# The HypHI project at GSI and FAIR

## Hypernuclear spectroscopy with stable heavy ion beams and rare-isotope beams

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**Abstract.** Even though both experimental and theoretical activities on hypernuclear physics have been extended by a number of international projects, direct measurements on hypernuclear magnetic moments and studies of hypernuclei at extreme isospins have never been performed. The international HypHI collaboration proposes to perform hypernuclear spectroscopy with stable heavy ion beams and rare isotope beams at GSI and FAIR in order to study neutron and proton rich hypernuclei and to measure directly hypernuclear magnetic moments. The project is divided into four phases. In the first Phase 0 experiment, the feasibility of precise hypernuclear spectroscopy with heavy ion beams will be demonstrated by observing  $\pi^-$  decay channels of  ${}^3_A$ H,  ${}^4_A$ H and  ${}^5_A$ He with  ${}^6$ Li projectiles at 2 A GeV impinging on a  ${}^{12}$ C target. In the later Phases 1 through 3, studies of proton and neutron rich hypernuclei, direct measurements of hypernuclear magnetic moments and the spectroscopy of hypernuclei toward the nucleon drip-lines are planned.

**PACS.** 21.80.+a Hypernuclei – 25.75.-q Relativistic heavy-ion collisions – 21.10.Dr Binding energies and masses – 21.10.Ky Electromagnetic moments – 07.05.Fb Design of experiments

# **1** Introduction

The information on hypernuclei is presently limited to cases with nuclear cores in the valley of beta-stability since stable target materials are used for their production through strangeness exchange or kaon-hyperon production with electron or meson beams. Neutron or proton rich hypernuclei at extreme isospins (we call them *exotic* hypernuclei) have never been produced even though hypernuclei have been investigated for almost four decades with accelerator based spectroscopy in CERN, BNL, KEK and JLab. Information on very neutron rich hypernuclei is essential to understand the nature of neutron stars because several model calculations predict that hyperons are even dominant ingredients in the core of neutron stars [1]. However, very neutron rich hypernuclei close to the neutron drip line, which could give unique information on hyperon(Y)-nucleon(N) interactions in neutron rich environments, have never been studied yet. Another important piece of information which has never been obtained so far is on hypernuclear magnetic moments, which will contribute to understand YN interaction on the quark level. In meson and electron beam induced experiments, recoil

momenta of produced hypernuclei are small. Therefore, it has been impossible so far to conduct a direct measurement on hypernuclear magnetic moments by means of spin precession in strong magnetic fields. It has been suggested by Hashimoto and his collaborators that heavy ion induced reactions at a few tens of A GeV could give an opportunity to perform direct measurements on hypernuclear magnetic moments [2]. A heavy ion induced reaction even at lower energies such as at 2 A GeV could provide an opportunity to reach exotic hypernuclei [3–5]. The HypHI project which has been recently proposed at GSI in Germany [3–6] is aiming to perform precise hypernuclear spectroscopy with heavy ion beam and rare-isotope (RI) beam induced reactions and to measure directly hypernuclear magnetic moments.

Hypernuclear production via a heavy ion collision was first theoretically studied by Kerman and Weiss [7]. In high energy heavy ion collisions, it is well known that the participant-spectator model explains the general feature of the reaction. The overlapped region between the two nuclei (participants) participates in the collision, while the nucleons in the off-overlapping region (spectators) pass by each other without experiencing a large disturbance. Hyperons such as  $\Lambda$  are produced in the participants region at around the mid-rapidity. Because of their wide rapidity distribution, one may produce a hypernucleus with a coalescence of hyperon(s) in the projectile fragments, thus the velocity of hypernuclei is close to the one of projectile. Because of the energy threshold of ~ 1.6 GeV for  $\Lambda$ production of an elementary process of  $NN \to \Lambda KN$ , the produced hypernuclei have a large velocity with  $\beta > 0.9$ and their effective lifetime is longer than at rest because of a large Lorentz factor. Decays of hypernuclei can be studied in-flight, and most of their decay vertexes are a few tens of centimeters behind the target at which hypernuclei are produced. In the late 80s, hypernuclear production with heavy ion beams was performed in JINR [8,9] with beams of  $3.7 \ A \ GeV ^4$ He and  $3.0 \ A \ GeV ^7$ Li impinged on a polyethylene target. They deduced a production cross section for  ${}^{4}_{\Lambda}$ H as ~ 0.3 µb, which was reproduced by the theoretical calculation based on a model of a  $\Lambda$  coalescence in projectiles [10,11]. Recently,  ${}^{3}_{4}$  H has also been produced and identified with central 11.5 A GeV/c Au+Pt collisions by the BNL AGS E864 experiment [12]. Even though the two experiments at JINR and BNL have shown the production of hypernuclei with heavy ion beams, the feasibility of the reliable hypernuclear spectroscopy with heavy ion beams has yet not been proven, and the answer to the question on the feasibility has to be given experimentally.

