STATUS OF THE WASA-FRS HypHI EXPERIMENT: STUDY OF LIGHT HYPERNUCLEI AT GSI-FAIR*

S. Escrig

for the WASA-FRS/Super-FRS Experiment Collaboration

Instituto de Estructura de la Materia — CSIC, Madrid, Spain

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Even though the hypernuclei, which are sub-atomic nuclei that contain the quark s, have been studied with nuclear emulsions for more than 50 years, their current understanding has been challenged in recent years by experiments using high-energy heavy-ion beams. Firstly, the significantly shorter hypertriton lifetime reported by three independent state-of-the-art experiments, namely ALICE, STAR, and HypHI, compared to the predictions of theoretical models was poorly understood for some time. Notwithstanding, the current status of the hypertriton puzzle is evolving with the latest experimental efforts. Secondly, the observed enhancement in the invariant mass distributions of the $t + \pi^-$ and $d + \pi^-$ final states, as reported by the HypHI Collaboration, cannot be accounted for by existing theoretical calculations, which indicate the absence of a neutral $nn\Lambda$ bound state. Consequently, the WASA-FRS HypHI Experiment aims at obtaining new accurate results for the invariant mass and lifetime of ${}^3_\Lambda$H and ${}^4_\Lambda$H to produce more precise and statistically significant experimental results that can provide clarification on the potential existence of $nn\Lambda$. This experiment was successfully conducted in 2022 at GSI-FAIR. Data analysis is still ongoing, while several preliminary results are reported.

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1. Introduction

The study of the hypernucleus, which is a bound state of nucleons and at least one hyperon, is of great interest because it opens a new method of examining the baryon–baryon interaction. Moreover, the hypernuclear spectroscopy allows for the investigation of hyperon–nucleon and hyperon–hyperon weak nuclear forces, which is difficult by nuclear scattering experiments [1–3] due to the short lifetime, below the nanosecond, of the bound states that include hyperons.

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The spectroscopic studies of hypernuclei have been originally performed in nuclear emulsion chambers, and later via electron, pion or kaon beams. In the last decade, the use of heavy-ion beams in collider or fix-target modes has arisen as an effective method for producing and researching hypernuclei [4–7]. These studies have provided unforeseen results related to the hypertriton, ${}^{3}_{\Lambda}$H, which is the lightest of the known bound hypernuclei with only one proton, one neutron, and one hyperon Λ. In the 1970s, the emulsion hypernuclear studies firstly indicated that the hypertriton could be considered as a weakly bound Λ orbiting a deuteron nuclear core [8, 9]. Nevertheless, in the last decade, the understanding of the hypertriton structure was questioned by the STAR, HypHI, and ALICE collaborations using heavy-ion beams since the experimentally measured hypertriton lifetime and Λ binding energy [5, 7, 10–15] was conflicting with the predictions of the different theoretical models at that time [5, 16]. The incompatibility of these experimental observations and their comparison with the original understanding of the hypertriton structure have resulted in the so-called "hypertriton puzzle".

Furthermore, the potential existence of a neutral bound state including one hyperon Λ and two neutrons, the $nn\Lambda$, is still questioning the current understanding of the light hypernuclei. On the one hand, the HypHI Collaboration reported signals in $t + \pi^-$ and $d + \pi^-$ invariant mass spectra, which could be generated from the mesonic weak decay of $nn\Lambda$ [17]. On the other hand, the theoretical efforts in this regard using different approaches and models conclude that the $nn\Lambda$ is not a bound system [18–21]. Recently, a new experiment to explore the $nn\Lambda$ existence [21, 22] was conducted by the Hall A Collaboration at Jefferson Lab, Virginia (USA), using electron beams. The results of this experiment, a missing-mass spectrum with no peak with enough statistical significance in the threshold region ($-\mathrm{B}_\Lambda \simeq 0$), could neither conclude nor discard the existence of a $nn\Lambda$ bound or resonant state [23–25]. Therefore, the conclusion of the "$nn\Lambda$ puzzle" still requires further experimental and theoretical studies.

