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WASA-FRS HypHI experiment at GSI for studying light hypernuclei

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Abstract. From January till March 2022, the WASA-FRS HypHI experiment performed a precise measurement of the hypertriton and the ${}^{4}_{\Lambda}$H hypernucleus lifetime at GSI. The data collected should also confirm whether or not the $nn\Lambda$ bound state can exist. The experiment were carried out with the WASA central detector with a complex of additional dedicated detectors mounted together at the mid-focal plane of the high-momentum-resolution forward spectrometer, the so-called fragment separator FRS. Hypernuclei of interest were produced by induced reactions of ^{6}Li projectiles at 1.96 A GeV on a diamond target with a thickness of 9.87 g/cm^2. Negatively charged π mesons from two-body decays of the hypernuclei of interest were measured by the WASA and the other detectors, and the residual nuclei after the π^- decay were measured by the FRS with a momentum resolving power of 10^4.

1 Introduction

Hypernuclei have been studied to investigate the baryon-baryon interaction [1]. In order to produce hypernuclei, secondary meson beams such as pion or kaon, or primary electron beams are mainly used. Hypernuclei can be also produced by using heavy-ion beams. The HypHI Phase 0 experiment was carried out at GSI in 2009 for the first time with heavy-ion beams [2–4]. In this experiment, ^{6}Li beams with 2 A GeV were injected into a ^{12}C target. Since the energy of the projectile is higher than the threshold to produce a Λ hyperon, the projectile fragments form a hypernuceus by capturing the Λ emitted from a hot participant zone. The hypernuclei can be identified from the invariant mass spectrum by detecting the π^- and decay residues emitted from their two-body decays. This experiment shows the feasibility of this method and reveals two major puzzles.

The first puzzle is induced by observing an indication of $nn\Lambda$ bound state [2]. The invariant mass distributions of deuteron + π^- and triton + π^- show bump structures on the top of background. In [2] it was concluded that the bump structures may indicate the possible $nn\Lambda$ bound state. However, these distributions are broad, and such a bound state is hardly reproduced from theoretical calculations. Therefore, the existence of $nn\Lambda$ is still unclear.

The second puzzle is initiated by observing of the short lifetime of hypertriton [3]. The binding energy of hypertriton is very small, 0.13 MeV, which was measured in old emulsion experiments [5, 6]. Therefore, hypertriton is regarded as a very loosely bound state between deuteron and Λ, and its lifetime is considered to be as almost the same as that of a free Λ, 263 ps. However, the HypHI Phase 0 experiment showed a shorter lifetime of hypertriton,

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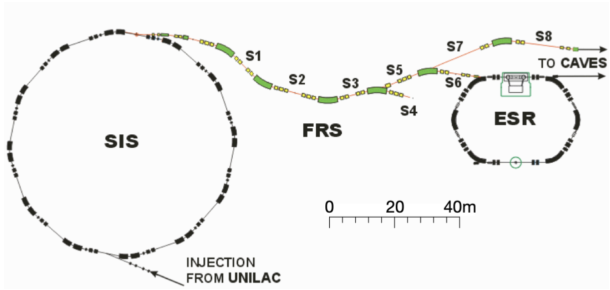

Figure 1. Schematic drawing of the SIS18 synchrotron and the fragment separator (FRS) at GSI.

$183^{+42}_{-32}(stat.) \pm 37(syst.)$ ps. Other heavy-ion experiments, ALICE and STAR, also reported short lifetimes, $142^{+24}_{-21}(stat.) \pm 29(syst.)$ ps [7] and $181^{+54}_{-39}(stat.) \pm 33(syst.)$ ps [8]. Later, their values were updated to be $221 \pm 15(stat.) \pm 19(syst.)$ ps [9] and $242^{+34}_{-38}(stat.) \pm 17(syst.)$ ps [10], respectively. Thus, the obtained average lifetime of hypertriton is 200 ± 13 ps [9], which is shorter than that of free Λ. Moreover, the STAR collaboration reported the binding energy of the hypertriton. Their deduced value is $0.41 \pm 0.12(stat.) \pm 0.11(syst.)$ MeV [11], which is much larger than the former measured value. Consequently, both the lifetime and the binding energy are not well confirmed for the hypertriton, which is even the lightest Λ-hypernuceus. In order to clarify this situation, a new and more precise measurement is necessary.

