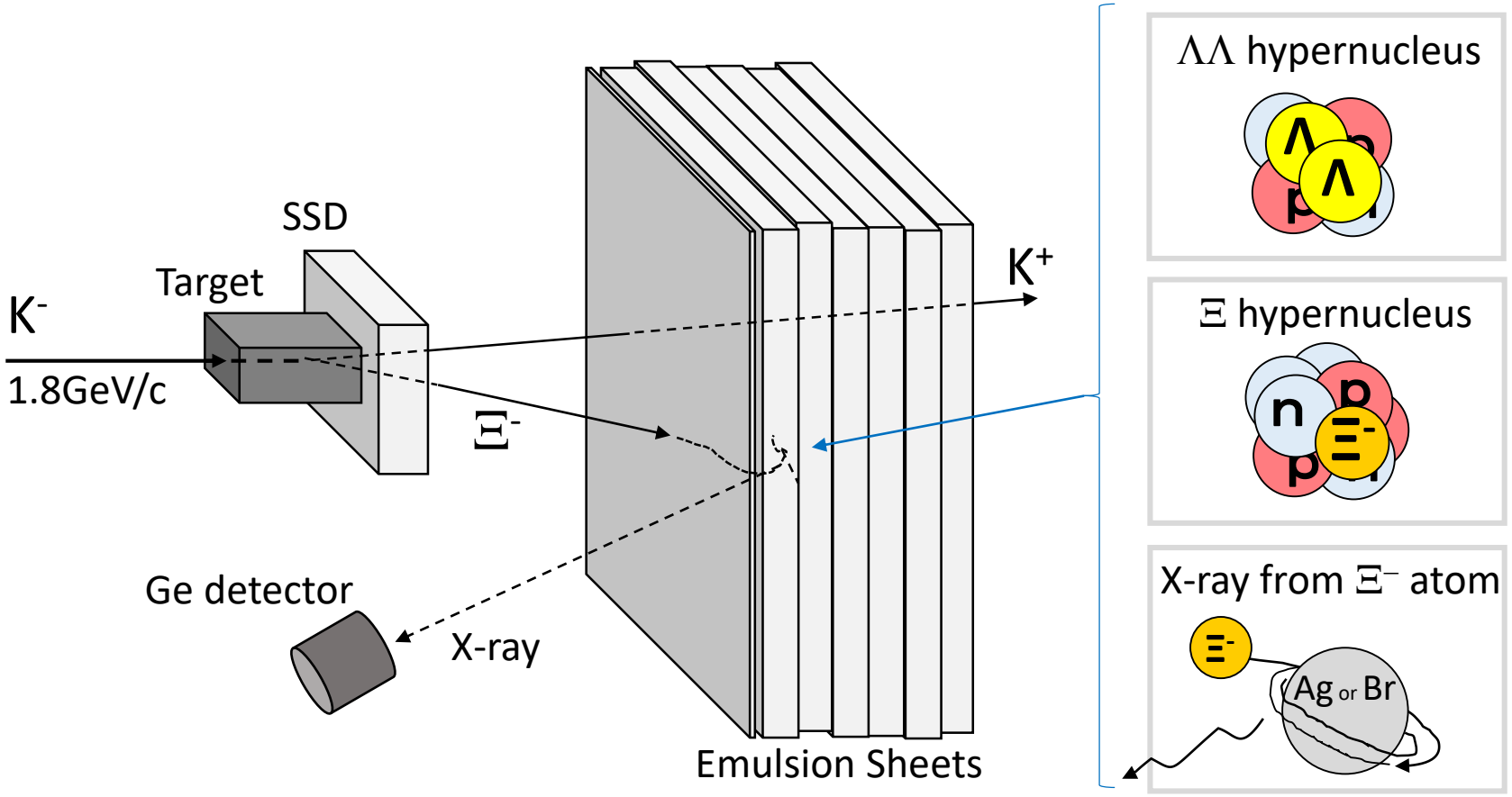
J-PARC E07

Systematic study of double strangeness system with hybrid emulsion method



Junya Yoshida (Advanced Science Research Center, JAEA)

