Study of light hypernuclei in Europe: the hypertriton and nnΛ puzzles

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Abstract. The current understanding of light hypernuclei, which are sub-atomic nuclei with strangeness, is being challenged and studied in detail by several European research groups and collaborations. In recent years, studies of hypernuclei using high-energy heavy ion beams have reported unexpected results on the three-body hypernuclear state $^{3}_{\Lambda}$H, named the hypertriton. For some time, reports of a shorter lifetime and larger binding energy than what was previously accepted have created a puzzling situation for its theoretical description; this is known as the "hypertriton puzzle". With the inclusion of the most recent experimental measurements, the current status of the hypertriton puzzle is evolving. Additionally, the possible neutral bound state of a Λ hyperon with two neutrons, nnΛ, has raised questions about our understanding of the formation of light hypernuclei either in bound or resonance states. These results have initiated several ongoing experimental programs all over the world to study these three-body hypernuclear states precisely. We are studying these light hypernuclear states by employing heavy ion beams at 2*A*GeV on a fixed carbon target with the WASA detector system and the Fragment Separator (FRS) at GSI. The WASA-FRS experimental campaign was performed during the first quarter of 2022, and this paper presents a short overview of the campaign and how it seeks to tackle the hypertriton and nnΛ puzzles. Data analysis is ongoing, and several preliminary results will be reported.

1 Introduction

Understanding the baryon-baryon interaction has been a major goal in studying the hypernucleus, which is a bound state of hyperons and nucleons. One key aspect of this research is determining the equation of state of baryonic matter, particularly in the strangeness sector. In recent years, nuclear spectroscopy using heavy-ion beams in collider mode or on fixed targets has emerged as an effective method for investigating hypernuclei. Several European research groups and collaborations are thoroughly investigating and testing our existing knowledge on light hypernuclei [1–5]. In the past ten years, studies of hypernuclear states using high-energy heavy-ion beams have yielded unexpected results regarding the three-body hypernuclear state ${}^{3}_{\Lambda}$H, also known as the hypertriton. The hypertriton is the lightest of the known bound hypernuclei. It is conventionally described as the state of the deuteron nuclear core with which a Λ hyperon is loosely bound. The indication of the weakly bound Λ was first observed in the nuclear emulsions used for hypernuclear studies in the 70s. A Λ binding energy of 130 ± 50 keV was reported [6, 7]. After an extended period, the understanding of the structure of the hypertriton was not challenged, until the first observation of the hypertriton by the STAR collaboration in the Au-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV in the ultra-relativistic energy regime [8]. An indication of a possible shorter lifetime than our current understanding was presented. Shortly after the report of the HypHI collaboration of their observation of light hypernuclei, a clear tendency for the experimental hypertriton lifetime leaned towards a shorter value than the different theoretical models predicted at that time [3, 9]. The ALICE collaboration shortly after also observed a hypertriton signal for the first time in Pb-Pb collisions at 2.76 TeV and initially measured a shorter lifetime [5]. Subsequently, more lifetime measurements by the collaborations using heavy-ion beams were obtained with conflicting tendencies [3, 5, 8, 10–13]. Furthermore, the STAR collaboration later published a larger Λ binding energy of 410 ± 120(stat) ± 110(sys) keV [14], while ALICE reported an estimation of a 50 ± 60 ± 100 keV Λ binding energy. All of these experimental observations and comparisons with our original understanding of the hypertriton structure have created a puzzle for its theoretical description, called the "hypertriton puzzle".

Moreover, the potential existence of a neutral bound state involving a Λ hyperon and two neutrons, nnΛ [15], has posed a challenge to the current understanding of the formation of resonance or bound states of light hypernuclei. The HypHI collaboration, besides observing the production of light hypernuclei in the ^{6}Li+^{12}C reaction [16], reported a possible signal in the t+π^- and d+π^- invariant mass spectrum. Those decay channels were associated with the mesonic weak decay of nnΛ $\rightarrow t + \pi^-$ and nnΛ $\rightarrow (d + n) + \pi^-$, where the neutron would not be observed. Extensive theoretical efforts were made to investigate the bound state of the system nnΛ using various approaches and models [17–20]. The results obtained by these efforts did not demonstrate a bound system, while in pionless effective field theory which its existence could not be excluded [21, 22]. Recently, a new experiment labelled E12-17-003 was conducted at JLab to explore the existence of the nnΛ state [20, 23]. The experiment utilized electron beams to bombard a tritium target. Two different interpretations of the results of the data analysis were published by the Hall A collaboration, one indicating possible existence of the nnΛ state with small significance [24], the other suggesting non-existence of nnΛ [25]. Hence, a definitive conclusion has not yet been reached, forming the so-called nnΛ puzzle. Further experimental studies that provide better precision and larger data samples are required to determine the possible existence of the nnΛ state conclusively.

Currently, several experimental efforts are ongoing around the world, particularly in Europe, to address these puzzles, as shown in Figure 1. These ongoing experimental programs across the globe aim at further investigating these three-body hypernuclear states with greater precision.

