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Summary of the HypHI Phase 0 experiment and future plans with FRS at GSI (FAIR Phase 0)

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Abstract

Results of the HypHI Phase 0 experiment with the reaction of ${}^6\text{Li}+{}^{12}\text{C}$ at 2 A GeV are summarised. Invariant mass distributions as well as the lifetime measurements for ${}^3_\Lambda\text{H}$ and ${}^4_\Lambda\text{H}$ are discussed. The lifetime values for both the hypernuclei are respectively observed to be 183^{+42}_{-32} ps and 140^{+48}_{-33} ps, being significantly shorter than those of the Λ -hyperon. Statistical analyses of existing lifetime data for ${}^3_\Lambda\text{H}$ up to 2014 confirm a significantly short lifetime of ${}^3_\Lambda\text{H}$, which is not explained by present models. Observed hypernuclear production cross section values for ${}^3_\Lambda\text{H}$ and ${}^4_\Lambda\text{H}$ are also summarised. In addition, observed signals for the final states of $d+\pi^-$ and $t+\pi^-$ are discussed. All the discussions on the results of the HypHI Phase 0

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experiment in this article are based on [1–4]. We also present a new proposed experiment with the FRS (FRagment Separator) at GSI (FAIR Phase 0) to improve the precision of the hypernuclear spectroscopy with peripheral heavy ion induced reactions.

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1. Introduction to the HypHI Phase 0 experiment

After the discovery of hypernuclei, subatomic-nuclei with hyperon(s), by Danysz and Pniewski in 1953 [5], hypernuclei have been studied to address the importance of the baryon–baryon interaction under the flavoured SU(3) symmetry. Among hypernuclei, bound systems with the lightest hyperon, Λ -hypernuclei, have been mostly studied. The most conventional ways to produce and study Λ -hypernuclei experimentally have been with emulsion techniques [6], secondary meson beams [7] and primary electron beams [8]. In these experiments, both ground and excited states of produced hypernuclei have been studied. However, the isospin of the produced hypernuclei has been restricted by the choice of the target nucleus since only one or two nucleons in the target nucleus can be converted to hyperon(s).

Complementary to these experimental techniques, projectile fragmentation reactions with heavy ion beams with an energy larger than approximately 1.7 A GeV can be used to produce hypernuclei. Hypernuclear production via heavy ion collision was first suggested by Kerman and Weiss [9]. A model of coalescence of Λ in projectile fragments was then theoretically discussed in [10,11], and recently, it has been studied theoretically in more detail by Gaitanos et al. [12]. In such reactions, a projectile spectator can capture a hyperon produced in the hot participant region to produce a hypernucleus. In this reaction, the velocity of the produced hypernucleus should be similar to that of the projectile, and therefore the produced hypernucleus in the projectile rapidity region has a large Lorentz factor. Thus the decay of the hypernucleus can take place well behind the production target. This makes it possible to study hypernuclei in flight. Since a hypernucleus is produced from a projectile fragment, isospin and mass values of the produced hypernuclei, unlike in other hypernuclear experiments, can be widely distributed. The first attempt was made with ^{16}O beams at 2.1 A GeV on a polyethylene target [13]. However, the measured cross section of the hypernuclear candidates greatly exceeded the theoretical expectations, which was ascribed to a difficulty with implementing the kaon trigger. Subsequently, an experiment performed by bombarding a polyethylene target with beams of ^4He at 3.7 A GeV and ^7Li at 3.0 A GeV was successful in producing light hypernuclei [14,15]. However, since the invariant mass of the final states was not measured, there remained an ambiguity in identifying the hypernuclei produced.

With relativistic and ultra-relativistic heavy ion beams, a central collision can be used to produce light hypernuclei. Platinum projectiles at 11.5 GeV/c on a gold target were used successfully to produce and identify $^3_\Lambda\text{H}$ (hypertriton) and $^4_\Lambda\text{H}$ hypernuclei [16]. Recently, the STAR collaboration at RHIC and the ALICE collaboration at LHC used relativistic heavy ion collisions at 200 A GeV and $\sqrt{s_{NN}} = 2.76$ TeV, respectively, to study hypertriton and anti-hypertriton [17, 18]. However, those central collisions up to date have not proven suitable for the production of hypernuclei with the mass value $A \geq 4$.

