Proposal for J-PARC 50 GeV Synchrotron

Decay Pion Spectroscopy of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ Produced by Ξ-hypernuclear Decay

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Abstract

Proposed is a novel method to produce a double-Λ hypernucleus without using nuclear emulsion. A Ξ^- bound in ^{6}He and a part of quasi-free Ξ^-'s, produced in $^7\mathrm{Li}(K^-, K^+)$ reactions, are absorbed in the reaction point, and $^{5}_{\Lambda\Lambda}$H may be formed via $\Xi^- p \to \Lambda\Lambda$ conversion. Decay pion spectroscopy for $^{5}_{\Lambda\Lambda}\mathrm{H} \to {}^{5}_{\Lambda}\mathrm{He} + \pi^-$ will be performed after event selection requiring a fast proton from non-mesonic weak decay of $^{5}_{\Lambda}$He. The experimental setup will be based on the Ξ-hypernuclear spectroscopy experiment E70; a new cylindrical detector system will be installed between the K1.8 beamline spectrometer and the S-2S spectrometer for detection of the decay pion and the proton. We request 77 days of beamtime under 80 kW beam-power and 4.8 sec cycle operation of the accelerator.

Contents

1 Physics Motivation

Investigation of Λ-hypernuclei comprising three kinds of baryons (proton, neutron, and Λ-hyperon) plays a central role in understanding Λ-N (nucleon) and Λ-Λ interaction. In particular, the mass of a hypernucleus, or equivalently the binding energy of Λ-hyperon(s) in it, is one of the fundamental observables.

Compared to single-Λ hypernuclei, experimental information on hypernuclei with strangeness $S = -2$, i.e. Ξ-hypernuclei and double-Λ hypernuclei, is still scarce, and J-PARC is the best place to investigate them extensively thanks to intense K^- beams. On the one hand, a high-resolution Ξ-hypernuclear spectroscopy is planned as the E70 (E05) experiment [1, 2]. As the first step, the ${}^{12}_{\Xi}$Be hypernucleus will be produced via the ^{12}C(K^-, K^+) reaction. On the other hand, the E07 experiment [3] has finished beam exposure on emulsion sheets, in which events with double-Λ hypernuclear production are being searched for. Very recently, the J-PARC E07 collaboration reported the observation of ${}_{\Lambda\Lambda}$Be (probably ${}^{11}_{\Lambda\Lambda}$Be) after scanning 30% of 118 nuclear emulsion modules irradiated with a K^- beam [4].

We propose a new experiment to produce and identify a particular double-Λ hypernucleus of ${}^{5}_{\Lambda\Lambda}$H in a different way without using the emulsion technique. The peculiarity of the proposed method is that only ${}^{5}_{\Lambda\Lambda}$H is expected to be produced exclusively, while Ξ^- capture at rest, adopted in nuclear emulsion experiments, can yield a variety of double-Λ hypernuclei.

1.1 Four Methods for Double-Λ Hypernuclear Production

1.1.1 Ξ^- capture at rest

The emulsion technique has been used for more than half a century in search of double-Λ hypernuclei except for the BNL-AGS E885 and E906 experiments, whose details will be given later. The first discovery of double-Λ hypernuclei was reported in 1963 by Danysz *et al.* [5] After the emulsion-counter hybrid method was established in the KEK-PS E176 experiment [6], the famous NAGARA event, exhibiting production and sequential decay of ${}^{6}_{\Lambda\Lambda}$He without any ambiguity, was discovered in the KEK-PS E373 experiment [7, 8]. In these experiments, a Ξ^- hyperon was produced in the quasi-free 'p'$(K^-, K^+)\Xi^-$ reaction, followed by its capture by a light nucleus (carbon, nitrogen, oxygen) in nuclear emulsion. After $\Xi^- p \to \Lambda\Lambda$ conversion took place in the nucleus, a double-Λ hypernucleus could be produced as a fragment. In this proposal, this process is referred to as Ξ^- capture at rest. Due to the fragmentation process, the species of produced double-Λ hypernuclei is far from unique. Nevertheless, a systematic study from ${}^{6}_{\Lambda\Lambda}$He to heavier ones such as ${}^{10}_{\Lambda\Lambda}$Be [8] and ${}^{13}_{\Lambda\Lambda}$B [6] has played an important role in exploring the $S = -2$ sector in hypernuclear physics and unravelling the $\Lambda\Lambda$ interaction [9]. In addition, the J-PARC E07 experiment is expected to yield one order of magnitude more double-Λ hypernuclear events, and discovery of a new double-Λ hypernucleus is foreseen.

Additionally, in the $\overline{\text{P}}$ANDA experiment at FAIR, this method will be utilized to perform a γ-ray spectroscopy of double-Λ hypernuclei [10]. Namely, a Ξ^- hyperon, produced in the $\overline{p} + A \to \Xi^- + \overline{\Xi}^+ + A'$ reaction, will be degraded by rescattering in the same target nucleus (see the next paragraph), and finally stop in a secondary target.

1.1.2 quasi-free Ξ^- rescattering

Another production mechanism of double-Λ hypernuclei (quasi-free Ξ^- rescattering) was proposed by Yamamoto *et al.* [11] Most of Ξ^- produced in the quasi-free (K^-,K^+) reaction on nuclei can escape from the target nucleus, while a part of Ξ^- will be absorbed in the same nucleus and a double-Λ compound nucleus is formed. They pointed out that a rescattering of the Ξ^- and a nucleon before absorption, resulting in slowdown of Ξ^- with knocking out the nucleon, enhances the formation probability of a double-Λ compound nucleus by more than one order of magnitude. For example, in case of a ^{9}Be target, a compound nucleus of $\left[{}^{8}_{\Lambda\Lambda}\mathrm{He}\right]^*$ and $\left[{}^{8}_{\Lambda\Lambda}\mathrm{H}\right]^*$ would be fragmented into normal nuclei, single-Λ hypernuclei, or double-Λ hypernuclei. It is found that the ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ production probability is the largest in case of a ^{9}Be target, while the production probability of ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ and ${}^{7}_{\Lambda\Lambda}\mathrm{He}$ increases for a target with a larger mass number (^{10}B, ^{11}B, ^{12}C). In addition, the pion energy distributions of decaying double-Λ hypernuclei and relevant single-Λ hypernuclei, which helps to identify the species of produced double-Λ hypernuclei, were also calculated.