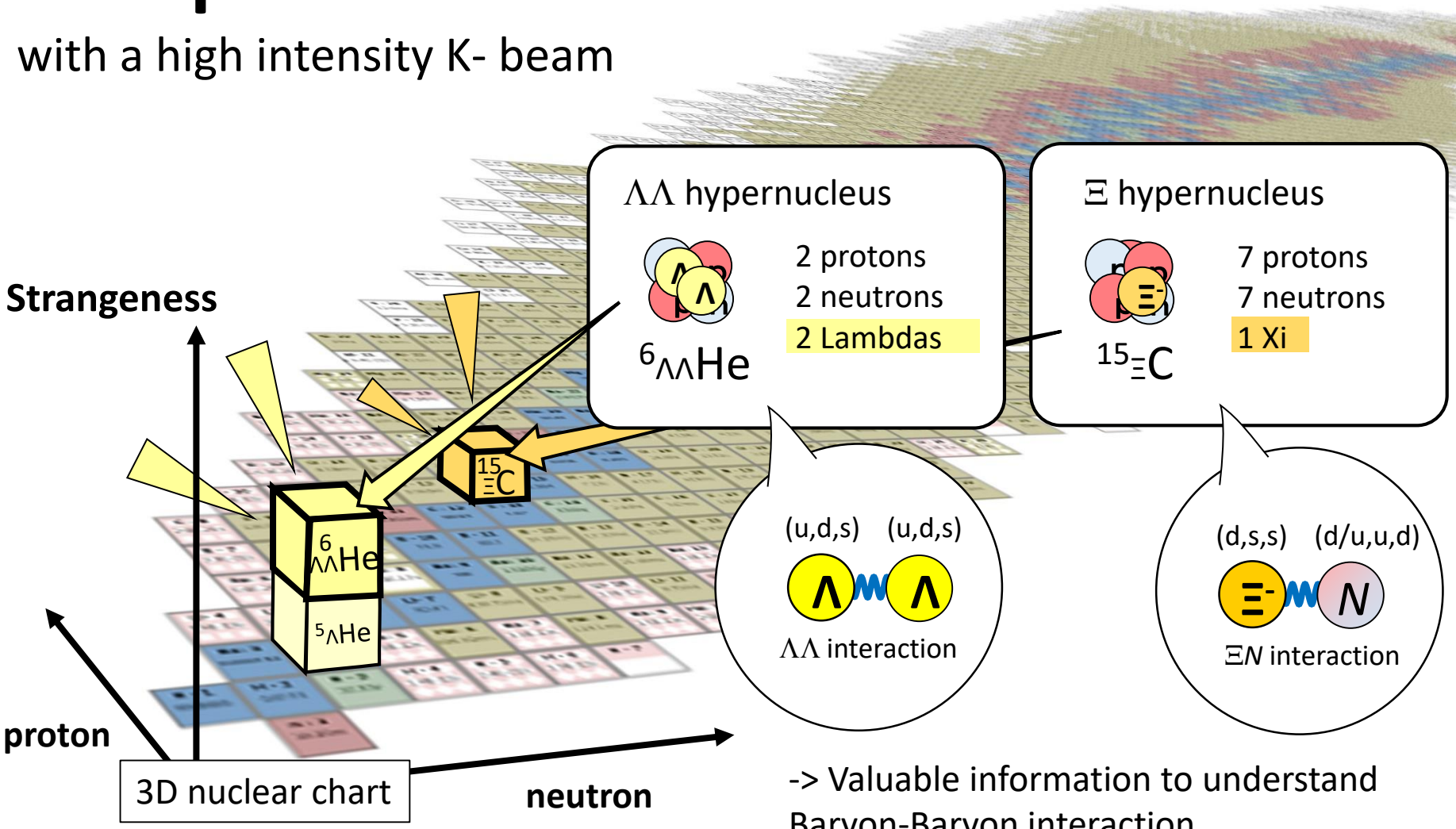
On behalf of J-PARC E07 Collaboration

10th Anniversary J-PARC Symposium 2019

One of the main roles of J-PARC Hadron facility is

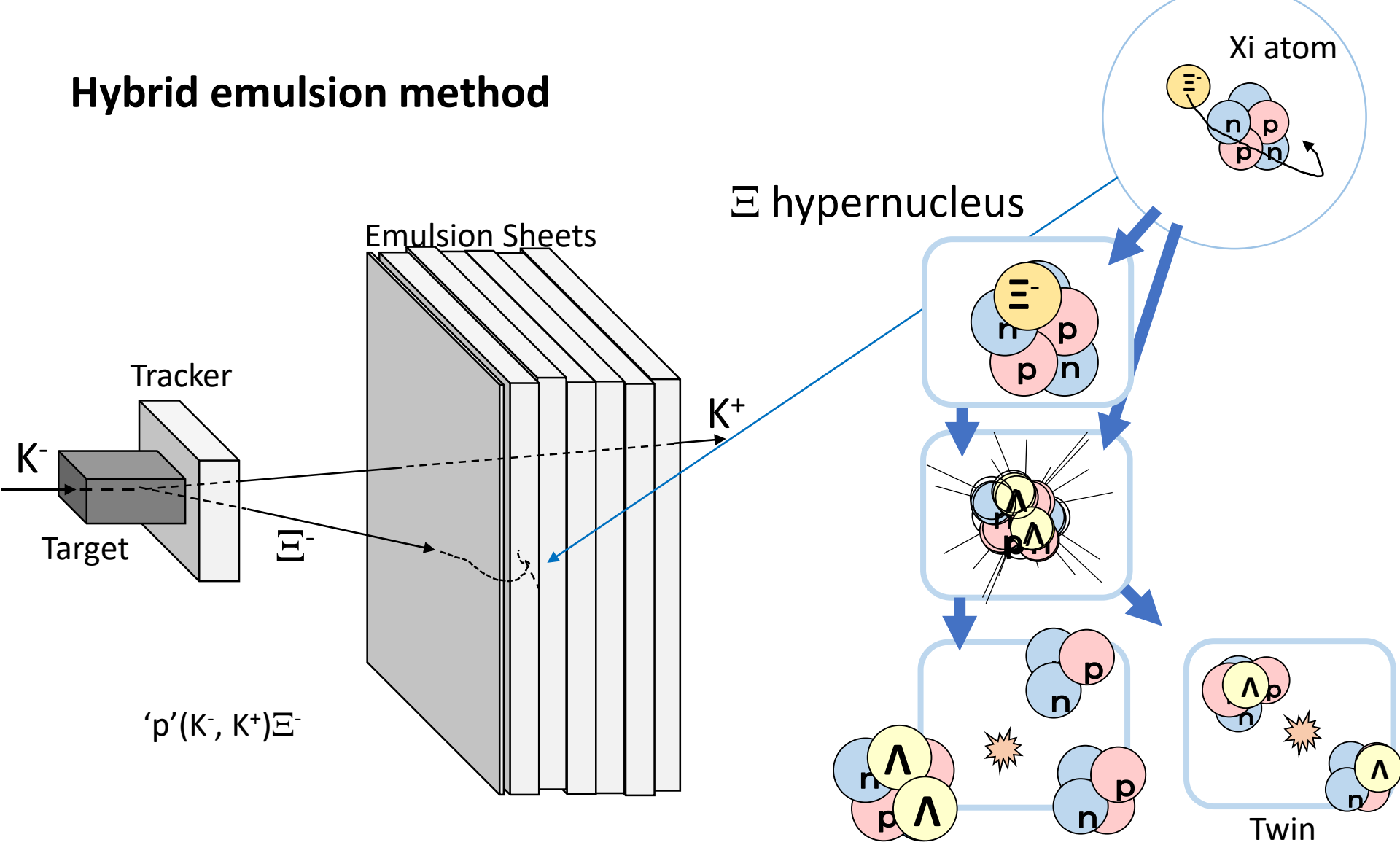
to explore the S=-2 world

with a high intensity K- beam



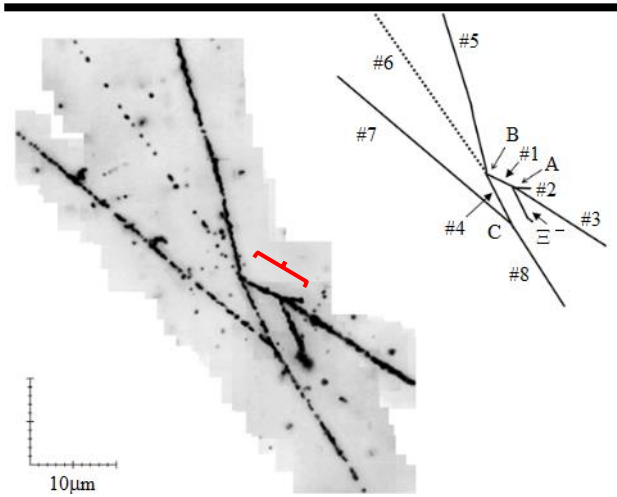
-> Valuable information to understand Baryon-Baryon interaction

Hybrid emulsion method



- Tagging Ξ^- production by K^+ spectrometer
- Tracking the Ξ^- with SSD-tracker
- Detecting the Ξ^- track in the 1st emulsion sheet
- Detecting double hypernucleus at the endpoint of Ξ^- track

NAGARA, ΛΛ hypernucleus (2001)

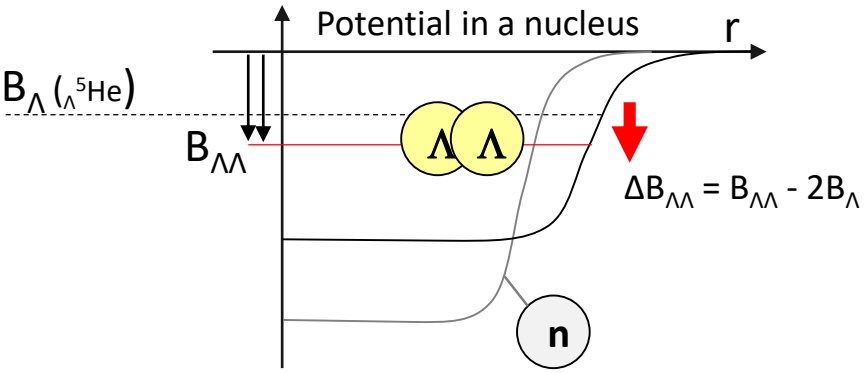


PHYSICAL REVIEW C 88, 014003 (2013)

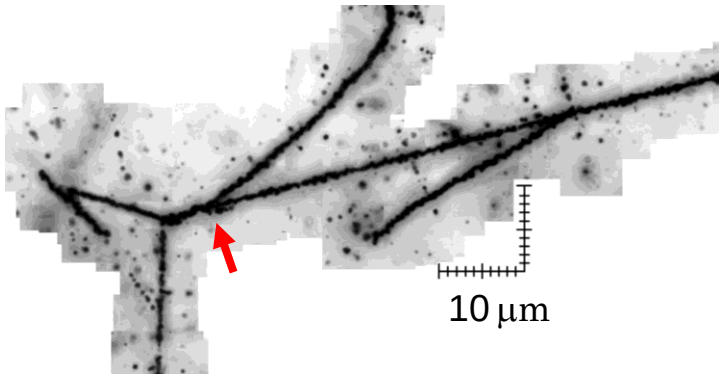
$\Xi^- + {}^{12}C \rightarrow {}^{6}_{\Lambda\Lambda}He + He + t$

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

$\Delta B_{\Lambda\Lambda} = 0.67 +- 0.17$ MeV



KISO, Ξ hypernucleus (2013)

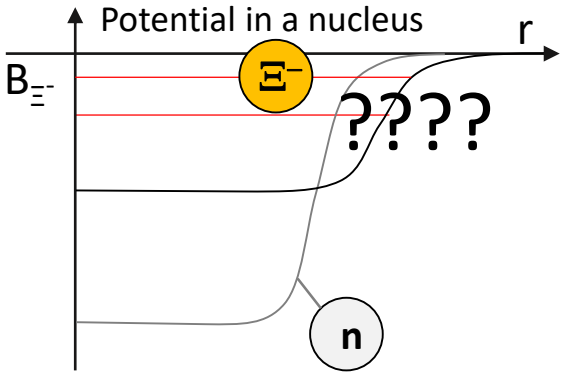


Prog. Theor. Exp. Phys. 2015, 033D02
Annu. Rev. Nucl. Part. Sci. 2018.68.131

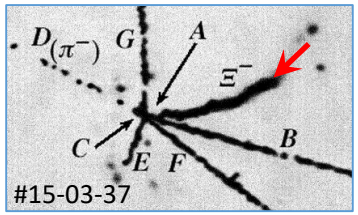
$\Xi^- + {}^{14}N \rightarrow {}^{15}_{\Xi}C \rightarrow {}^{10}_{\Lambda}Be + {}^{5}_{\Lambda}He$

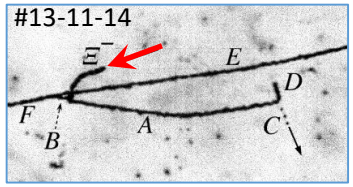
$(\rightarrow {}^{10}_{\Lambda}Be^* + {}^{5}_{\Lambda}He)$

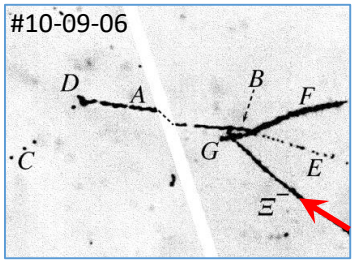
$B_{\Xi^-} = 1.03 +- 0.18$ or $3.87 +- 0.21$ MeV

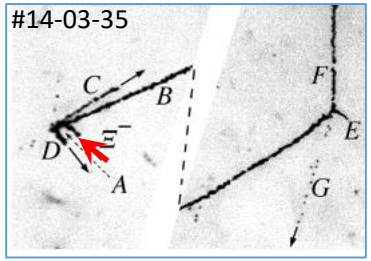


KEK-PS E176 (1988-89)







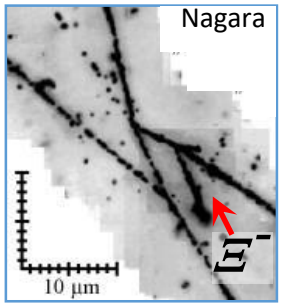


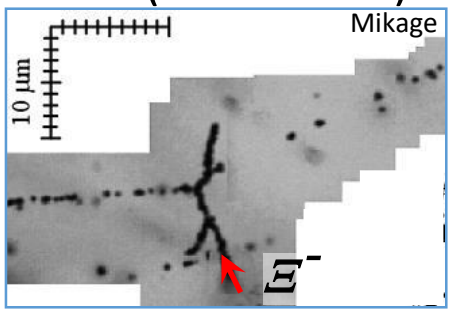
Nuclear Physics A 828 (2009) 191–232

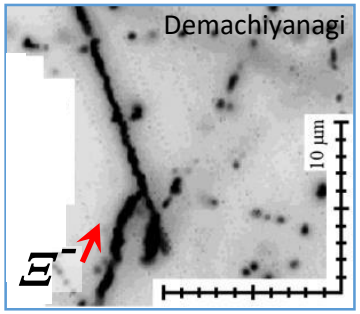
* ~80 Ξ^- stop events
* Existence of double Lambda hypernucleus has been confirmed