The HypHI collaboration has proposed a series of experiments at the GSI Helmholtz Centre for Heavy Ion Research and FAIR, using induced reactions of stable heavy ion beams and rare-isotope beams [19]. In the proposed experiments, hypernuclei are observed by the invariant mass method by measuring the four-momenta of decayed particles. Lifetime values of observed hypernuclei can be deduced by studying the distribution of the *proper decay time*, obtained from the measured decay length, in the rest frame of the mother state of interest, thus making the deduced lifetime values independent of the detectors' time resolution. The lifetimes of hypernuclei are of interest since they are sensitive to the overall wave function of the hyperon located within the core nucleus. The lifetime of light Λ -hypernuclei has been conjectured to be similar to the lifetime of a free Λ hyperon if it is weakly bound to the core nucleus [20]. Deviations from the value of 263.2 ps of the Λ lifetime would possibly provide new information on Lambda's wave-function sitting within hypernuclei. One of the advantages of the HypHI experiments with heavy ion induced reactions is to measure the hypernuclear lifetime precisely aiming a resolution of a few percent with large statistics.

The first HypHI experiment, Phase 0, to study ${}^3_\Lambda\text{H}$ and ${}^4_\Lambda\text{H}$ hypernuclei was performed at the GSI Helmholtz Centre for Heavy Ion Research in 2009 by means of projectile fragmentation reactions of ${}^6\text{Li}$ projectiles at 2 A GeV delivered on a carbon target. The main goal of the Phase 0 experiment was to demonstrate the feasibility of the HypHI method by producing and observing known three- and four-body hypernuclei such as ${}^3_\Lambda\text{H}$ and ${}^4_\Lambda\text{H}$. The second experiment, Phase 0.5, used the ${}^{20}\text{Ne}$ projectiles to study heavier hypernuclei. Data analyses of the Phase 0 experiment have been completed, and we will briefly summarise the results in this article. Details of the Phase 0 experiments and of the analyses discussed in this article can be found in [1–4]. Results of the Phase 0.5 experiments will be published later. In the end of this article, we also discuss on the ideas of future experiments at GSI (FAIR Phase 0).

2. Results of the HypHI Phase 0 experiment

A brief overview of the data analyses is discussed in this section, and the details of the analyses can be found in [1]. The reconstruction of particle tracks and the secondary vertices was made mainly by scintillating fibre detector arrays and the two drift chambers, and the four scintillating hodoscope detector systems also participated in the particle tracking. These hodoscopes also performed time-of-flight measurements of charged particles. Track reconstruction and fitting were made by means of the Kalman filter technique as summarised in [21]. With particle tracking and time-of-flight measurements together with ΔE information obtained by the plastic hodoscopes, four momenta of the reconstructed particles were deduced, then invariant mass values were calculated when two tracks are passing within a closest track distance of 4 mm.

The top panels of Fig. 1 show the invariant mass distributions for $p + \pi^-$, ${}^3\text{He} + \pi^-$, and ${}^4\text{He} + \pi^-$ candidates. It has been shown in each distribution that there is a signal peak at around the mass of Λ , ${}^3_\Lambda\text{H}$ and ${}^4_\Lambda\text{H}$. For the estimation of the background contributions to the invariant mass distributions, the event mixing method was initially employed. Estimated background distributions are shown in Fig. 1 by the open symbols. After the first estimation of the background contributions by the mixed event method, the background contribution was then modelled by a Chebychev polynomial probability density function with a signal in the invariant mass distributions represented by a Gaussian probability density function. An extended maximum likelihood estimator provided the share of signal and background in each invariant mass spectrum. For estimating the significance of the signals, a hypothesis test was applied, and a profiled maximum likelihood ratio test gives us a significance of 6.7σ , 4.7σ , 4.9σ for Λ hyperon, ${}^3_\Lambda\text{H}$ and ${}^4_\Lambda\text{H}$,

Fig. 1. Invariant mass distribution for candidates of Λ , $\Lambda^3\text{H}$ and $\Lambda^4\text{H}$, are represented by the filled circles in panels (1a), (1b), and (1c), respectively. The shaded orange region represents one standard deviation of the fitted model centred at the solid blue line. The dotted lines show the separate contributions of the signal and the background with, respectively, black and coloured lines. The data represented by open triangles correspond to invariant mass distributions of the mixed event analysis. The local p-value distribution of the background-only hypothesis in full range of fit of Λ , $\Lambda^3\text{H}$ and $\Lambda^4\text{H}$, are shown in panels (2a), (2b) and (2c), respectively. The red dashed lines illustrate the p-values corresponding to significances of 1σ , 2σ , 3σ , 4σ , 5σ and 6σ . The figures are taken from [1]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

respectively. Details of the analyses on the invariant mass as well as particle tracking and identification were already discussed in [1].

