Article ID: 1007－4627(2009)Suppl.－0022－06

Hypernuclear Spectroscopy with Stable Heavy Ion Beams and Rare-isotope Beams: HypHI Project at GSI and FAIR*

T. R. Saito[1] (on behalf of the HypHI collaboration)
(*GSI Helmholtz Center for Heavy Ion Research*, 64291 *Darmstadt*, *Germany*)

Abstract: 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 for the first time. 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 π^- decay channels of ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ and ${}^{5}_{\Lambda}He$ with ${}^{6}Li$ projectiles at 2 AGeV 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.

Key words: hypernuclear spectroscopy; heavy ion collision; rare-isotope beam

CLC number: O571.23　　**Document code**: A

1 Introduction

The information on hypernuclei is presently limited to cases with nuclear cores in the valley of β-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

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* **Received date**: 10 Nov. 2008; **Revised date**: 2 Dec. 2008

* **Foundation item**: The Helmholtz Association and GSI as Helmholtz-University Young Investigators Group VH-NG-239 at GSI with Mainz University; German Research Foundation(DFG)(SA1696/1-1)

Biography: T. R. Saito(1971－), male(Japanese Nationality), Tokyo, Japan, Professor Dr., working on the field of hypernuclear and hadron physics; E-mail: t.saito@gsi.de for the HypHI collaboration: the HypHI Project at GSI and FAIR

and his collaborators that heavy ion induced reactions at a few tens of AGeV 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 AGeV 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 Λ 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 Λ production of an elementary process of $NN \rightarrow \Lambda KN$, 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 1980s, hypernuclear production with heavy ion beams was performed in JINR[8, 9] with beams of 3.7 AGeV ^{4}He and 3.0 AGeV ^{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 Λ coalescence in projectiles[10, 11]. Recently, $^3_\Lambda$H has also been produced and identified with central 11.5 AGeV/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 not yet 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 AGeV, 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]: (1) magnetic moments of hypernuclei; (2) hypernuclei toward the proton and neutron driplines; (3) Λ-Σ coupling in the nuclear matter; (4) decay of exotic hypernuclei; (5) charge symmetry breaking in ΛN interaction; (6) coulomb dissociation of loosely-bound hypernuclei; (7) 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]. Phases 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 AGeV 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 ^{6}Li beam. The experiment aims at least to produce and identify $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H and $^{5}_{\Lambda}$He by means of an invariant mass spectroscopy by observing decay channels of $^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$, $^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$ and $^{5}_{\Lambda}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + p + \pi^{-}$. It will be performed in cave C at GSI in 2009, and a schematic experimental setup is shown in Fig. 1. A beam of ^{6}Li at 2 AGeV will impinge on a high density carbon graphite target with a thickness of 8 g/cm^{2} to produce hypernuclei, and the proposed averaged beam intensity is 10^{7} ions/s.

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 are currently developing an array of plastic finger hodoscopes with plastic scintillators BC420 and HAMAMATSU R7400-06 MOD. It is designed to accept an intensity of ^{6}Li beams of 10^{7} ions/s and will be mounted in front of the target.

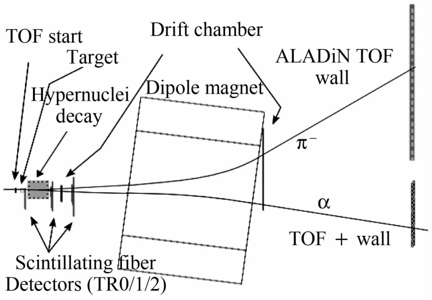

Fig. 1 A schematic drawing of the experimental setup for the Phase 0 experiment in cave C at GSI.

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. 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 layout has been 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 position active area of TR0 is approximately 4 cm × 4 cm. 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 cm × 7.6 cm for TR1 and 24.5 cm × 11.3 cm 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 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-position in TR0 to achieve an energy resolution of 10%—20% in σ

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[8]. 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 developed for the HypHI project at GSI. Each VUPROM module has 256 channels I/O with a LVDS standard and is equipped with a FPGA with 400 MHz and a DSP with 1 GHz. Eighty VUPROM modules have been already produced and tested at GSI. These are used to produce tracking triggers as discussed later. These detectors have been already tested at GSI with cosmic-rays, proton beams, pion beams and light secondary fragments at GSI.

