New directions in hypernuclear physics

Takehiko R. Saito[1, 2, 3, *], Wenbou Dou[1, 4], Vasyl Drozd[2, 5], Hiroyuki Ekawa[1], Samuel Escrig[6], Yan He[3], Nasser Kalantar-Nayestanaki [5], Ayumi Kasagi[1, 7], Myroslav Kavatsyuk[5], Enqiang Liu[1, 8, 9], Yue Ma[1], Shizu Minami[2], Abdul Muneem[1, 10], Manami Nakagawa[1], Kazuma Nakazawa[7, 11], Christophe Rappold[6], Nami Saito[1], Christoph Scheidenberger[2], Masato Taki[12], Yoshiki K. Tanaka[1], Junya Yoshida[1, 13], Masahiro Yoshimoto[11], He Wang[1], and Xiaohong Zhou[8]

[1]High Energy Nuclear Physics Laboratory, Cluster for Pioneering Research, RIKEN, Wako, Japan
[2]GSI Helmholtz Center for heavy-ion Research, Darmstadt, Germany
[3]School of Nuclear Science and Technology, Lanzhou University, Lanzhou, China
[4]Department of Physics, Saitama University, Saitama, Japan
[5]Energy and Sustainability Research Institute Groningen, University of Groningen, Groningen, the Netherlands
[6]Instituto de Estructura de la Materia, CSIC, Madrid, Spain
[7]Graduate School of Engineering, Gifu University, Gifu, Japan
[8]Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou, China
[9]University of Chinese Academy of Sciences, Beijing, China
[10]Faculty of Engineering Sciences, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Topi, Pakistan
[11]Faculty of Education, Gifu University, Gifu, Japan
[12]Graduate School of Artificial Intelligence and Science, Rikkyo University, Tokyo, Japan
[13]Department of Physics, Tohoku University, Sendai, Japan
[*]e-mail: takehiko.saito@riken.jp

ABSTRACT

A hypernucleus, a sub-atomic bound system with at least one hyperon, is a great test ground to investigate nuclear forces and general baryonic interactions with up, down and strange quarks. Hypernuclei have been extensively studied for almost seven decades in reactions involving cosmic-rays and with accelerator beams. In recent years, experimental studies of hypernuclei have entered a new stage using energetic collisions of heavy-ion beams. However, these investigations have revealed two puzzling results related to the lightest three-body hypernuclear system, the so-called hypertriton and the unexpected existence of a bound state of two neutrons with a Λ hyperon. Solving these puzzles will not only impact our understanding of the fundamental baryonic interactions with strange quarks, but also of the nature of the deep interior of neutron stars. In this Perspective, we discuss approaches to solving these puzzles including experiments with heavy-ion beams and the analysis of nuclear emulsions using state-of-the-art technologies. We summarise on-going projects and experiments at various facilities worldwide and outline future perspectives.

Website summary:

The study of hypernuclei contributes to the understanding of the fundamental baryonic interactions and the physics of neutron stars. This Perspective discusses different experimental approaches to answer open questions regarding hypernuclei.

[H1] Introduction

One of the ultimate goals in nuclear physics is to understand the nuclear force that holds sub-atomic nuclei together. The nuclear force results from the fundamental interactions between nucleons, such as neutrons and protons, which are composed of three up and down quarks. Interactions between nucleons have been studied in detail in experiments using various nuclear reactions with nuclear beams from particle accelerators. From these studies, the basic nature of the nuclear force, especially at long and medium ranges, is now understood. For a deeper understanding of the nuclear force, especially at short range, it is essential to increase the number of the quark degrees of freedom in the nuclear system by adding an additional quark with a different type since it can be distinguished from the other up and down quarks inside the nucleus of interest. This has been achieved by introducing a hyperon (a type of baryon with three quarks, similar to nucleons, but containing at least one heavier strange quark, see Box 1) into the nuclear system. Because of the typical lifetime of hyperons is of the order of 10^{-10} s, it has not been practical to perform reaction experiments involving hyperons in a target or a projectile since hyperons inside the target or beams decay before the reaction occurs. However, the lifetime of hyperons is much longer than the typical time scale of the strong interactions ($\lesssim 10^{-22}$ s) dominating the nuclear force; therefore, sub-atomic bound states with hyperon(s), so-called hypernuclei (Box 1), have been used as a micro-laboratory for investigating the extended fundamental interactions with up, down and strange quarks. Information on these interactions can be obtained by studying the structures, production and decay of hypernuclei.

It has been predicted that hyperons are major ingredients in the deep interiors of neutron stars, on par with neutrons[1,2]; however, observations of two-solar-mass neutron stars[3–5] have shown that the equations of states of neutron matter with hyperon-mixing are unable to reproduce such heavy neutron stars[3–5]. One of the proposed solutions to reproduce these heavy neutron stars with hyperon-mixing is to introduce three-baryon repulsive interactions that include a hyperon[6]. However, the properties of three-baryon interactions with two neutrons and a hyperon in a neutron-rich nuclear environment are still unclear. These properties could be deduced via studies of very neutron-rich hypernuclei that are hard to produce with conventional methods. Furthermore, the details of baryonic interactions with multiple hyperons have not yet been understood since only a few double-strangeness hypernuclei have been experimentally identified[7–10].

The observation of the two-solar mass neutron stars has prompted renewed interest in hypernuclear physics both from experimentalists and theorists. Single-strangeness hypernuclei (hypernuclei containing one strange quark) are or are planed to be studied extensively with induced reactions of meson- and electron-beams at Japan Proton Accelerator Research Complex (J-PARC), the Thomas Jefferson National Accelerator Facility (JLab), the Mainzer Microtron (MAMI) and the Research Center for Electron-Photon Science (ELPH). Double-strangeness hypernuclei (hypernuclei containing two strange quarks) were further studied using kaon K^- beams at KEK and J-PARC. With these experiments, the nature of single- and double-strangeness hypernuclei will be understood in more detail. However, experiments with heavy-ion beams have revealed the puzzling nature of the known lightest hypernucleus ${}^{3}_{\Lambda}\mathrm{H}$, the so-called hypertriton. Since the hypertriton is a benchmark in the field of the hypernuclear physics and given that the solution of this puzzle may impact the understanding of the other hypernuclei and the baryonic interaction with hyperon(s), a resolution is urgently needed.

This Perspective overviews the current state of the field of the hypernuclear physics focusing on on the puzzles of the hypertriton and the Λnn bound state. We discuss on-going approaches to resolving these puzzles future directions for further studies of hypernuclei.

[H1] Puzzles of hypernuclei

The hypertriton or/and anti-hypertriton have been studied using ultra-relativistic heavy-ion collisions by the HypHI collaboration so-called Phase 0, at the Heavy Ion Accelerator Facility of GSI (the GSI Helmholtz Center for Heavy Ion Research) (see Box 2), the STAR collaboration at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL) and the ALICE collaboration at the Large Hadron Collider (LHC) at CERN. The recently derived hypertriton lifetime by the HypHI Phase 0 experiment[11], STAR[12–15] and ALICE[16,17] together with the new measurement of the hypertriton binding energy by ALICE[18] have shown that the nature of the hypertriton can differ from the previous understanding. Furthermore, a signature of the unexpected Λnn bound state has been observed[19] by HypHI , but theoretical considerations do not predict the existence of this bound state, and whether or not the Λnn bound state can exist should also be experimentally clarified.

[H3] Mystery of the hypertriton

The lightest hypernucleus, the hypertriton, was extensively studied until the 1970s by using nuclear emulsions and bubble chambers[20]. 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 (Refs[21,22]). This binding energy has become a benchmark in theoretical calculations for hypernuclei. There have also been attempts at measuring the lifetime of the hypertriton[23–28], but no firm result was established due to inaccuracies in the measurements. Therefore, the lifetime of the hypertriton has been assumed to be very close to the lifetime of free Λ hyperons, that is, 263 ps (Ref.[29]), due only to its small binding energy.

The HypHI experiment at GSI used the ${}^{6}\mathrm{Li}+{}^{12}\mathrm{C}$ reaction at $2\,A$ GeV and showed that the derived lifetime of the hypertriton, 183^{+42}_{-32}(stat.)±37(syst.) ps (Ref.[30]), is significantly shorter than the assumed value (the first and second errors represent the statistical and systematic uncertainty, respectively). In addition, ultra-relativistic heavy-ion collisions have also become a powerful tool for studying the hypertriton. The lifetime of the hypertriton was also measured by the STAR collaboration at RHIC to be 182^{+89}_{-45}(stat.)±27(syst.) ps by combining their observations on the hypertriton and anti-hypertriton with collisions of ${}^{197}\mathrm{Au}+{}^{197}\mathrm{Au}$ at nucleon-nucleon (NN) centre-of-mass energy $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. However, the value overlaps with the free Λ-lifetime within a standard deviation[12]. Later, STAR remeasured the hypertriton lifetime by considering its three-body decay channel to a proton (p), a deuteron (d) and pion (π^-), ${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{p} + \mathrm{d} + \pi^-$, and discovered a significantly smaller value[13], 155^{+25}_{-22}(stat.)±31(syst.) ps . The ALICE collaboration at LHC also measured the lifetime of the hypertriton with collisions of ^{208}Pb+^{208}Pb at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, and their result[16] was also significantly shorter lifetime than that of the free Λ hyperon, 181^{+54}_{-39}(stat.)±33(syst.) ps. Any theoretical calculation could hardly reproduce these short lifetimes due to the observed weakly binding nature of the hypertriton with a binding energy of 0.13 ± 0.05 MeV because the Λ hyperon has almost no influenece from the deuteron core, although these three state-of-the-art experiments presented a short lifetime of the hypertriton.