After reconstructing the invariant mass, the lifetime values of Λ , $\Lambda^3\text{H}$ and $\Lambda^4\text{H}$ were extracted. As described in the previous section, one of the merit in the present work is to deduce the lifetime value of the observed hypernuclei in a different way to the other conventional hypernuclear experiments since the deduction of the hypernuclear lifetime is completely independent of the time response of the detector systems but dependent to the sensitivity to the particle tracking. The procedure of the analyses to deduce the lifetime values was already discussed in [1]. It has also to be noted that an *unbinned* maximum likelihood fitting method was employed to infer the lifetime values in order to improve the accuracy of the estimation of the lifetime values with limited statistics.

For deducing the lifetime values of the signals of interest, first the signal contribution was determined by subtracting the background contribution from the signal-plus-background contribution, and thus two data sets were built. To obtain the contribution of signal-plus-background contribution, the data in the fitted peak region with $\bar{m} \pm 2\sigma_m$ were selected. While, for the background-only data set, the adjacent sideband regions within the intervals of $[\bar{m} - 4\sigma_m, \bar{m} - 2\sigma_m]$ and $[\bar{m} + 2\sigma_m, \bar{m} + 4\sigma_m]$ were selected. The portion of background inside the signal-plus-background region was estimated deductively by using the mixed event method, and the normalisation of the integrated area to the sideband region was made. Since hypernuclei of in-

Fig. 2. Profiled likelihood ratio for interval estimation of Λ hyperon (a1), $\Lambda^3\text{H}$ (b1), and $\Lambda^4\text{H}$ hypernuclei (c1). Interval estimation for 1 standard deviation is shown on each profiled likelihood ratio. Binned decay length distributions of the signal region of Λ hyperon (a2), $\Lambda^3\text{H}$ (b2), and $\Lambda^4\text{H}$ hypernuclei (c2) with the fitted model, which included the exponential function resulted from the *unbinned* maximum likelihood fit and the background contribution estimated by the sidebands. The black line represents the fitted model, while the blue dotted line represents the contribution of the exponential function. The figures are taken from [1]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

terest as well as Λ -hyperons decay well behind the production target, a cut for the longitudinal vertex position was applied to be more than 6 cm distant from the target in order to minimise contamination from reaction events at the target and at the tracking detector immediately behind the target. With the conditions described above, the proper decay time $t = l/(\beta\gamma c)$ is calculated for the two data sets in the rest frame of the mother state of interest by the measured decay length l , where $\beta\gamma c = p/m$, p and m the momentum and the mass of the mother state of interest. Then signal contributions were obtained by subtracting the background-only data set from the signal-plus-background data set. The correction by the acceptance and reconstruction efficiency was made by means of full Monte Carlo simulations, as discussed in [1]. Because of the limited statistics, we employed an *unbinned* maximum likelihood fitting method to deduce the lifetime values. As discussed in [1], a model of an exponential probability density function with the background was chosen to represent the distribution of the proper decay time $l/(\beta\gamma c)$ with a lifetime τ . Likelihood profiles for estimation of the mean decay length $c\tau$ of Λ hyperon, $\Lambda^3\text{H}$ and $\Lambda^4\text{H}$ hypernuclei are shown in the top panels of Fig. 2, and deduced lifetime values for Λ , $\Lambda^3\text{H}$ and $\Lambda^4\text{H}$ are respectively 262^{+56}_{-43} ps, 183^{+42}_{-32} ps and 140^{+48}_{-33} ps with the error values estimated by a standard deviation of $\pm 1\sigma$ (68.3% confidence level).

In order to check the goodness of the extraction of the lifetime values, a χ^2 test was performed with the *binned* data of decay length $l/\beta\gamma$ in the signal region. The fitted model of the signal region included the binned contribution of the exponential probability density function added to

Fig. 3. World data comparison of ${}^3_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{H}$ lifetimes. The combined average is represented by the arrow at the top, while the width of the hatched band corresponds to the one standard deviation of the average. The vertical line at 263.2 ps with width of ± 2 ps shows the known lifetime of Λ hyperon. References to counter experiments is marked by an asterisk. Figures are taken from [2] but with difference reference number according to the list of references in the present article.