Based on this theoretical work, the BNL-AGS E906 experiment [12] searched for light double-Λ hypernuclei using a thick ^{9}Be target. Two π^-'s from sequential weak decay of a double-Λ hypernucleus were detected. Figure 1 shows a two-dimensional scatter plot of the momenta of two detected π^-'s. Two regions of event concentration near $(\mathrm{P_L}, \mathrm{P_H}) = (114, 133)$ and $(104, 114)$ (MeV/c) were attributed to originate from production of ${}^{3}_{\Lambda}\mathrm{H} + {}^{4}_{\Lambda}\mathrm{H}$ (twin hypernuclei) and ${}^{4}_{\Lambda\Lambda}\mathrm{H}$ (double-Λ hypernuclei), respectively. Two-body decay of ${}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He} + \pi^-$ and ${}^{4}_{\Lambda}\mathrm{H} \to {}^{4}\mathrm{He} + \pi^-$ generates monochromatic π^-'s with the momenta of 114.3 MeV/c and 132.9 MeV/c. On the other hand, ${}^{4}_{\Lambda\Lambda}\mathrm{H}$ is considered to decay as follows:

$$
\begin{aligned}
{}^{4}_{\Lambda\Lambda}\mathrm{H} &\to {}^{4}_{\Lambda}\mathrm{He}^* + \pi^-, &(1)\\
{}^{4}_{\Lambda}\mathrm{He}^* &\to {}^{3}_{\Lambda}\mathrm{H} + p, &(2)\\
{}^{3}_{\Lambda}\mathrm{H} &\to {}^{3}\mathrm{He} + \pi^-, &(3)
\end{aligned}
$$

where the resonance of ${}^{4}_{\Lambda}\mathrm{He}^*$ had not been reported before. The bond energy of $\Delta B_{\Lambda\Lambda} \equiv B_{\Lambda\Lambda}({}^{4}_{\Lambda\Lambda}\mathrm{H}) - 2B_{\Lambda}({}^{3}_{\Lambda}\mathrm{H})$, where $B_{\Lambda\Lambda}$ and B_{Λ} denote the binding energy of two Λ's and a single Λ, respectively, was not determined due to unknown excitation energy of ${}^{4}_{\Lambda}\mathrm{He}^*$ under consideration. A proposal of the P961R experiment [13], in which the target was to be replaced by ^{7}Li and the experimental setup was to be improved in view of the resolution and the yield, was submitted, but unfortunately the experiment was not realized because the AGS operation was cancelled except for the RHIC experiments.

As for the event concentration near $(104, 114)$ (MeV/c), there are two different interpretations to attribute it to twin hypernuclei of ${}^{3}_{\Lambda}\mathrm{H} + {}^{6}_{\Lambda}\mathrm{He}$ [14], and different double-Λ hypernuclei ${}^{7}_{\Lambda\Lambda}\mathrm{He}$ [15]. The momentum distributions of the two pions in each scenario are different one by one, but our current understanding does not allow us to rule out all but one scenario. As far as the ^{9}Be target is considered, a double-Λ hypernucleus ${}^{A}_{\Lambda\Lambda}Z$ or twin hypernuclei ${}^{A_1}_{\Lambda}Z_1 + {}^{A_2}_{\Lambda}Z_2$ produced as a fragment of a double-Λ compound nucleus of $\left[{}^{8}_{\Lambda\Lambda}\mathrm{He}\right]^*$ and $\left[{}^{8}_{\Lambda\Lambda}\mathrm{H}\right]^*$ must satisfy ($A \le 7$ and $Z \le 2$)[1] or ($A_1 + A_2 \le 8$ and $Z_1 = Z_2 = 1$)[2]. The condition is slightly relaxed, if Ξ^- capture at rest by other nucleus is considered, as ($A \le 9$ and $Z \le 3$) or ($A_1 + A_2 \le 10$ and $Z_1 + Z_2 \le 3$). Needless to say, all the three scenarios fulfill these conditions.

This constraint will be more strict when a target with a smaller mass number is adopted. For a ^{7}Li target, the constraint will be ($A \le 7$ and $Z \le 2$) or ($A_1 + A_2 \le 8$ and $Z_1 = Z_2 = 1$). If we ignore

[1] At least one nucleon must be evaporated from the compound nucleus because of the conservation of energy, hence $A < 8$.
[2] Fragmentation into twin hypernuclei with nothing else, i.e. $A_1 + A_2 = 8$, is possible.

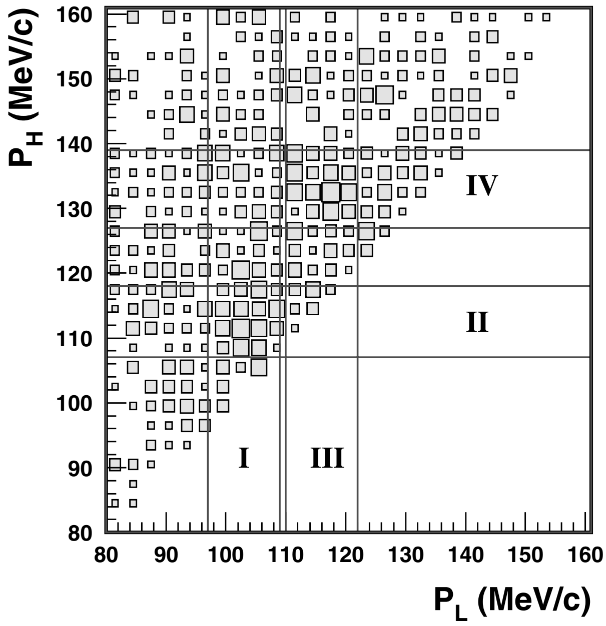

Figure 1: Correlation of two π^-'s momenta for Ξ^- production events. P_H and P_L correspond to pions with higher and lower momenta, respectively. Taken from Ref. [12].

the production via Ξ^- capture at rest due to a smaller stopping probability of Ξ^- in lithium with a smaller density (0.53 g/cm^3) compared to beryllium (1.85 g/cm^3), only the production of a double-Λ hypernuclei with $A \leq 5$ and $Z = 1$ from a fragmentation of $\left[{}^{6}_{\Lambda\Lambda}\mathrm{H}\right]^*$ is allowed and twin hypernuclei cannot be formed[3]. Therefore, in order to obtain more robust identification of double-Λ hypernuclei, an experiment with a ^{7}Li target is highly desired.

