

Studies of hypernuclei with heavy-ion beams, nuclear emulsions and machine learning

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Abstract. The lightest hypernucleus, the hypertriton, has been a benchmark in the field of hypernuclear physics. However, some of recent experiments employing energetic heavy-ion beams have revealed that the hypertriton lifetime is significantly shorter than 263 ps which is expected by considering the known weakly binding nature of the hypertriton. The STAR collaboration has also measured the hypertriton binding energy, and the deduced value is contradicting to its formerly known small binding energy. These measurements have indicated that the fundamental physics quantities of the hypertriton such as its lifetime and binding energy have not been understood, therefore, they have to be measured very precisely. Furthermore, an unprecedented Λ bound state observed by the HypHI collaboration has to be studied in order to draw a conclusion whether or not such a bound state exists. These three-body hypernuclear states are studied by the heavy-ion beam data in the WASA-FRS experiment and by analysing J-PARC E07 nuclear emulsion data with machine learning.

1 Introduction

The hypertriton lifetime and binding energy have recently become hot topics in the field of hypernuclear and few-body physics. The hypertriton was extensively studied until the 1970s by using nuclear emulsions and bubble chambers. Those experiments concluded that a Λ hyperon is very weakly bound to a deuteron core with a small binding energy of 0.13 ± 0.05 MeV [1, 2]. The lifetime of the hypertriton was also measured [3–8] but did not deliver a firm conclusion on the lifetime due to inaccuracies in the measurement. Therefore, the lifetime of the hypertriton has been considered to be very close to the lifetime of a free Λ hyperons, i.e., 263 ps [9], without having precise experimental data.

Recently, studies of light hypernuclei by means of induced reactions [10] of and collisions of heavy-ion beams have provided new precise data on the hypertriton lifetime. The HypHI experiment at GSI studied hypertritons produced in the ${}^6\text{Li}+{}^{12}\text{C}$ reactions at 2 A GeV and showed that the deduced lifetime of the hypertriton, $183_{-32}^{+42}(\text{stat.})\pm 37(\text{syst.})$ ps [10], is significantly shorter than the presently considered value [9]. Ultra-relativistic heavy-ion collisions have also become a powerful tool for studying the hypertriton, and the lifetime of the

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hypertriton was also measured by the STAR collaboration at the RHIC and the ALICE collaboration at the LHC. All recently published values are summarised in Table 1. Additionally, the HADES collaboration measured the lifetime of hypertritons produced in $^{197}\text{Au}+^{197}\text{Au}$ at 1.23 A GeV, and the tentative deduced value is $256_{-36}^{+22} \pm 27$ ps [18]. The STAR collaboration performed the combined analysis for all the published hypertriton lifetime values, and they have concluded that the averaged value is 200 ± 13 ps and that it is considerably lower than that of the Λ hyperon [15]. However, as shown in Table 1, the measured values have a large span even for measurements obtained by one collaboration. Furthermore, the precision of the current measurements does not allow us to conclude about the value of the hypertriton lifetime. Therefore, at least one measurement with an excellent accuracy is needed to clarify the situation. The binding energy of the hypertriton is also of great interest since it is expected to be strongly correlated to its lifetime. After the binding energy was deduced by employing nuclear emulsions in 1968 [1] and 1973 [2], additional experimental studies have not been performed for the hypertriton binding energy. However recently, the STAR collaboration deduced the binding energy of the hypertriton B_Λ to be $0.41 \pm 0.12(\text{stat.}) \pm 0.11(\text{syst.})$ MeV [19]. This value is significantly larger than the previously known binding energy of 0.13 ± 0.05 MeV from the nuclear emulsions, however, the accuracy of the STAR result is not sufficient to reach a firm conclusion.