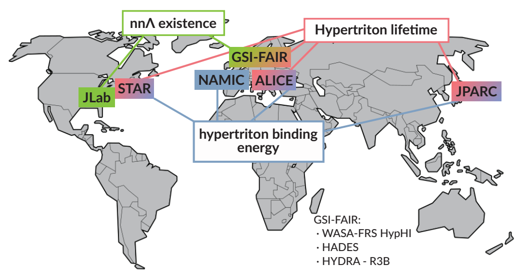

Figure 1. World effort to tackle the hypertriton and nnΛ puzzles.

One such effort in Europe is the WASA-FRS HypHI experiment, which focuses on the precise spectroscopy of light hypernuclei. The experimental objectives include the measurement of the lifetime of ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H, followed by the possible observation of the nnΛ state. The study is conducted using heavy ion beams at a kinetic energy of around 2 *A*GeV on a fixed carbon target, with the WASA detector system and the Fragment Separator (FRS) at the GSI-FAIR facility [4]. The WASA-FRS experimental campaign was

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conducted in the first quarter of 2022, with data analysis currently underway. The results of this research will help shed light on the puzzles surrounding three-body hypernuclear states.

2 WASA-FRS HypHI experiment

A new project has been proposed at GSI-FAIR to study hypernuclei using the WASA central detector. This detector, previously located at COSY in Jülich, Germany [26, 27], was transported to GSI-FAIR in 2019. It is used for pion measurement in conjunction with the high-resolution fragment separator (FRS) for measuring decay residues. The objective of this novel experiment, which has been approved for the FAIR-Phase 0 beam-time period, is to investigate the existence of a possible bound state of nnΛ and the hypertriton lifetime puzzle. To assess the feasibility of the experimental method, the experiment was carried out under conditions similar to those of the previously successful HypHI experiment. In particular, the focus is on reconstructing and identifying light hypernuclei, such as ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, and nnΛ, using the invariant mass method.

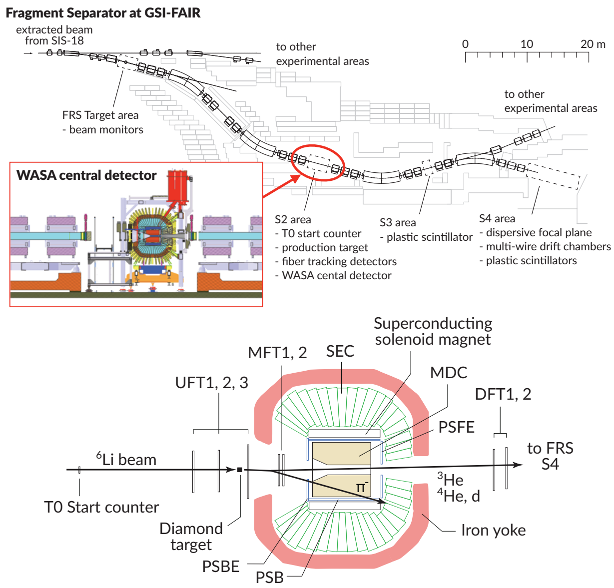

Figure 2. Experimental setup of the WASA-FRS experimental campaign. Top panel: the layout of the FRS, where the beam is directed towards the experimental area S2 for the production of hypernuclei. The FRS segment from S2 to S4 serves as a high-resolution forward spectrometer for the decay fragments. Bottom panel: the cylindrical WASA detector apparatus located in the S2 area, which is used to measure light particles such as pions within the solenoid magnet.

In an exclusive measurement, the mesonic weak decay of ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$, ${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$, and $\mathrm{nn}\Lambda \rightarrow \mathrm{d} + \mathrm{n} + \pi^{-}$ is the focus of the experiment. After the decay, a narrow magnetic rigidity acceptance window is set for the FRS in order to measure precisely the momentum of the outgoing decay fragment (^{3}He, ^{4}He, d). The layout of the FRS is illustrated in the top panel of Figure 2. The detection apparatus at the S2 experimental area is responsible for measuring a large portion of the emitted π^{-}, as depicted in the bottom panel of Figure 2. The experimental setup for our study utilized the WASA central detector, which consists of a superconducting solenoid magnet capable of producing magnetic fields up to 1 T, iron yokes, and a cryogenic system. The WASA detection system includes a calorimeter with CsI crystals (SEC), an inner drift chamber with straw tubes (MDC), and newly developed arrays of plastic barrel hodoscopes (PSB) [28] and end-cap hodoscopes (PSFE and PSBE). In the first quarter of 2022, two experiments encompass a data-taking campaign: S490 to search for η'-nuclei and S447 to study hypernuclei. The experimental setup used for studying hypernuclei (S447, WASA-FRS-HypHI) is illustrated in the bottom panel of Figure 2. In addition to the conventional WASA apparatus, extra scintillating fiber detectors were mounted. Three fiber detector stations, namely UTF1, UTF2, and UTF3, were placed in front of the WASA detectors. Two fiber detector stations, DFT1, and DFT2, were positioned behind the WASA detector. Furthermore, a Mini-fiber detector comprising two fiber complexes, MFT1 and MFT2, was situated inside the iron yoke of the superconducting solenoid magnet of the WASA. Additionally, a small hodoscope, made up of small plastic scintillator fingers referred to as T0 start counter, was mounted in front of the UFT1 to assess the beam particles. A diamond target with a thickness of 9.87 g/cm^{2} was located between the tracking station UFT2 and UFT3, where the hypernuclear production would occur during the collision between the ^{6}Li beam at 1.96 *A*GeV directed at the ^{12}C of the target. Negatively charged pions from decays of hypernuclei are to be measured by the WASA detectors with the stations MFT1 and MFT2. Residual nuclei of hypernuclear decays were transferred to and analyzed by the S2-S4 sections of the FRS. Details of the experimental concept and the simulated expectations were discussed in [4]. We evaluated the acceptance and efficiencies and expect the invariant mass resolution to be at least twice as good, with at least an order of magnitude more statistics than collected during the first HypHI experiment.