1.1.3 direct production

Third method to form a double-Λ hypernuclear system is direct production by use of the (K^-,K^+) reaction. Harada *et al.* theoretically investigated a one-step $^{16}\mathrm{O}(K^-, K^+)\,{}^{16}_{\Lambda\Lambda}\mathrm{C}$ reaction, in which two Λ's are created via Ξ^- doorways through $\Xi^- p$-$\Lambda\Lambda$ conversion [17]. The production cross section depends on the ΞN-$\Lambda\Lambda$ coupling strength or the Ξ^- admixture probability of the double-Λ hypernuclei. From the experimental side, an upper limit of the ${}^{12}_{\Lambda\Lambda}\mathrm{Be}$ production cross section in the $^{12}\mathrm{C}(K^-, K^+)$ reaction was obtained in the BNL-AGS E885 experiment [18]. In addition, an experiment with the S-2S spectrometer is planned as one of possible future plans [19]. Much better energy resolution compared to the previous experiment at BNL will improve the sensitivity.

1.1.4 Ξ-hypernuclear decay

Yet another method, Ξ-hypernuclear decay, was proposed by Kumagai-Fuse and Akaishi [20]. They pointed out that a Ξ hypernucleus ${}^{7}_{\Xi}\mathrm{H}$ will decay into ${}^{5}_{\Lambda\Lambda}\mathrm{H} + 2n$ with a very large branching

[3]Neutral single- and double-Λ hypernuclei such as $nn\Lambda$ (recently reported by the HypHI experiment [16]) and $nn\Lambda\Lambda$, as well as a bound H-dibaryon are not considered in this proposal.

ratio of about 90%. The possible decay modes of ${}_{\Xi^-}^{7}\mathrm{H}$ are

$$
\begin{aligned}
{}_{\Xi^-}^{7}\mathrm{H} &\to {}_{\Lambda\Lambda}^{5}\mathrm{H} + 2n + 11\,\mathrm{MeV}, &(4)\\
&\to {}_{\Lambda}^{4}\mathrm{H} + \Lambda + 2n + 7\,\mathrm{MeV}, &(5)\\
&\to {}_{\Lambda}^{4}\mathrm{H}^{*} + \Lambda + 2n + 6\,\mathrm{MeV}, &(6)\\
&\to {}_{\Lambda}^{3}\mathrm{H} + 2\Lambda + 2n + 5\,\mathrm{MeV}, &(7)
\end{aligned}
$$

where the reaction Q-values are only approximate because of assumptions on the binding energies of ${}_{\Xi^-}^{7}\mathrm{H}$ and ${}_{\Lambda\Lambda}^{5}\mathrm{H}$. A small Q-value disfavors decay into many body because of the available phase space, and as a result, the three-body decay (4) will be the dominant channel. According to Ref. [20], the branching ratio reaches as large as 90%. It is worth stressing that a small Q-value is owed to a substantial cancellation between the energy released in $\Xi^- p \to \Lambda\Lambda$ conversion and the neutron separation energy of ${}^{4}\mathrm{He}$ in the ${}_{\Xi^-}^{7}\mathrm{H} \to {}_{\Lambda\Lambda}^{5}\mathrm{H} + 2n$ (i.e. $[\alpha nn\Xi^-] \to [t\Lambda\Lambda] + 2n$) reaction.

Inspired by this theoretical calculation, we have conceived an experimental concept to populate ${}_{\Lambda\Lambda}^{5}\mathrm{H}$ from decay of ${}_{\Xi^-}^{7}\mathrm{H}$ produced in the ${}^{7}\mathrm{Li}(K^-, K^+)$ reaction. Unlike Ξ^- capture at rest in the emulsion-counter hybrid method, a particular double-Λ hypernuclei of ${}_{\Lambda\Lambda}^{5}\mathrm{H}$ is expected to be selectively produced in Ξ-hypernuclear decay and quasi-free Ξ^- rescattering with a ${}^{7}\mathrm{Li}$ target.

1.2 $\Lambda\Lambda$-ΞN Mixing in ${}_{\Lambda\Lambda}^{5}\mathrm{H}$

One of the most important features in ${}_{\Lambda\Lambda}^{5}\mathrm{H}$ in comparison with ${}_{\Lambda\Lambda}^{6}\mathrm{He}$ is the role of the $\Lambda\Lambda$-ΞN mixing [21]. While the two protons and two neutrons occupy the $0s$ shell and the $\Lambda\Lambda$-ΞN mixing is Pauli-suppressed in ${}_{\Lambda\Lambda}^{6}\mathrm{He}$, a lack of one proton in the $0s$ shell allows the $\Lambda\Lambda$-ΞN mixing, in which the second proton can occupy the $0s$ shell. An enhancement of the $\Lambda\Lambda$ bond energy due to the $\Lambda\Lambda$-ΞN mixing was stressed by Myint *et al.* [22], and independently by Lanskoy–Yamamoto [23] and by Yamamoto–Rijken [24]. A full-coupled channel calculation resulted in a large Ξ probability even in case of a weak $\Lambda\Lambda$-ΞN potential [25]. In contrast, Filikhin *et al.* argued that the $\Lambda\Lambda$-ΞN mixing effect is not significantly different between ${}_{\Lambda\Lambda}^{5}\mathrm{H}$ and ${}_{\Lambda\Lambda}^{6}\mathrm{He}$ [26].

Therefore, the first determination of the bond energy of ${}_{\Lambda\Lambda}^{5}\mathrm{H}$, which is the main motivation of this proposal, is of great importance. At least, all these theoretical calculations support the existence of particle-stable ${}_{\Lambda\Lambda}^{5}\mathrm{H}$ against the ${}_{\Lambda}^{4}\mathrm{H} + \Lambda$ channel, with the $\Lambda\Lambda$ bond energy more than 0.5 MeV [27]. It should be noted that these calculations relied on the old value for the binding energy of ${}_{\Lambda\Lambda}^{6}\mathrm{He}$ [7], 0.34 MeV larger than the updated value [8], and that an up-to-date calculation for ${}_{\Lambda\Lambda}^{5}\mathrm{H}$ and ${}_{\Lambda\Lambda}^{6}\mathrm{He}$ with a weaker $\Lambda\Lambda$ interaction is awaited.

1.3 Perspective

"Mass production" of double-Λ hypernuclei in a counter experiment will enable us to derive not only the $\Lambda\Lambda$ bond energy, but also the lifetime and the branching ratio of weak decay modes, which cannot be investigated in emulsion-based experiments. While production, structure, and decay of single-Λ hypernuclei have been studied for a long time in great detail [27–30], available quantitative information on double-Λ hypernuclei is limited to the bond energy. The ${}_{\Lambda\Lambda}^{5}\mathrm{H}$ production experiment is expected to serve as a step forward to detailed understanding of double-Λ hypernuclear systems.