In the HypHI project hypernuclei are produced by heavy ion induced reactions at relativistic energies with associated kaon productions in facilities of GSI and FAIR which is the future facility of GSI [13]. In the experiment at 2 A GeV, the decay of hypernuclei takes place well behind the target with a mean flight length of approximately 20 cm, and in the experiment at FAIR at 20 AGeV, the lifetime of hypernuclei is about 4 ns thus the separation of hypernuclei by a superconducting magnetic spectrometer could be feasible, which will give an opportunity to perform direct measurements of hypernuclear magnetic moments. From the decay vertex of hypernuclei behind the target, the production and decay of hypernuclei are tagged by observing charged particle channels of mesonic and non-mesonic weak decays of hypernuclei, and hypernuclear events are reconstructed by tracking charged particles across a bending magnet, Time-Of-Flight (TOF) measurements, and neutron measurements at the forward directions. We will perform an invariant mass spectroscopy to reconstruct hypernuclear events.

The physics subjects of the HypHI project are [3],

- Magnetic moments of hypernuclei,
- Hypernuclei toward the proton and neutron drip-lines,
- $-\Lambda \Sigma$  coupling in the nuclear matter,
- Decay of exotic hypernuclei,
- Charge symmetry breaking in  $\Lambda N$  interaction,
- Coulomb dissociation of loosely-bound hypernuclei,
- Measurements of the binding energy of exotic hypernuclei.

The HypHI project consists of four phases defined as Phase 0 to 3 [3]. The Phase 0 experiments planned with the current GSI facility aims to prove the experimental principle of the HypHI project by confirming the result of the experiment at JINR [8,9]. In the Phase 1 experiment at the current GSI facility, proton rich hypernuclei will be studied with stable heavy ion beams and RI-beams from FRS [14]. Phase 2 and 3 experiments are proposed to be performed at FAIR. Phase 2 experiment will concentrate on studies of neutron rich hypernuclei in the high energy branch (R3B) [15] in the NuSTAR framework [16] with stable heavy ion beams and RI-beams from super-FRS [17]. It is suggested in the Phase 3 project to develop a hypernuclear separator with stable heavy ion beams at 20 A GeV in order to measure directly hypernuclear magnetic moments and to reach hypernuclei at nucleon drip-lines.

#### 2 Phase 0 experiment

The Phase 0 experiment aims to demonstrate the feasibility of precise hypernuclear spectroscopy with heavy ion beams by reproducing the experimental results obtained in the experiment in JINR [8,9], with a <sup>6</sup>Li beam. The experiment aims to produce and identify  ${}_{A}^{3}$ H,  ${}_{A}^{4}$ H and  ${}_{A}^{5}$ He by means of an invariant mass spectroscopy by observing decay channels of  ${}_{A}^{3}$ H $\rightarrow$ <sup>3</sup>He $+\pi^{-}$ ,  ${}_{A}^{4}$ H $\rightarrow$ <sup>4</sup>He $+\pi^{-}$  and  ${}_{A}^{5}$ He $\rightarrow$ <sup>4</sup>He+p $+\pi^{-}$ . It will be performed in cave C at GSI, and a schematic experimental setup is shown in Fig. 1. A beam of <sup>6</sup>Li at 2 *A* GeV will impinge on a high density carbon graphite target with a thickness of 8 g/cm<sup>2</sup> to produce hypernuclei, and the proposed averaged beam intensity is 10<sup>7</sup> per second.

