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Unique approach for precise determination of binding energies of hypernuclei with nuclear emulsion and machine learning

Manami Nakagawa[1,*], *Ayumi* Kasagi[1,2], *Enqiang* Liu[1,3,4], *Hiroyuki* Ekawa[1], *Junya* Yoshida[5], *Wenbo* Dou[1,6], *Yan* He[1,11], *Abdul* Muneem[1,7], *Kazuma* Nakazawa[1,8], *Christophe* Rappold[9], *Nami* Saito[1], *Takehiko R.* Saito[1,10,11], *Shohei* Sugimoto[1,6], *Masato* Taki[12], *Yoshiki K.* Tanaka[1], *He* Wang[1], *Yiming* Gao[1,3,4], *Ayari* Yanai[1,6], and *Masahiro* Yoshimoto[13]

[1]High Energy Nuclear Physics Laboratory, Cluster for Pioneering Research, RIKEN, 2-1 Hirosawa, Wako, Saitama, 351-0198, Japan

[2]Graduate School of Engineering, Gifu University, 1-1 Yanagido, Gifu 501-1193, Japan

[3]Institute of Modern Physics, Chinese Academy of Sciences, 509 Nanchang Road, Lanzhou, Gansu Province, 730000, China

[4]School of Nuclear Science and Technology, University of Chinese Academy of Sciences, No.19(A) Yuquan Road, Shijingshan District, Beijing, 100049, China

[5]Department of physics, Tohoku University, Aramaki, Aoba-ku, Sendai 980-8578, Japan

[6]Department of Physics, Saitama University, Saitama, 338-8570, Japan

[7]Faculty of Engineering Sciences, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Topi, 23640, KP, Pakistan

[8]Faculty of Education, Gifu University, 1-1 Yanagido, Gifu 501-1193, Japan

[9]Instituto de Estructura de la Materia, CSIC, Madrid, Spain

[10]GSI Helmholtz Centre for Heavy Ion Research, Planckstrasse 1, D-64291 Darmstadt, Germany

[11]School of Nuclear Science and Technology, Lanzhou University, 222 South Tianshui Road, Lanzhou, Gansu Province, 730000, China

[12]Graduate School of Artificial Intelligence and Science, Rikkyo University, 3-34-1 Nishi Ikebukuro, Toshima-ku, Tokyo, 171-8501, Japan

[13]RIKEN Nishina Center for Accelerator-Based Science, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

Abstract. Hypertriton is the lightest hypernucleus and a benchmark in hypernuclear physics. However, it has recently been suggested that its lifetime and binding energy values may differ from the established values. To solve this puzzle, it is necessary to measure both values with a higher precision. For the precise measurement of the binding energy, we are aiming at developing a novel technique to measure the hypertriton binding energy with unprecedented accuracy by combining nuclear emulsion data and machine learning techniques. The analysis will be based on the J-PARC E07 nuclear emulsion data. Furthermore, a machine-learning model is being developed to identify other single and double-strangeness hypernuclei.

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[*] e-mail: manami.nakagawa@riken.jp

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1 Introduction

From the 1950s untill the 1970s, hypernuclei were studied using nuclear emulsions and bubble chambers, which recorded the tracks of the produced hypernuclei and their decay particles as photographic images [1]. In those studies, nuclides of hypernuclei were determined from production and decay kinematics, and their masses and the binding energies were obtained. Those studies have provided fruitful information on the potential and interaction associated with Lambda hyperons in hypernuclei. Recently, the Λ-Λ and Ξ-nucleon interactions have also been studied. To investigate the interactions associated with hyperons in detail, precise measurements of the binding energy of hypernuclei are important in the hypernuclear physics.

Since the hypertriton (${}^{3}_{\Lambda}$H) is a benchmark in the hypernuclear physics, information on its lifetime and binding energy is a basis for various theoretical calculations of hypernuclei. The structure of hypertriton is formed by a Λ hyperon which is very weakly bound to a deuteron core with a small binding energy of 0.13 ± 0.05 MeV [1]. The distance between the Λ and deuteron is approximately 10 fm. By considering the small binding energy, it has been suggested that the lifetime of a hypertriton is comparable to the lifetime of a free Λ which is 263 ps. However, in 2013, the HypHI experiment measured hypertriton production using heavy ion beams and found a significantly smaller lifetime than that of a free Λ [2]. Subsequently, various experiments reported smaller values [4], raising questions about the binding energy of the hypertriton.

In 2020, the STAR experiment reported the binding energy of hypertriton based on measured samples of hypertritons and anti-hypertritons, and the combined value was deduced to be 0.41 ± 0.16 MeV [3]. This value differs significantly from the world average, however, the accuracy of the STAR measurement was not sufficient to draw a conclusion. The current reported values of the binding energy and lifetime are summarized in Ref. [5] and [4], respectively. Thus, even fundamental properties of a hypertriton, the simplest hypernucleus, are still not well understood, in spite of the fact that it is a benchmark in the hypernuclear physics. This situation demands that the binding energy of a hypertriton should be measured with high precision. Measuring the binding energy of other hypernuclei with high precision is also important in the hypernuclear physics.

2 Detection of Hypertriton

2.1 Nuclear emulsion

We utilize a nuclear emulsion to measure the binding energy precisely. A nuclear emulsion has the capability to record three-dimensional trajectories of charged particles as they travel through these detectors. An experiment with nuclear emulsions (the J-PARC E07 experiment) was conducted at J-PARC from 2016 untill 2017 to search for Ξ^- or $\Lambda\Lambda$ hypernuclei with two strange quarks [6]. The experiment reported the so-called MINO, IBUKI, and IRRAWADDY events [7–9].