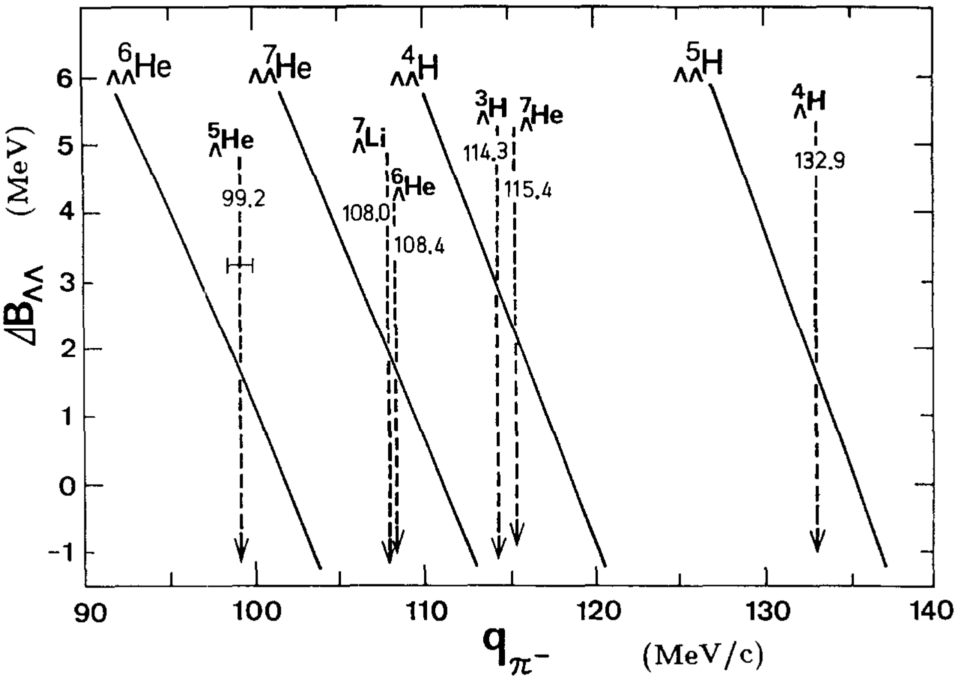

Figure 2: The relationship between the $\Lambda\Lambda$ bond energy and the two-body-decay pion momentum for double-Λ hypernuclei (solid line). The two-body-decay pion momentum for single-Λ hypernuclei are also indicated by dashed arrows. Taken from Ref. [11].

2 Decay Pion Spectroscopy

If a hypernucleus at rest undergoes two-body weak decay such as:

$$^{A}_{\Lambda}Z \rightarrow {}^{A}(Z+1) + \pi^-, \tag{8}$$

or

$$^{A}_{\Lambda\Lambda}Z \rightarrow {}^{A}_{\Lambda}(Z+1) + \pi^-, \tag{9}$$

the resultant π^- has a fixed momentum. Inversely, by measuring the momentum of decay π^-, one can obtain the mass of the parent hypernucleus by using conservation of energy and momentum. Figure 2 shows the momentum of π^-'s from two-body decay of typical light single- and double-Λ hypernuclei.

A recent experiment by the A1 collaboration at MAMI established the technique of decay pion spectroscopy by measuring the momentum of π^-'s from $^{4}_{\Lambda}$H $\rightarrow$ ^{4}He + π^- with an unprecedented precision [31, 32]. $^{4}_{\Lambda}$H was produced by irradiating a ^{9}Be target with an intense electron beam, and strangeness production, including Λ-hypernuclei, was confirmed by tagging a K^+ in coincidence. Because the scattered e' in the $(e, e'K^+)$ reaction was not measured at all, quasi-free Λ, Σ production could not be rejected in the analysis. The decay π^- from these hyperons yielded a continuous background in the π^- momentum distribution, above which a distinct peak due to the $^{4}_{\Lambda}$H decay was observed, as shown in Fig. 3.

Historically, the decay π^- from $^{4}_{\Lambda}$H was observed in stopped K^- reaction absorption on ^{4}He, ^{7}Li, ^{9}Be, ^{12}C, and ^{16}O targets [33]. Figure 4 exhibits a peak near 133 MeV/c due to the $^{4}_{\Lambda}$H two-body decay, as well as two peaks originating from production of $^{12}_{\Lambda}$C at much higher momenta.

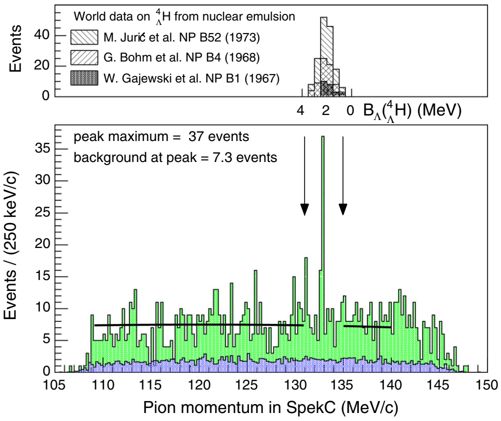

Figure 3: Pion momentum distribution observed in electron scattering. Taken from Ref. [31].

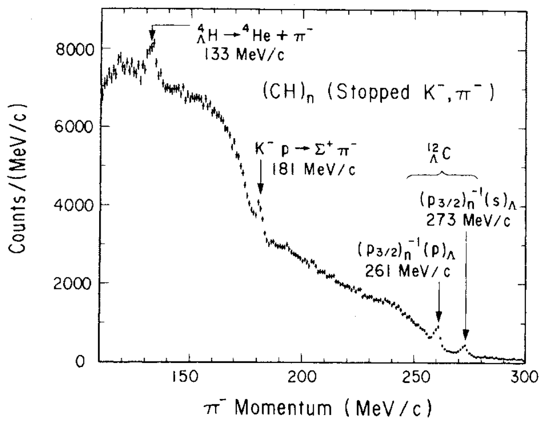

Figure 4: Pion momentum distribution in ^{12}C(stopped K^-,π^-) reaction. Taken from Ref. [33].

We will apply the technique of decay pion spectroscopy to $^{5}_{\Lambda\Lambda}$H. Unlike the case of the experiment at MAMI and KEK, we will momentum-analyze not only pions from $^{5}_{\Lambda\Lambda}$H decay as well as ejectile particles from $^{7}_{\Xi^-}$H production, enabling decay pion spectroscopy and missing-mass spectroscopy, respectively. The purpose of the latter is to reduce background such as in-flight decay of quasi-free Ξ^- hyperons. The detail will be discussed in the next section.