As a bending magnet for produced charged particles from the target and hypernuclear decay vertexes, the existing ALADiN magnet will be used as shown in Fig. 1. A magnetic field of 0.7 T will be applied. The distance between the target and the center of the ALADiN magnet is 2.35 m.

As a start counter for TOF measurements, we currently consider to employ a large-area polycrystalline diamond detector in order to accept beams with an intensity larger than  $10^7$  particles per second, with a thickness of approximately 1.0 mm. The detector will be placed in front of the target.

There are three layers of scintillating fiber detectors as indicated as TR0, TR1 and TR2 in Fig. 1. TR0 is placed right behind the target with four layers of fibers for x and y position measurements for outgoing particles from the target. Energy deposit of charged particles through TR0 will be also measured. The detector is similar to the one developed for the MAMI C KaoS experiment [18]. For the detectors, Kuraray SCSF-78 scintillating fibers with an outer diameter of 0.83 mm and an active core of 0.73 mm will be used. A preliminary layout chosen in order to meet our requirements consists of four layers of fibers at a pitch of 0.59 mm in both x- and y planes. The active area of TR0 is approximately  $4 \times 4$  cm<sup>2</sup>. TR1 and TR2 are located between the target and the ALADiN magnet, which are similar to TR0 but with different size of the active areas as  $13.2 \times 7.6$  cm<sup>2</sup> for TR1 and  $24.5 \times 11.3$  cm<sup>2</sup> for TR2. The distance of TR1 and TR2 from the target center is respectively 40 and 70 cm. The read-out of scintillating photons is performed with the Hamamatsu Photonics



Fig. 1. A schematic drawing of the experimental setup for the Phase 0 experiment in cave C at GSI.

H7260 multi-anode photomultiplier tubes (PMT), which are also used in the MAMI C KaoS experiment [18]. PMTs are connected to the one end or both ends of the scintillating fibers for both x- and y-planes in TR0 to achieve an energy resolution of  $10 \sim 20$  % in  $\sigma$  thus permitting to measure the energy deposit of the outgoing particles from the target. This plays an essential role in selecting hypernuclear events. For TR1 and TR2, PMTs are connected only to the one end, and the energy information will not be taken from them. For the front-end electronics of logic signals for TR0, TR1 and TR2, a chip with 4 integrated low walk double-threshold discriminators (DTDs), the GSI-chip3, has been chosen [3]. The electronics workshop of the Institut für Kernphysik has developed a discriminator board housing 8 DTD chips and a front-end board to be connected directly to the multi-anode photomultiplier. Each discriminator board processes 32 channels and is controlled via VME bus. LVDS logic signals from the discriminator board will be guided to a FPGA based logic module with 1 GHz DSP, VUPROM, which has been already designed for the HypHI project at GSI. Each VUPROM module has 256 channels I/O with an LVDS standard and is equipped with an FPGA with 400 MHz and a DSP with 1 GHz. These are used to produce tracking triggers as discussed later. A prototype of the MAMI C scintillating fiber detector was tested in cave C at GSI with  ${}^{12}C$  beams at 2 A GeV [19,20], and position and energy resolutions of 0.27 mm in FWHM and 20 %in FWHM, respectively, have been observed [19]. Another prototype with two layers at GSI has been tested with cosmic-rays and a  $\beta$ -radiation source, and it will be tested with a <sup>12</sup>C primary beam 2 A GeV and  $\pi^+$  cocktail beam at 1 GeV/c [21].

