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Decay Pion Spectroscopy of Double-Λ Hypernuclei at J-PARC

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Double-Λ hypernuclei provide invaluable information on Λ-Λ interaction, as a scattering experiment with a hyperon target is impossible. For more than half a century, double-Λ hypernuclei have been searched for by using nuclear emulsion. We will propose a novel counter experiment (J-PARC P75 experiment), aiming at investigating a light double-Λ hypernucleus, ${}^{5}_{\Lambda\Lambda}$H. The ΛΛ binding energy will be determined by decay pion spectroscopy. The experimental method of production and identification of ${}^{5}_{\Lambda\Lambda}$H is discussed.

KEYWORDS: Double-Λ hypernuclei, Ξ hypernuclei, decay pion spectroscopy

1. Introduction

One of the important goals in hypernuclear physics is to reveal baryon-baryon interaction for the $SU_f(3)$ baryon octet, especially hyperon-nucleon and hyperon-hyperon interaction. For example, detailed studies on the structure of Λ-hypernuclei have provided rich information on Λ-nucleon interaction, as a scattering experiment between a Λ and a nucleon is difficult.

On the contrary, little is known about the interaction between two Λ's, while it is strongly related to the fate of the *H*-dibaryon. Experimentally, the first double-Λ hypernuclear event was discovered in nuclear emulsion by Danysz *et al.* [1], and since then double-Λ hypernuclei were investigated mainly in nuclear emulsion experiments, including the J-PARC E07 experiment carried out in 2016 and 2017 [2–4]. In these experiments, a Ξ^- hyperon produced in a (K^-, K^+) reaction was stopped and captured by light nuclei in emulsion, and a double-Λ nucleus with the mass number between 4 and 17 may be produced. For example, from the observation of ${}^{6}_{\Lambda\Lambda}$He [5, 6], Λ-Λ interaction in *s*-wave was found to be weakly attractive. Furthermore, a number of events with double-Λ hypernuclei as well as twin hypernuclei were already observed in a part of the irradiated emulsion sheets in the E07 experiment [3]; the observation of a double-Λ hypernucleus of $_{\Lambda\Lambda}$Be (probably ${}^{11}_{\Lambda\Lambda}$Be) was reported very recently [4].

While a nuclear emulsion experiment has an advantage in systematic study of double-Λ hypernuclei with different mass numbers, the J-PARC P75 experiment [7,8] aims to produce ${}^{5}_{\Lambda\Lambda}$H exclusively. The essence of the experimental concept is to produce ${}^{5}_{\Lambda\Lambda}$H from a decay of a Ξ-hypernucleus ${}^{7}_{\Xi^-}$H

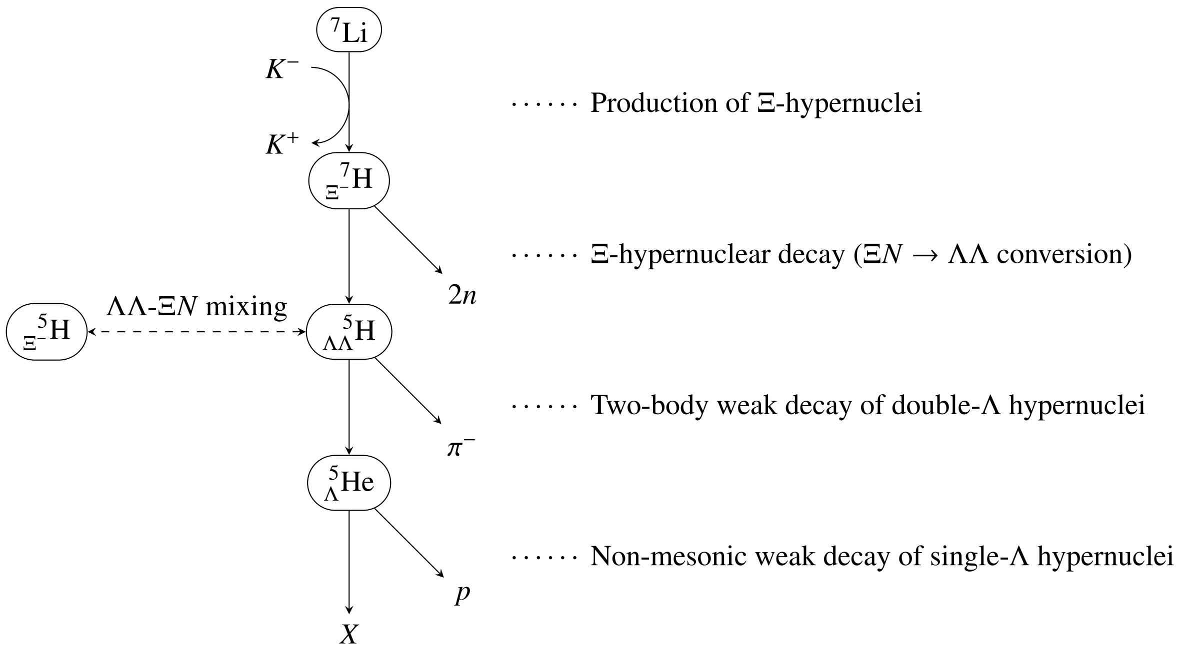

Fig. 1. A flow chart for production, structure, and decay of $^{\ \ 5}_{\Lambda\Lambda}$H. See text for details.