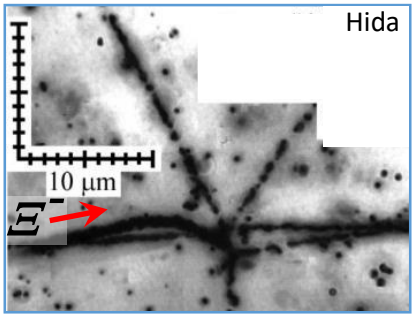
X10 statistics

KEK-PS E373 (1998-2000)









PHYSICAL REVIEW C 88, 014003 (2013)

* At least ~650 Ξ^- stop events
* NAGARA, KISO

X10 statistics

J-PARC E07 (2016-17)

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

	Emulsion gel	K^- purity	Beam intensity
KEK-PS E373	0.8 tons	25%	$1*10^4$/spill
↓	↓	↓	↓
J-PARC E07	2.1 tons	~85%	$3*10^5$/spill

J-PARC E07 Collaboration

Japan
Gifu University
JAEA
KEK
Kyoto University
Nagoya University
Osaka University
RIKEN
Tohoku University

Korea
Gyeongsang National University
Korea Research Institute of Standards and Science
Korea University
Seoul National University

China
Chinese Academy of Sciences
Institute of High Energy Physics China
Shanxi Normal University

Germany
Helmholtz Institute Mainz
Johannes Gutenberg-Universität

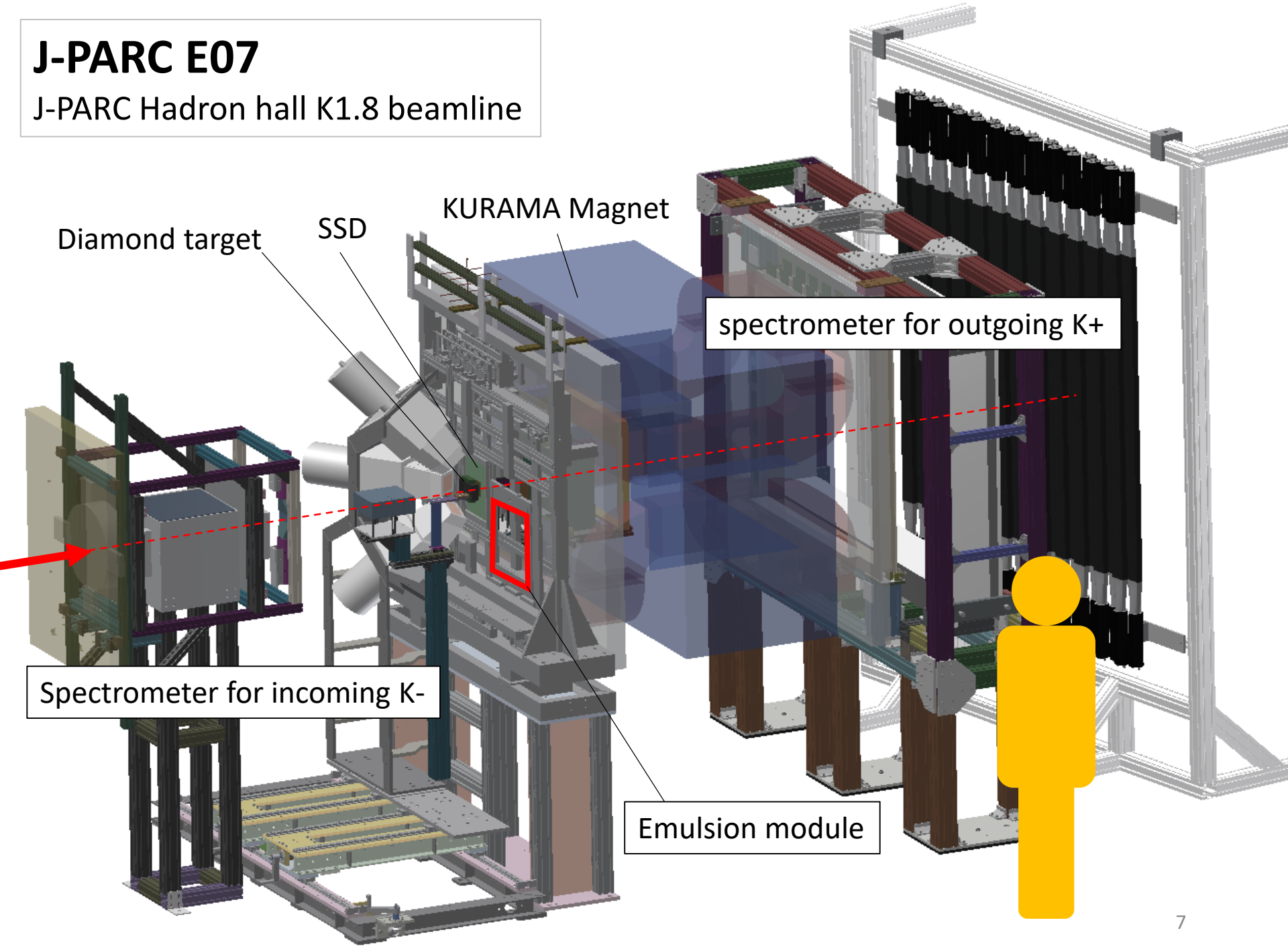
Myanmar
Lashio University
University of Yangon

USA
Ohio University
University of New Mexico

6 Countries
24 Institutes
~100 Members

J-PARC E07

J-PARC Hadron hall K1.8 beamline

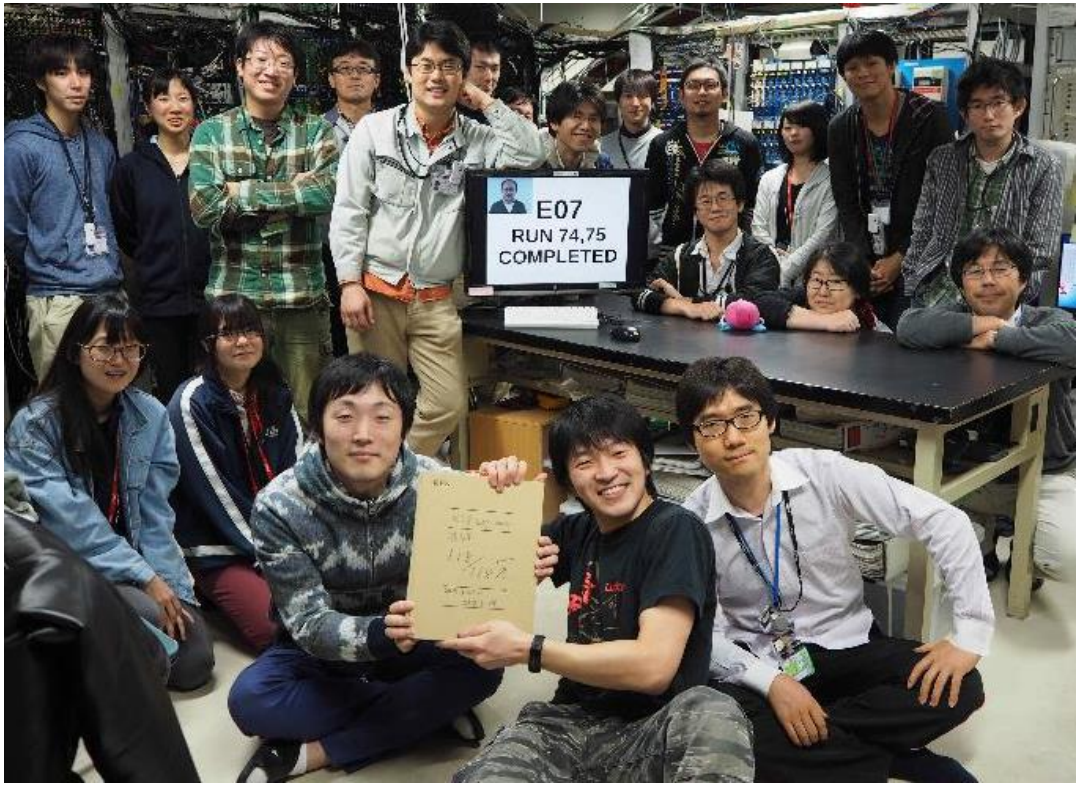


Beam exposure

2016 May-Jun.
KURAMA Commissioning : 5.0 days
Physics : 4.9 days

2017 4/15 - 4/19 (44 kW)
Emulsion exposure : 50 h
calibration : 19 h

2017 5/25 - 6/29 (10 - 37.5 kW)
Emulsion exposure : 23.4 days
calibration : 8.5 h