The ALADIN TOF wall which already exists at GSI will be used as a stop counter for TOF measurements

and tracking behind the ALADiN magnet for negatively charged particles (mainly  $\pi^-$  and electrons), which are bent downwards in Fig. 1. It consists of two walls with 96 plastic strips (BC 408) each with a width of 2.5 cm and a thickness of 1 cm. It covers 2.4 m in the x-direction. The granularity of the position measurement is a half of the strip width in this direction. The readout is done with HAMAMATSU PMTs R3478 at both sides of the plastic strips. A time resolution of 100 ps (RMS) has been measured for fragments with Z > 20 in the Au+Au experiment at 600 A MeV, permitting approximately 3 cm position accuracy in RMS in the y-direction. For lighter ions which are expected to be detected in the Phase 0 experiment, the time resolution is expected to be worse than for Z > 20 particles, however, the time resolution could be still good enough for the particle identification for Z < 4ions and pions. In the current setup, the distance between the ALADIN TOF wall from the target center is 5.5 m, and it should cover from -20 to -260 cm in x.

Positively charged particles are bent upwards in Fig. 1, and they are measured by a detector, indicated as TOF+ in the figure. It consists of 1 m long plastic bars with a width of 4.5 cm and a thickness of 2.5 cm. They are arranged perpendicularly to the xz-plane thus having the xposition granularity. Adjacent plastic bars are overlapped in 1.5 cm, therefore, an x-position granularity is 1.5 cm. The size of TOF+ in the x direction is approximately 1 m in order to have a reasonable acceptance for protons from the decay of free- $\Lambda$  and  ${}^{5}_{\Lambda}$ He. Readout of scintillating light is performed at both ends with the PMTs HAMA-MATSU R3478. The position of the center of TOF+ is  $(x,y,z)=(30,0,550)~{\rm cm}.$  There will be a hole in TOF+ designed in order not to observe <sup>6</sup>Li beams because of the counting rate restrictions of the plastic scintillators and PMTs. The size of the hole is  $60 \times 60 \text{ mm}^2$ , of which the

center is at (x, y) = (170, 0) mm. With the hole of the stated position and area, the loss of  $\alpha$  particles by the whole is approximately 7 % [22].

In order to confirm a production of strangeness in the reactions, we consider to cross check the experimental data with  $K^+$  detection. Since produced  $K^+$  at the target is expected to have rather low momentum, most of  $K^+$  do not come out of the ALADiN magnet thus hitting the side yoke of the magnet. Therefore, we are developing an array of plastic bars, which could be mounted on the side gap of the ALADiN magnet. According to preliminary Monte Carlo simulations, a detection efficiency of approximately 20 % is expected for  $K^+$  events. The  $K^+$  detector is not shown either in Fig. 1. Three layers of drift chambers from KEK are also considered to be employed in the setup, which are not either shown in the figure. A high rate chamber will be located behind TR2 and two large layers are mounted at the exit of the ALADiN magnet and in front of TOF+, respectively.

There will be a trigger system with three levels [5]. The Level-1 trigger is a tracking trigger which is made of signals from the scintillating fiber tracking arrays. The logic signals from the discriminator board will be fed to newly developed VME universal logic modules with FPGA and DSP, VUPROM, which examines if there is a secondary vertex behind the target caused by free- $\Lambda$  and hypernuclear decays. If there is one, the modules will create a signal which is used as a tracking trigger. VUPROM for the tracking trigger has been already designed at GSI. Level-2 trigger is associated with  $\pi^-$  detection. Negatively charged pions from hypernuclear decay are bent downwards in Fig. 1, and  $\pi^-$  particles with large momenta are detected by the ALADIN TOF wall. The  $\pi^-$  trigger is simply requiring a hit in the ALADiN TOF wall above a certain energy threshold. Level-3 trigger employs Z = 2 particles in TOF+. It requires in TOF+ a hit with an energy-loss cut corresponding to Z = 2 particles which are the decay products of  ${}^{3}_{A}$ H,  ${}^{4}_{A}$ H and  ${}^{5}_{A}$ He. Trigger efficiencies are investigated by using Monte Carlo simulations with  ${}^{4}_{4}$ H events which include the associated particles. The efficiency of the tracking trigger is found to be 14~% with reduction of the background down to 1.7 %. The efficiencies of the  $\pi^-$  trigger and the TOF+ trigger are deduced as 28 % and 95 % with reduction of background down to 15 and 14 %, respectively, for the positively charged particle decay channel of  ${}^{4}_{4}$ H. By combining these three triggers the total trigger efficiency is to be 7 % with a reduction of background down to 0.017 %. A trigger rate of 340 Hz is expected in the Phase 0 experiment.