Another type of three-body hypernuclear states have also become to be of special interest. The HypHI collaboration observed an enhancement in the invariant mass distributions of the $d+\pi^-$ and $t+\pi^-$ final states [20]. Although the significance of the possible signals is not large, approximately 5σ , those results may indicate the existence of an unprecedented neutral bound state formed by a Λ hyperon and two neutrons, i.e., Ann [20]. This observation has initiated theoreticians and experimentalists to study this state. A large theoretical effort has been carried out using various approaches to check the existence of the Ann bound state [21–24], however, the obtained results did not show that the system Ann is bound. On the other hand, pionless effective field theory studying the Ann state with $I = 0$ has not ruled out the bound state [25, 26]. Possible resonance states associated with Ann have also been studied theoretically [24, 27]. Very recently, the E12-17-003 experiment was performed at JLab to search for bound and resonance states with Ann by employing electron beams to bombard a tritium target, and an indication of the existence of the Ann state has been observed with small significance [28]. It should be, however, noted that the same collaboration published different interpretations of the data, which suggest non-existence of Ann [29], therefore, a conclusion has not been reached yet. The existence of the Ann should be thus further studied experimentally with better precision and more data samples.

As discussed above, there are puzzles associated with three-body hypernuclear states, namely on the hypertriton and Ann . We are aiming to solve these puzzles by performing precise measurements. We will exploit data from heavy-ion collisions collected by the WASA-FRS experiment to address the issues of the hypertriton lifetime and the Ann bound state, and we will apply machine learning techniques to identify hypertritons produced in nuclear emulsions use them to determine hypertriton binding energy [30].

2 The WASA-FRS experiment with heavy-ion beams

We have developed a novel technique for producing and measuring hypernuclei by utilising the GSI fragment separator (FRS) [31] as a high momentum-resolution forward magnetic spectrometer. A schematic layout of the FRS is presented in Figure 1. Inside of the mid focal plane (F2) of the FRS indicated by a red circle in the figure, the WASA central detector [32] is mounted. The WASA central detector that is used in our experiment consists of a superconducting solenoid magnet (up to 1 T magnetic field) with its associated iron yokes and

Table 1. Summary of the measured hypertriton lifetimes obtained by the HypHI, the STAR and the ALICE collaborations. The values are shown with their statistical and systematic uncertainties.

Exp.	Reaction and energy	Prod. meth.	Lifetime [ps]	Year of pub.
HypHI at GSI	${}^6\text{Li}+{}^{12}\text{C}$ at 2 A GeV	Projectile fragmentation	$183^{+42}_{-32} \pm 37$	2013 [10]
STAR at RHIC	${}^{197}\text{Au}+{}^{197}\text{Au}$ at $\sqrt{s_{\text{NN}}} = 200$ GeV	Central collision	$182^{+89}_{-45} \pm 27$	2010 [11]
			$155^{+25}_{-22} \pm 31$	2017 [12]
			$142^{+24}_{-21} \pm 29$	2018 [13, 14]
ALICE at the LHC	${}^{208}\text{Pb}+{}^{208}\text{Pb}$ at $\sqrt{s_{\text{NN}}} = 3$ & 7.2 GeV	Central collision	$221^{+15}_{-19} \pm 27$	2022 [15]
			$181^{+54}_{-39} \pm 33$	2016 [16]
			$242^{+34}_{-38} \pm 17$	2019 [17]