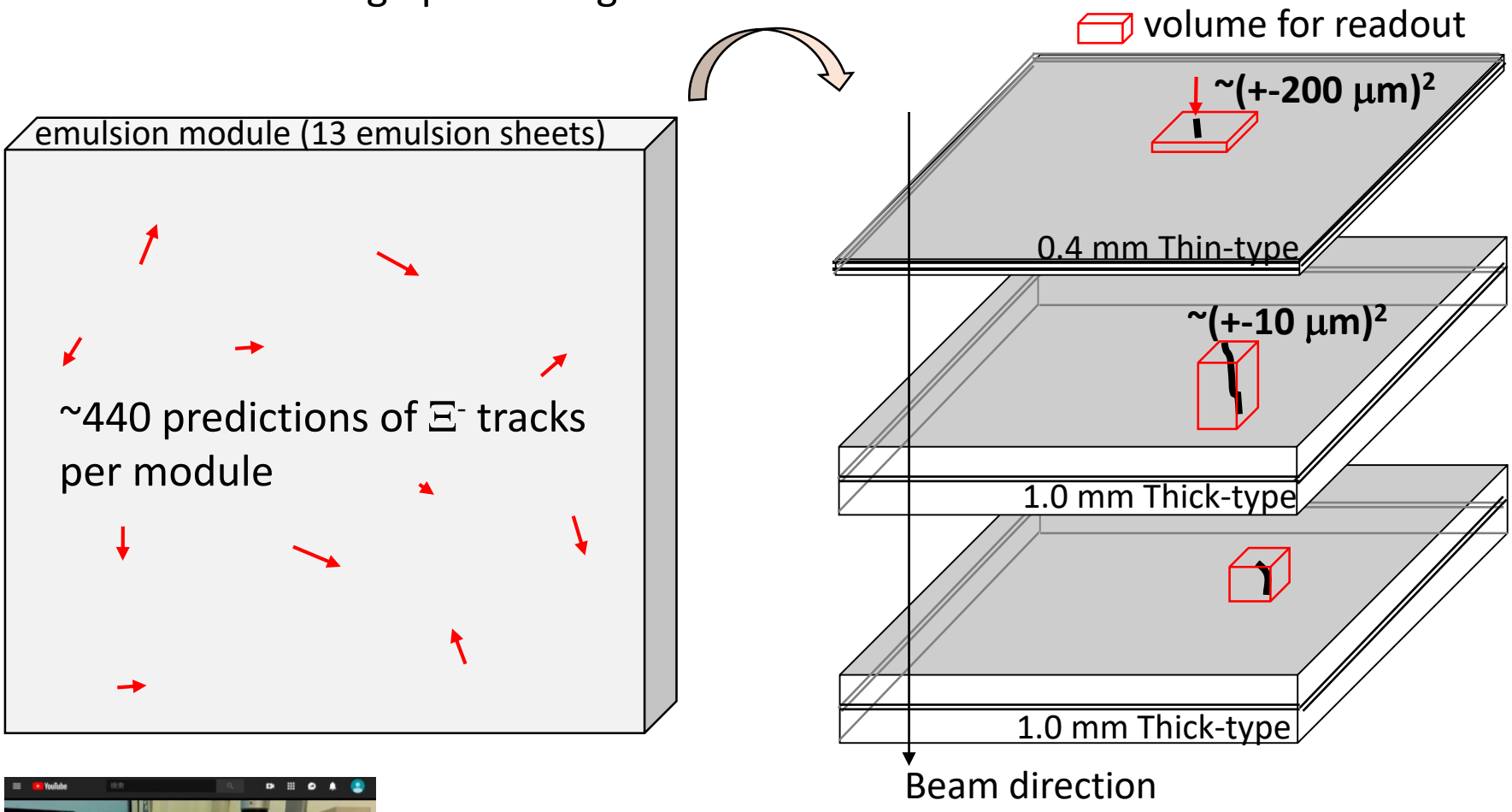
Jul. 1st 2017, Run end photo @K1.8 counting room

Year	Beam power [kW]	K^- intensity [/spill]	K^- purity	Time [h/mod.]	Integrated K^- [G/mod.]	DAQ Eff.	Emulsion modules
2016	42	260	81%	6.5	0.92	83%	18
2017	44	310	83%	5.6	1.0	84%	8
2017	37.5	280	82%	6.0	1.0	89%	78
2017	10 - 35	120 - 270	50% - 82%	6.5 – 9.0	0.52 – 1.0	89-92%	14

118 emulsion modules * 13 emulsion sheets

Track following for Ξ^- stop event
with dedicated image processing

* Disassembling
* Photographic developing

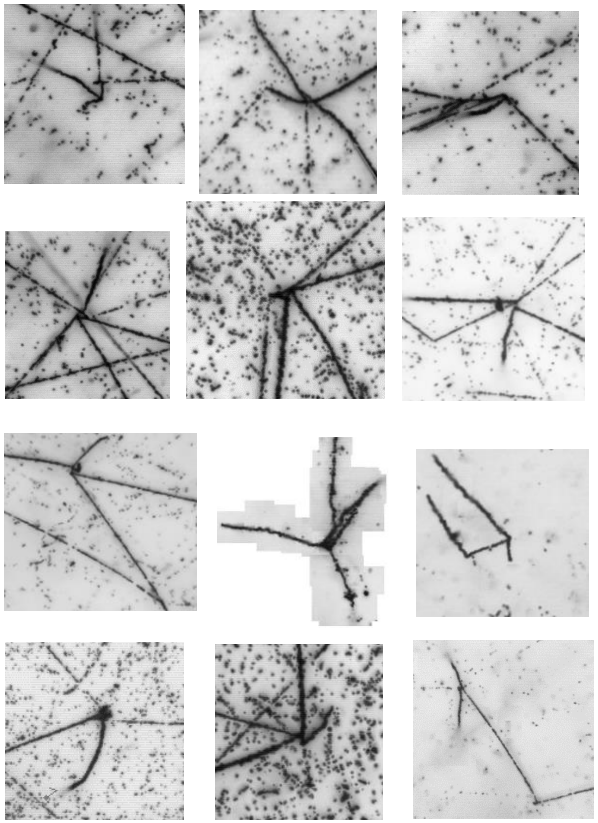


Automated Track Following (Sample Movie)
https://youtu.be/3fiWI5tDx2U

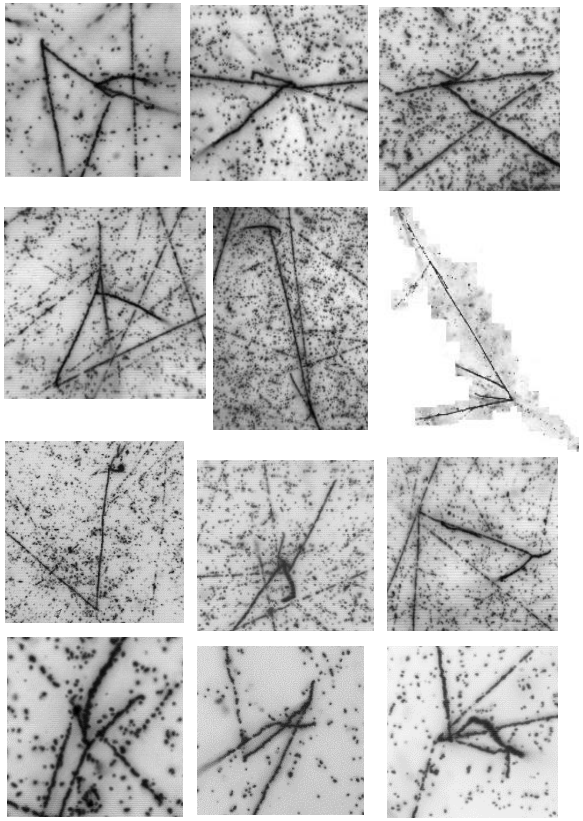
Found event list (2019 Aug.)

	KEK-PS E373	J-PARC E07
Event search	~7 years	18 months (2018 Apr. – 2019 Sep.)
S=-2 system	9	31

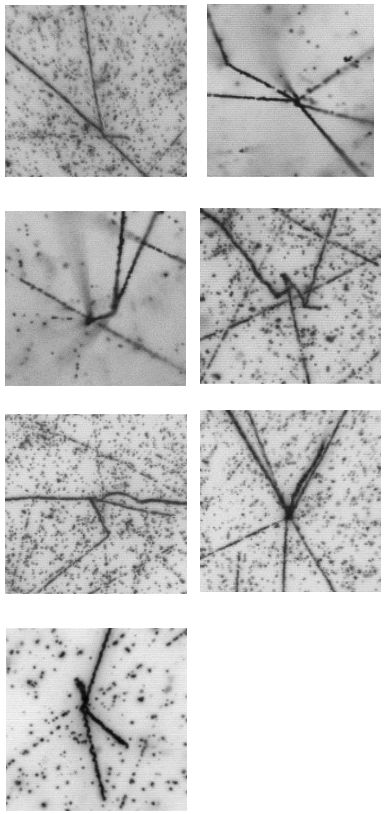
12 double Lambda events



12 twin events



7 others

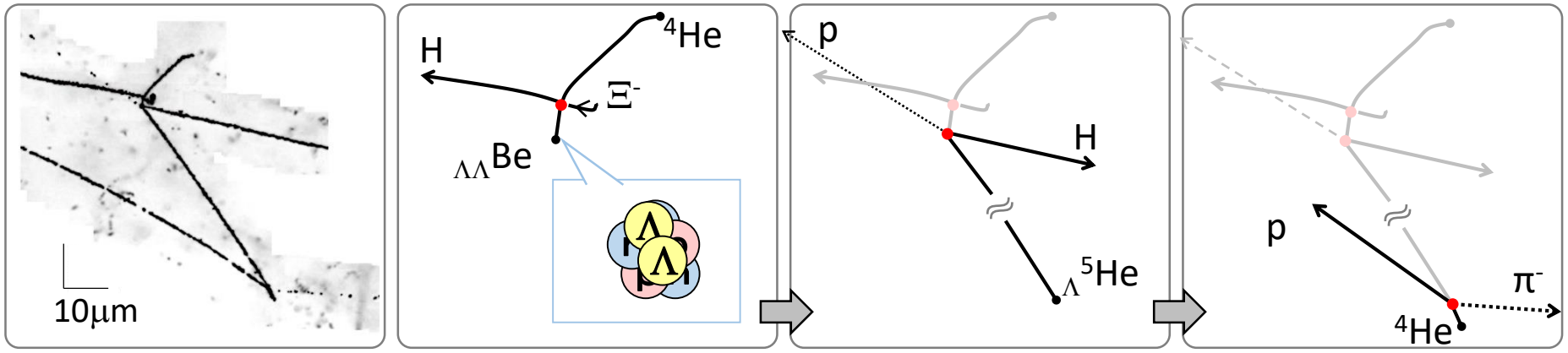


New events are being accumulated successfully and rapidly.