The STAR and ALICE collaborations recently updated their measurements on the hypertriton lifetime. The STAR collaboration reported an even shorter lifetime[14,15], 142^{+24}_{-21}(stat.)±29(syst.) ps, whereas the value measured by the ALICE collaboration became larger[17], 242^{+34}_{-38}(stat.)±17(syst.) ps. The HypHI measured value is between these two. Therefore, no conclusion can yet be drawn from these measurements of the hypertriton lifetime. Additional experimental projects are planned at J-PARC and Research Center for ELectron PHoton Science (ELPH) in Japan with secondary meson and photon beams, respectively. However, the accuracy in these experiments will be similar to that of the other measurements and therefore, they will not drastically improve the accuracy of the hypertriton lifetime. Table 1 summarises the lifetime of the hypertriton measured by the HypHI, STAR and ALICE experiments, together with their reactions and production methods. It shows that their accuracies are similarly large and that the measured values overlap within the errors as summarised in Ref.[31]. To reach a more definitive conclusion on the value of the hypertriton lifetime, at least one more precise measurement is needed.

Revisiting 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 using the nuclear emulsions in 1968 (Ref.[21]) and 1973 (Ref.[22]), additional experimental studies of the hypertriton binding energy have not been performed. Only recently, the STAR collaboration derived[18] the binding energy of the hypertriton B_{Λ} to be $0.41 \pm 0.12(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})$ by combining the data of hypertritons and anti-hypertritons assuming the charge, parity and time reversal (CPT) symmetry invariance. This value is significantly larger than the previously known binding energy of 0.13 ± 0.05 MeV; however, the accuracy of this result is not sufficient to reach a firm conclusion. In addition, the binding energy and lifetime of the hypertriton were theoretically calculated by means of a chiral effective field theory approach, showing a strong correlation between the binding energy and lifetime[32]. An effective field theory has also been used to study the lifetime of the hypertriton[33], and partial decay widths with $R = \Gamma_{3\mathrm{He}}/(\Gamma_{3\mathrm{He}} + \Gamma_{\mathrm{pd}})$ has shown a strong dependence on the hypertriton binding energy, where Γ_X denotes a partial decay width involving the X final states, however, a firm conclusion has not yet been drawn. Further theoretical calculations are awaiting experimental data on both the biding energy and quantities related to the lifetime with improved precision.

To summarise the recent situation regarding our understanding of the hypertriton, the HypHI and STAR experiments have shown a short lifetime of the hypertriton, which can be hardly reproduced by theoretical models due to its known small binding energy, whereas the ALICE experiment has shown a longer lifetime close to that of the free Λ hyperon. This tensions should be resolved by another measurement with improved precision. The recently derived binding energy of the hypertriton by the STAR experiment is significantly larger than the previously known value, but its precision is not sufficient to draw a definitive conclusion.

[H3] Existence of an unexpected Λnn bound state

One surprising result from the HypHI collaboration is the observation of the enhancement in the invariant mass distributions of the d+π^- and t+π^- final states[19]. Although the significance of the possible signals is not large, approximately 5 σ, these results, together with the derived lifetime of the mother state decaying to these final states, may indicate the existence of an unexpected neutral bound state with both a Λ hyperon and two neutrons, that is, Λnn (Ref.[19]). This observation has attracted the interest of both theorists and experimentalists. Significant theoretical effort has been dedicated to various approaches to check the existence of the Λnn bound state[34–37]. However, all of these calculations show negative results for reproducing the bound state. However, the Λnn state with the isospin $I = 0$ has also been studied using pion-less effective field theory and these works have not ruled out the bound state[38,39]. Possible resonance states[37,40] of Λnn have also been studied theoretically. The HypHI collaboration did not observe the prompt resonance states because events without having a displaced decay-vertex taking place behind the production target were hugely suppressed in their data acquisition system in order to enhance hypernuclear events of interest in the taken data[30]. The E12-17-003 experiment performed at JLab was meant to search for bound and resonance states with Λnn using electron beams to bombard a tritium target[41] and the new data analysis is currently in progress. This experiment used a well-known and controlled elementary process induced by virtual photons to convert a proton to a Λ hyperon in the tritium target nucleus, and thus the production of a Λnn bound state or associated resonance states could be clearly observed if they are produced in this reaction. However, the Λnn state may not be observed in this experiment even though it may exist because the production mechanism of Λnn is very different from that of HypHI. Interest in neutral hypernuclear systems such as Λnn has been extended to double strangeness. A reanalysis of the former BNL-AGS E906 experiment at BNL has shown the possibility of a bound double-strangeness neutral hypernucleus, $^{4}_{\Lambda\Lambda}$n although it yields a null result on the observation of Λnn (Ref.[42]).

The existence of the Λnn bound state requires a significantly larger Λ-binding energy in the hypertriton than the currently known value[34] and, therefore, it is strongly related to the puzzle introduced in the previous subsection. As discussed in Ref.[18], an increase in the binding energy of the hypertriton, similar to the value deduced by the STAR collaboration, significantly decreases the scattering length, suggesting a stronger interaction between the Λ hyperon and the nuclear core in the hypertriton[43]. It requires SU(3)-symmetry breaking and more repulsive hyperon–nucleon interactions at high density, which is consistent with the observation of two-solar-mass neutron stars[44].

[H1] Solving the puzzles

As discussed in the previous section, to solve these puzzling observations, both the binding energy and the lifetime of the hypertriton should be measured very precisely. Additionally, the existence of the Λnn bound state observed by the HypHI collaboration should be reinvestigated using the same reaction that was used in the HypHI experiment, ^{6}Li+^{12}C at 2 *A* GeV, but with better accuracy, a better signal-to-background ratio and a larger data sample. The acceptance for measuring π^- mesons from decays of hypernuclei of interest should also be improved to increase the data sample.

[H3] The WASA-FRS hypernuclear experiment at GSI

A proposal was made to overcome the limitations of the HypHI experiment by using the projectile fragment separator (FRS), at GSI[45] as a high momentum-resolution forward magnetic spectrometer for measuring the residual nuclei after the emission of pions in the hypernuclear mesonic weak-decay. A schematic of the FRS is presented in of Figure 1a. Beams of ^{6}Li at 2 *A* GeV from the synchrotron are delivered to the mid-focal plane of the FRS, denoted as "S2" in a red square, and hypernuclei of interest are produced on the production target installed at S2. Residual nuclei after the emission of a π^- meson are forward boosted since they are produced from the decay of hypernuclei populated as projectile fragments. Therefore, approximately 10 % of the residual nuclei from the hypernuclei of interest fall within the acceptance of the FRS behind the S2 and are further transported from S2 through S4. The optics parameters of the FRS are optimised for maximising the transmission for the residual nuclei of interest, but minimising it for other nuclei. The particle rate at S4 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 S4. Therefore, it provides an opportunity to implement a simpler data-acquisition system without a complicated displaced vertex trigger, as used in the HypHI[30].

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 S2 area and π^- mesons from the hypernuclear decay are emitted widely, from 0 to approximately 25 degrees with respect to the beam direction. Therefore, π^- mesons from the hypernuclear decay should be measured by an additional detector inside the S2 area. Because of the small size of the S2 area, a detector for this π^- measurement should be compact enough to be accommodated with other devices at S2. A larger acceptance for measuring π^- mesons is also required. The central part of the Wide Angle Shower Apparatus (WASA) detector[46] was chosen to study the structures of hadrons. The acceptance of the WASA central detector for π^- mesons from the hypernuclear decay is approximately four times larger than that of the HypHI. The WASA central detector consists of a superconducting solenoid magnet as shown in Figure 1b.

The international collaboration succeeding the HypHI collaboration, called the WASA-FRS hypernuclear experiment[47], proposed an experiment that uses the same reaction as the HypHI experiment, ^{6}Li+^{12}C at 2 *A* GeV. It aims to improve the accuracy of the lifetime of the hypertriton by measuring its decay channel of ^{3}He+π^-. The lifetime of the known hypernucleus, $^{4}_{\Lambda}$H, would also be measured with the ^{4}He+π^- decay channel to provide calibration data. The lifetime of the $^{4}_{\Lambda}$H hypernucleus was precisely measured to be 194^{+24}_{-26} ps (Ref.[48]) — a value serves as calibration point. The WASA-FRS hypernuclear experiment will also try to confirm the existence or not of the Λnn bound state by measuring the d+π^- final state and will search for resonance states associated with Λnn.