the *binned* data of the sideband regions. The binned fitted model at the bin i can be expressed as discussed in [1] as:

$$\text{ModelFit}_i = \left\{ \int_{\text{bin}_i} A/(\tau\gamma) \exp(-l/(\beta\gamma\tau)) dl \right\} \cdot 1/w'_i + B_l[l_i/(\beta_i\gamma_i)] + B_h[l_i/(\beta_i\gamma_i)] \quad (1)$$

where A is the normalisation factor of the exponential probability density function, $B_l[l_i/(\beta_i\gamma_i)]$ and $B_h[l_i/(\beta_i\gamma_i)]$ are the two sideband data sets at bin i . In the bottom panels of Fig. 2, fitted model distributions are shown by solid lines together with binned data of the signal region of the signal-plus-background data shown by filled circles with error bars. By comparing the two distributions, reduced χ^2 values of the modelled proper decay time function over the *binned* data as $\chi^2 = \sum_{\text{bin}_i} (\text{SB}[l_i/(\beta_i\gamma_i)] - \text{ModelFit}_i)^2 / (\text{SB}[l_i/(\beta_i\gamma_i)])$ was calculated. They are 0.43 for Λ , 1.14 for ${}^3_{\Lambda}\text{H}$ and 0.71 for ${}^4_{\Lambda}\text{H}$. It has to be emphasised once more here that the deduced lifetime values have been obtained by the *unbinned* fitting, and the reduced χ^2 from the binned representation was used only to cross check the goodness-of-fit.

One of striking results in the present work is the observation of a significantly shorter lifetime value of ${}^3_{\Lambda}\text{H}$ than that of the Λ -hyperon. With the former data [22–28], it had been difficult to conclude the lifetime of ${}^3_{\Lambda}\text{H}$ since these experimental data are distributed widely with large error bars. Therefore, it had been concluded that the lifetime of ${}^3_{\Lambda}\text{H}$ should be similar to that of the Λ -hyperon without strong experimental evidences due to its small Λ -binding energy. However, as shown above, our result on the lifetime of ${}^3_{\Lambda}\text{H}$ reveals 183^{+42}_{-32} ps. Thus, in order to summarise the former results for the lifetime of ${}^3_{\Lambda}\text{H}$ together with our result, all the existing data till 2014 for the lifetime observations of ${}^3_{\Lambda}\text{H}$ were combined with a similar methodology of PDG, and results were already discussed in [2]. We also performed the same analyses for the lifetime of ${}^4_{\Lambda}\text{H}$ [2]. For ${}^3_{\Lambda}\text{H}$, data set used are taken from [1,22–28] and for ${}^4_{\Lambda}\text{H}$ from [1,15,22,24,29–31]. Results of the combined analyses are shown in Fig. 3. Details are also discussed in [32] including an alternative statistical analysis applying a Bayesian approach [2]. Fig. 3 shows that the combined lifetime values of ${}^3_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{H}$ are significantly smaller than that of the Λ -hyperon. The exclusion band at 95% confidence level, useful for discarding theoretical models, was also deduced.

Table 1

Summary of the estimations of the parameters of interest such as the cross sections and the yield ratios. $\langle x \rangle$ and σ_{stat} correspond to the expected value and the statistical standard deviation of the posterior probability density function. σ_{sys} and σ_{prior} stand for the systematic uncertainties and the prior sensitivity uncertainties. The table is taken from [3].

	$\langle x \rangle$	σ_{stat}	σ_{sys}	σ_{prior}
Λ_{tot} (mb)	1.7	± 0.7 (stat)	± 0.4 (sys)	± 0.2 (prior)
Λ_{obs} (mb)	0.3	± 0.1 (stat)	± 0.06 (sys)	± 0.03 (prior)
${}^3_{\Lambda}\text{H}$ (μb)	3.9	± 1.3 (stat)	± 0.3 (sys)	± 0.3 (prior)
${}^4_{\Lambda}\text{H}$ (μb)	3.1	± 1.0 (stat)	± 0.3 (sys)	± 0.1 (prior)
${}^3_{\Lambda}\text{H}/{}^4_{\Lambda}\text{H}$	1.4	± 0.7 (stat)	± 0.1 (sys)	± 0.2 (prior)
${}^3_{\Lambda}\text{H}/\Lambda$ ($\times 10^{-3}$)	2.6	± 1.4 (stat)	± 0.3 (sys)	± 0.2 (prior)
${}^4_{\Lambda}\text{H}/\Lambda$ ($\times 10^{-3}$)	2.1	± 1.1 (stat)	± 0.1 (sys)	± 0.2 (prior)

Theoretical values outside of the ranges between 186 ps and 254 ps for ${}^3_{\Lambda}\text{H}$ and between 158 ps and 233 ps for ${}^4_{\Lambda}\text{H}$ can be excluded with 95% confidence level [2]. In the analyses of the HypHI data with the Bayesian approach described in detail in [2], lifetime values of ${}^3_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{H}$ were estimated to be approximately 217^{+19}_{-16} ps and 194^{+20}_{-18} ps, respectively, and the upper limit at 95% confidence level was also deduced to be 250 ps and 227 ps, respectively, excluding the possible theoretical prediction above this limit with 95% confidence level [2]. The most recent theoretical model predict 256 ps [20] for ${}^3_{\Lambda}\text{H}$, and it has to be noted that the result of this theoretical calculation is above the upper limit at 95% confidence level obtained by both the combined analyses and the Bayesian approach.