2 WASA-FRS HypHI experiment

2.1 Overview

The WASA-FRS HypHI experiment aims at studying light hypernuclei produced with heavy-ion beams. This experiment was carried out as the WASA-FRS campaign together with the η' mesonic nuclei experiment. These have been conducted at the fragment separator, so-called FRS [12] with the WASA central detector [13] at GSI. The WASA (Wide Angle Shower Apparatus), which was used at COSY-Jülich, consists of a superconducting solenoid magnet and associated detectors. The WASA-FRS HypHI experiment aims to produce and detect hypertriton, ${}^{4}_{\Lambda}$H and $nn\Lambda$. Heavy-ion beams accelerated up to 1.96 A GeV by the SIS18 synchrotron were injected into the FRS (Fig.1). The hypernuclei were produced on a diamond target with a thickness of 9.87 g/cm^2 at the mid-focal plane (S2) in the FRS. The second half of the FRS was used to identify their decay residues with high momentum resolution ($\delta p/p = 10^{-4}$). The π^- mesons were detected by the WASA detectors at the S2 with reasonably large acceptance.

Figure 2 shows the setup around the WASA solenoid. The WASA solenoid is located at the center surrounded by CsI calorimeters to measure energy deposit of charged particles and electromagnetic showers from photons. The magnetic field at the center of the solenoid magnet was 1 T in the experiment. Mini Drift Chamber (MDC) and plastic scintillators (PSB[14], PSBE and PSFE) are located inside of the solenoid magnet to measure the momentum of charged particles and time-of-flight (TOF), respectively. These scintillators have barrel and end-cap shapes to surround the MDC. Fiber trackers (UFTs, DFTs and MFT) are located outside of the solenoid to measure the trajectory of incoming and outgoing charged particles. One of the fiber trackers, Mini Fiber Tracker (MFT), is located inside of the iron yoke to measure the hypernuclear decay vertex precisely.

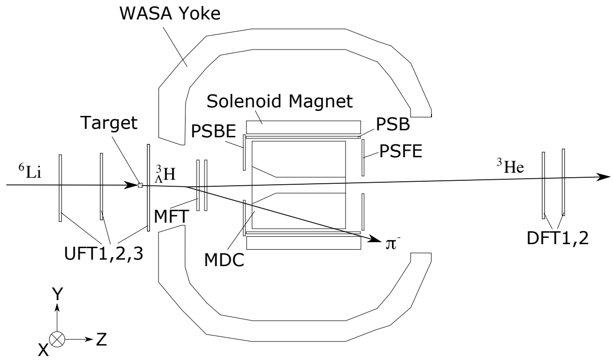

Figure 2. Experimental setup of the WASA-FRS HypHI experiment.

2.2 Monte Carlo simulation

A Monte Carlo (MC) simulation was carried out to evaluate the performance of the WASA detector system before performing the experiment. In the MC simulation, the detectors were implemented with realistic detector resolutions that were obtained by test measurements. The particles were generated by the transport model UrQMD [15] with an assumption of coalescence factor to produce hypernuclei and ordinary nuclei that can reproduce the cross sections measured in the HypHI phase 0 experiment [4]. The amount of observed hypertriton in four days was estimated to be 5800 with a peak width of 3.2 MeV(σ) in the invariant mass distribution [16]. The significance is estimated to be 120 σ. From this result, the accuracy of the lifetime measurement is estimated to be 8 ps. The simulation shows that the values have become several times more accurate compared to the previous measurement by the HypHI Phase 0 experiment.

Additionally, a track finding analysis with the graph neural network, so-called GNN, has been developed based on data obtained by the MC simulation. Since the heavy-ion collision induces many charged particles, track finding is an important issue in this experiment. The GNN can treat graph data structure, which can express data nodes and their relations. Because of this feature, by using the machine learning technique, detector hits can be clusterized by learning true connection in which the hits belong to the same track. We have confirmed more than 98 % of π^- tracks can be found with the GNN analysis [17].