In addition, the WASA-FRS experiment is expected to contribute to establishing new techniques for detectors, electronics, and on/off-line data analyses for experiments at future heavy-ion accelerator facilities, such as, FAIR (Facility for Antiproton and Ion Research)[49] in Germany and HIAF (High-Intensity heavy-ion Accelerator Facility)[50] in China.

The WASA detector has already been transported to GSI. The superconducting solenoid magnet has been assembled, and it has already reached the liquid-helium temperature at approximately 4 K. The drift chamber was already commissioned, and upgrading an array of plastic scintillators surrounding the drift camber is in progress with multi-pixel photon counters (MPPCs). In addition to the WASA detector, a dedicated charged particle detectors with scintillating fibres and MPPCs and new read-out electronics boards will be included. Further details regarding the preparations are given in the Supplementary Information. The experiment is scheduled to start operation in the first half of 2022.

[H3] Machine learning analysis of nuclear emulsion tracks

In addition to improving the accuracy of the hypertriton lifetime with the WASA-FRS experiment discussed above, the precise determination of the hypertriton binding energy is needed. The STAR experiment[18] recently reported a significantly larger binding energy than the known value measured in the 1970s using nuclear emulsions[22], however, the precision was insufficient to draw a definite conclusion. Hence, a new measurement with better precision is needed, which prompted the re-analysis the existing nuclear emulsion data to derive the binding energy.

The E07 experiment[51] at J-PARC, aiming to search for double-strangeness hypernuclei, such as double-Λ- and Ξ-hypernuclei, was performed in 2016-2017. This experiment used dedicated nuclear emulsion sheets (for details see the Supplementary Information), and approximately 1300 nuclear emulsion sheets were irradiated by intense negatively-charged kaon K^- beams. Searches for double-strangeness hypernuclei were performed by using the so-called hybrid method[7,8,51]. 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 with an optical microscope were performed only around the estimated stop position. Therefore, only a small portion of all the irradiated emulsions could be analysed.

Hypertritons were also produced by induced reactions of K^- beams on nuclei inside the E07 nuclear emulsion and the tracks associated with their production and decay have been recorded. However, in contrast to the hybrid method, there is no information on the production position of the hypertriton obtained by the other detectors since the outgoing K^+ meson is not produced in the hypertriton production and the data of the other detectors were not recorded. Therefore, in this case a complete scan of the entire nuclear emulsion sheets is necessary. Figure 2a illustrates an event of a hypertriton at rest decaying via the ^{3}He+π^- two-body decay, which can be used to measure the invariant mass to deduce the binding energy. The advantage of this hammer-like event with decay into ^{3}He+π^- is that the track length of the π^- meson is well defined only by the Q-value, being approximately 28 mm. This length is unique and very different from the other hypernuclear decays (for example, the π^- track length for the case of $^4_\Lambda$H is approximately 42 mm). Therefore, the hypertriton event can be clearly identified. However, since the shape of the hypertriton decay event is too simple and is associated with a very sparse π^- track, analytical filters have difficulty classifying these shapes from other backgrounds with high efficiency; therefore, candidate events need to 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, which would require over 500 years to analyze. 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 amount of data to analyse and the extremely small signal-to-background ratio, the hypertriton and other single-strangeness hypernuclei have never been observed in the data of the E07 experiment[7,8,51] or that of previous experiments at KEK[9,10,52,53].

Machine learning models can help to detect candidates for hypertriton events in the E07 nuclear emulsion data. The first attempt to use machine learning relied on one of the most commonly used Convolutional Neural Networks (CNNs)[54,55] to sort out alpha-decay events that are traces of spontaneous decay chain of long-lived radioisotopes such as uranium and thorium in the emulsion. A typical image of the alpha-decay recorded in the nuclear emulsion is shown in Figure 2b. For the training, validation and testing of the model a number of real α-decay events already observed in the nuclear emulsion were used. The developed model has achieved a reasonable level of performance, as discussed in Ref.[56], decreasing the human load for visual inspections by a factor seven in comparison to the conventional manual procedure.

Although no hypertriton event was observed in the E07 nuclear emulsion training data are needed for the machine learning model. Monte Carlo simulations were used to produce data for the production and decay of the hypertriton in the emulsion material. These Monte Carlo simulations provide particle tracks as combinations of sharp lines, and these lines are converted to diffuse line shapes similar to the track images in the emulsion. This is achieved using another machine learning technique, Generative Adversarial Networks (GANs)[57,58]. Background images are taken randomly from the real emulsion data and mixed with the converted diffused lines to mimick hypertriton events in the nuclear emulsion. Figure 2c shows such a surrogate hypertriton event in the nuclear emulsion which is hard to tell apart from the real emulsion image in panel b.

An object detector for hypertriton events is currently being developped with another machine learning model called Mask R-CNN[59]. The surrogate images are used for training the object detection model. For the analysis, the emulsion sheets of the E07 experiment are scanned with dedicated automated microscope scanning devices and all the raw images are recorded on the storage disk. The trained machine learning models analyse the stored data to detect tracks of interest in the real emulsion images. It has already been shown that this approach improves the signal-to-background ratio from $\sim 10^{-7}$ to 2×10^{-4}. The human load decreased by a factor of 2000. These improvements have enabled the mining of hypertriton events with the support of visual inspection which sorts out candidates to undergo a detailed analysis of the tracks. Approximately 29% of one emulsion sheets (2.2×10^{-4} of the total data) have been analysed as of March 2021, and three hypertriton events have been inedtified. The first hypertriton event discovered in February is displayed in Figure 2d. Additionally, eleven $^4_\Lambda$H events have been identified.

The discovery of these hypertriton events in the E07 emulsion data opens the way to the improved determination of the hypertriton binding energy. For each event, track lengths of ^{3}He and π^- are measured with the microscope. With the emulsion density and the well-established range-energy relations in the emulsion[60], the energy of the ^{3}He and π^- are derived, and the invariant mass is calculated. From the invariant mass together with the mass values of deuteron, Λ hyperon and electron, the Λ-binding energy can be deduced for each event. Since the binding energy is calculated from the measured range of ^{3}He and π^- meson from the decay of the hypertriton, the accuracy of the derived binding energy is mainly originates from the range straggling of these particles in the emulsion, and the average accuracy is approximately 0.5 MeV in one event. Therefore, with 100 hypertriton events, an accuracy of approximately 0.05 MeV for the measurement of the hypertriton binding energy can be reached. This is the same precision as that of the current best accuracy using former emulsion studies combining different measurements[22]. With further developments and improvements, it will be possible to discover 400 events pushing the expected accuracy to 0.025 MeV, two times better than the current best accuracy. The ultimate accuracy in the binding energy after the analysis of all the E07 nuclear emulsions could be better than 0.005 MeV, which could be reached within the next five years.

The systematic error induced by the uncertainty in the determination of the emulsion density needs to be quantified. With the information reported in Ref.[22], the systematic error can be evaluated using Monte Carlo simulations. The estimated systematic uncertainty due to the emulsion density is about 0.025 MeV. However, they did not measure the local density of the emulsion recording the tracks of interest, therefore, this estimated systematic uncertainty is largely underestimated. To estimate the systematic uncertainty properly, the local emulsion density will be measured for each hypernuclear event of interest using the already developed CNN model for detecting alpha-decay events[56].

[H1] Beyond the puzzles

Further directions of research can include the following:

- Obtain very precise measurements of the binding energy and lifetime of a variety of Λ-hypernuclei for a better understanding of the Λ-nucleon (N) interaction, using nuclear emulsions and experiments with heavy-ion beams,
- Search for very-neutron-rich hypernuclei and the corresponding resonance states to understand the nature of the Λ-N interaction in neutron-rich nuclear matter, using experiments with heavy-ion beams,
- Extend the understanding of double-strangeness hypernuclei with studies of the Λ-Λ and Ξ-N interactions, using nuclear emulsions and experiments with heavy-ion beams,
- Search for unobserved hypernuclei such as Σ-hypernuclei, using nuclear emulsions and experiments with heavy-ion beams.

Experiments with heavy-ion beams will be performed at FAIR[49] in Germany and HIAF[50] in China, both of which will be operational around 2025.

[H3] Deep mining for more strangeness in the E07 emulsions

As discussed above, the E07 experiment at J-PARC was designed to search for double-strangeness hypernuclei with the hybrid method[7,8,51]. The analysis of the E07 emulsion data has already revealed 33 event candidates for double-strangeness hypernuclei. Together with 14 candidates of double-strangeness hypernuclei found in previous experiments[52,53,61–65], there are 47 event candidates so far. However, only three of them have been uniquely identified and published[8,9,64] with two more candidates reported recently[66]. For the remaining candidates, the constraints on the kinematics in the reconstruction of the events are not sufficient to enable a unique identification. When there are several similar events, each event candidate has a different constraint on the kinematics, but each constraint can induce an additional limitation on the other similar events. Therefore, those events have more information than that with only a single event, which can lead to a unique identification. Therefore, it is important to increase the total number of event candidates, but this can no longer be achieved with the hybrid method on the E07 emulsion data.