Fragment Separator at GSI

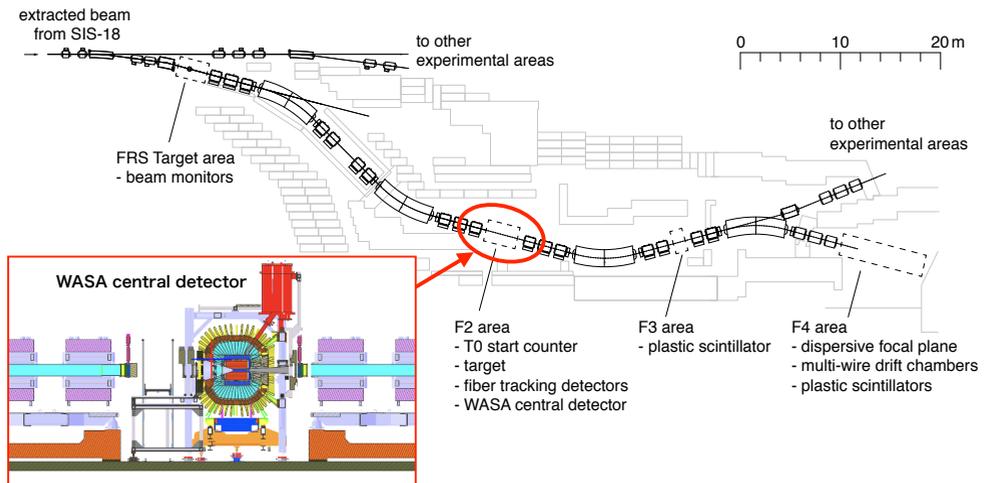


Figure 1. The Fragment Separator (FRS) and the WASA detector.

a cryogenic system, a calorimeter with CsI crystals, inner drift chambers with straw tubes, and newly developed arrays of plastic barrel hodoscopes [33] and end-cap hodoscopes [34]. Additionally, we have supplemented the detector with six scintillating fibre detectors and a start counter for Time-of-Flight measurements dedicated to the WASA-FRS hypernuclear experiments [34]. The experiments which are using the WASA detector and the FRS are called "the WASA-FRS experiments" [30]. The WASA-FRS experiments studying the hypertriton and Λ_{nn} production use beams of ${}^6\text{Li}$ at 2 A GeV provided by the SIS-18 synchrotron. These beams are delivered to the mid-focal plane of the FRS, and hypernuclei of interest are produced on the production target installed in front of the WASA detector. Residual nuclei after the emission of a π^- meson are forward boosted since they are produced from the decay of hypernuclei that emerge as projectile fragments. Therefore, approximately 10% of the residual nuclei from the hypernuclei of interest fall within the acceptance of the FRS behind the F2 and are further transported from F2 through the final focal plane (F4). The particle rate

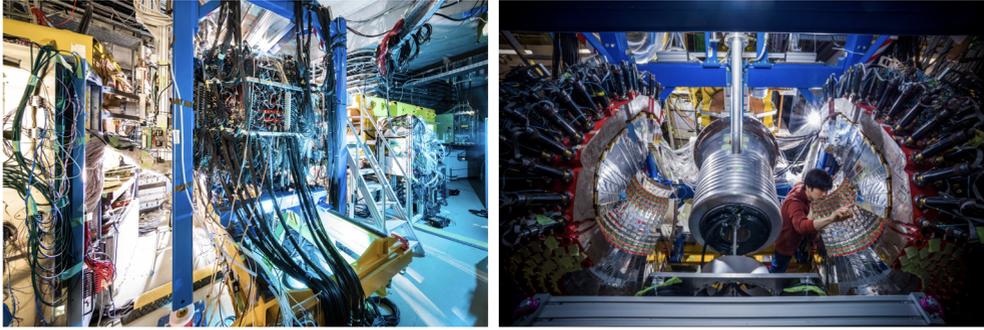


Figure 2. Photographs of the WASA setup with a side view (left) and the iron-yoke opened (right). The photos are provided by Jan Hosan and GSI/FAIR.

at F4 is estimated to be only a few hundreds Hz even with 10 times larger beam intensity than that in the HypHI, which is sufficiently small to take data only with a requirement of particle detection at F4. Therefore, it provides an opportunity to implement a simpler data-acquisition system without a complicated displaced vertex trigger, as employed in the HypHI [10]. The use of the FRS for measuring the residual nuclei produced by the hypernuclear decay of interest without the displaced vertex trigger will increase the size of the data sample by approximately a factor 100 in comparison to the HypHI. Furthermore, the standard resolving power of the FRS is 10^4 for the measurement of the momentum of the residual nuclei, which is approximately three orders of magnitude better than the HypHI. Decays of hypernuclei of interest take place inside the F2 area and π^- mesons from the hypernuclear decay are emitted widely, and they are measured by the WASA detector with additional detectors at F2 of the FRS.