It should be worth stressing here that the momentum of decay pion from $^{4}_{\Lambda}$H was measured with an unprecedented precision. We will make use of the $^{4}_{\Lambda}$H peak in the pion momentum distribution for momentum calibration. In this point of view, it is fortunate that the decay-pion momentum of $^{4}_{\Lambda}$H and $^{5}_{\Lambda\Lambda}$H is very close to each other. $^{4}_{\Lambda}$H is expected to be produced as a hyperfragment in the ^{7}Li(in-flight K^-,π^-) reaction [34] or the ^{7}Li(π^+,K^+) reaction without changing the target. As there is no room to install detectors for rejecting K^--decay events like in the E63 experiment [34], the missing-mass spectroscopy of the (K^-,π^-) reaction is very difficult. Instead, we will seek for a peak corresponding to $^{4}_{\Lambda}$H decay in an inclusive pion momentum distribution (cf. Fig. 4 for stopped K^- absorption) without requiring a track in the S-2S spectrometer. If the peak has an intensity strong enough relative to the underlying background, an in-situ calibration will be realized. Otherwise, we have to collect data in a dedicated run with the ^{7}Li(π^+,K^+) reaction from time to time.

3 Experimental Principle

We will consider two kinds of production methods, i) Ξ-hypernuclear decay and ii) quasi-free Ξ^- rescattering, in order to produce $^{5}_{\Lambda\Lambda}$H from a ^{7}Li target. A Ξ^- hyperon can be produced by the ^{7}Li(K^-,K^+) reaction. Events below and above the Ξ^- + ^{6}He$_{\mathrm{g.s.}}$ threshold in the missing-mass spectrum for this reaction (cf. Fig. 5) correspond to production of $^{7}_{\Xi^-}$H and quasi-free Ξ production, respectively. More details will be given in Section 3.1. In practice, a finite missing-mass resolution obscures the distinction between them, and this is why we would like to use the S-2S spectrometer instead of the KURAMA spectrometer, in spite of a smaller acceptance.

Following the discussion in Sect. 1.1.2 and 1.1.4, most of bound $^{7}_{\Xi^-}$H decays into $^{5}_{\Lambda\Lambda}$H, whereas a part of quasi-free Ξ^-, rescattered and absorbed by the same nucleus, forms $^{5}_{\Lambda\Lambda}$H as a fragment of a double-Λ compound nucleus. In both cases, identification of $^{5}_{\Lambda\Lambda}$H with rejection of background

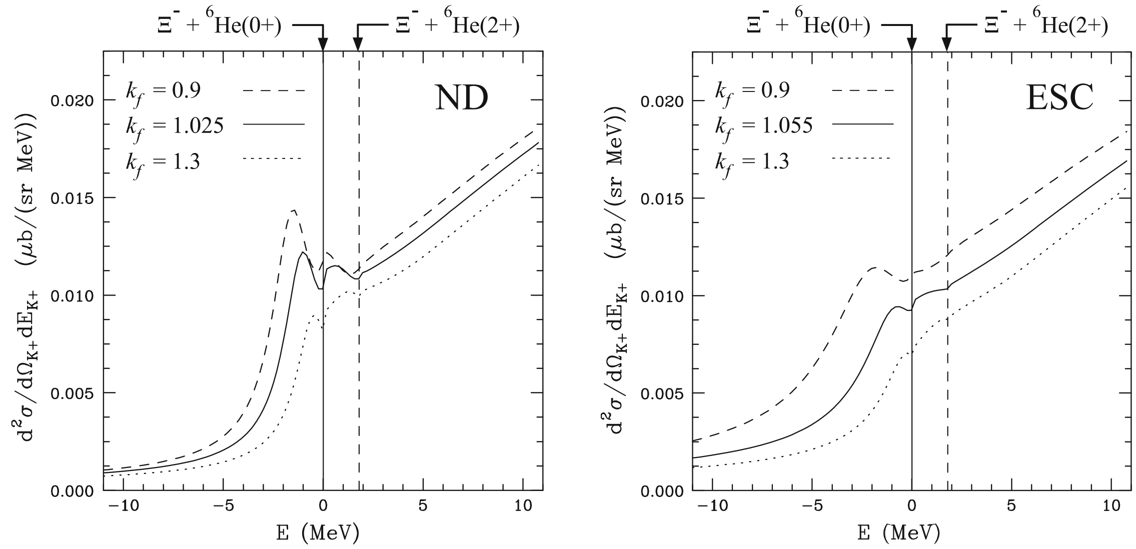

Figure 5: Theoretically calculated (K^-, K^+) spectrum for two kinds of ΞN interaction models (ND and ESC). k_f is the Fermi momentum of nuclear matter, and is chosen within a reasonable range. Taken from Ref. [35].

such as $^4_\Lambda\mathrm{H} + \Lambda$ is vitally important, in order to confirm the existence of $^{5}_{\Lambda\Lambda}\mathrm{H}$ and derive the $\Lambda\Lambda$ bond energy by means of decay pion spectroscopy, which is the goal of this experiment. The procedure will be thoroughly explained in Sect. 3.2.

Figures 6 and 7 depict flow charts of $^{5}_{\Lambda\Lambda}\mathrm{H}$ production and decay, exhibiting the experimental principle. After event selection requiring a fast proton ($\gtrsim$ 15 MeV) in coincidence, decay pion spectroscopy for the two-body decay of $^{5}_{\Lambda\Lambda}\mathrm{H}$, i.e. $^{5}_{\Lambda\Lambda}\mathrm{H} \to {}^{5}_{\Lambda}\mathrm{He} + \pi^-$, will be performed. The partial decay width was calculated to be $0.38\Gamma_\Lambda$ compared to the total decay width of $1.30\Gamma_\Lambda$ [11], where Γ_Λ is the free-Λ decay width. As the lifetime of $^{5}_{\Lambda\Lambda}\mathrm{H}$ is long enough to stop inside the target before its decay, the measurement of the π^- momentum will determine the mass of $^{5}_{\Lambda\Lambda}\mathrm{H}$, hence its $\Lambda\Lambda$ bond energy.

3.1 Production of Ξ-hypernuclei

A Ξ-hypernucleus, $^{7}_{\Xi^-}\mathrm{H}$, will be populated by the $^7\mathrm{Li}(K^-, K^+)$ reaction. The reaction is essentially the same as that to be investigated in the E70 (E05) experiment [1, 2], except for the target nucleus, hence the same setup, i.e. the S-2S spectrometer together with the K1.8 beamline, can be adopted.

Koike and Hiyama calculated the spectrum of the $^7\mathrm{Li}(K^-, K^+)$ reaction, at the beam momentum $p_{K^-} = 1.65\,\mathrm{GeV}/c$ and the scattering angle $\theta_{K^+} = 0°$, as shown in Fig. 5 [35]. A clear peak of the bound $^{7}_{\Xi^-}\mathrm{H}$, whose structure was already investigated in Ref. [36], is seen except for the case of the ESC model with $k_f = 1.3$.