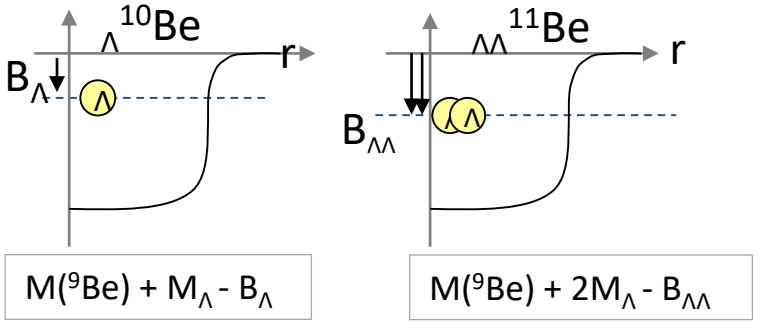
MINO event

Mod#069 pl07
ID : 22381499289376

H. Ekawa et al.,
Prog. Theor. Exp. Phys. 2019, 021D02



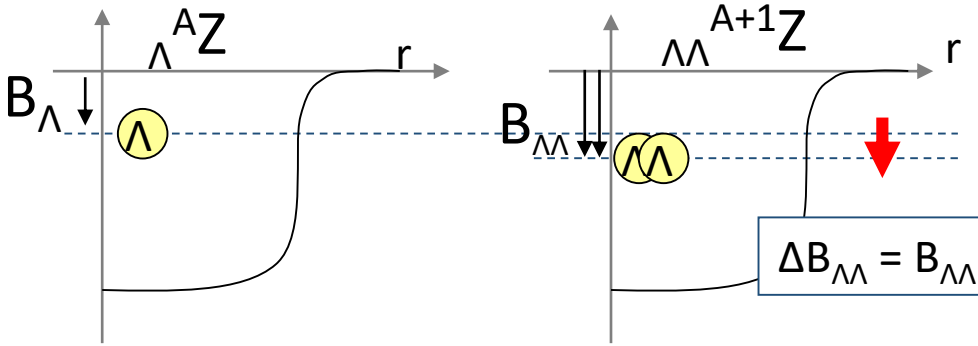
$$^{16}\mathrm{O} + \Xi^- \rightarrow (^{10}_{\Lambda\Lambda}\mathrm{Be},\ ^{11}_{\Lambda\Lambda}\mathrm{Be},\ ^{12}_{\Lambda\Lambda}\mathrm{Be}) + {}^4\mathrm{He} + (t,\ d,\ p),$$
$$\hookrightarrow {}^{5}_{\Lambda}\mathrm{He} + (p, d, t) + p + xn,$$
$$\hookrightarrow {}^4\mathrm{He} + p + \pi^-.$$



Possible interpretations	$B_{\Lambda\Lambda}$ [MeV]	kinematic fitting χ^2 (DOF=3)
Ξ^- + ^{16}O -> $_{\Lambda\Lambda}^{10}$Be + ^{4}He + t	15.05 +- 0.11	11.5
⇨ Ξ^- + ^{16}O -> $_{\Lambda\Lambda}^{11}$Be + ^{4}He + d	19.07 +- 0.11	7.3
Ξ^- + ^{16}O -> $_{\Lambda\Lambda}^{12}$Be* + ^{4}He + p	13.68 +- 0.11 + E_{ex}	11.3

- $_{\Lambda\Lambda}^{11}$Be is the most probable in term of kinematic analysis.

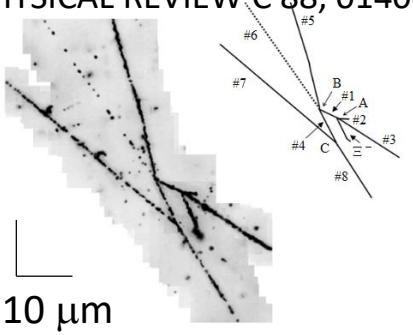
On ΛΛ interaction



$\Delta B_{\Lambda\Lambda}$, An index of ΛΛ interaction

NAGARA Event (2001)

PHYSICAL REVIEW C 88, 014003 (2013)

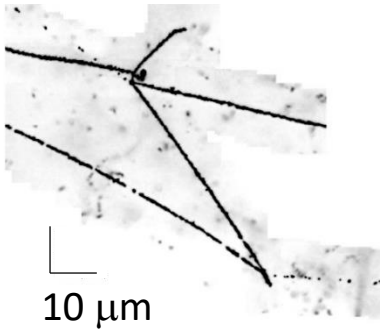


	$\Delta B_{\Lambda\Lambda}$ [MeV]
$_{\Lambda\Lambda}{}^{6}$He	0.67 +- 0.17

where, B_{Ξ^-} = 0.13 MeV

MINO Event (2019)

Prog. Theor. Exp. Phys. 2019, 021D02



	$\Delta B_{\Lambda\Lambda}$ [MeV]
$_{\Lambda\Lambda}{}^{11}$Be	1.87 +- 0.37

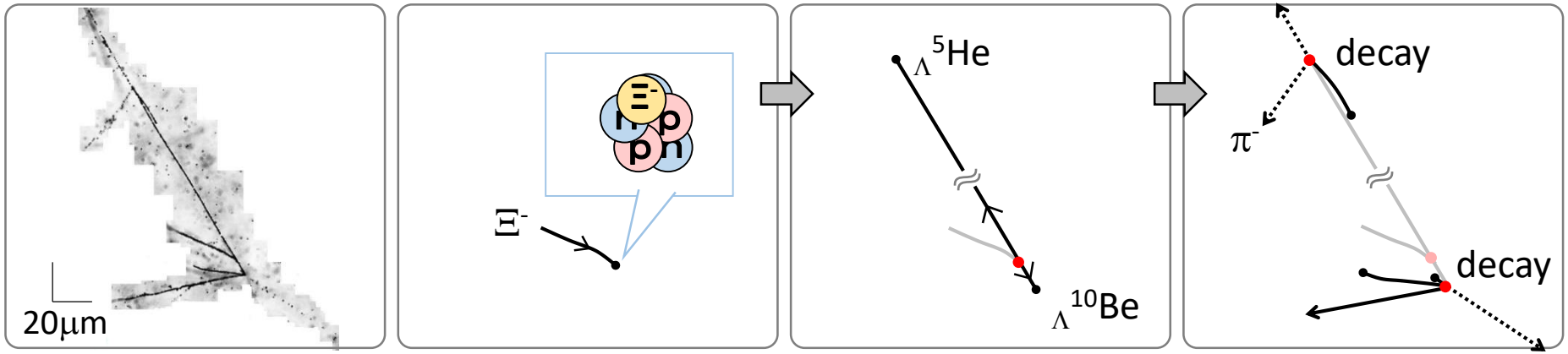
where, B_{Ξ^-} = 0.23 MeV

- ΛΛ interaction is weak attractive force.
- New information on ΛΛ interaction in nuclide.

IBUKI event

Mod#047 pl10
ID : 20864938633496

S. H. Hayakawa, Ph.D. Thesis, Osaka Univ. (2019)



$\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C$

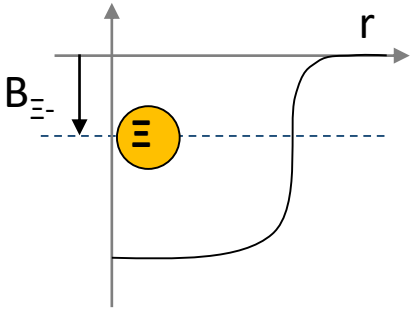
${}_{\Xi}{}^{15}C \rightarrow {}_{\Lambda}{}^{10}Be + {}_{\Lambda}{}^{5}He$

Only ${}_{\Lambda}{}^{10}Be$ is acceptable

${}_{\Lambda}{}^{5}He$ -> 3-prong with π^-

${}_{\Lambda}{}^{10}Be$ -> 4-prong

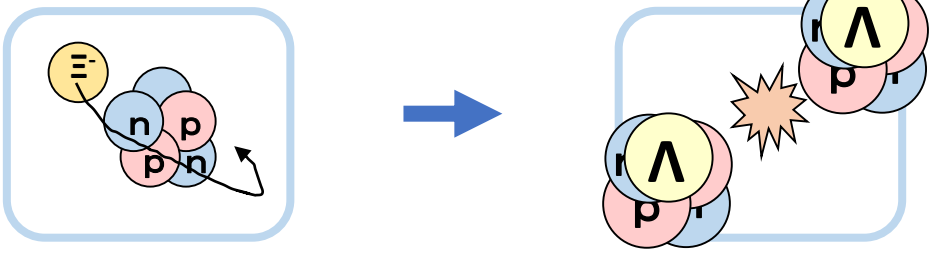
- This event is the 2nd candidate of Ξ hypernucleus.
- The mass and B_{Ξ^-} are determined precisely.
- See also poster-PN-27 by Shuhei Hayakawa.