The WASA-FRS HypHI Experiment focuses on the precise spectroscopy of light hypernuclei, aiming at the lifetime measurement of ${}^{3}_{\Lambda}$H and ${}^{4}_{\Lambda}$H and the observation of the possible $nn\Lambda$ state. The WASA-FRS experimental campaign, including the HypHI Experiment and η' Experiment, was carried out in the first quarter of 2022 at the GSI-FAIR facility, and the data analysis is currently ongoing.

2. Experimental setup

The measurement of the mesonic weak decay of ${}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He} + \pi^-$, ${}^{4}_{\Lambda}\mathrm{H} \to {}^{4}\mathrm{He} + \pi^-$, and $\mathrm{nn}\Lambda \to d + n + \pi^-$ is the main goal of the WASA-FRS HypHI Experiment. The production of the hypernuclei is achieved by bombarding a diamond target with a ^{6}Li beam at 1.96A GeV. In this collision, Λ hyperon can coalesce with the nuclear fragment, forming a hypernucleus. The production of hypernuclei in the spectator rapidity region, with a similar velocity of the incident beam, allows for the in-flight study of the hypernuclei behind the target material. The hypernuclear events are identified by detecting both the residual nuclei and the π^- particles emitted from the mesonic weak decay of the hypernuclei.

The second half of the FRagment Separator FRS [26] serves as a high-resolution spectrometer ($\Delta P/P \sim 10^{-4}$) for measuring the decay fragments: ^{3}He, ^{4}He, and d. Additionally, the Wide Angle Shower Apparatus WASA [27], placed in the mid-focal plane of the FRS, is employed for tracking the decay π^- particle. The WASA system, as depicted in figure 1, consists of a superconducting magnet capable of generating 1T magnetic field, and a group of detectors, including a calorimeter with CsI crystals (SEC), a drift chamber of 17 layers of strawtubes (MDC), plastic scintillator barrel (PSB) [28], and end-caps (PSFE and PSBE). Additionally to the standard WASA apparatus, scintillating fiber trackers (UFT1,2,3, MFT1,2, and DFT1,2) and a small hodoscope (T0 Start counter) were installed.

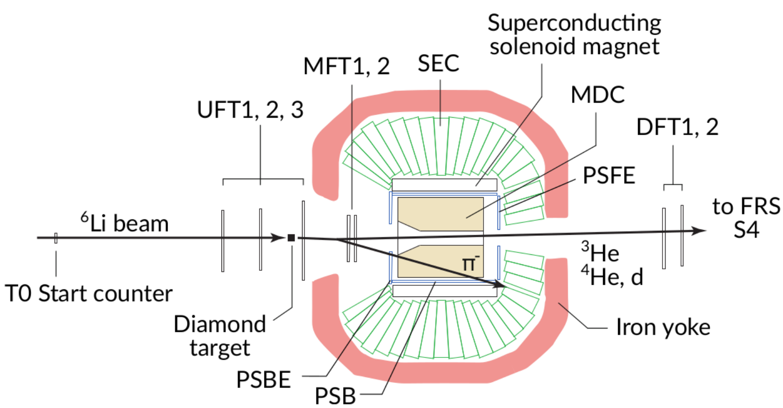

Fig. 1. Scheme of the cylindrical WASA detector apparatus located in the S2 area, which is used to measure light particles such as pions within the solenoid magnet.

3. Preliminary results

The experiment was performed successfully, storing 3.3×10^8, 0.9×10^9, and 1.8×10^8 events at the final focal plane S4 of the FRS of ^{3}He, ^{4}He, and deuteron, respectively. The data taking occurred during 40.9 hours for the ${}^3_\Lambda$H, while it lasted 43.9 hours for the ${}^4_\Lambda$H and $nn\Lambda$. In addition, 1.0×10^8 events with ^{3}He and 2.5×10^5 events with ^{9}C at S4 were recorded using ^{12}C beams over 13.5 hours, which enables a study of the decay channel ${}^9_\Lambda\mathrm{B} \to {}^9\mathrm{C} + \pi^-$.