From the experimental side, the missing-mass resolution is dominated by the energy-loss straggling in the target, which is proportional to the target thickness [2]. If we use a $10\,\mathrm{g/cm^2}$-thick target, the missing-mass resolution will be $3.5\,\mathrm{MeV}/c^2$ in FWHM.

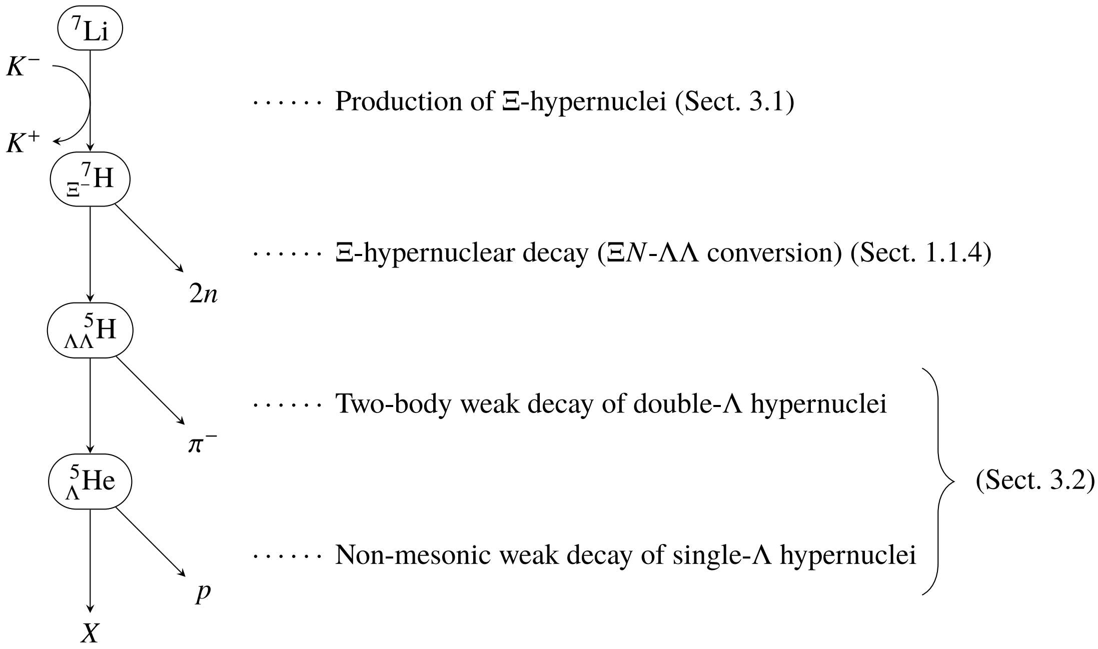

Figure 6: A flow chart for the Ξ-hypernuclear decay method

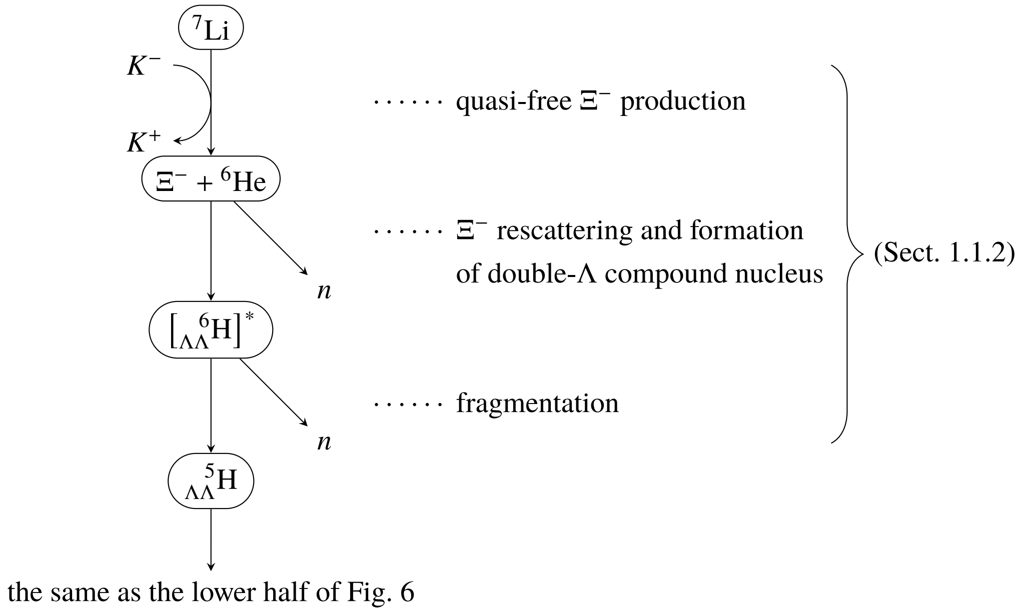

Figure 7: A flow chart for the quasi-free Ξ^- rescattering method.

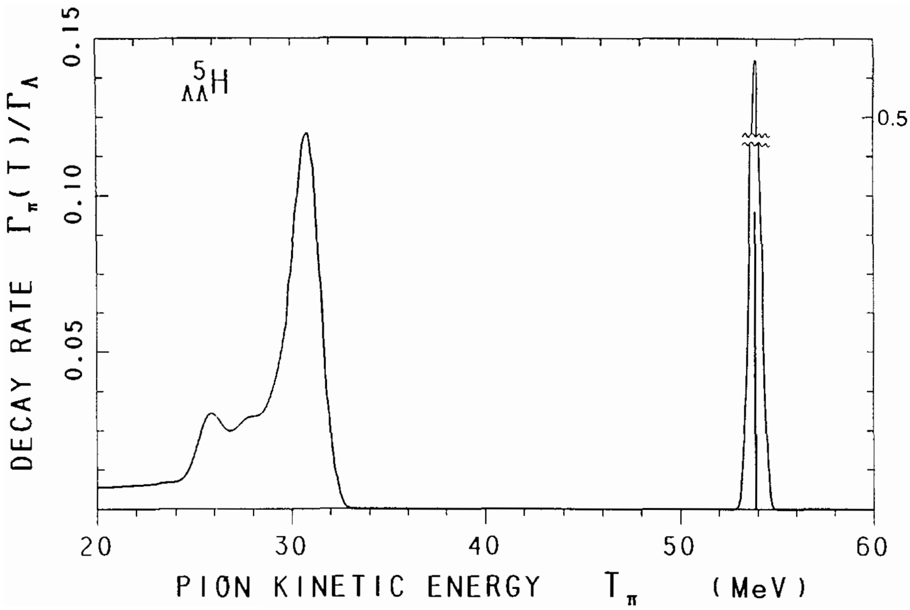

Figure 8: Theoretically calculated π^- energy spectrum from $^{5}_{\Lambda\Lambda}$H decay. Taken from Ref. [11].