Possible interpretation	B_{Ξ^-} [MeV]	uncertainty of B_{Ξ^-} [MeV]
$\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C \rightarrow {}_{\Lambda}{}^{10}Be + {}_{\Lambda}{}^{5}He$	1.27	0.21

Furthermore, other Ξ hypernucleus candidates have been detected.

Nuclides of found twin single Λ events



		Ξ⁻ Captured by…			Daughter					
		^{12}C	^{14}N	^{16}O	H	He	Li	Be	B	C
Atomic state	E176#10-9-6	●			1			1		
	E176#13-11-14	●			1			1		
	T008, atomic	●			1	2				
	T009, atomic	●				1	1			
	T004, atomic			●		1			1	
	E373 Ichikawa's		●			3				
	T002		●			1		1		
Ξ hypernuclei	**E373 KISO**		●			1		1		
	T006, IBUKI		●			1		1		
	T007		●			1		1		
	E373 KINKA		●			1		1		
	T003		●			1		1		
	T010		●			3				
	E176#14-03-35		○	○						
	T001									
	T005									

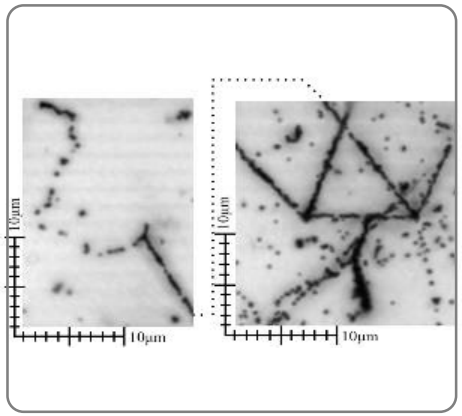
preliminary

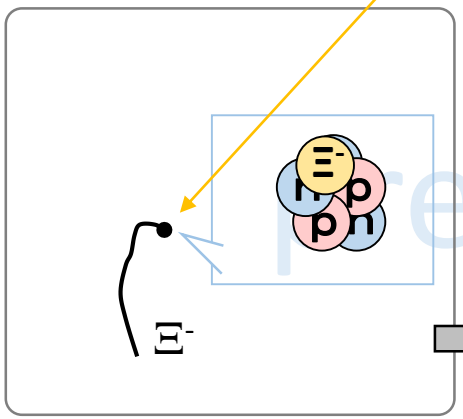
●: Uniquely identified,
○: Multiple interpretations

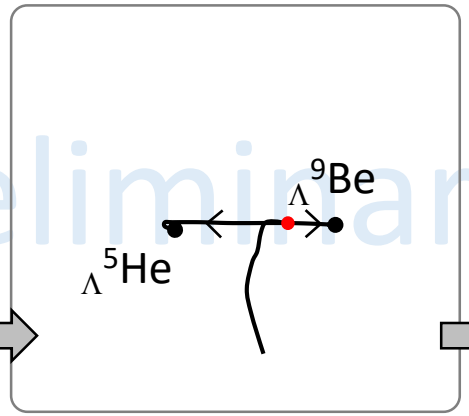
Several events are identified as ($\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C \rightarrow {}_{\Lambda}Be + {}_{\Lambda}He$)
although ^{14}N is the most dominant element in the emulsion layer.

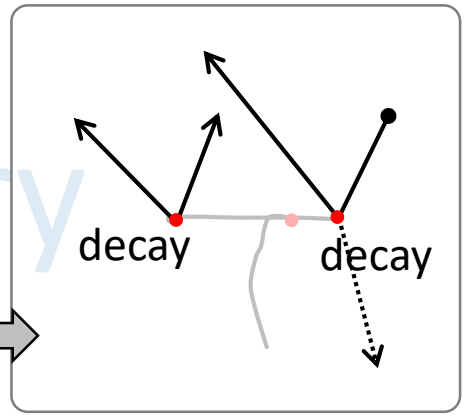
E373 KINKA

B_{Ξ^-} ~= 5 MeV ($_{\Lambda}{}^{9}$Be*) or 8 MeV ($_{\Lambda}{}^{9}$Be)









$\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C$

${}_{\Xi}{}^{15}C \rightarrow {}_{\Lambda}{}^{9}Be + {}_{\Lambda}{}^{5}He + n$

$_{\Lambda}{}^{9}$Be or $_{\Lambda}{}^{9}$Be*

$_{\Lambda}{}^{9}$Be -> 2-prong

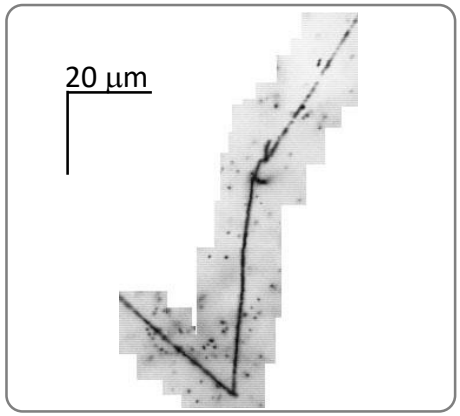
$_{\Lambda}{}^{5}$He -> 2-prong

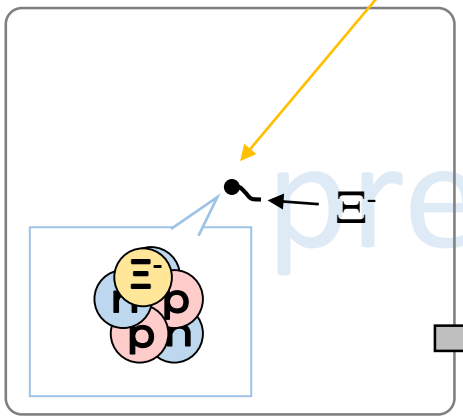
preliminary

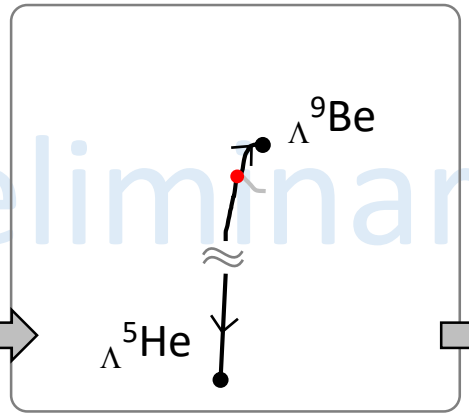
Twin #007

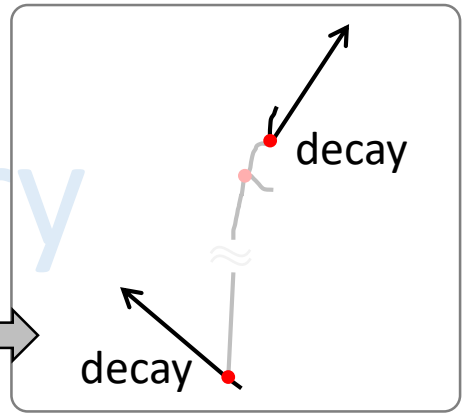
Mod#043 pl04
ID : 205891673629

B_{Ξ^-} ~= 1.6 MeV









$\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C$

${}_{\Xi}{}^{15}C \rightarrow {}_{\Lambda}{}^{9}Be + {}_{\Lambda}{}^{5}He + n$

Only $_{\Lambda}{}^{9}$Be is acceptable

$_{\Lambda}{}^{9}$Be -> 2-prong

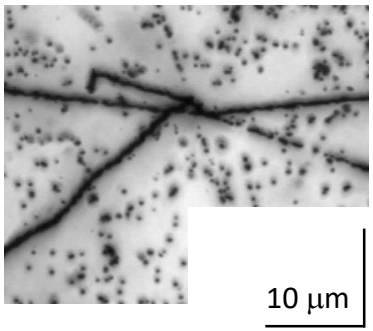
$_{\Lambda}{}^{5}$He -> 2-prong

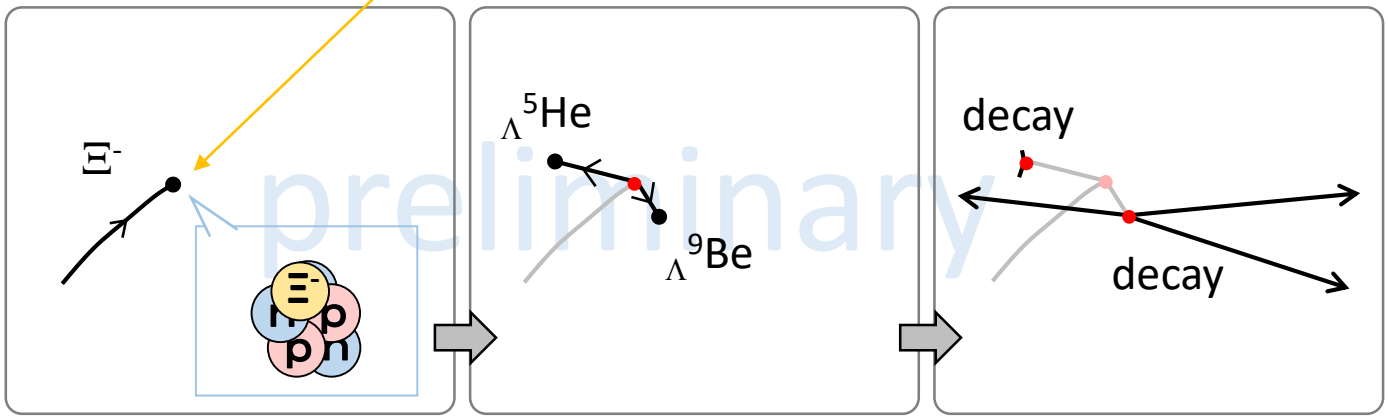
preliminary

Twin #003

Mod#075 pl07
ID : 22794968788904

B_{Ξ^-} ~= 5 MeV ($_{\Lambda}{}^{9}$Be*) or 8 MeV ($_{\Lambda}{}^{9}$Be)