Similar to the hypertriton analysis discussed before, a complete scanning of the entire emulsion data can lead to the increase in the number of candidates for double-strangeness hypernuclei, and it has been estimated that approximately 1000 candidates in total could be observed[67]. Figure 2e shows one of the observed event candidates for double-strangeness hypernuclei. It is characterised by three vertices a feature that can be identified by analytical filtering. However, the current method[68] requires a lot of human effort after the classification, and the analysis of the entire data set will still take approximately 200 years so a machine learning model with Mask R-CNN[59] was developed to mine for double-strangeness hypernuclei events. Surrogate emulsion images generated by Monte Carlo simulations and the GAN technique[57,58] were again used for training the detection model. The trained model was tested with the existing double-strangeness hypernuclear event candidates from previous experiments. This is currently work in progress.

The search for double-strangeness hypernuclei can be performed together with the hypertriton searches and therefore, approximately 10 event candidates for double-strangeness hypernuclei are expected to be identified within a year. An additional 30 candidates could be observed within two years, and a total of 1000 event candidates are expected within 5 years.

Studies of single-strangeness hypernuclei will also use the E07 emulsions, and searches to multi-body decays are anticipated[21,22]. For example, one can search for Λ-hypernuclear candidates up to approximately A=20, and deduce their binding energies very precisely, similarly to the case of the hypertriton. The lifetime of these Λ-hypernuclei will be measured at HIAF with an excellent accuracy of 0.5 ps. The combination of data will reveal the detailed nature of these hypernuclei. In particular, the ${}^{4}_{\Lambda}$He hypernucleus is of special interest because the re-measurement of its binding energy should contribute to a further understanding of the observed charge-symmetry breaking in ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He hypernuclei[69]. The expected accuracy for the measurement of the binding energy of ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He is approximately 25 keV or better.

Other searches in the E07 emulsions with machine learning include the Σ-hypernuclei via the Σ^- hyperon capture in a nucleus in the emulsion. Assuming that a Σ^--hypernucleus, ${}^{A}_{\Sigma^-}$Z, is bound and produced, it will immediately be converted to unstable ${}^{A}_{\Lambda}$Z* because a pair of Σ^--p inside the nucleus is mixed with Σ^0-n by the strong interaction and the Σ^0 hyperon decays with the lifetime of the order of 10^{-20} s. Due to the large mass difference between Σ and Λ, an energetic dissociation of ${}^{A}_{\Lambda}$Z* will take place. Very rarely, a two-body dissociation to a Λ-hypernucleus and a residual nucleus with a back-to-back geometry may take place. To detect such an event, a machine learning model to search for an event with a track along which Σ^- hyperon is stopped and such a dissociation needs to be developed.

[H3] Hypernuclear experiments at super-FRS at FAIR

Further experimental studies on neutron- and proton-rich hypernuclei using primary heavy-ion beams and rare isotope beams are planned at the Super-FRS facility[70] at FAIR[49], which will be operational in 2025. Figure 3 shows the FAIR accelerator complex and its NUSTAR facility. The development of a dedicated experimental setup as a post-WASA central detector for hypernuclear experiments at Super-FRS is under consideration. The construction of the new setup will begin after the completion of the WASA-FRS experiment in 2022. The dedicated detector in the current proposal consists of a superconducting solenoid magnet with an inner diameter of approximately 2 m and a field length of 2 m, providing a magnetic field of up to 2 T. Inside the magnet, there will be a stack of planar drift chambers, a barrel of plastic scintillators with MPPCs surrounding the drift chambers, and front and end caps with plastic scintillators with MPPCs or resistive plate chambers (RPCs). In front of the magnet, scintillating fibre detectors similar to those for the WASA-FRS hypernuclear experiment and new Si-strip detectors will be mounted. The planned detector is the same as the one used as a part of the experimental setup for the hypernuclear experiments at HIAF (see Figure 3e). This dedicated detector system will be installed in the mid-focal plane of the Super-FRS, indicated by the light-blue circle in Figure 3b. Measurements for hypernuclei of interest will be performed using the invariant mass method, similar to the WASA-FRS hypernuclear experiment. In addition to primary beams, rare isotope beams produced and identified by the pre-separator and the first half of the main separator of the Super-FRS will be used to produce proton- and neutron-rich hypernuclei. The possibility of producing these exotic hypernuclei has already been investigated[71]. In experiments using rare-isotope beams, proton-rich hypernuclei will mainly be studied since neutron measurements from hypernuclear decay in the planned setup have not yet been considered.

To study neutron-rich hypernuclei with the Super-FRS, a new method was proposed[72,73]. In this method, very-neutron-rich hypernuclei will be produced via single- and double-charge exchange reactions with primary beams on various nuclear targets, combined with ΛK^+ production in the target nucleus. As described in Refs[72,73], one or two protons in a target nucleus are converted to neutron(s) by the charge-exchange reaction, and an additional proton in the target nucleus is converted to a Λ hyperon. Thus, very-neutron-rich hypernuclei can be produced at the target located at the mid-focal plane of the Super-FRS. The produced neutron-rich hypernuclei will be identified using the missing mass method by measuring the incident beams, the outgoing projectile residue and the K^+ meson. Incident projectiles and outgoing projectile residues are measured very precisely by the Super-FRS, and K^+ mesons are measured by the dedicated detector discussed above with reasonable resolution and acceptance. To avoid ambiguity in the missing mass calculations, the outgoing residues should be bound only at their ground states, of which ^{9}C and ^{12}C are good cases because missing mass for hypernuclei of interest can not be determined when outgoing residues are bound at excited states. Therefore, two reaction channels exist: (^{12}C, ^{12}N K^+), single-charge-exchanged with p→ ΛK^+, and (^{9}Be, ^{9}C K^+), double-charge-exchanged with p→ ΛK^+. Feasibility studies have already been performed on the events generated by the UrQMD calculations[74,75], and it has been demonstrated that very-neutron-rich hypernuclei and associated resonances will be produced and could be studied, including Λnn, Λnnn, Λnnnnn, Λnnnnnn, ${}^{6}_{\Lambda}$H, ${}^{7}_{\Lambda}$H, ${}^{9}_{\Lambda}$H, ${}^{9}_{\Lambda}$He, ${}^{10}_{\Lambda}$He, ${}^{10}_{\Lambda}$Li, ${}^{11}_{\Lambda}$Li, ${}^{12}_{\Lambda}$Li, and so on[72,73].

[H3] Hypernuclear experiments at HIAF

Another large-scale heavy-ion accelerator facility that will enable the study of single- and double-strangeness hypernuclei with heavy-ion beams is the HIAF facility[50] in China. It will also be operational in 2025 and experiments have been proposed to take place in the high-energy cave and the high-energy fragment separator (HFRS) at HIAF. Figure 3c,d shows a bird's-eye view of a rendered image of the HIAF facility and a schematic layout of the HIAF accelerator complex, respectively. Hypernuclear production and measurements are planned with primary heavy-ion beams from the main booster ring with 34 Tm magnetic rigidity, providing heavy-ion beams at 4.25 A GeV for $N = Z$, delivered to the high-energy cave indicated by the red square in the figure[50,76]. A dedicated setup, shown in Figure 3e, will be built behind the dedicated beam line. In the proposed setup, there are two magnets, a superconducting solenoid magnet and a dipole magnet, both with up to 2 T magnetic field. In front of the solenoid magnet surrounding the target, a complex of vertex detectors with Si-strip detectors (SSD) and scintillating fibres is mounted for measuring the interaction point of the beam in the target. A stack of drift chambers or GEM (Gas Electron Multiplier) detectors to measure tracks of light charged particles is placed inside the solenoid magnet. Surrounding these detectors, a barrel composed of plastic scintillators is placed for measuring Time-of-Flight, energy deposition and hit positions of light charged particles. Behind the solenoid and dipole magnets, there are arrays of detectors with RPCs (Resistive Plate Chambers), straw-tube detectors and plastic scintillator hodoscopes to measure Time-of-Flight, energy deposition and hit positions of charged particles.

The solenoid magnet and its inner detectors are the same or similar to those developed for the experiment involving Super-FRS at FAIR, discussed above. The proposed setup will combine the techniques from previous experiments, that is techniques for the detectors around the dipole magnet from the HypHI project and those associated with the solenoid magnet from the WASA-FRS experiment.