3.2 Identification of $^{5}_{\Lambda\Lambda}$H

As described in Sect. 1.1.4, $^{7}_{\Xi^-}$H is supposed to decay predominantly into $^{5}_{\Lambda\Lambda}$H + $2n$. However, other decay channels such as $^{4}_{\Lambda}$H + Λ + $2n$ are also allowed energetically. The same holds for the quasi-free Ξ^- rescattering. Thus, an experimental confirmation and event selection of $^{5}_{\Lambda\Lambda}$H production by using information on decay particles of $^{5}_{\Lambda\Lambda}$H is mandatory.

Similar to the case for weak decay of single-Λ hypernuclei, $^{5}_{\Lambda\Lambda}$H is expected to decay as follows:

$$^{5}_{\Lambda\Lambda}\mathrm{H} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + \pi^-, \tag{10}$$

$$\rightarrow {}^{4}_{\Lambda}\mathrm{H} + p + \pi^-, \tag{11}$$

$$\rightarrow {}^{4}_{\Lambda}\mathrm{H} + n + \pi^0. \tag{12}$$

Among them, the two-body decay (10) with the momentum of emitted $\pi^- \approx 133\,\mathrm{MeV}/c$ is of interest for decay pion spectroscopy. Unfortunately, it is very close to that in $^{4}_{\Lambda}$H $\rightarrow$ ^{4}He + π^- decay (132.9 MeV/c [31]), because the recombination of triton (in $^{5}_{\Lambda\Lambda}$H or $^{4}_{\Lambda}$H) with proton (from Λ decay) results in the formation of an α particle with a large energy released. Their distinction without further information is very challenging from the point of view of experimental resolution. It should be noted that the π^- momentum in decay of other single Λ-hypernuclei or three-body decay of $^{5}_{\Lambda\Lambda}$H does not exceed 120 MeV/c (Fig. 2), and that a faster π^- must stem from either $^{5}_{\Lambda\Lambda}$H or $^{4}_{\Lambda}$H.

Consequently, we should take into account sequential weak decay of $^{5}_{\Lambda\Lambda}$H, starting from the two-body decay (10). The weak decay of $^{5}_{\Lambda}$He was investigated by the KEK-PS E462 experiment and the FINUDA experiment. In general, weak decay of Λ hypernuclei is categorized into two types: mesonic decay ($\Lambda \rightarrow N\pi$) and non-mesonic decay ($\Lambda N \rightarrow NN$ or $\Lambda NN \rightarrow NNN$).

In contrast to the identification of $^{4}_{\Lambda\Lambda}$H in the BNL-AGS E906 experiment [12], the use of the following mesonic decay of $^{5}_{\Lambda}$He

$$^{5}_{\Lambda}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + p + \pi^- \tag{13}$$

will complicate the analysis of decay pion spectroscopy, because two different sequential decay modes give a pair of π^- with almost the same kinetic energies. As shown in Fig. 9, the energy distribution of π^- in the ${}^{5}_{\Lambda}\mathrm{He} \to {}^{4}\mathrm{He}+p+\pi^-$ decay [37], centered at 32 MeV, resembles that in the ${}^{5}_{\Lambda\Lambda}\mathrm{H} \to {}^{4}_{\Lambda}\mathrm{H}+p+\pi^-$ decay, indicated by the left component in Fig. 8. Furthermore, approximately half of ${}^{4}_{\Lambda}\mathrm{H}$ decay into ${}^{4}\mathrm{He} + \pi^-$, emitting a π^- with almost the same momentum as that from the two-body decay (10) of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$. Therefore, the observation of two π^-'s with the momenta of $\approx$ 99 MeV/c and $\approx$ 133 MeV/c may indicate the production of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$, aside from another process of ${}^{7}_{\Xi^-}\mathrm{H} \to {}^{4}_{\Lambda}\mathrm{H} + \Lambda + 2n$, while the determination of the binding energy ($B_{\Lambda\Lambda}$) of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ by using the π^- in the two-body decay (10) is very difficult.

This overlapping problem may be avoided by looking into non-mesonic weak decay without emitting a pion:

$$ {}^{5}_{\Lambda}\mathrm{He} \to p + n + {}^{3}\mathrm{H}. \tag{14} $$

Due to the absence of a pion in the final state in the $\Lambda N \to NN$ weak decay, a large energy of 176 MeV is released, and shared by the nucleons in the final state. The proton energy spectrum was investigated by the KEK-PS E462 experiment [38] and the FINUDA experiment [39], and it exhibits a peak around 70 MeV, as shown in Fig. 10.

Let us consider a case of ${}^{4}_{\Lambda}\mathrm{H}$ production, emitting a π^- whose momentum is comparable to that from ${}^{5}_{\Lambda\Lambda}\mathrm{H}$. It must originate from the decay of ${}^{7}_{\Xi^-}\mathrm{H}$ [(5), (6)], the fragmentation of $\left[{}^{6}_{\Lambda\Lambda}\mathrm{H}\right]^*$ into ${}^{4}_{\Lambda}\mathrm{H} + \Lambda + n$, or the decay of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ [(11), (12)]. In any case, the kinetic energy of the accompanied proton, which exists except for (12), cannot be as large as that from non-mesonic weak decay of ${}^{5}_{\Lambda}\mathrm{He}$. By requiring a fast proton ($\gtrsim$ 15 MeV) in coincidence with a fast π^-, all the background events are expected to be removed. At the same time, in-flight decay of $\Xi^- \to \Lambda + \pi^- \to p + \pi^- + \pi^-$, which was the main source of background in the $2\pi^-$ event samples of the BNL-AGS E906 experiment, may be distinguished, because the decay proton is concentrated in the forward direction.

In conclusion, the binding energy of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ or the $\Lambda\Lambda$ bond energy can be estimated by decay pion spectroscopy for ${}^{5}_{\Lambda\Lambda}\mathrm{H}$, by measuring the momentum of a π^- and tagging a fast proton at the same time. The coincidence of the fast proton guarantees that the π^- originates exclusively from the two-body decay of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ (10). For this purpose, we plan to build and install a new cylindrical detector system surrounding the ${}^{7}\mathrm{Li}$ target.

