Recent results on double-Lambda and Xi hypernuclei

Junya Yoshida, Tohoku-U, RIKEN

J-PARC E07 collaboration and High Energy Nuclear Physics Lab at RIKEN

5th Symposium on Clustering as a window on the hierarchical structure of quantum systems

Double hypernuclei: information source of baryon-baryon interaction with u,d,s quarks



Baryon-baryon interaction

- · Generalization of nuclear force
- Neutron star
- Via study of hypernuclei



KEK-PS E176 (1988-89)







* ~80 Ξ^{-} stop events

Nuclear Physics A 828 (2009) 191-232

* Existence of double Lambda hypernucleus has been confirmed



KEK-PS E373 (1998-2000)







PHYSICAL REVIEW C 88, 014003 (2013)

* At least ~650 Ξ⁻ stop events * NAGARA, KISO



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*10⁵/spill

Principle of the experiment using nuclear emulsion







1. The capture point of Ξ^-

- 2. The weak decay point of the 1st Λ
- 3. The weak decay point of the 2nd Λ

The number of detected events has nearly tripled in the past.



MINO event

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



$${}^{16}\text{O} + \Xi^{-} \rightarrow ({}^{10}_{\Lambda\Lambda}\text{Be}, {}^{11}_{\Lambda\Lambda}\text{Be}, {}^{12}_{\Lambda\Lambda}\text{Be}) + {}^{4}\text{He} + (t, d, p),$$

$$\hookrightarrow {}^{5}_{\Lambda}\text{He} + (p, d, t) + p + xn,$$

$$\hookrightarrow {}^{4}\text{He} + p + \pi^{-}.$$

$$M({}^{9}\text{Be}) + M_{\Lambda} {}^{-}B_{\Lambda}$$

$$M({}^{9}\text{Be}) + 2M_{\Lambda} {}^{-}B_{\Lambda\Lambda}$$

	Possible interpretations	B _{^^} [MeV]	Kinematic fitting χ^2 (DOF=3)
	Ξ^{-} + ¹⁶ O -> $_{\Lambda\Lambda}^{10}$ Be + ⁴ He + t	15.05 +- 0.11	11.5
\Rightarrow	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.

IBUKI event

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



- The 1^{st} candidate of Ξ hypernucleus in E07.
- The mass and B₋₋ are measured precisely.



Possible interpretation	B _{Ξ-} [MeV]	Uncertainty of B ₌₋ [MeV]
$\Xi^{-} + {}^{14}N \rightarrow {}^{15}C \rightarrow {}^{10}Be + {}^{5}He$	1.27	0.21

- Decay without neutron -> Kinematic fit (Avery P., CLEO Note CBX, 91–72, 1991.)
- Dominant uncertainty is from the mass of Λ^{10} Be (0.13MeV)



Precise track measurement in depth direction using image processing

Z-axis





$B_{\Xi-}$ Uncertainty

Dominant one is from spatial resolution of AgBr crystal in emulsion.



Level scheme of $\Xi^{-14}N$ system



List of twin Λ hypernuclear events

		Ξ^- captured by			daughter hypernuclei						
		¹² C	¹⁴ N	¹⁶ O	н	Не	Li	Ве	В	С	n
omic state	E176 #10-9-6 (2 <i>p</i> ?)				⁴ H			⁹ Be			
	E176 #13-11-14 (2 <i>p</i> ?)				⁴ H			⁹ Be			
	T008, atomic				t	2⁵He					
	T009, atomic					⁵He	⁸ Li				
	T004, atomic					⁵He			¹² B		
Ato	E373 - 1					2⁵He,α					1
	E176 #14-03-35(2 <i>p</i> ?)		\bigcirc	\bigcirc							
	T002 (2 <i>p</i> ?)					⁵He		⁹ Be			1
	T013 (2 <i>p</i> ?)	0	0		(<i>t</i>)	2⁵He, (α)					(1)
E hypernuclei	E373 : KISO				•	⁵ Ηε		¹⁰ Be			
	T006 : IBUKI					5, le		¹⁰ Be			
	T003	?		?		⁵He		⁹ Be			1
	E373 : KINKA	nľ				⁵He		⁹ Be			1
	Т007	Y				⁵He		⁹ Be			1
	T010 : IRRAWADDY		\bullet			2 ⁵ He, α					1
	T011 (under analysis)					2 ⁵ He, α					1
			Excess	?		alpha c	luste	r struc [.]	ture?		

: Uniquely identified

 \bigcirc : Multiple interpretations

Untriggerable reactions



Trigger efficiency is approximately 0.3

Double cross section to (K⁻,K⁺)

Expected event number: 1 / sheet. Totally 10^3 events in emulsion sheet of J-PARC E07



Scanning

Vertex detection using image processing

Image and line information

Under x20 objective





Under x20 objective













Roadmap

Detection of Double hypernuclear events using machine learning

* Enough training data are necessary but double hypernucler events are rare.

Training using double hypernuclear events generated by simulation

* Statistical performance evaluation is not possible.

Training and validation using alpha decay events generated by simulation

alpha decay events



~10 events / 1cm*1cm*0.5mm

* As a first step,

Training and validation using real alpha decay

* Implementing machine learning* Comparison with existing method

J. Yoshida, et al., arXiv:2009.05770 [nucl-ex]

比較対象用のデータセット・線分情報による識別法



For Comparison

	# of candidates	Precision	Recall
Conventional (line information)	2489	0.081 +- 0.006	0.788 +- 0.056
Machine leargning	???	???	???

Model (Convolutional Neural Network: CNN) and training

Binary classifier





Loss: The value to minimize during the training (cross entropy)

Epoch: Iteration number of optimization

Best: at the epoch providing the minimum validation loss

The performance is depend on random number → Averaged performance of four trials

Datasets



How to conduct training with small imbalanced dataset?

Techniques to conduct training with a small imbalanced dataset

- Using a pre-trained model with large scale image dataset
- Over sampling
- Data Augmentation

An Important technique

Data Augmentation by RandAugment

https://arxiv.org/abs/1909.13719

- N $(1 \sim 8)$, how many image transformations are executed randomly in defined 8 ones.
- M (0 ~ 30), the magnitude of image transformation
- Only 2 parameters



 \rightarrow We conduct a (N, M) search



Area under the Precision – Recall curve for the Validation dataset

Result

Performance with dataset for comparison



A foundation for the further development to discover a number of double hypernuclei



Scanning stage for Overall scanning



In 2020 Dec.,

1 scanning system for test operation.

In 2021 Mar.,

3 scanning systems will be in operation.

- Development of piezo actuator at Gifu-U
- Scanning at HENP, RIKEN
- Online process

	New scanning system (2020)		
Objective lense	x20		
N pictures	80 (Focal depth: 6 μm)		
Area of Field of view $[\mu m^2]$	530*530		
Frame rate [fps]	160 $\int \rightarrow \frac{4 \text{Mpix CMOS sensor}}{4 \text{Mpix CMOS sensor}}$		
Dead time ratio	0.2 \rightarrow by a piezo actuator		
scanning speed/day	540 cm ²		
To scan the all E07 sheets	15 years \rightarrow 3 years using 5 stages		

X-ray measurement from Ξ^- atom with Hybrid method combined Ge detector and emulsion



summary

- Result of precise analyses of twin Λ hypernuclear events
- Overall scanning method
- Selection of alpha decay event using Precision is 0.547 +- 0.025 when recall is 0.788 Improvement: 6.8 +- 0.6 times Basic development using CNN (image classification) is established
- Upgrade of scanning stage

• We aim to detect more events of double hypernucleus