A primary beam at 4.25 A GeV, for example, of ^{20}Ne projectiles, will be used to bombard a massive diamond target, and a large variety of single- and double-strangeness hypernuclei will be produced. These will be measured by the invariant mass method. The rates of the observed hypernuclei were estimated assuming that the intensity of the ^{20}Ne beams is 10^7 per second. For single hypernuclei, the expected observation rate is 8×10^5 per day for each type. With 1.25 days of measurement with a million observed counts, the accuracy of the lifetime measurement will be approximately 0.5 ps, which is similar to the present precision for the Λ hyperon. Particularly interesting is the measurement of the lifetime of the Λ-hypernuclei because accurate data for both their binding energy and their lifetime can be obtained. These data sets will test the theoretical models very precisely. For double-strangeness hypernuclei, the expected observation rate per week for each kind is 6×10^2, and measurements for four weeks will provide an accuracy of approximately 10 ps for the lifetime measurements. Measuring the lifetime of the double-strangeness hypernuclei is also of interest because of the availability of both accurate binding energy and lifetime values. Additionally, neutral hypernuclei such as Λnn, $\Lambda\Lambda$n and $\Lambda\Lambda$nn can be produced and studied very precisely. Furthermore, the large observation rates for the Λ-hypernuclei offer a great opportunity to analyse elastic and inelastic scattering on a secondary nuclear target, providing Λ-hypernuclear scattering data for the first time.

The solenoid magnet and its inner detector can also be mounted at the mid-focal plane of the HFRS, indicated by the red circle in Figure 3d. Hypernuclear production with single- and double-charge-exchange reactions with ΛK^+ production can also be performed similarly to the experiments at Super-FRS, but at higher energies up to approximately 2.9 A GeV for $N = Z$ nuclei. These reactions at this energy provide opportunities to search for neutron-rich Σ-hypernuclei. The ΛN-ΣN coupling may become stronger with larger neutron excess and may provide more binding for a state of the Σ-nucleus system.

[H1] Outlook

The present conundrums regarding light hypernuclei, namely, the nature of the hypertriton and the existence of the Λnn bound state, are expected to be clarified by the WASA-FRS hypernuclear experiment at GSI and the machine learning analysis of the J-PARC E07 nuclear emulsion data. After that experiments will study hypernuclei with heavy-ion beams at FAIR and HIAF and a further analysis of the nuclear emulsion data will provide more information.

We expect a derivation of the binding energy with an accuracy of a few keV and the lifetime with an accuracy of 0.5 ps for single-strangeness hypernuclei. The size of the data sample of double-strangeness hypernuclei will be increased with an expected number of approximately 1000 event candidates. Many of these will provide precise information on the Λ-Λ interaction energy, with an accuracy of a few hundred keV for a single event. The accuracy of the lifetime of the double-strangeness hypernuclei is expected to be better than 10 ps in the experiments with heavy-ion beams at HIAF. Furthermore, the stability of single- and double-strangeness hypernuclei could be revealed, especially on neutron-rich hypernuclei and resonance states with strangeness, and we will search for the limit of the bound neutron number (neutron drip-line) for light hypernuclei in order to investigate the stability of neutron rich hypernuclei. Some of the Σ-hypernuclei may be observed. Data on the scattering of Λ-hypernuclei on a nuclear target could also be obtained.

All these future measurements will raise questions in theoretical nuclear physics, which we hope theorists will start tackling.

- Do or will we comprehensively understand both the binding energy and lifetime of Λ-hypernuclei? Will theoretical calculations achieve a similar precision to the improved experimental accuracy?
- Do or will theoretical calculations be able to deduce Λ-Λ and Ξ-N interactions precisely with drastically increased data-sample size for double-strangeness hypernuclei by the nuclear emulsion and experiments with heavy-ion beams?

Can the nature of nuclear matter in the interior of the neutron stars be manifested by the deduced interactions?

- How will the information on very-neutron-rich hypernuclei be applied to understand comprehensively the dense neutron-rich nuclear matter in the core of the neutron stars? Are there any theoretical frameworks?
- If we discover some unknown Σ-hypernuclei, how the existence will modify our understanding on the neutron stars? Is there any theory to predict it?

We foresee that the field of hypernuclear physics will enter a new era with high-precision and large data samples which, together with theoretical advances will contribute to understanding the stability of hypernuclei.

References

1. Weber, F. Strangeness in neutron stars. *J. Phys. G: Nucl. Part. Phys.* **27**, 465–474, DOI: 10.1088/0954-3899/27/3/326 (2001).
2. Weber, F., Ho, A., Negreiros, R. P. & Rosenfield, P. Strangeness in neutron stars. *Int. J. Mod. Phys. D* **16**, 231–245, DOI: 10.1142/S0218271807009966 (2007). https://doi.org/10.1142/S0218271807009966.
3. Demorest, P. B., Pennucci, T., Ransom, S. M., Roberts, M. S. E. & Hessels, J. W. T. A two-solar-mass neutron star measured using Shapiro delay. *Nature* **467**, 1081–1083, DOI: 10.1038/nature09466 (2010).
4. Antoniadis, J. *et al.* A Massive Pulsar in a Compact Relativistic Binary. *Science* **340**, 1233232, DOI: 10.1126/science.1233232 (2013). https://science.sciencemag.org/content/340/6131/1233232.full.pdf.
5. Barr, E. D. *et al.* A massive millisecond pulsar in an eccentric binary. *Mon. Notices Royal Astron. Soc.* **465**, 1711–1719, DOI: 10.1093/mnras/stw2947 (2016). https://academic.oup.com/mnras/article-pdf/465/2/1711/13481220/stw2947.pdf.
6. Yamamoto, Y., Furumoto, T., Yasutake, N. & Rijken, T. A. Hyperon mixing and universal many-body repulsion in neutron stars. *Phys. Rev. C* **90**, 045805, DOI: 10.1103/PhysRevC.90.045805 (2014).
7. Ekawa, H. *et al.* Observation of a Be double-Lambda hypernucleus in the J-PARC E07 experiment. *Prog. Theor. Exp. Phys.* **2019**, DOI: 10.1093/ptep/pty149 (2019). 021D02, https://academic.oup.com/ptep/article-pdf/2019/2/021D02/27970468/pty149.pdf.
8. Hayakawa, S. H. *et al.* Observation of coulomb-assisted nuclear bound state of $\Xi^- - ^{14}$N system. *Phys. Rev. Lett.* **126**, 062501, DOI: 10.1103/PhysRevLett.126.062501 (2021).
9. Takahashi, H. *et al.* Observation of a $^{6}_{\Lambda\Lambda}$He double hypernucleus. *Phys. Rev. Lett.* **87**, 212502, DOI: 10.1103/PhysRevLett.87.212502 (2001).
10. Nakazawa, K. & Takahashi, H. Experimental Study of Double-Λ Hypernuclei with Nuclear Emulsion. *Prog. Theor. Phys. Suppl.* **185**, 335–343, DOI: 10.1143/PTPS.185.335 (2010). https://academic.oup.com/ptps/article-pdf/doi/10.1143/PTPS.185.335/5337597/185-335.pdf.
11. Rappold, C. *et al.* Hypernuclear production cross section in the reaction of ^{6}Li + ^{12}C at 2 *A* GeV. *Phys. Lett. B* **747**, 129–134, DOI: https://doi.org/10.1016/j.physletb.2015.05.059 (2015).
12. The STAR collaboration. Observation of an antimatter hypernucleus. *Science* **328**, 58–62, DOI: 10.1126/science.1183980 (2010). https://science.sciencemag.org/content/328/5974/58.full.pdf.
13. Xu, Y. for the STAR Collaboration. Measurement of Hypertriton Lifetime at STAR. *Proc. 12th Int. Conf. on Hypernucl. Strange Part. Phys. (HYP2015)* 021005, DOI: 10.7566/JPSCP.17.021005 (2017). https://journals.jps.jp/doi/pdf/10.7566/JPSCP.17.021005.
14. Adamczyk, L. *et al.* Measurement of the $^{3}_{\Lambda}$H lifetime in Au+Au collisions at the BNL Relativistic Heavy Ion Collider. *Phys. Rev. C* **97**, 054909, DOI: 10.1103/PhysRevC.97.054909 (2018).
15. Chen, J., Keane, D., Ma, Y.-G., Tang, A. & Xu, Z. Antinuclei in heavy-ion collisions. *Phys. Reports* **760**, 1–39, DOI: https://doi.org/10.1016/j.physrep.2018.07.002 (2018). Antinuclei in Heavy-Ion Collisions.
16. Adam, J. *et al.* $^{3}_{\Lambda}$H and $\overline{^{3}_{\Lambda}\mathrm{H}}$ production in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV. *Phys. Lett. B* **754**, 360 – 372, DOI: https://doi.org/10.1016/j.physletb.2016.01.040 (2016).
17. Acharya, S. *et al.* $^{3}_{\Lambda}$H and $\overline{^{3}_{\Lambda}\mathrm{H}}$ lifetime measurement in Pb-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV via two-body decay. *Phys. Lett. B* **797**, 134905, DOI: https://doi.org/10.1016/j.physletb.2019.134905 (2019).