2.3 Data taking

The WASA-FRS experiment was carried out from January to March in 2022 as summarized in Table 1. After a detector commissioning, we have taken data for the η' mesonic nuclei experiment and the WASA-FRS HypHI experiment. The acquired fragments at the S4 focal plane in the WASA-FRS HypHI experiment are summarized in Table 2, which includes ordinal fragments from heavy-ion collisions and the decay residues from hypernuclei. For ^{6}Li beams, data have been taken in three settings to detect different fragments. A fragment of ^{3}He was used to reconstruct hypertriton production events, and ^{4}He and deuteron were taken for $^4_\Lambda$H and $nn\Lambda$, respectively. Since ^{4}He and deuteron have the same A/Z, they can be obtained in the same magnetic setting. Additionally, protons in the mid-rapidity region were collected to detect the Λ decay as a calibration measurement. Moreover, ^{12}C beams were used to produce hypernuclei. This measurement is a first feasibility study for proton-rich

Table 1. Data obtained in the WASA-FRS experimnet.

Run	Period	Data size
Commissioning	28th Jan.– 7th Feb.	7 TB
Physics run for η' nuclei	22th Feb.– 28th Feb.	40 TB
Physics run for WASA-FRS HypHI	10th Mar.– 19th Mar.	48 TB

Table 2. Acquired fragments at the S4 focal plane in the WASA-FRS HypHI experiment. Decay channels of the objective hypernuclei are listed for each fragment.

Beam	Fragment at S4	Decay channel	Amount of fragments	Time [h]	Accepted trigger rate [Hz]
^{6}Li	^{3}He	${}^{3}_{\Lambda}\mathrm{H} \rightarrow \pi^- + {}^{3}\mathrm{He}$	3.3×10^{8}	40.9	2600
	^{4}He	${}^{4}_{\Lambda}\mathrm{H} \rightarrow \pi^- + {}^{4}\mathrm{He}$	0.9×10^{8}	43.9	1800
	deuteron	$nn\Lambda \rightarrow \pi^- + d + n$	1.8×10^{8}		
	proton (mid-rapidity)	$\Lambda \rightarrow \pi^- + p$	5.3×10^{6}	3.2	680
^{12}C	^{3}He	${}^{3}_{\Lambda}\mathrm{H} \rightarrow \pi^- + {}^{3}\mathrm{He}$	1.0×10^{8}	13.5	2400
	^{9}C	${}^{9}_{\Lambda}\mathrm{B} \rightarrow \pi^- + {}^{9}\mathrm{C}$	2.4×10^{5}		

hypernuclei such as ${}^{9}_{\Lambda}$B in future experiments. In this case, fragments of ^{3}He and ^{9}C were collected.

3 Data analysis

The accumulated data are being analyzed. A fragment that passes through the FRS behind the S2 focal plane is identified by measuring the TOF and energy deposit obtained by scintillators located at the S3 and S4 focal plane (Fig.1). Figure 3 (a) and (b) show the correlations between the TOF between S3–S4 and the energy deposit of the S4 scintillator for ^{3}He and ^{4}He (deuteron), respectively. The fragments are clearly observed confirming that fragment identification in the FRS performed reasonably well.

Charged particles emitted to the WASA detector system are analyzed by the tracking and TOF detectors. As a first step, particle tracks are found by requiring hits in all layers of MFT, which has six layers. The tracks are extrapolated to MDC, and associated MDC hits are chosen based on their residuals. Figure 4 (a) shows a difference of ϕ angles between hit wires of MDC and the tracks obtained by MFT. The MDC hits with a residual within ± 0.2 radian are selected as the associated hits. Associated PSB hits are also chosen based on similar criteria. Momenta of reconstructed particles are obtained by applying the Kalman filter with a tracking tool Genfit [18] using hits in MFT, MDC and PSB. Figure 4 (b) shows the correlation between particle velocity β and momentum. Three types of particles, proton, π^{+} and π^{-}, are identified. In the current analysis, the tracking efficiency is reduced because hits on all layers of MFT are required to find tracks. Track finding is going to be replaced by the developed GNN analysis to increase the number of reconstructed tracks.