The experimental data is currently being analysed. Firstly, the nuclear fragments are identified by considering the correlation of both the time-of-flight (TOF) and energy-deposition measurements obtained from the plastic scintillators placed at the focal planes S3 and S4 of the FRS. The momentum measurements in the second half of the FRS are obtained by means of the ion-optics calibration.

Secondly, the momentum of the charged particles emitted to the WASA detectors is reconstructed using the Graph Neural Network [29] as a track finder and Kalman Filter [30] as a track fitter for the hits of MFT1,2, MDC, and PSB or PSFE. Figure 2 shows the correlation between the velocity β and the momentum of the light hadrons, such as π^-, π^+, and protons, that can be preliminarily identified.

Finally, the data analysis for the hypernuclear reconstruction is currently in progress and is still to be completed.

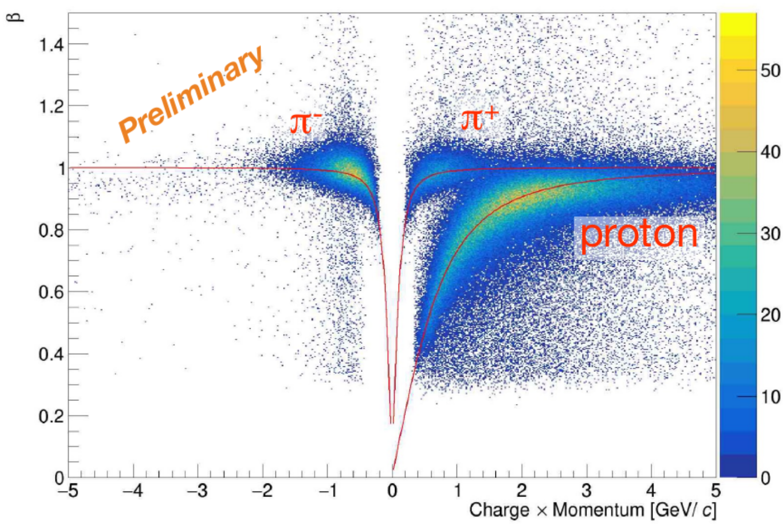

Fig. 2. The particle identification plot of the particles whose momentum has been experimentally reconstructed by means of the WASA detectors measurements.

4. Conclusion

The hypernuclear spectroscopy is a research field of great interest due to its relation with the study of the baryon–baryon nuclear weak interaction. Specifically, there are two main puzzles that need to be shed some light on for a better understanding of the light hypernuclei: the hypertriton lifetime and the $nn\Lambda$ existence. The WASA-FRS HypHI Experiment, which was performed successfully in 2022 at GSI-FAIR, focuses on the mesonic weak decays of ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^-$, ${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^-$, and $nn\Lambda \rightarrow d + n + \pi^-$. Currently, the data analysis for the hypernuclear reconstruction is ongoing.

Both WASA-FRS experiments, HypHI (S447) and η' (S490), were conducted in 2022 at the FRS facility at the GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt (Germany), as a component of the FAIR Phase-0 Physics Program, within the Super-FRS Experiment Collaboration. We express our gratitude to the GSI staff for their unwavering support during the experiment. The WASA-FRS project has received funding from the following sources: JSPS KAKENHI (grant No. JP18H01242), JSPS Grant-in-Aid for Early-Career Scientists (grant No. JP20K14499), JSPS Fostering Joint International Research (B) (grant No. JP20KK0070), Proyectos I+D+i 2020 ref: PID2020-118009GA-I00, grant 2019-T1/TIC-13194 of the Atracción de Talento Investigador program of the Community of Madrid, the Regional Government of Galicia under the Postdoctoral Fellowship grant No. ED481D-2021-018, the SciMat and qLife Priority Research Areas budget under the program Excellence Initiative — Research University at the Jagiellonian University, and the European Union's Horizon 2020 research and innovation programme under grant agreement No. 824093. We would like to acknowledge Luise Doersching-Steitz, Rita Krause, Daniela Press from GSI, Yukiko Kurakata of RIKEN, Miao Yang and Xiaohua Yuan of IMP for the valuable support provided throughout the projects, including administrative arrangements.

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