18. Adam, J. *et al.* Measurement of the mass difference and the binding energy of the hypertriton and antihypertriton. *Nat. Phys.* **16**, 409–412, DOI: 10.1038/s41567-020-0799-7 (2020).

19. Rappold, C. *et al.* Search for evidence of ${}^{3}_{\Lambda}n$ by observing $d+\pi^{-}$ and $t+\pi^{-}$ final states in the reaction of ^{6}Li+^{12}C at $2A$ GeV. *Phys. Rev. C* **88**, 041001, DOI: 10.1103/PhysRevC.88.041001 (2013).

20. Davis, D. 50 years of hypernuclear physics: I. the early experiments. *Nucl. Phys. A* **754**, 3 – 13, DOI: https://doi.org/10.1016/j.nuclphysa.2005.01.002 (2005). Proceedings of the Eighth International Conference on Hypernuclear and Strange Particle Physics.

21. Bohm, G. *et al.* A determination of the binding-energy values of light hypernuclei. *Nucl. Phys. B* **4**, 511–526, DOI: https://doi.org/10.1016/0550-3213(68)90109-0 (1968).

22. JuriÄ, M. *et al.* A new determination of the binding-energy values of the light hypernuclei ($A \leq 15$). *Nucl. Phys. B* **52**, 1 – 30, DOI: https://doi.org/10.1016/0550-3213(73)90084-9 (1973).

23. Prem, R. J. & Steinberg, P. H. Lifetimes of hypernuclei, ${}_{\Lambda}\mathrm{H}^{3}$, ${}_{\Lambda}\mathrm{H}^{4}$, ${}_{\Lambda}\mathrm{H}^{5}$. *Phys. Rev.* **136**, B1803–B1806, DOI: 10.1103/PhysRev.136.B1803 (1964).

24. Keyes, G. *et al.* New measurement of the ${}_{\Lambda}\mathrm{H}^{3}$ lifetime. *Phys. Rev. Lett.* **20**, 819–821, DOI: 10.1103/PhysRevLett.20.819 (1968).

25. Phillips, R. E. & Schneps, J. Lifetimes of light hyperfragments. ii. *Phys. Rev.* **180**, 1307–1318, DOI: 10.1103/PhysRev.180.1307 (1969).

26. Bohm, G. *et al.* On the lifetime of the ${}^{3}_{\Lambda}\mathrm{H}$ hypernucleus. *Nucl. Phys. B* **16**, 46–52, DOI: https://doi.org/10.1016/0550-3213(70)90335-4 (1970).

27. Keyes, G. *et al.* Properties of ${}_{\Lambda}\mathrm{H}^{3}$. *Phys. Rev. D* **1**, 66–77, DOI: 10.1103/PhysRevD.1.66 (1970).

28. Keyes, G., Sacton, J., Wickens, J. & Block, M. A measurement of the lifetime of the ${}^{3}_{\Lambda}\mathrm{H}$ hypernucleus. *Nucl. Phys. B* **67**, 269–283, DOI: https://doi.org/10.1016/0550-3213(73)90197-1 (1973).

29. Particle Data Group *et al.* Review of Particle Physics. *Prog. Theor. Exp. Phys.* **2020**, DOI: 10.1093/ptep/ptaa104 (2020). 083C01, https://academic.oup.com/ptep/article-pdf/2020/8/083C01/34673722/ptaa104.pdf.

30. Rappold, C. *et al.* Hypernuclear spectroscopy of products from ^{6}Li projectiles on a carbon target at 2A GeV. *Nucl. Phys. A* **913**, 170 – 184, DOI: https://doi.org/10.1016/j.nuclphysa.2013.05.019 (2013).

31. Ma, Yu-Gang. (anti)hypertriton lifetime puzzle. *EPJ Web Conf.* **117**, 03003, DOI: 10.1051/epjconf/201611703003 (2016).

32. Perez-Obiol, A., Gazda, D., Friedman, E. & Gal, A. Revisiting the hypertriton lifetime puzzle. *Phys. Lett. B* **811**, 135916, DOI: https://doi.org/10.1016/j.physletb.2020.135916 (2020).

33. Hildenbrand, F. & Hammer, H.-W. Lifetime of the hypertriton. *Phys. Rev. C* **102**, 064002, DOI: 10.1103/PhysRevC.102.064002 (2020).

34. Hiyama, E. *et al.* Three-body structure of the $nn\Lambda$ system with $\Lambda N-\Sigma N$ coupling. *Phys. Rev. C* **89**, 061302, DOI: 10.1103/PhysRevC.89.061302 (2014).

35. Gal, A. & Garcilazo, H. Is there a bound ${}^{3}_{\Lambda}\mathrm{n}$? *Phys. Lett. B* **736**, 93 – 97, DOI: https://doi.org/10.1016/j.physletb.2014.07.009 (2014).

36. Garcilazo, H. & Valcarce, A. Nonexistence of a Λnn bound state. *Phys. Rev. C* **89**, 057001, DOI: 10.1103/PhysRevC.89.057001 (2014).

37. Schafer, M. *et al.* The continuum spectrum of hypernuclear trios. *Phys. Lett. B* **808**, 135614, DOI: https://doi.org/10.1016/j.physletb.2020.135614 (2020).

38. Ando, S.-I., Raha, U. & Oh, Y. Investigation of the $nn\Lambda$ bound state in pionless effective theory. *Phys. Rev. C* **92**, 024325, DOI: 10.1103/PhysRevC.92.024325 (2015).

39. Hildenbrand, F. & Hammer, H.-W. Three-body hypernuclei in pionless effective field theory. *Phys. Rev. C* **100**, 034002, DOI: 10.1103/PhysRevC.100.034002 (2019).

40. Afnan, I. R. & Gibson, B. F. Resonances in the Λnn system. *Phys. Rev. C* **92**, 054608, DOI: 10.1103/PhysRevC.92.054608 (2015).

41. Tang, L. *et al.* Determining the Unknown Λ-n Interaction by Investigating the Λnn Resonance. *approved proposal E12-17-003 by PAC at Jefferson Lab.* (2017). https://www.jlab.org/exp_prog/proposals/17/PR12-17-003.pdf.

42. Bleser, S. *et al.* Has the neutral double hypernucleus ${}^{4}_{\Lambda\Lambda}$n been observed? *Phys. Lett. B* **790**, 502 – 508, DOI: https://doi.org/10.1016/j.physletb.2019.01.047 (2019).

43. Le, H., Haidenbauer, J., Meiner, U.-G. & Nogga, A. Implications of an increased λ-separation energy of the hypertriton. *Phys. Lett. B* **801**, 135189, DOI: https://doi.org/10.1016/j.physletb.2019.135189 (2020).

44. Haidenbauer, J., Meißner, U.-G. & Nogga, A. Hyperon–nucleon interaction within chiral effective field theory revisited. *The Eur. Phys. J. A* **56**, 91, DOI: 10.1140/epja/s10050-020-00100-4 (2020).

45. Geissel, H. *et al.* The gsi projectile fragment separator (frs): a versatile magnetic system for relativistic heavy ions. *Nucl. Instruments Methods Phys. Res. Sect. B: Beam Interactions with Mater. Atoms* **70**, 286–297, DOI: https://doi.org/10.1016/0168-583X(92)95944-M (1992).

46. Bargholtz, C. *et al.* The WASA detector facility at CELSIUS. *Nucl. Instruments Methods Phys. Res. Sect. A: Accel. Spectrometers, Detect. Assoc. Equip.* **594**, 339–350, DOI: https://doi.org/10.1016/j.nima.2008.06.011 (2008).

47. Saito, T. R. *et al.* Studies of the d+π^- signal and lifetime of the ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H hypernuclei by new spectroscopy techniques with FRS. *approved proposal S447 by GSI G-PAC* (2017).

48. Outa, H. *et al.* Mesonic and non-mesonic decay widths of ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He. *Nucl. Phys. A* **639**, 251c–260c, DOI: https://doi.org/10.1016/S0375-9474(98)00281-4 (1998). Proceedings of the International Conference on Hypernuclear and Strange Particle Physics.

49. Webpage of Facility for Antiproton and Ion Research in Europe (FAIR). https://fair-center.eu.

50. Webpage of High Intensity Heavy-ion Accelerator Facility (HIAF). http://hiaf.impcas.ac.cn/hiaf_en/public/c/news.html.

51. Imai, K., Nakazawa, K. & Tamura, H. J-PARC E07 experiment: Systematic study of double-strangeness system with an emulsion-counter hybrid method. *Propos. for Nucl. Part. Phys. Exp. at J-PARC* (2006).

52. Aoki, S. *et al.* Nuclear capture at rest of Ξ^--hyperons. *Nucl. Phys. A* **828**, 191–232, DOI: https://doi.org/10.1016/j.nuclphysa.2009.07.005 (2009).