and determine the mass of $^{\ \ 5}_{\Lambda\Lambda}$H by measuring a monochromatic π^- emitted in the two-body decay of $^{\ \ 5}_{\Lambda\Lambda}\mathrm{H} \to {}^{5}_{\Lambda}\mathrm{He} + \pi^-$.

Besides the P75 experiment, studies of double-Λ hypernuclei in counter experiments are planned. The $\overline{\mathrm{P}}$ANDA experiment [9] at FAIR, Germany will perform a γ-ray spectroscopy of double-Λ hypernuclei, which will be produced by Ξ^- capture. Different from the nuclear emulsion experiments at KEK-PS and J-PARC, low-momentum Ξ^- hyperons will be produced in an internal nuclear target inside an antiproton storage ring. Furthermore, light double-Λ hypernuclei, as well as single-Λ hypernuclei such as $^{3}_{\Lambda}$H, may be produced in high-energy heavy-ion collisions. For instance, the result of feasibility studies in the CBM experiment at FAIR was reported [10], and an experimental investigation may be also possible in the HIAF project in China as well [11]. Both FAIR and HIAF will start their operations in 2020's.

Under such a circumstance, it is very timely to prepare for the new experiment for studying double-Λ hypernuclei at J-PARC.

2. Concept of the J-PARC P75 Experiment

The concept of the proposed experiment is schematically depicted in Fig. 1. In this section, each step from the top to the bottom, relevant to production, structure, and decay of $^{\ \ 5}_{\Lambda\Lambda}$H, will be briefly explained. For details, please refer to Refs. [7, 8].

First of all, a Ξ-hypernucleus, $^{\ 7}_{\Xi^-}$H will be produced in the $^{7}\mathrm{Li}(K^-, K^+)$ reaction. It is expected to be bound below the $^{6}\mathrm{He} + \Xi^-$ threshold [12], and the formation cross section in the reaction was calculated by Koike and Hiyama [13].

Ξ-hypernuclear spectroscopy is one of the important experiments at J-PARC Hadron Experimental Facility, being enabled thanks to an intense K^- beam. The first experiment, E70 [14, 15], will investigate $^{12}_{\Xi}$Be in the $^{12}\mathrm{C}(K^-, K^+)$ reaction. A high-resolution spectrometer S-2S together with the K1.8 beamline will be used for a missing-mass spectroscopy of the reaction. In principle, by changing the nuclear target from an active fiber target (to be used in the E70 experiment) to a ^{7}Li target, the production of ${}^{7}_{\Xi^-}\mathrm{H}$ can be tagged event by event by gating the Ξ-bound region in the missing-mass spectrum.

A Ξ hypernucleus is unstable against the $\Xi N \to \Lambda\Lambda$ conversion, and will decay into free Λ's or Λ-hypernuclei. In case of ${}^{7}_{\Xi^-}\mathrm{H}$, due to a large cancellation of the proton separation energy of ${}^{6}\mathrm{He}$ and the released energy in the $\Xi^- p \to \Lambda\Lambda$ conversion, only four decay channels are allowed energetically, i.e. with positive decay Q-values. According to a calculation by Kumagai-Fuse and Akaishi [16], the branching ratio into ${}^{5}_{\Lambda\Lambda}\mathrm{H} + 2n$ can be as large as 90%. We will make use of this particular feature in order to produce ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ exclusively.

The reason to focus on ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ is not only the characteristic decay channel of ${}^{7}_{\Xi^-}\mathrm{H}$ but also the importance of the $\Lambda\Lambda$–ΞN mixing with regard to the structure of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$. Hyperon mixing is considered to play an important role especially in the strangeness -2 sector, due to a small mass difference between $\Lambda\Lambda$ and ΞN. The $\Lambda\Lambda$-ΞN mixing will be Pauli-suppressed in ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ and heavier double-Λ hypernuclei, because two protons and neutrons occupy the $0s_{1/2}$ shell, and a nucleon generated by the mixing cannot be transferred to the same $0s_{1/2}$ shell. On the other hand, the $\Lambda\Lambda$-$\Xi^- p$ mixing in ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ is Pauli-allowed, as it has only one proton. Recalling that the mixing contributes in $\Lambda\Lambda$ interaction in free space as well, the investigation of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ will shed light on hyperon mixing in the strangeness -2 sector of hypernuclear physics.