The J-PARC E07 nuclear emulsions irradiated with K^- mesons are expected to record millions of single hypernuclear and thousands of double-strangeness hypernuclear events. Those events are recorded with a high position resolution of less than 1 μm for charged particle tracks from hypernuclear production and decay. The accuracy for measuring the binding energy of hypertriton by the nuclear emulsion can be approximately 30 keV(stat.) + 30 keV (syst.) [10]. The J-PARC E07 experiment aims to detect and sort out hypertriton events in nuclear emulsion data. Since the only hypernuclei that decay in a two-body decay with helium isotopes in a final state are hypertritons and ${}^{4}_{\Lambda}$H, which can be easily distinguished by the difference in the range of pion, we focused on this two-body decay mode of hypertriton. However, with the conventional image analysis techniques for nuclear emulsions, a large number of background events are misdetected [11]. Furthermore, required visual inspection by human's eyes would take 560 years to analyse all the nuclear emulsion images. Therefore, we have developed machine learning techniques to detect events efficiently.

2.2 Machine learning

A machine learning model for detecting hypertriton events of interest from images in the nuclear emulsions requires a large amount of training data. Such images with hypertriton events were missing since hypertritons were never been detected from the J-PARC E07 nuclear emulsions. Therefore, we have developed a machine learning model to generate artificial microscopic images by employing physics simulations based on Geant4 [12]. The algorithm for generation artificial nuclear emulsion images works as follows.

First, hypertriton events associated with the production and decay of hypertritons are generated by the Geant4 simulation, and real nuclear emulsion images are synthesized as a background image. For the synthesis method, an image transfer technique with pix2pix [13], a machine learning technique that utilizes the GAN technique [14], is used. These artificial microscopic images are used as training data for an object detection model with Mask R-CNN [15]. The hypertriton events that appear in the microscopic images provide the ground truth for the machine learning algorithm. The trained model was then applied to the real microscope images. As a result, hypertriton events have been successfully observed for the first time oin our nuclear emulsion [16]. Data collection, analysis, and energy calibrations still continues.

3 Development for Single- and Double-strangeness hypernuclei

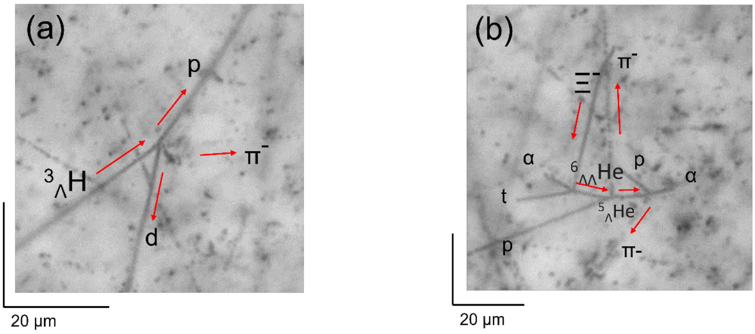

Figure 1. Artificial microscopic images of (a) a ${}^{3}_{\Lambda}\mathrm{H} \rightarrow p + d + \pi^-$ decay event and (b) a ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ decay event

We are currently developing other models for hypernuclei detections. Since hypernuclei with a many-body decay are dominant, as a first step, we are developing a model for detecting hypernuclei with a three-body decay. Among these, especially important hypernuclei are hypertriton, ${}^{4}_{\Lambda}\mathrm{H}$, and ${}^{4}_{\Lambda}\mathrm{He}$. The hydrogen hypernuclei, hypertriton and ${}^{4}_{\Lambda}\mathrm{H}$ are important to cross-check the results obtained with the analysis of the two-body decay channels. Let us note that the ${}^{4}_{\Lambda}\mathrm{He}$ is a nuclide for which charge symmetry breaking is observed in the results of the γ-ray spectroscopy while the ${}^{4}_{\Lambda}$H is a mirror hypernucleus of ${}^{4}_{\Lambda}$He [17]. The recent binding energy data of the ground state of ${}^{4}_{\Lambda}$H are known to be consistent with the results of former nuclear emulsion experiments [18]. However, the binding energy data for the ground state of ${}^{4}_{\Lambda}$He is only available for former nuclear emulsions [1]. Thus, it is important to develop the detection model for hypernuclei with three-body decay modes such as hypertriton, ${}^{4}_{\Lambda}$H, and ${}^{4}_{\Lambda}$He. In addition, we are developing a detection model for double-strangeness hypernuclei. statistical and systematic uncertainties related to parameters of double-strange nuclei are too large to draw conclusions on the nature of baryonic interaction involving double strangeness. Therefore, it is necessary to discover and identify many double-strangeness hypernuclei, which would also allow to improve the accuracy of the binding energy for those double-strangeness hypernuclei that have already been observed. Panels in Figure 1 show artificial microscopic images of a three-body decay ${}^{3}_{\Lambda}\mathrm{H} \rightarrow p + d + \pi^{-}$ event and of a ${}^{6}_{\Lambda\Lambda}$He decay event generated by our current framework.

4 Summary

A combination of a nuclear emulsion and a machine learning technique is employed to measure the hypertriton binding energy with high precision. The hypertriton events are searched for in nuclear emulsion data collected by the J-PARC E07 experiment. The machine learning technique also allows to search for many other single- and double-strangeness hypernuclei decay channels.

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