preliminary

$\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C$

${}_{\Xi}{}^{15}C \rightarrow {}_{\Lambda}{}^{9}Be + {}_{\Lambda}{}^{5}He + n$

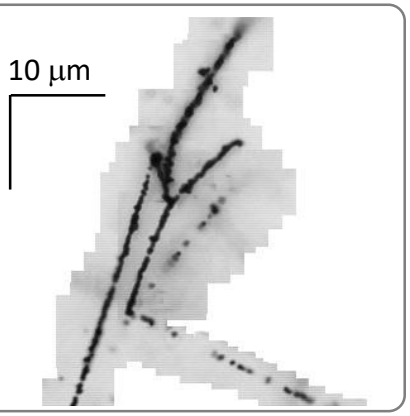
$_{\Lambda}{}^{9}$Be or $_{\Lambda}{}^{9}$Be*

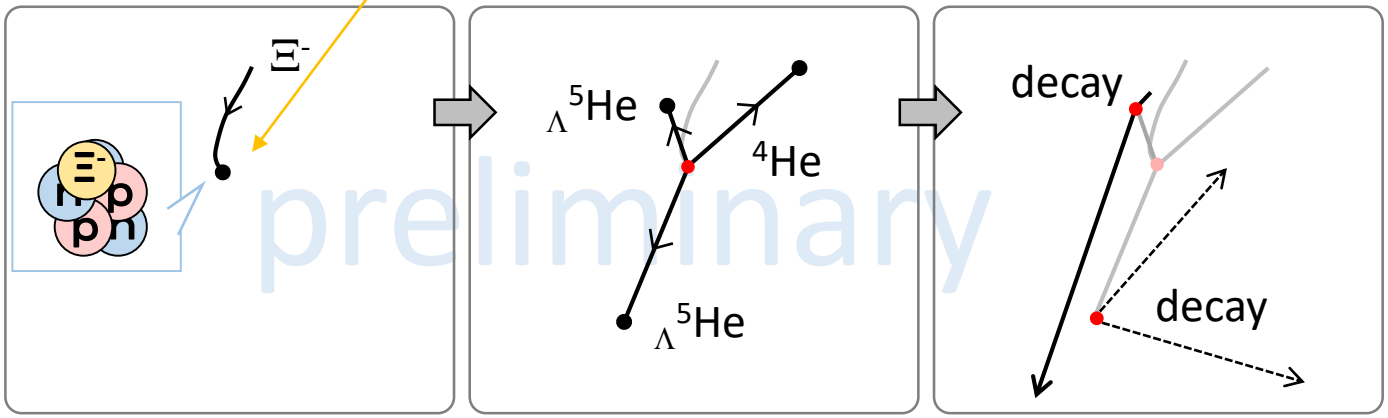
$_{\Lambda}{}^{9}$Be -> 3-prong
$_{\Lambda}{}^{5}$He -> 2-prong

Twin #010

Mod#019 pl05
ID : 18933242806664

B_{Ξ^-} ~= 6 MeV





preliminary

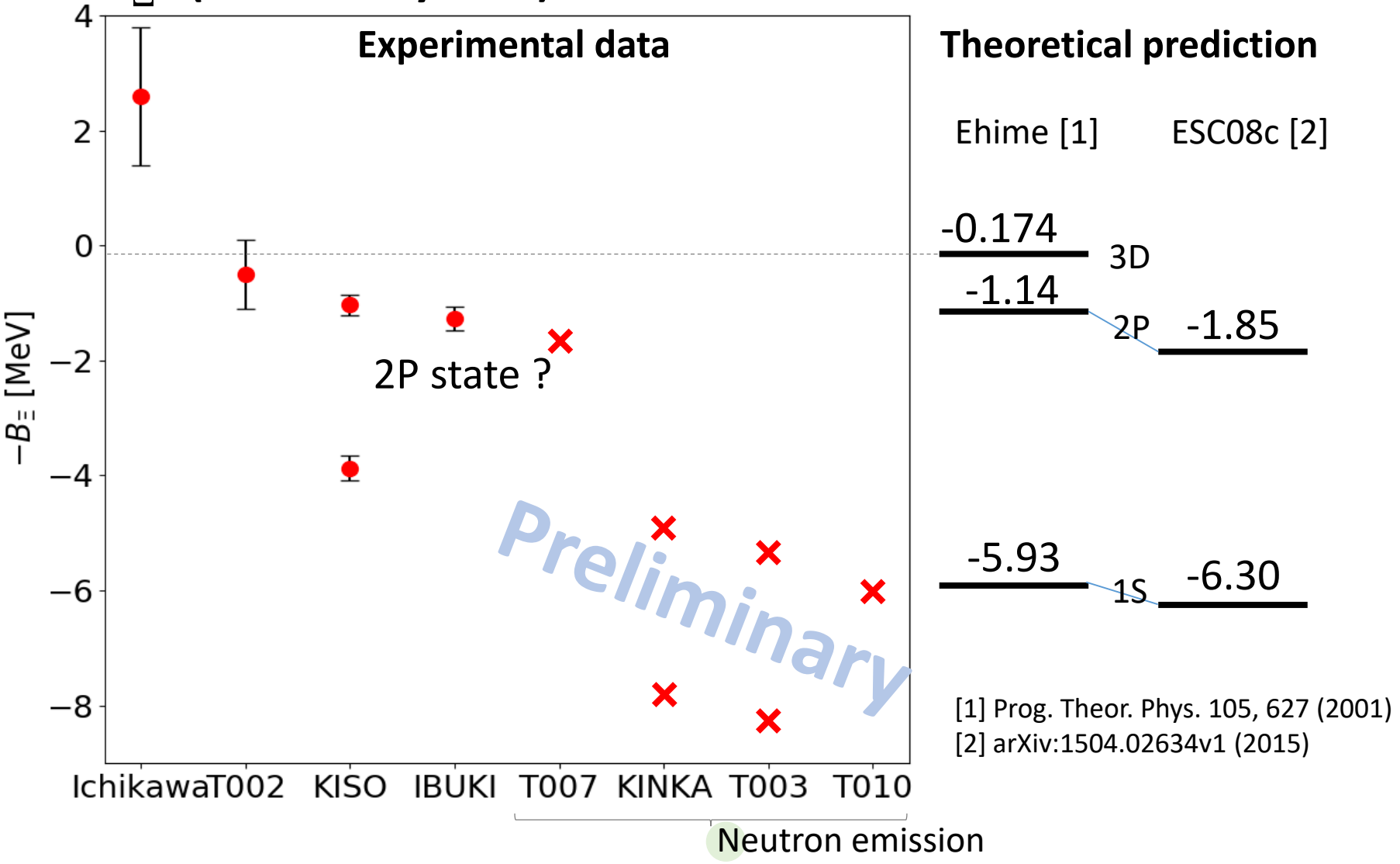
$\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C$

${}_{\Xi}{}^{15}C \rightarrow {}_{\Lambda}{}^{5}He + {}_{\Lambda}{}^{5}He + {}^{4}He + n$

No excited state

$_{\Lambda}{}^{5}$He -> 2-prong
$_{\Lambda}{}^{5}$He -> 2-prong

B_{Ξ^-} (^{14}N + Ξ^- System)



[1] Prog. Theor. Phys. 105, 627 (2001)
[2] arXiv:1504.02634v1 (2015)

- **Multiple candidates of Ξ hypernucleus has been detected.**
- The errors for neutron emission case are under validation.
- These events suggest multiple bound states of Ξ^- in the Ξ^- + ^{14}N system.

summary

J-PARC E07 makes a breakthrough in the study of S=-2 system.

New nuclide events and $B_{\Lambda\Lambda}$ and B_{Ξ^-} are being accumulated by event-by-event analysis.