According to Monte Carlo simulations [30, 34], the signal integral is approximately 5.8×10^3 , and the significance of the peak was calculated with the amount of the signal and background to be approximately 120σ . In comparison to the HypHI, the peak integral has been increased by a factor of approximately 38, and the significance is approximately 25 times higher [10]. The peak width is ~ 3.18 MeV which is 1.5 times narrower than that observed in the HypHI [10]. The accuracies for the lifetime have also been estimated for different lifetime values and they are 5 ps for the lifetime value of 150 ps, 8 ps for 200 ps and 13 ps for 250 ps. Additionally, we have estimated that the performance of the measurements should be similar for the case when one searches for the existence of the Λ_{nn} bound state. This measurement should reach the same level of significance as for the hypertriton case, which is approximately 120σ .

The WASA-FRS experiment to study the hypertriton, ${}^4_{\Lambda}\text{H}$ and Λ_{nn} was already performed at GSI in the first quarter of 2022 with ${}^6\text{Li}$ projectiles at 2 A GeV bombarding a diamond target with a thickness of 9.87 g/cm^2 , and the data analysis is in progress. Developments of new data analysis algorithms for track recognition with the Graph Neural Network (GNN) [35] have already been completed and are being prepared for publication [36]. Details of the performed WASA-FRS experiment and its performance are discussed by Ekawa in these proceedings [34].

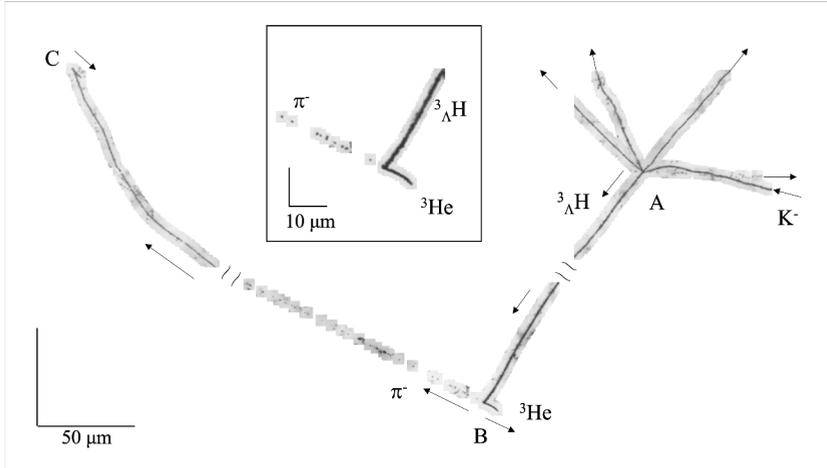


Figure 3. The first discovered hypertriton event in the nuclear emulsion of the E07 experiment at J-PARC [30]. A K^- meson enters the emulsion from outside the emulsion modules and then propagates to the point A. Here the K^- meson is stopped and it is absorbed by one of the nuclei in the emulsion to produce five visible nuclear fragments and ${}^3_{\Lambda}\text{H}$. The hypertriton (${}^3_{\Lambda}\text{H}$) proceeds towards the point B, where it stops. The hypertriton decays to ${}^3\text{He}$ and π^- . The inset of the figure shows a magnification around the point B.

3 Precise measurement of the hypertriton binding energy with nuclear emulsion and machine learning

In order to solve the hypertriton puzzle, in addition we plan to determine the hypertriton binding energy very precisely, in addition to improving the accuracy of the hypertriton lifetime with the WASA-FRS experiment discussed in the previous subsection. We are currently re-analysing the existing J-PARC E07 nuclear emulsions by means of machine learning techniques to deduce the binding energy of the hypertriton to exploit this large data sample and to achieve the best possible precision.