Very recently, the STAR and ALICE collaborations also observed significantly shorter lifetime of ${}^3_{\Lambda}\text{H}$ than Λ respectively to be 155^{+25}_{-22} ps [33] and 181^{+54}_{-39} ps [18]. These two new data are not included in the calculations in the present work since calculation with those data are in progress, and new results will be published in a separate article.

We have also deduced hypernuclear production cross sections for ${}^3_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{H}$ as well as the production cross section of the Λ -hyperon in the reaction of ${}^6\text{Li}+{}^{12}\text{C}$ at 2 A GeV or $\sqrt{s_{NN}} = 2.70$ GeV with the data of the Phase 0 experiment. Details of the analyses are given in [3]. A production cross section of $3.9 \pm 1.4 \mu\text{b}$ for ${}^3_{\Lambda}\text{H}$ and of $3.1 \pm 1.0 \mu\text{b}$ for ${}^4_{\Lambda}\text{H}$ in the projectile rapidity region was inferred. Also the yield of Λ -hyperons in the projectile rapidity region was deduced, and the total production cross section of the Λ -hyperon was extracted by employing UrQMD theoretical calculations [34,35] that are considered to model the Λ phase space reasonably [36–42]. It is found to be equal to 1.7 ± 0.8 mb. A global fit based on a Bayesian approach was performed in order to include and propagate statistical and systematic uncertainties. Production ratios of ${}^3_{\Lambda}\text{H}/{}^4_{\Lambda}\text{H}$, ${}^3_{\Lambda}\text{H}/\Lambda$ and ${}^4_{\Lambda}\text{H}/\Lambda$ were included in the inference procedure. A summary of the cross sections as well as the production ratios is given in Table 1.

In addition to the analyses discussed above, the invariant mass distributions of all the other possible final states were studied with the data of the Phase 0 experiment. Surprisingly, we observed signals in the $d+\pi^-$ and $t+\pi^-$ final states. Details of the analyses were already discussed in [4]. Fig. 4 shows the invariant mass distributions of $d+\pi^-$ in panels (a1) and (a2) and $t+\pi^-$ in panels (b1) and (b2). The longitudinal decay vertex position (Z) was requested to be set between $-10 \text{ cm} < Z < 30 \text{ cm}$ in panels (a1) and (b1) and between $-2 \text{ cm} < Z < 30 \text{ cm}$ in (a2) and (b2). The production target was placed between -6 cm and -2 cm , thus the cut condition of

Fig. 4. Invariant mass distributions of $d+\pi^-$ final state candidate in panels (a1) (a2), and of $t+\pi^-$ in panels (b1) (b2). Panels (a1) and (b1) are for $-10 \text{ cm} < Z < 30 \text{ cm}$, and (a2) and (b2) are for $-2 \text{ cm} < Z < 30 \text{ cm}$. Observed distributions are represented by the filled-in circles. The hashed orange region represents one standard deviation of the fitted model centred at the solid blue line of the total best fit. The black and coloured dotted-lines respectively show the separate contributions of the signal and the background. The open triangle represents the data corresponding to invariant mass distribution of the mixed event analysis. The figures are taken from [4]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$-10 \text{ cm} < Z < 30 \text{ cm}$ includes vertices from the production target while the other condition excludes the target region. The deduced invariant mass distributions are represented by the filled-in circles. The mass values were calibrated by using the data for the reconstructed invariant mass peak positions of Λ , ${}^3_\Lambda\text{H}$ and ${}^4_\Lambda\text{H}$. Fitting of the distributions of signal-plus-background from the data were performed in the similar fashion to ${}^3_\Lambda\text{H}$ and ${}^4_\Lambda\text{H}$. By hypothesis testing via profiled likelihood ratio tests, the significance values of observed peaks of $d+\pi^-$ for $-10 \text{ cm} < Z < 30 \text{ cm}$ and $-2 \text{ cm} < Z < 30 \text{ cm}$ were determined to be respectively 5.3 and 3.7σ , and for $t+\pi^-$ they are 5.0 and 5.2σ , respectively. Vertex distributions of the $d+\pi^-$ and $t+\pi^-$ were analysed to deduce the lifetime values of the initial states decaying those final states by using a similar manner for ${}^3_\Lambda\text{H}$ and ${}^4_\Lambda\text{H}$. As shown in Fig. 5, resultant lifetime values with the $d+\pi^-$ and $t+\pi^-$ final states are respectively $181^{+30}_{-24} \text{ ps}$ and $190^{+47}_{-35} \text{ ps}$.