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 π^- and electrons), which are bent upwards in Fig. 1. 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 downwards in Fig. 1, and they are measured by a detector, indicated as TOF+ in the figure, which has been developed at GSI. 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 x-position 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-Λ and ${}^{5}_{\Lambda}\mathrm{He}$. Readout of scintillating light is performed at both ends with the PMTs HAMAMATSU R3478. The position of the center of TOF+ is $(x, y, z)=(30, 0, 550)$ cm. There will be a hole in TOF+ designed in order not to observe ${}^{6}\mathrm{Li}$ beams because of the counting rate restrictions of the plastic scintillators and PMTs. The size of the hole is 60 mm×60 mm, of which the center is at $(x, y)=(170, 0)$ mm. With the hole of the stated position and area, the loss of α particles by the whole is approximately 7%[19].

In addition to these detectors, there are two drift-chambers from KEK, which are also shown in Fig. 1.

The trigger system for the data acquisition electronics is 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 modules, VUPROMs, which examines if there is a secondary vertex behind the target caused by free-Λ and hypernuclear decays. If there is one, the modules will create a signal which is used as a tracking trigger. Level-2 trigger is associated with π^- detection. Negatively charged pions from hypernuclear decay are bent upwards in Fig. 1, and π^- particles with large momenta are detected by the ALADiN TOF wall. The π^- 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 ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{5}_{\Lambda}\mathrm{He}$. Trigger efficiencies are investigated by using Monte Carlo simulations with ${}^{4}_{\Lambda}\mathrm{H}$ 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 π^- 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 $^{4}_{\Lambda}\mathrm{H}$. 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.

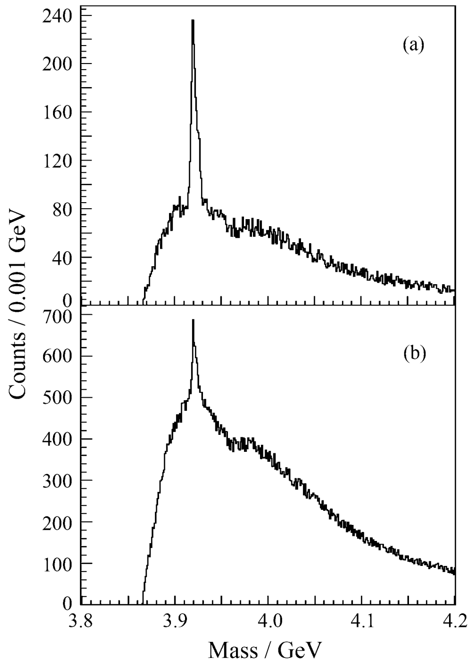

Fig. 2 Simulated spectrum of $^{4}_{\Lambda}\mathrm{H}$ invariant mass with background with events of 46 900 $^{4}_{\Lambda}$ production for (a) event rejection with TR0 energy deposition cut of >5 MeV and (b) with >5.5 MeV. Details are discussed in Ref. [5].

Expected performance in the Phase 0 experiment has been investigated by means of Monte Carlo simulations with the GEANT4 package[20]. As an event generator, we performed Ultra Relativistic Quantum Molecular Dynamics (UrQMD) calculations[21], and the results of the calculations are fed into the simulations. Details on the Monte Carlo simulations are discussed in Refs. [5, 22]. Fig. 2 shows the reconstructed $^{4}_{\Lambda}\mathrm{H}$ invariant mass distribution with background with (a) event rejection with TR0 energy deposition cut of >5 MeV and (b) with >5.5 MeV. Details of the Monte Carlo simulations are described in the HypHI Phase 0 proposal[5]. The width of the $^{4}_{\Lambda}\mathrm{H}$ invariant mass is observed at 3 MeV in σ. 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 $^{4}_{\Lambda}\mathrm{H}$ and $^{3}_{\Lambda}\mathrm{H}$ to be 0.1 μb for each and $^{5}_{\Lambda}\mathrm{He}$ to be 0.5 μb. In accordance with the Monte Carlo simulations, the reconstructed events of $^{3}_{\Lambda}\mathrm{H}$, $^{4}_{\Lambda}\mathrm{H}$ and $^{5}_{\Lambda}\mathrm{He}$ per week are 2.8×10^3, 2.6×10^3 and 6.5×10^3, respectively.

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