Expected performance in the Phase 0 experiment has been investigated by means of Monte Carlo simulations with the GEANT4 package [23]. As an event generator, we performed Ultra Relativistic Quantum Molecular Dynamics (UrQMD) calculations [24], and the results of the calculations are fed into the simulations. Details on the Monte Carlo simulations are discussed in references [5, 25]. At the current stage, we have finished detailed simulation studies for the case of free- $\Lambda$  and  $^{4}_{\Lambda}$ H, and simulations for  $^{3}_{\Lambda}$ H and  $^{5}_{\Lambda}$ He are still in progress. Since the most



Fig. 2. Simulated spectrum of  ${}^{4}_{A}$ H invariant mass with background with events of 46900  ${}^{4}_{A}$  production for (a) event rejection with TR0 energy deposition cut of > 5 MeV and (b) with > 5.5 MeV. Details are described in ref. [5].

unique feature of the HypHI Phase 0 experiment is that the hypernuclear decay takes place behind the target with a mean decay path of approximately 15 cm, it is essential to achieve the best possible resolutions for all the vertex coordinates and especially in z. With  ${}^{4}_{\Lambda}$ H, secondary vertex was reconstructed by using the position information of hits in TR1 and TR2. For x and y, excellent resolutions of approximately 0.30 mm are observed, while, the z-vertex resolution was found at 4.7 mm. Since the mean decay length of hypernuclei is approximately 15 cm, this z-vertex resolution is good enough for the hypernuclear event reconstructions. Another important cut condition to reconstruct  ${}^{4}_{A}$ He is on the energy deposition cut in TR0 in order to reject events with an  $\alpha$ -particle from the target. Fig. 2 shows the reconstructed  ${}^{4}_{\Lambda}$ H invariant mass distribution with background with (a) event rejection with TR0 energy deposition cut of > 5 MeV and (b) with > 5.5MeV. Details of the Monte Carlo simulations are described in the HypHI Phase 0 proposal [5]. The width of the  ${}^{4}_{\Lambda}$ H invariant mass is observed at 3 MeV in  $\sigma$ . The spectra were produced without considering drift chambers and the  $K^+$  detector, and it is expected that with these detectors the width of the peak in the figure is at least two times narrower and the level of the background much smaller.

For the rate estimate, we assumed a production cross section of  ${}^{4}_{\Lambda}$ H and  ${}^{3}_{\Lambda}$ H to be 0.1  $\mu$  barn for each and  ${}^{5}_{\Lambda}$ He to be 0.5  $\mu$  barn. In accordance with the Monte Carlo simulations, the reconstructed events of  ${}^{3}_{\Lambda}$ H,  ${}^{4}_{\Lambda}$ H and  ${}^{5}_{\Lambda}$ He per week are 2.8 × 10<sup>3</sup>, 2.6 × 10<sup>3</sup> and 6.5 × 10<sup>3</sup> per week, respectively.

# **3** Perspective

After the success of the Phase 0 experiment, the HypHI project will be continued at GSI and FAIR [3]. As Phase 1, an experiment for proton rich hypernuclei will be performed in cave C at GSI with a setup similar to that of Phase 0 but with heavier primary projectiles and proton rich beams. In Phase 1, the decay of hypernuclei will also

be tagged by measuring protons and neutrons from the non-mesonic weak decay. The Phase 2 experiment will be performed in the R3B cave at FAIR, and the spectroscopy of neutron rich and heavy proton rich hypernuclei up to Z = 14 will be performed. In the Phase 2 experiment, neutron measurements at forward directions will be more crucial. As Phase 3, a development of a hypernuclear separator with a superconducting magnet is being discussed. The basic concept of Phase 3 is described in LOI [3]. In Phase 3, we will aim to measure directly hypernuclear magnetic moments and to extend hypernuclear chart to nucleon drip-lines. In the experiments of Phase 3, spectroscopy on multiple- $\Lambda$  hypernuclei,  $\Xi$ -hypernuclei and more exotic hypernuclei with multiple-strangeness could also be performed.

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