As discussed in [4], we studied systematic uncertainties and possibility to produce peaks in the $d+\pi^-$ and $t+\pi^-$ invariant mass distributions by mis-reconstructing the other possible decay channels. It was concluded that the other channels could not create peaks like those observed in the $d+\pi^-$ and $t+\pi^-$ final states. Therefore, a possible interpretation for the observed $t+\pi^-$ and $d+\pi^-$ final states might be the two- and three-body decays of an unknown bound state of two neutrons associated with Λ , ${}^3_\Lambda\text{n}$, via ${}^3_\Lambda\text{n} \rightarrow t+\pi^-$ and ${}^3_\Lambda\text{n} \rightarrow t^*+\pi^- \rightarrow d+n+\pi^-$, respectively. With this interpretation, the production mechanism of ${}^3_\Lambda\text{n}$ might be the Fermi break-up of excited heavier hyperfragments [43]. On the other hand, the direct coalescence of a Λ -hyperon and a di-neutron state is unlikely, because the di-neutron state is known to be unbound.

Fig. 5. Profiled likelihood ratio for interval estimation of the lifetime of $d+\pi^-$ (a1) and $t+\pi^-$ (b1) final states. Interval estimation for 1 standard deviation is shown on each profiled likelihood ratio. Binned decay length distributions of the signal region of $d+\pi^-$ (a2) and $t+\pi^-$ (b2) are shown with the fitted model. The model includes the exponential function that resulted from the unbinned maximum likelihood fit and the background contribution estimated by the sidebands. The fitted model is represented by the black line, while the contribution of the exponential function is represented by the dotted blue line. The figures are taken from [4]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The possibility of a bound state made of Λ -hyperon and two neutrons, ${}^3_{\Lambda}\text{n}$, was studied recently in several theoretical works [44–47], all concluding that the n - n - Λ system is unlikely to be bound. These calculations are based on quite general arguments relying on existing, well established hypernuclear data.

Since the results from the HypHI collaboration on ${}^3_{\Lambda}\text{n}$ are not conclusive, the origin of the observed structures in the $d+\pi^-$ and $t+\pi^-$ final states must be experimentally verified and clarified. The ALICE collaboration studied $d+\pi^-$ final states, and there is no signal observed [48]. Since the ALICE and HypHI are observing particles in the different rapidity regions, the origin of the structures in the $d+\pi^-$ and $t+\pi^-$ final states should be experimentally studied in the projectile rapidity region like the HypHI Phase 0 experiment, which will be conducted at GSI (FAIR Phase 0) and FAIR. In the next section, we will discuss on newly proposed experiments to study the $d+\pi^-$ and $t+\pi^-$ structures as well as to measure lifetime values of ${}^3_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{H}$ with better accuracy.

3. Plan of a new experiment with FRS at GSI (FAIR Phase 0)

As discussed in the previous section, further experimental works should be conducted with a better precision than the HypHI Phase 0 experiment to confirm the short lifetime of ${}^3_{\Lambda}\text{H}$ as well as to clarify the origin of the $d+\pi^-$ and $t+\pi^-$ signals. An experiment has been proposed by a part of the HypHI collaboration together with the Super-FRS collaboration [49] to perform

Fig. 6. Layout of the FRS at GSI. In the proposed experiment, a conventional production target located in the entrance of the FRS is not used, but the hypernuclear production target will be located at S2. A system of the π^- measurements will be installed at the mid-focal plane S2.

Fig. 7. Proposed setup for the future HypHI experiment with the Fragment separator FRS at GSI.

hypernuclear spectroscopy with the Fragment separator FRS [50] at GSI as a high-resolution forward magnetic spectrometer. In the proposed experiment, the same production reaction of the HypHI Phase 0 experiment, ${}^6\text{Li} + {}^{12}\text{C}$ at 2 A GeV, will be employed since the hypernuclear production cross section and kinematics in this reaction are already investigated by the HypHI Phase 0 experiment.