"MINO event" ($_{\Lambda\Lambda}$Be): Prog. Theor. Exp. Phys. 2019, 021D02.
"IBUKI event" ($_{\Xi}{}^{15}$C): Under preparation for publication

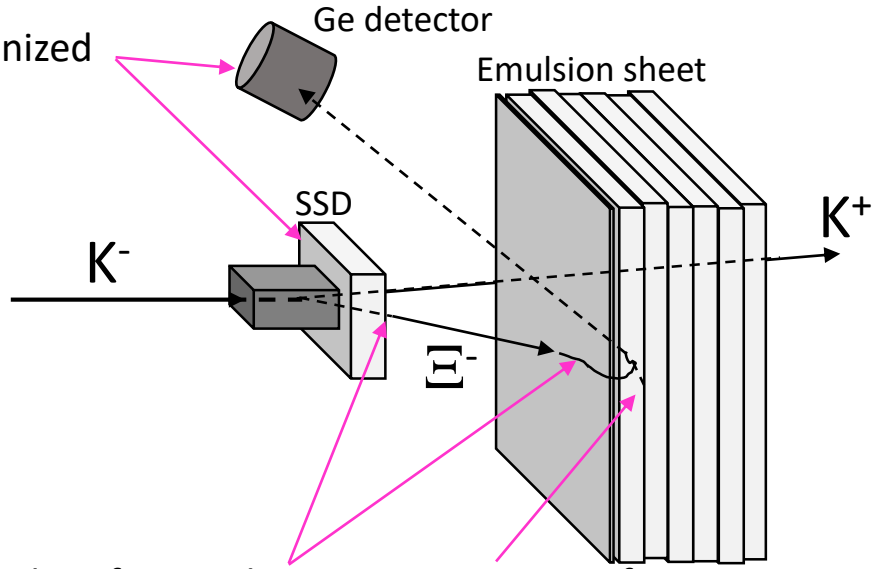
Multiple candidates of Ξ hypernucleus have been detected.
The Identification efficiency of "twin" events and the fraction of $\Xi^- + {}^{14}N \rightarrow {}_{\Xi}{}^{15}C$ are high.
The events suggest multiple bound states (2P and 1S state?) of Ξ- in the Ξ^- - ^{14}N.

Event hunting is ongoing.
We will detect additional several tens events within a year.

"X-ray measurement from Ξ^- atoms" is ongoing.

X-ray measurement from Ξ⁻ atom

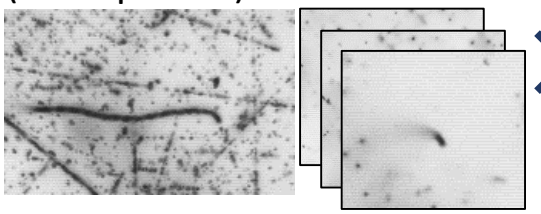
with Hybrid method combined Ge detector and emulsion



Ξ⁻ track identification by angle and position consistency

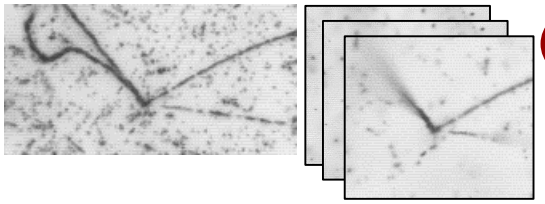
Stop confirmation in emulsion sheets

Stop without nuclear fragment (Ξ- or proton)

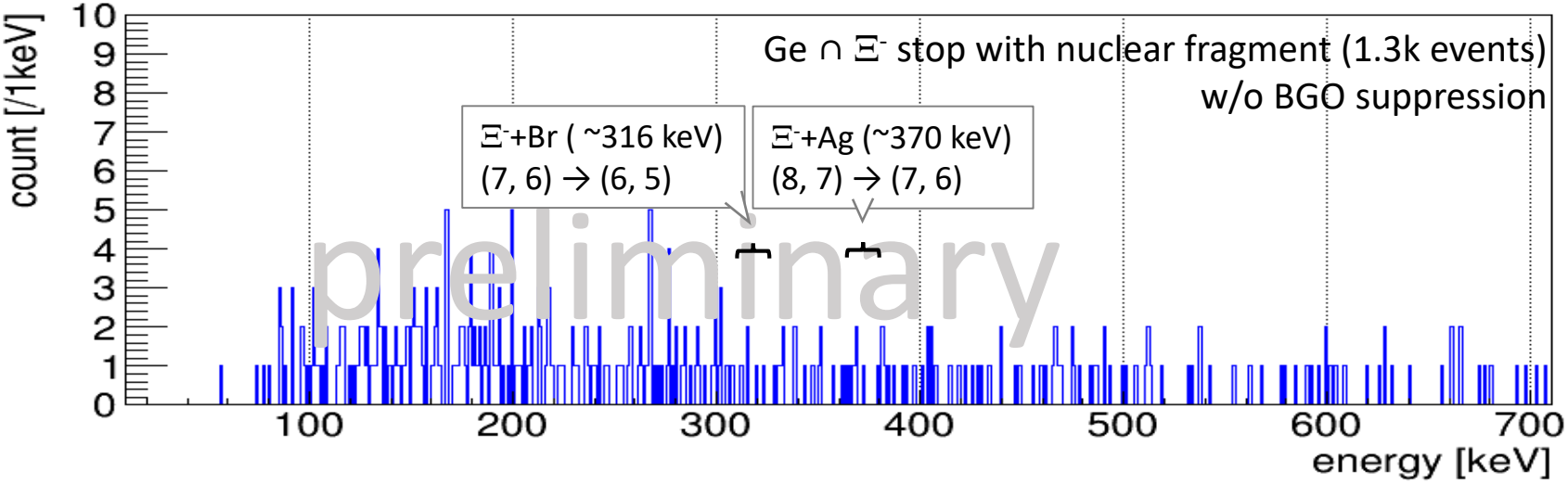


Not used

Stop with nuclear fragment (almost Ξ-)

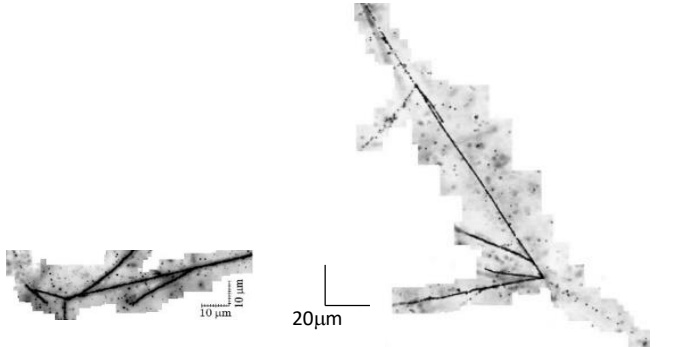


Used



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

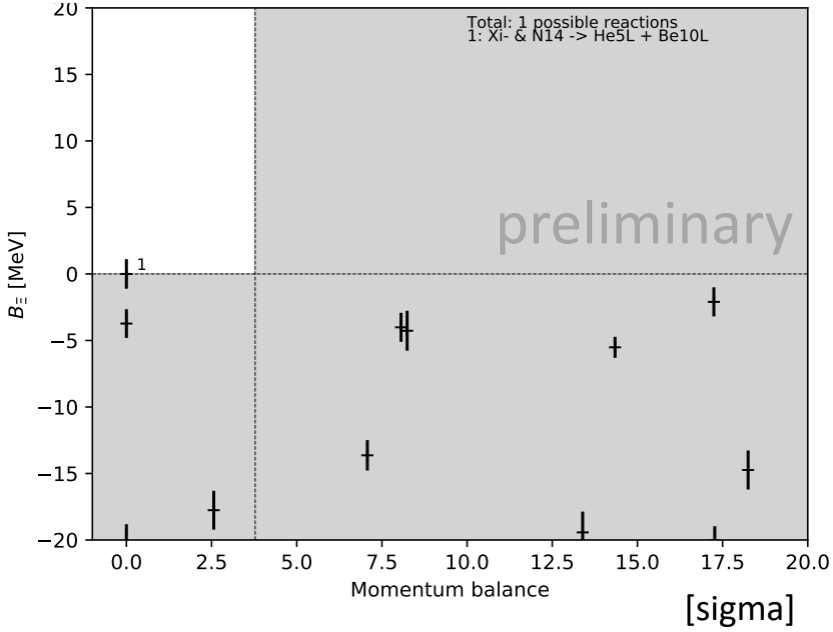
The Q-value of this decay mode is the highest among any channel producing "Twin single Λ hypernucleus".

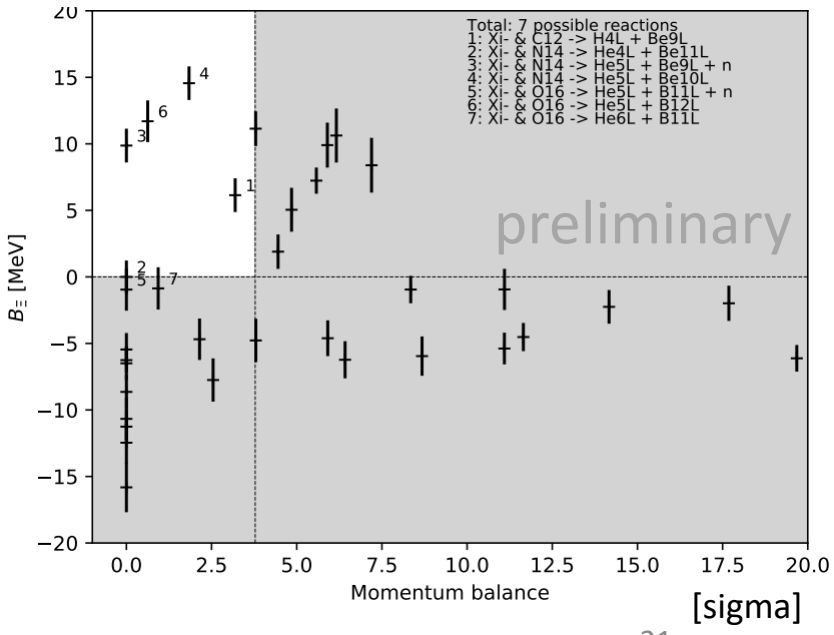


KEK-PS E373 KISO **J-PARC E07 IBUKI**

Q-value: 22.1 MeV

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



Q-value: 7.3 MeV

$\Xi^- + {}^{14}N \rightarrow {}_{\Lambda}{}^{11}Be + {}_{\Lambda}{}^{4}He$