53. Ahn, J. K. *et al.* Double-Λ hypernuclei observed in a hybrid emulsion experiment. *Phys. Rev. C* **88**, 014003, DOI: 10.1103/PhysRevC.88.014003 (2013).

54. LeCun, Y., Bengio, Y. & Hinton, G. Deep learning. *Nature* **521**, 436–444, DOI: 10.1038/nature14539 (2015).

55. He, K., Zhang, X., Ren, S. & Sun, J. Deep residual learning for image recognition. *arXiv preprint* (2015). http://arxiv.org/abs/1512.03385.

56. Yoshida, J. *et al.* CNN-based event classification of alpha-decay events in nuclear emulsion. *Nucl. Instruments Methods Phys. Res. Sect. A: Accel. Spectrometers, Detect. Assoc. Equip.* 164930, DOI: https://doi.org/10.1016/j.nima.2020.164930 (2020).

57. Goodfellow, I. J. *et al.* Generative Adversarial Networks. *arXiv preprint* (2014). https://arxiv.org/abs/1406.2661.

58. Wang, T. *et al.* High-resolution image synthesis and semantic manipulation with conditional gans. *arXiv preprint* (2017). http://arxiv.org/abs/1711.11585.

59. He, K., Gkioxari, G., Dollár, P. & Girshick, R. B. Mask R-CNN. *arXiv preprint* (2017). https://arxiv.org/abs/1703.06870.

60. Barkas, W. H. Nuclear Research Emulsions. Pure & Applied Physics series 15-I.

61. Danysz, M. *et al.* The identification of a double hyperfragment. *Nucl. Phys.* **49**, 121–132, DOI: https://doi.org/10.1016/0029-5582(63)90080-4 (1963).

62. Dalitz, R. H. *et al.* The Identified $\Lambda\Lambda$-Hypernuclei and the Predicted H-Particle. *Proc. Royal Soc. London. Ser. A, Math. Phys. Sci.* **426**, 1–17, DOI: 10.2307/2398533 (1989).

63. Aoki, S. *et al.* Direct Observation of Sequential Weak Decay of a Double Hypernucleus. *Prog. Theor. Phys.* **85**, 1287–1298, DOI: 10.1143/PTP.85.1287 (1991). https://academic.oup.com/ptp/article-pdf/85/6/1287/5211910/85-6-1287.pdf.

64. Nakazawa, K. *et al.* The first evidence of a deeply bound state of Xi$^-$-14N system. *Prog. Theor. Exp. Phys.* **2015**, DOI: 10.1093/ptep/ptv008 (2015). 033D02, https://academic.oup.com/ptep/article-pdf/2015/3/033D02/9720010/ptv008.pdf.

65. Ichikawa, A. *et al.* Production of twin Λ-hypernuclei from Ξ^- hyperon capture at rest. *Phys. Lett. B* **500**, 37–46, DOI: https://doi.org/10.1016/S0370-2693(01)00049-1 (2001).

66. Yoshimoto, M. *et al.* First observation of a nuclear *s*-state of ξ hypernucleus, ${}^{15}_{\Xi}$c. *arXiv preprint* (2021). https://arxiv.org/abs/2103.08793.

67. Yoshida, J., Nakazawa, K. & Umehara, K. *New Methods and Technologies for Double-Lambda Hypernucleus Search in Nuclear Emulsion in J-PARC E07*. https://journals.jps.jp/doi/pdf/10.7566/JPSCP.1.013070.

68. Yoshida, J. *et al.* A new scanning system for alpha decay events as calibration sources for range-energy relation in nuclear emulsion. *Nucl. Instruments Methods Phys. Res. Sect. A: Accel. Spectrometers, Detect. Assoc. Equip.* **847**, 86–92, DOI: https://doi.org/10.1016/j.nima.2016.11.044 (2017).

69. Yamamoto, T. O. *et al.* Observation of Spin-Dependent Charge Symmetry Breaking in ΛN Interaction: Gamma-Ray Spectroscopy of ${}^{4}_{\Lambda}$He. *Phys. Rev. Lett.* **115**, 222501, DOI: 10.1103/PhysRevLett.115.222501 (2015).

70. Webpage of Super-FRS. https://fair-center.eu/en/for-users/experiments/nustar/super-frs.html.

71. Rappold, C. & López-Fidalgo, J. Examination of experimental conditions for the production of proton-rich and neutron-rich hypernuclei. *Phys. Rev. C* **94**, 044616, DOI: 10.1103/PhysRevC.94.044616 (2016).

72. Saito, T. R., Ekawa, H. & Nakagawa, M. Novel method for producing very-neutron-rich hypernuclei via charge-exchange reactions with heavy ion projectiles. *The Eur. Phys. J. A* **57**, 159, DOI: https://doi.org/10.1140/epja/s10050-021-00470-3 (2021).

73. Saito, T., Ekawa, H. & Nakagawa, M. Novel method for producing very-neutron-rich hypernuclei via charge-exchange reactions with heavy ion projectiles. *arXiv preprint* (2021). https://arxiv.org/abs/2104.08990.

74. Bass, S. *et al.* Microscopic models for ultrarelativistic heavy ion collisions. *Prog. Part. Nucl. Phys.* **41**, 255–369, DOI: https://doi.org/10.1016/S0146-6410(98)00058-1 (1998).

75. Bleicher, M. *et al.* Relativistic hadron-hadron collisions in the ultra-relativistic quantum molecular dynamics model. *J. Phys. G: Nucl. Part. Phys.* **25**, 1859–1896, DOI: 10.1088/0954-3899/25/9/308 (1999).

76. Yang, J. *et al.* High intensity heavy ion accelerator facility (hiaf) in china. *Nucl. Instruments Methods Phys. Res. Sect. B: Beam Interactions with Mater. Atoms* **317**, 263–265, DOI: https://doi.org/10.1016/j.nimb.2013.08.046 (2013). XVIth International Conference on ElectroMagnetic Isotope Separators and Techniques Related to their Applications, December 2,Äì7, 2012 at Matsue, Japan.

77. Danysz, M. & Pniewski, J. Delayed disintegration of a heavy nuclear fragment. *Phil. Mag.* **44**, 348, DOI: https://doi.org/10.1080/14786440308520318 (1953).

78. Hashimoto, O. & Tamura, H. Spectroscopy of Λ hypernuclei. *Prog. Part. Nucl. Phys.* **57**, 564–653, DOI: https://doi.org/10.1016/j.ppnp.2005.07.001 (2006).

79. Saito, T. R. *et al.* Hypernuclei with Stable Heavy Ion Beam and RI-beam Induced Reactions at GSI (HypHI). *Lett. Intent submitted to GSI G-PAC* (2005).

80. Saito, T. R. *et al.* Phase 0 experiment of the HypHI project: Hypernuclear spectroscopy of ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H and ${}^{5}_{\Lambda}$He with a ^{6}Li beam at 2 A GeV on a ^{12}C target . *Propos. approved by GSI G-PAC* (2006).

81. Kalantar-Nayestanaki, N. & Bruce, A. Nustar: Nuclear structure astrophysics and reactions at fair. *Nucl. Phys. News* **28**, 5–11, DOI: 10.1080/10619127.2018.1495476 (2018). https://doi.org/10.1080/10619127.2018.1495476.

Acknowledgements

Discussions presented for the WASA-FRS experiment here are based on the experiment S447, which is currently scheduled in 2022 at the FRS at the GSI Helmholtzzentrum fuer Schwerionenforschung, Darmstadt (Germany) in the context of FAIR Phase-0. The authors thank the accelerator departments at GSI and IMP, the FRS department at GSI and the Experiment Electronics department at GSI for the technical support. The authors thank the J-PARC E07 collaboration to provide us the nuclear emulsion data. The authors thank Luise Doersching-Steitz of GSI, Rita Krause of GSI, Yukiko Kurakata of RIKEN, Daniela Press of GSI, Miao Yang of IMP and Xiaohua Yuan of IMP for supporting the projects, including the administrative works. The authors also thank Risa Kobayashi of RIKEN and Yoko Tsuchii of Gifu University for their technical support in mining hypertriton events in the E07 nuclear emulsions. KN, JY, and MY acknowledge support by JSPS KAKENHI Grant Numbers JP23224006, JP16H02180, JP20H00155, and JP20J00682, and MEXT KAKENHI Grant Numbers JP24105002 (Grant-in-Aid for Scientific Research on Innovative Areas 2404), JP18H05403, and JP19H05147 (Grant-in-Aid for Scientific Research on Innovative Areas 6005). SE and CR are supported by the grant 2019-T1/TIC-13194 of the program "Atracción de Talento Investigador" of the Community of Madrid.

Author contributions

All authors contributed to the manuscript. TRS, VD, HE, SE, NK, AK, MK, EL, SM, AM, MN, CR, NS, CS, MT, YKT, JY and HW contributed to the WASA-FRS experiment at GSI and will contribute to future hypernuclear projects at FAIR. TRS, WD, HE, AK, EL, AM, MN, KN, CR, NS, MT, YKT, JY, MY and HW contributed to the development of the method to analyse the nuclear emulsion with machine learning. TRS, HE, YH, EL, YM, MN, CR, HW and XZ are working on the hypernuclear project at HIAF.