Fig. 6 shows the layout of the SIS 18 synchrotron and the FRS at GSI. The ${}^6\text{Li}$ beams will be accelerated up to an energy of 2 A GeV and will be injected to the FRS. Through the FRS via S1, the beams will arrive at the mid-focal plane of the FRS, indicated as S2 in the figure. In the S2 area, a fixed carbon target is situated together with a spectrometer complex.

A proposed experimental setup in the S2 area of the FRS is shown in Fig. 7 schematically. The ${}^6\text{Li}$ projectiles with an intensity of an order of 10^6 particles per second are delivered from the left side of the figure, and they are bombarded to the fixed carbon target with a thickness of 8 g/cm^2 . In front of the target, a small plastic hodoscope which is similar to TOF-start employed in the HypHI Phase 0 experiment [1] will be mounted to measure beam particles as well as to define start-time for time-of-flight measurements. It is shown together with the target as indicated as “START + TARGET” in the figure. Hypernuclei of interest are produced at the target and fly to

the forward direction. Then, hypernuclei decay in flight, and they emit particles. Particles from the decay also fly to the forward direction, and they are injected to the dipole magnet indicated as D-magnet in the figure. We will reconstruct π^- -decay channels of hypernuclei of interest, that take place inside “Decay volume” as shown in the figure. Across the “Decay volume”, several tracking detectors will be mounted, that consist of scintillating fibre detectors and the drift chamber (SDC) used in the HypHI Phase 0 experiment [1]. These tracking detectors will contribute to find decay vertices of hypernuclei. The π^- mesons from the hypernuclear decay are bent in D-magnet and swept upward in the figure. Approximately 10% of π^- from the hypernuclear decay are registered in the detector system indicated as “ π^- detectors” in the figure. These detectors will consist of a plastic hodoscope and a drift chamber. The plastic hodoscope will be implemented by rearranging the TOF+ detector used in the HypHI Phase 0 experiment, and the drift chamber will be SDC which was also used in HypHI Phase 0 [1]. For π^- , four momenta will be obtained by tracking across the magnet, time-of-flight measurements and the information of ΔE in the plastic hodoscope. In the proposed system, a momentum resolution of π^- is expected to be 1–2%.

In the proposed experiment, positively charged decay residues of hypernuclear π^- decay, such as ${}^2\text{H}$, ${}^3\text{He}$ and ${}^4\text{He}$, should be injected to the second half of the FRS, and they should be in the aperture of the magnet located at the exit of S2 indicated as “S2 Exit Magnet” in the figure. However, decay residues are also bent inside the D-magnet downward in the figure, therefore, the bending of the decay residues must be compensated in order to deliver them to the second half of the FRS. For this purpose, another dipole magnet located in the right side of the D-magnet will be installed. With this magnet, decay residues can be measured from S2 to S4 in Fig. 6. A momentum resolution of measured decay residues from S2 through S4 is expected to be better than 10^{-3} . One of the disadvantages in this setup is small momentum and spatial acceptance for decay residues. However, it will make a counting rate at S4 drastically smaller (about three order of magnitude lower than the rate of the projectiles), and one can make a trigger to the data acquisition system only by coincident measurements of particle registrations in the detectors at S4 and “ π^- detectors” at S2. Because of a small trigger rate of an order of 10^2 – 10^3 per second with this coincidence trigger, a secondary vertex trigger, which played an important role in the HypHI Phase 0 experiment [1], will be unnecessary. Without the vertex trigger, the efficiency of the data accumulation will be at least ten times larger than that in the HypHI Phase 0 experiment.

With reconstructed π^- from the hypernuclear decay and decay residues together with finding of hypernuclear decay vertices in “Decay volume”, an invariant mass of produced hypernuclei will be calculated. Though a small momentum acceptance of decay residues due to the second half of the FRS, a resultant invariant mass resolution will not be narrow around the observed peak region since π^- will be measured with a large momentum range at S2 in the proposed setup. In order to observe ${}^3_\Lambda\text{H}$ and ${}^4_\Lambda\text{H}$ as well as the $d + \pi^-$ signal, only four magnetic setups of the FRS between S2 and S4 including the magnets at S2 will be required; 1) 12.5 Tm for measuring ${}^3_\Lambda\text{H}$, 2) 16.5 Tm for both ${}^4_\Lambda\text{H}$ and the $d + \pi^-$ final state, 3) 11.0 Tm for ${}^4_\Lambda\text{H}$ and 4) 14.0 Tm for all the three states. Monte Carlo simulations have been performed, and expected invariant mass distributions for ${}^3_\Lambda\text{H}$ and $d + \pi^-$ final state are shown in the left and right panels, respectively, of Fig. 8. For ${}^3_\Lambda\text{H}$ a ratio of the signal to the background is assumed to be 0.24. For $d + \pi^-$, a smaller ratio of the signal to the background, 0.20, is assumed because the background for $d + \pi^-$ was observed larger than ${}^3_\Lambda\text{H}$ in the analyses of the HypHI Phase 0 experiment. Resultant mass resolution for the both cases are approximately $800 \text{ keV}/c^2$, which is much better than the results of the Phase 0 experiment ($\sim 5 \text{ MeV}/c^2$). The expected mass resolution for the reconstruction of ${}^4_\Lambda\text{H}$ will be similar to the case of $d + \pi^-$ because of the similarity of the magnetic rigidity