The E07 experiment [37] at J-PARC, aims to search for double-strangeness hypernuclei such as double- Λ - and Ξ -hypernuclei. The experiment was already performed in 2016–2017, and it employed dedicated nuclear emulsion sheets. Approximately 1300 nuclear emulsion sheets were irradiated by intense K^- beams. Searches for double-strangeness hypernuclei were performed by using the so-called hybrid method [37]. In this method, a Ξ^- hyperon produced by the (K^-, K^+) reaction is identified and tracked by other detectors when the outgoing K^+ mesons are also detected, and the position of the stopped Ξ^- hyperon that induces the production of double-strangeness hypernuclei is estimated. Visual inspections by an optical microscope were performed only around the estimated stop position. Therefore, a very tiny portion of all the irradiated emulsions was analysed, which greatly reduced the human workload. Hypertritons were also produced by induced reactions of K^- beams on nuclei inside the E07 nuclear emulsions. Tracks of produced hypertritons and charged particles originated from their decays are also recorded in the emulsions. However, in order to identify these hypertriton decays, a complete scan of the entire nuclear emulsion sheets is necessary since the information associated with the hypertriton production is not recorded by the hybrid method.

We are aiming at detecting hypertriton decay at rest via the ${}^3\text{He}+\pi^-$ two-body decay, which can be used to measure the invariant mass which is necessary to deduce the binding energy. The advantage of using this hammer-like event with decay into ${}^3\text{He}+\pi^-$ is that the track length of the π^- meson is well defined only by the two-body decay kinematics, being approximately 28 mm. This length is unique and very different for the other hypernuclear decays (for example, the π^- track length for the case of ${}^4_{\Lambda}\text{H}$ is approximately 42 mm). Therefore, the hypertriton event can be firmly identified. However, since the shape of the hypertriton decay event is too simple and is associated with a very sparse π^- track, analytical filters can hardly classify these shapes from other backgrounds with high efficiency; therefore, candidates should be sorted out by human visual inspection with the current technology for emulsion analysis. There are approximately 1.4 billion images per emulsion sheet to be inspected, hence an analysis of one emulsion sheet would require about 560 years [30]. Furthermore, the ratio of the number of candidates to be found by visual inspection over the number of images without candidates is expected to be only $\sim 10^{-7}$. Because of the huge human load and the extremely small signal-to-background ratio, hypertritons were never observed in the data of the E07 [37] experiment and the former experiments at KEK, and only a small amount of other single-strangeness hypernuclei were observed in the same data sets.

For overcoming the difficulties discussed above, we have developed machine learning models to detect candidates for hypertriton events in the E07 nuclear emulsion data [30]. One of difficulties in the development is that there is no real training data with hypertriton events since no hypertriton event was observed in the E07 nuclear emulsion. Therefore, we employed Monte Carlo simulations to produce data emulating production and decay of the hypertriton in the emulsion material. The Monte Carlo simulations calculate particle trajectories as sharp lines. These lines have to be converted to defused line shapes like track images in the emulsion by considering the size of grains in the emulsion. This is achieved by employing one of the machine learning techniques, i.e., Generative Adversarial Networks (GANs) [38]. Background images are taken randomly from the real emulsion data and mixed with the converted defused lines to imitate hypertriton events in the nuclear emulsion. With this technique, we have produced a sufficient amount of training data for developing the machine learning models. We have already developed an object detector for hypertriton events with one machine learning model called Mask R-CNN [39]. We employ the surrogated images for training the object detection model. For the analysis, the emulsion sheets of the E07 experiment are scanned by the dedicated automated microscope scanning devices and all the raw images are recorded on a storage disk. The trained machine learning models are applied to the stored data to detect tracks of interest within real emulsion images. It has already been shown that the current model improves the signal-to-background ratio from $\sim 10^{-7}$ to 2×10^{-4} . The human load decreased by a factor of 2000. This improvement has already allowed us to mine hypertriton events with the support of visual inspection. After the detection of candidates of the images that may be associated to the hypertriton events, they are again visually inspected, and clear candidates are sorted out. Then, we perform a detailed analysis of the tracks by using the microscopes. The procedure is already established and the number of the discovered hypertriton decays increases day by day. The first hypertriton event discovered on February 2nd in 2021 [30, 40] is displayed in Figure 3. We have already analysed approximately 0.9% of the total emulsion data (1300 sheets) until August 25th in 2022, and we have already discovered few tens of hypertriton events. Additionally, four times more ${}^4_{\Lambda}\text{H}$ events have been discovered and identified. The discovery of these hypertriton events in the E07 emulsion data already guarantees the improvement in the accuracy for the determination of the hypertriton binding energy. The systematic uncertainty for the determination of the hypertriton binding energy has been estimated to be 28 keV by revisiting the former emulsion data and by employing Monte Carlo simulations [41], and this uncertainty will be improved by introducing