3 Preliminary outcomes of the S447 data taking campaign

In the experiment, we maintained the counting rate at S4 in the FRS to be below a few kHz. It is essential to note that the standard resolving power of the FRS to measure the momentum of the residual nuclei is 10^{4}. As such, specific ion-optics settings were developed and used to obtain high acceptance and high resolving power. With the ^{6}Li beam, we have stored 3.3×10^{8}, 0.9×10^{9}, and 1.8×10^{8} events at S4 of ^{3}He, ^{4}He, and deuterons, respectively. The accumulated data-taking occurred over 40.9, 43.9, and 43.9 hours, respectively. Additionally, we collected data using ^{12}C beams, recording 1.0×10^{8} events with ^{3}He at S4 and 2.4×10^{5} events with ^{9}C at S4 over 13.5 hours. It will give us a chance to analyze the decay channel $^{9}B \rightarrow \pi^{-} + {}^{9}\mathrm{C}$. The collected data from the experiment is currently undergoing analysis. To identify a fragment that has passed through the FRS beyond the S2 focal plane, the time-of-flight (TOF), and energy deposit measurements obtained from scintillators located at the S3 and S4 focal plane are considered. As shown in Figure 3 top panel, the correlations between the TOF and the energy deposit obtained from the S4 scintillator for ^{3}He, ^{4}He, and deuteron are observed in the left and right panels, respectively. This enables us to clearly identify the fragments. The momentum measurement and analysis in the S2-S4 section of the FRS spectrometer are obtained by ion-optics calibration, and a momentum reconstruction resolution of 5×10^{-4} was preliminarily estimated, as shown in the bottom-left panel of Figure 3. Overall, the identification and analysis performance of fragments in the FRS is reasonably good. Charged particles emitted to the WASA detector system

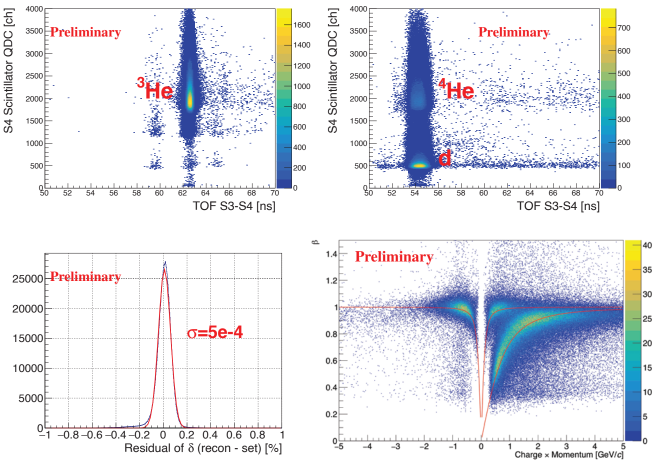

Figure 3. Preliminary results from the calibration are presented. Top panel: the fragment identification at the S2-S4 section of the FRS. The left and right top panels clearly show the identification of ^{3}He, ^{4}He, and deuteron ions, respectively. Bottom left panel: the preliminary momentum resolution achieved after ion-optics analysis of the fragments using the FRS S2-S4 spectrometer is showcased. A resolution of 5×10^{-4} has been achieved. Bottom right panel: the particle identification within the WASA central detection system is presented. Thanks to the β-momentum correlation, light hadrons such as π^-, π^+, and protons can be preliminarily identified.

undergo analysis by the tracking and TOF detectors. The momentum of these particles is estimated using Kalman filter track reconstruction for the hits of MFT, MDC, and PSB. A correlation between velocity β and momentum of the particles is observed, as depicted in the bottom-right panel of Figure 3. Light hadrons, such as π^-, π^+, and proton, can be preliminarily identified. Further data analyses for the hypernuclear reconstruction are in progress and are to be completed.

Experimental activities with the WASA-FRS setup will continue at FAIR Phase 0. Data analysis of the data-taking of 2022 is ongoing, with the hypernuclear reconstruction of the decay channels ^{3}He+π^-, ^{4}He+π^-, d+π^-, contributing to find a solution for the hypertriton and nnΛ puzzle. With the continued experimental efforts at FAIR Phase 0 and 1, we will perform further studies of exotic hypernuclei, including proton-rich [29] and neutron-rich [30] hypernuclei.

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