For this purpose, the weak decay of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ can be utilized; by measuring the momentum of a π^- from the two-body decay of ${}^{5}_{\Lambda\Lambda}\mathrm{H} \to {}^{5}_{\Lambda}\mathrm{He} + \pi^-$, the mass or the $\Lambda\Lambda$ binding energy of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ will be reconstructed by using the conservation of momentum [17], because ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ will decay at rest thanks to its long lifetime of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$. This method is named "decay pion spectroscopy", and has been already applied to a single-Λ hypernucleus, ${}^{4}_{\Lambda}\mathrm{H}$, decaying into ${}^{4}\mathrm{He} + \pi^-$ [18, 19]. The momenta of the decay pion from ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ are 132–135 MeV/c (depending on the $\Lambda\Lambda$ binding energy to be determined) and 132.9 MeV/c, respectively, while decay pions from other hypernuclei will have a momentum less than 120 MeV/c [17]. The decay pion from ${}^{4}_{\Lambda}\mathrm{H}$ can be utilized for a momentum calibration, whereas misidentification of decay pion from ${}^{4}_{\Lambda}\mathrm{H}$ as that from ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ will distort the decay-pion momentum distribution of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$, from which the mass of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ will be evaluated.

In order to select decay pions from ${}^{5}_{\Lambda\Lambda}\mathrm{H}$, a non-mesonic weak decay process of the accompanying ${}^{5}_{\Lambda}\mathrm{He}$ will be traced. $25 \pm 7\%$ of ${}^{5}_{\Lambda}\mathrm{He}$ will emit a proton with the kinetic energy larger than 15 MeV, due to ${}^{5}_{\Lambda}\mathrm{He} \to p + n + {}^{3}\mathrm{He}$ [20]. Such a fast proton will be hardly emitted from other processes involving ${}^{4}_{\Lambda}\mathrm{H}$, such as

$$ {}^{7}_{\Xi^-}\mathrm{H} \to {}^{4}_{\Lambda}\mathrm{H} + \Lambda + 2n, \text{ followed by } \Lambda \to p + \pi^-, \quad (1) $$

and

$$ {}^{7}_{\Xi^-}\mathrm{H} \to {}^{5}_{\Lambda\Lambda}\mathrm{H} + 2n, \text{ followed by } {}^{5}_{\Lambda\Lambda}\mathrm{H} \to {}^{4}_{\Lambda}\mathrm{H} + p + \pi^-, \quad (2) $$

in both of which a proton is associated with a pion from mesonic decay of Λ and ${}^{5}_{\Lambda\Lambda}\mathrm{H}$. Therefore, it is expected that tagging a fast proton will eliminate the contamination of ${}^{4}_{\Lambda}\mathrm{H}$ events.

The yield of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ after the event selection is estimated to be approximately 25 events for two-month beamtime, corresponding to 1.4×10^{12} K^-'s on target [8]. Theoretical calculations on the formation cross section of ${}^{7}_{\Xi^-}\mathrm{H}$ [13] and the branching ratio of ${}^{7}_{\Xi^-}\mathrm{H} \to {}^{5}_{\Lambda\Lambda}\mathrm{H} + 2n$ [16], followed by ${}^{5}_{\Lambda\Lambda}\mathrm{H} \to {}^{5}_{\Lambda}\mathrm{He} + \pi^-$ [17], as well as the experimental result of the emission probability of a fast proton from ${}^{5}_{\Lambda}\mathrm{He}$ [20], are taken into account.

3. Experimental Setup

To realize the above-mentioned concept, the missing-mass spectroscopy of the ${}^{7}\mathrm{Li}(K^-, K^+)$ reaction and the decay pion spectroscopy of the ${}^{5}_{\Lambda\Lambda}\mathrm{H} \to {}^{5}_{\Lambda}\mathrm{He} + \pi^-$ decay will be performed at the same time. We plan to utilize the experimental setup for the E70 experiment [14], with a cylindrical detector system (CDS) installed around the target. The CDS will be used not only for momentum analysis of a decay pion from ${}^{5}_{\Lambda\Lambda}$H but also for tagging a fast proton emitted from ${}^{5}_{\Lambda}$He. We plan to borrow a superconducting solenoid magnet and a time projection chamber from the SPring-8/LEPS group.

4. Conclusion and Outlook

We have proposed the J-PARC P75 experiment, whose purpose is to determine the mass of ${}^{5}_{\Lambda\Lambda}$H by means of decay pion spectroscopy. As the method is much different from other experiments in the past and in the future, verification of production and identification of ${}^{5}_{\Lambda\Lambda}$H will make an impact in the strangeness −2 sector of hypernuclear physics. For example, properties of ${}^{5}_{\Lambda\Lambda}$H such as the lifetime and the branching ratio of a weak-decay process may be investigated, which is almost impossible in a nuclear emulsion experiment.

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