a new method for calibrating the density of nuclear emulsions, which will be completed soon [40]. The developed machine learning technique will be applied to search for three-body decay events, therefore, the binding energy of, for example, ${}^4_{\Lambda}\text{He}$ and ${}^5_{\Lambda}\text{He}$ will be precisely determined [42]. The current status of the precise determination of the hypertriton binding energy in this project and its perspective are discussed by Nakagawa in these proceedings [42].

4 Summary and outlook

Physicists dealing with few-body hypernuclei systems are highly interested to improve precision of the lifetime and the binding energy of the hypertriton. In addition, it needs to be clarified whether or not the Λ_{nn} bound state exists. Recently, experiments with heavy-ion beams such as ALICE, HADES, HypHI and STAR measured the hypertriton lifetime, however, the obtained results vary a lot thus a conclusion has not been yet drawn. The recent measurement of the hypertriton binding energy by STAR has indicated that the hypertriton binding energy could be significantly larger than the formerly known value of 130 ± 50 keV, however, the precision of the deduced binding energy by STAR does not allow us to come to a firm conclusion. Therefore, the precise measurements on the both lifetime and binding energy of the hypertriton are awaited. We will provide the most accurate data on both the lifetime and binding energy of the hypertriton for improving our understanding of the real nature of the hypertriton drastically. Furthermore, the existence of the Λ_{nn} state has to be experimentally studied with high precision. We have already performed the WASA-FRS experiment at GSI with the ${}^6\text{Li}+{}^{12}\text{C}$ reaction at 2 A GeV for measuring the hypertriton lifetime with an accuracy of approximately 10 ps and for studying whether or not the Λ_{nn} state can exist. The analysis is in progress and the results will be presented in near future. For the hypertriton binding energy, we are analysing the J-PARC E07 nuclear emulsions by developing the machine learning models, and the detection of the hypertriton events have already been accomplished. Determination of the hypertriton binding energy with an accuracy of 28 keV or better is foreseen in near future.

Similar experiments like the WASA-FRS will be continued with the Super-FRS [43] at FAIR (Facility of Anti-proton and Ion Research) [44] in Germany. The upgrade of the superconducting solenoid magnet of the WASA detector is planned, and we are aiming at achieving a maximum central magnetic field of 2 T by using a cryocooler. The upgrade of the inner drift chamber is also in progress. With the upgraded WASA at Super-FRS, lifetime and binding nature of hypernuclei, especially for proton rich hypernuclei [30, 45], will be investigated. Furthermore, very neutron rich hypernuclei will be studied by employing charge-exchange-reactions combined with strangeness production [46]. We are also preparing hypernuclear experiments with heavy-ion beams at HIAF (High-Intensity Heavy Ion Accelerator Facility) [47] in China, and it is planned to extend hypernuclear studies to double-strangeness [30]. The analysis of the E07 nuclear emulsions will be continued, and the analysis for single-strangeness hypernuclei will be completed in near future. The development of machine learning models for detecting events associated with double-strangeness hypernuclei has already been started, and it is expected to detect approximately 1000 double-strangeness hypernuclear events by analysing the entire E07 emulsion data. Design studies for future experiments with nuclear emulsions at J-PARC and elsewhere have also been started.

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