Competing interests

The authors declare no competing interests.

Peer review information

Nature Reviews Physics thanks Yu-Gang Ma, Stefano Trogolo, Ed Hungerford and the other anonymous reviewer for their contribution to the peer review of this work.

Publisher's note

Supplementary information

Supplementary information is available for this paper at

Experiment	Reaction and energy	Production method	Lifetime (ps)	Year of publication
HypHI at GSI	^{6}Li+^{12}C at 2 A GeV	Projectile fragmentation	$183^{+42}_{-32} \pm 37$	2013 (Ref.[30])
STAR at RHIC	^{197}Au+^{197}Au at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV	Central collision	$182^{+89}_{-45} \pm 27$	2010 (Ref.[12])
			$155^{+25}_{-22} \pm 31$	2017 (Ref.[13])
			$142^{+24}_{-21} \pm 29$	2018 (Ref.[14,15])
ALICE at LHC	^{208}Pb+^{208}Pb at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV	Central collision	$181^{+54}_{-39} \pm 33$	2016 (Ref.[16])
	^{208}Pb+^{208}Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV		$242^{+34}_{-38} \pm 17$	2019 (Ref.[17])

Table 1. Summary of the measured lifetimes of the hypertriton obtained by the HypHI, STAR and ALICE collaborations. Note: The first and second errors represent the statistical and systematic uncertainty, respectively. $\sqrt{s_{\mathrm{NN}}}$ denotes the nucleon-nucleon (NN) centre-of-mass energy.

Box 1: Hypernuclear physics terminology

A particle composed of three, or an odd number of, quarks is called a baryon. An ordinary nucleus is formed by baryons called neutrons and protons. As illustrates in the figure below, a neutron consists of a single up quark and two down quarks (udd), whereas a proton consists of two up quarks and a single down quark (uud). Baryons with strange quarks (s) are known as hyperons. An example of a hyperon with a single strange quark is a Λ hyperon with one up, one down and one strange quark (uds). The isospin excitation of the Λ hyperon yields the so-called Σ hyperons: Σ^{+} (uus), Σ^{0} (uds) and Σ^{-} (dds). Hyperons with two strange quarks are Ξ^{0} (uss) and Ξ^{-} (dds). A Ξ^{-} hyperon is illustrated in the figure. There is also a hyperon with three strange quarks (sss), referred to as Ω^{-}.

A hypernucleus is defined as a bound state with hyperon(s) and nucleons, and an example of a single-Λ-hypernucleus is shown in the figure. When a single Ξ hyperon or two Λ hyperons are bound in the nucleus, they are called a Ξ-hypernucleus or a double Λ-hypernucleus, respectively. A hypernucleus is denoted in a similar manner as ordinary nuclei, but with an additional subscript, such as $^{A}_{Y}Z$. The total baryon number is denoted by A, and Z corresponds to the total charge number, but one can also use an atomic symbol. The subscript Y indicates the type of hyperons bound in the hypernucleus. For example, a hypernucleus with two neutrons, two protons and a Λ hyperon is denoted as $^{5}_{\Lambda}$He, and with an additional Λ hyperon, it is represented as $^{6}_{\Lambda\Lambda}$He.

Box 2: Experimental production of hypernuclei

After the discovery of the first hypernucleus[77] in 1953, hypernuclei have been extensively studied by using cosmic rays and beams from accelerators such as secondary meson beams and primary electron beams, and these conventional experimental methods have provided interesting observations on the production, structure and decay of approximately 40 hypernuclei[20,78]. In experiments with beams from accelerators, hypernuclei are produced from fixed stable target nuclei (such as ^{7}Li, ^{12}C) by converting one or two nucleon(s) to hyperon(s), and the isospin values of the produced hypernuclei are similar to those of the stable target nuclei.

The HypHI collaboration proposed performing experiments with reactions induced by relativistic heavy-ion beams bombarded onto a fixed nuclear target[79,80] combined with the invariant mass method in which hypernuclei of interest are produced via projectile fragments capturing hyperon(s) produced in a hot participant zone of the collisions, as illustrated below.

Due to the nature of projectile fragmentation reactions, the isospin of the produced hypernuclei is widely distributed; therefore, this approach can produce very-neutron-rich hypernuclei (also proton-rich hypernuclei). This method also provides opportunities to produce and study, heavy hypernuclei, complementary to ultra-relativistic heavy-ion collisions, which face limitations in observing hypernuclei with $A \lesssim 4$ since the yield is decreased by a factor of 1000 as as the mass number A is increased by one unit. The HypHI collaboration performed the first experiment, the so-called Phase 0, at the heavy-ion accelerator facility of GSI with a reaction of ^{6}Li+^{12}C at 2 A GeV, successfully producing and identifying the hypertriton and $^{4}_{\Lambda}$H, as projectile fragments, and Λ hyperons[30]. The production cross section of those hypernuclei in this reaction was also derived[11].

Schematic explanation of how hypernuclei can be produced by induced reactions of heavy-ion beams on a fixed target. Projectiles from an accelerator are bombarded onto a fixed nuclear target with sufficiently large energies to produce hyperon(s), which should exceed at least approximately 1.7 A GeV for the case of productions of a Λ-hypernucleus. After the collision, a hot and dense nuclear matter is produced in the overlapping region between the projectile and target nucleus, the so-called hot participant zone. The non-overlapping region of the projectile (called projectile fragment or spectator) proceeds almost in the same direction and with nearly the same velocity as the projectile, without having a large influence on the collision. A hyperon is produced together with other associated particles in the hot participant zone with a wide momentum distribution, and sometimes, a hyperon with a large longitudinal momentum is captured in the projectile fragment, forming a hypernucleus.

Figure 1. The WASA-FRS hypernuclear experiment. a. Schematic drawing of the fragment separator (FRS) at GSI. The ^{6}Li primary beams at 2 A GeV are delivered to the diamond target located at the mid-focal plane of the FRS, referred to as S2, to produce hypernuclei of interest. Residual nuclei of the π^- weak-decays of hypernuclei are transported from S2 to S4 in the FRS, and measured precisely with a momentum resolving power of 10^{-4}. The π^- mesons produced by the hypernuclear decays are measured at S2 by the WASA central detector. b. The WASA central detector. Panel b is reproduced with permission from Ref.[81].

Figure 2. Nuclear emulsion analysis. a. A schematic diagram of the two-body decay of the hypertriton at rest. b. An α-decay event recorded in the nuclear emulsion. c. A surrogate image of an event of a hypertriton two-body decay at rest in a nuclear emulsion produced by Monte Carlo simulations and Generative Adversarial Networks. The simulated images were used for the training of the detection model. d. The first discovered hypertriton event in the nuclear emulsion of the E07 experiment at J-PARC. A K^- meson flies into the emulsion from outside the emulsion modules and then propagates to point A by decreasing its energy. The K^- meson is stopped at A and is absorbed by one of the nuclei in the emulsion to produce five visible nuclear fragments: #1, #2, #3, #4 and $^3_\Lambda$H. Fragments #1, #2 and #3 are stopped at F, G and H, respectively, whereas fragment #4 penetrates away from the emulsion module. The hypertriton ($^3_\Lambda$H) produced at position A proceeds towards point B and then stops. In this figure, track #1 and the hypertriton track appear connected as a single line; however, they are not in the same plane. The hypertriton decays to ^{3}He and π^-, and they proceed towards points C and D, respectively, after which they are stopped. At point D, where π^- is stopped, another charged particle (#5) is emitted as a result of nuclear fragmentation. This is one of the indications that the negatively charged hadrons stopped and were absorbed by the other nucleus at the stop position. The measured ranges of each track are indicated in the figure. The inset shows the magnified region around point B. The numbers with errors indicate the measured track lengths. e. An event of a decay of a double-strangeness hypernucleus. π^- denotes a pion and p denotes a proton. See Box 1 for the hypernuclear physics terminology.

Figure 3. Upcoming hypernuclear experiments. a. A bird's-eye view of a rendered image of the FAIR facility. b. A schematic layout of the NUSTAR facility. The Super-FRS is shown with its pre- and main separators in light brown and orange, respectively. A dedicated experimental setup for hypernuclear experiments will be installed in the mid-focal plane, indicated by the light-blue circle. c. A bird's-eye view of a rendering image of the HIAF facility together with the China Initiative Accelerator Driven System (CiADS). d. A layout of the HIAF accelerator complex. e. The proposed detector setup in the high-energy cave. A part of the setup with the superconducting solenoid magnet will also be used in the mid-focal plane (indicated by the red circle) of the high-energy fragment separator (HFRS). RPC stands for resistive plate chambers; GEM Gas Electron Multiplier; SSD Si-strip detectors; TOF Time of Flight. Panel b is reproduced with permission from Ref.[81].