4 Summary

The WASA-FRS HypHI experiment aims at studying light hypernuclei produced with heavy-ion beams. The lifetimes of hypertriton and ${}^{4}_{\Lambda}$H are going to be measured precisely from their decay lengths, and whether or not the $nn\Lambda$ bound state exists is going to be confirmed. Data of the WASA-FRS experiment were successfully taken in January–March 2022. The analysis of the obtained data is in progress.

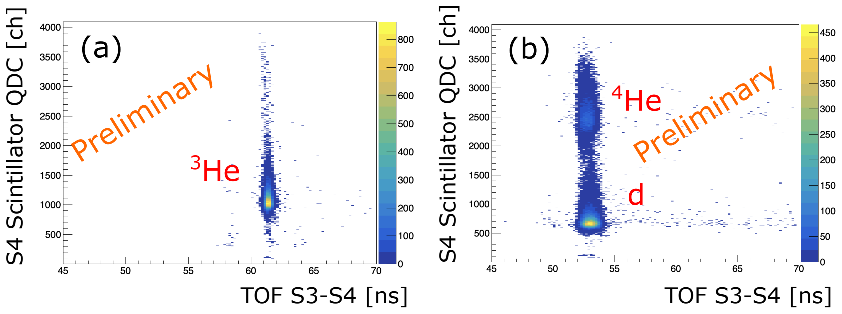

Figure 3. Correlation between S3–S4 TOF and the energy deposit on the S4 scintillator for ^{3}He (a) and ^{4}He/d (b).

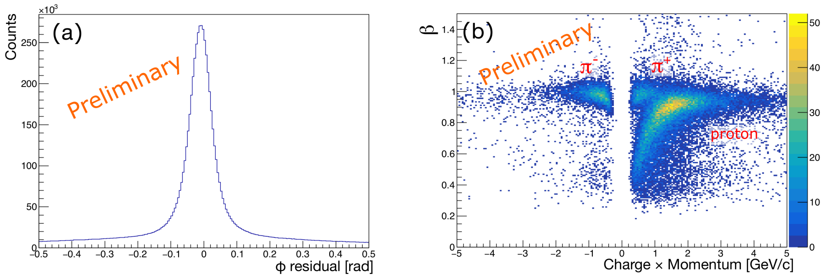

Figure 4. Analysis of the WASA detectors. (a) Difference of the ϕ angle between MDC hit wire and track obtained by MFT. (b) Correlation between β and momentum.

References

[1] O. Hashimoto, H. Tamura, Progress in Particle and Nuclear Physics **57**, 564 (2006)
[2] C. Rappold et al. (HypHI), Phys. Rev. C **88**, 041001 (2013)
[3] C. Rappold et al., Nucl. Phys. A **913**, 170 (2013)
[4] C. Rappold et al., Phys. Lett. B **747**, 129 (2015)
[5] M. Juric et al., Nucl. Phys. B **52**, 1 (1973)
[6] G. Bohm et al., Nucl. Phys. B **4**, 511 (1968)
[7] L. Adamczyk et al. (STAR Collaboration), Phys. Rev. C **97**, 054909 (2018)
[8] J. Adam et al. (ALICE Collaboration), Phys. Lett. B **754**, 360 (2016)
[9] M.S. Abdallah et al. (STAR Collaboration), Phys. Rev. Lett. **128**, 202301 (2022)
[10] S. Acharya et al. (ALICE Collaboration), Phys. Lett. B **797**, 134905 (2019)
[11] J. Adam et al. (STAR Collaboration), Nat. Phys. **16**, 409–412 (2020)
[12] H. Geissel et al., Nucl. Instrum. Meth. B **70**, 286 (1992)
[13] C. Bargholtz et al., Nucl. Instrum. Meth. A **594**, 339 (2008)
[14] R. Sekiya et al., Nucl. Instrum. Meth. A **1034**, 166745 (2022)
[15] M. Bleicher et al., J. Phys. G: Nucl. Part. Phys. **25**, 1859 (1999)
[16] T. Saito et al., Nat. Rev. Phys. **3**, 803–813 (2021)
[17] H. Ekawa et al., submitted to Eur. Phys. J. A
[18] T. Bilka et al., arXiv (2019), 1902.04405