Fig. 8. Expected invariant mass distributions for ${}^3\Lambda\text{H}$ (left) and $d + \pi^-$ final state (right). In the panels, “S/B” indicates a ratio of the signal to the background. “MC” indicates Monte Carlo simulations.

of decay residues. Measurements with all the four magnetic setups mentioned above can be achieved within two weeks. This method will be extended to measure other hypernuclei including those towards the proton drip line with Super-FRS [51] at FAIR.

4. Summary

The HypHI collaboration has proposed series of experiments to produce and study hypernuclei by means of induced reactions of stable heavy ion beams and rare-isotope beams at GSI and FAIR. In order to demonstrate the feasibility of the experimental method, the Phase 0 experiment was performed at GSI to produce and identify known light hypernuclei, ${}^3\Lambda\text{H}$ and ${}^4\Lambda\text{H}$ with a reaction of ${}^6\text{Li} + {}^{12}\text{C}$ at 2 A GeV. Observations of the both hypernuclei were successful and their lifetime values have been deduced by utilising an *unbinned* maximum likelihood fitting method. The striking result of the Phase 0 experiment is to reveal that the lifetime of ${}^3\Lambda\text{H}$ is significantly shorter than that of the Λ -hyperon. We have performed statistical analyses to consider all the existing lifetime data for ${}^3\Lambda\text{H}$ and ${}^4\Lambda\text{H}$ till 2014, and the results also indicated that the lifetime of the two hypernuclei is significantly shorter than Λ . We also estimated by using a Bayesian approach the upper limit for the lifetime values of ${}^3\Lambda\text{H}$ and ${}^4\Lambda\text{H}$, and any theoretical model calculations above these upper limits values should be invalidated with a confidence level of 95%. The recent results by the STAR and ALICE collaborations also reveals that the lifetime of ${}^3\Lambda\text{H}$ is shorter than Λ . Currently there have been no theories to explain the short lifetime of ${}^3\Lambda\text{H}$, and it still remains a puzzle. Values of the hypernuclear production cross section in a reaction of ${}^6\text{Li} + {}^{12}\text{C}$ at 2 A GeV have also been deduced.

With the same data set, an invariant mass was also reconstructed with the $d + \pi^-$ and $t + \pi^-$ channels. Surprisingly, signals in the invariant mass distributions have been observed for the both cases. The lifetime values of the mother states finalising the both channels have been also deduced with similar ways to ${}^3\Lambda\text{H}$ and ${}^4\Lambda\text{H}$, and they are respectively 181^{+30}_{-24} ps and 190^{+47}_{-35} ps. With these results, the HypHI collaboration suggested that these final states may be populated by decays of unknown bound states with two neutron and Λ , ${}^3_{\Lambda}\text{n}$. The possibility of a bound state made of Λ -hyperon and two neutrons, ${}^3_{\Lambda}\text{n}$, was studied recently in several theoretical works [44–47], all concluding that the n - n - Λ system is unlikely to be bound. Since the results from the HypHI collaboration are not conclusive, signals observed by HypHI should be verified and clarified with new experimental techniques.

A new idea to study hypernuclei by using the FRS as a high momentum resolution forward spectrometer has been also presented in this article. In the proposed setup, a coincident measurement of π^- at the mid focal plane of the FRS and the π^- decay residues by the second half of the FRS will be performed. According to the Monte Carlo simulations, a mass resolution of approximately $800 \text{ keV}/c^2$ could be achieved. With the proposed setup, a precise measurement of the lifetime of ${}^3_\Lambda\text{H}$ as well as further studies of the $d + \pi^-$ signal will be performed. After the success of the proposed experiment, the method will be extensively applied with Super-FRS at FAIR.

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