4 Experimental Setup

In order to combine two types of spectroscopy:

- missing-mass spectroscopy for the (K^-, K^+) reactions,
- decay pion spectroscopy for ${}^{5}_{\Lambda\Lambda}\mathrm{H} \to {}^{5}_{\Lambda}\mathrm{He} + \pi^-$,

we will use three spectrometers:

- K1.8 beamline spectrometer and S-2S spectrometer for missing-mass spectroscopy,
- a new cylindrical detector system surrounding a target for decay pion spectroscopy.

The experimental setup under consideration is shown in Fig. 11. The setup for missing-mass spectroscopy will be the same as for the E70 experiment [2]. Additionally, we will install a cylindrical detector system (CDS) around the target in order to momentum-analyze π^- from ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ two-body decay

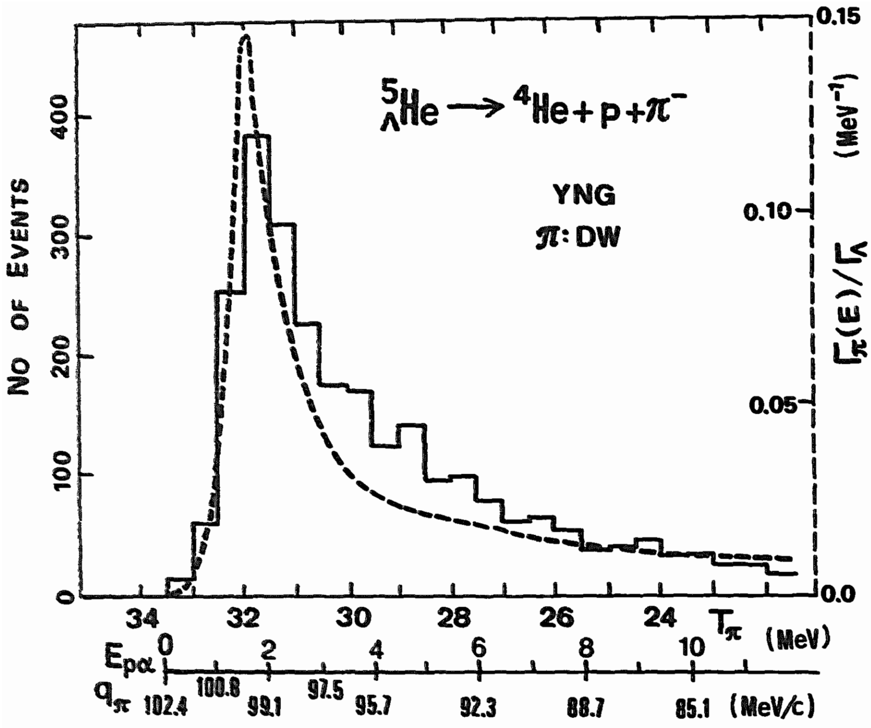

Figure 9: Theoretically calculated π^- energy spectrum (dashed line) and experimental one (solid line) in $^5_\Lambda$He → ^{4}He + p + π^- decay. Taken from Ref. [37].

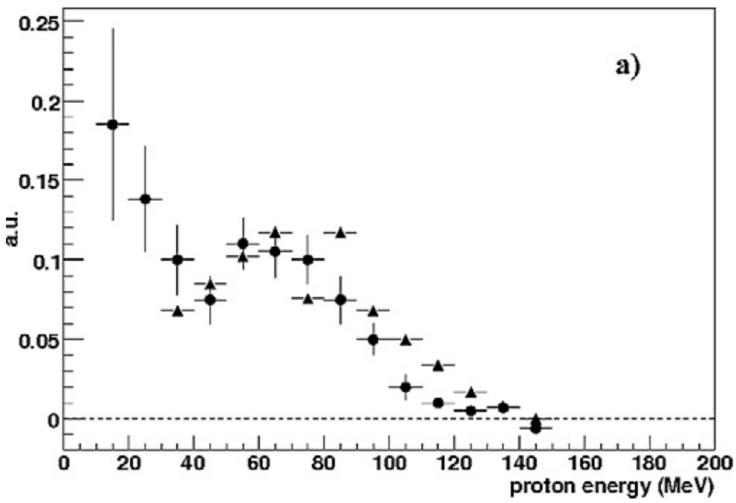

Figure 10: Proton energy spectrum from proton-induced non-mesonic weak decay of $^5_\Lambda$He. Dots and triangles correspond to the FINUDA and KEK experiments, respectively. Taken from Ref. [39].

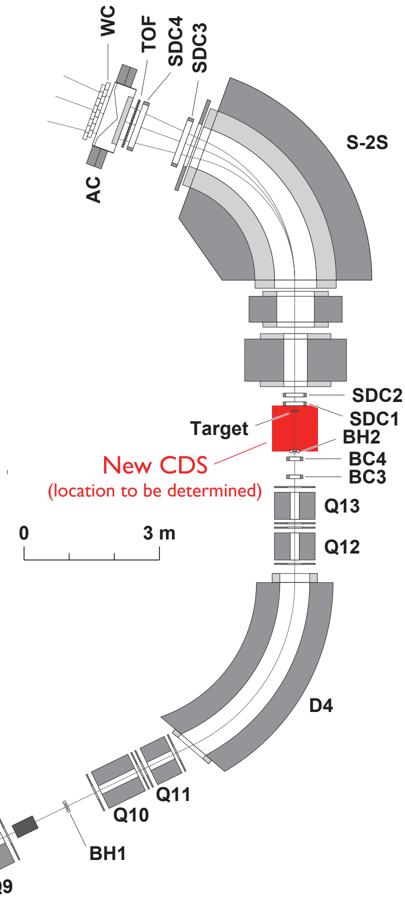

Figure 11: Experimental setup for missing-mass spectroscopy (K1.8 beamline spectrometer plus S-2S spectrometer) and decay pion spectroscopy (cylindrical detector system (CDS)). The location of CDS needs to be optimized in future.

and a proton from ${}^{5}_{\Lambda}$He decay with a large acceptance. Since the target area is spatially limited, a solenoid magnet should be $\approx$ 1 m in length at longest. Otherwise, BC3 and BC4 (drift chambers) will be replaced by a small detector such as a silicon strip detector to be installed inside a solenoid magnet.

We plan to borrow a superconducting solenoid magnet and a time projection chamber (Fig. 12) from the SPring-8/LEPS group [40,41]. The inner and outer radii of the solenoid magnet are 300 mm and 623 mm, respectively, and the length is approximately 1 m, probably fit between the beamline spectrometer and the S-2S spectrometer. During an experiment at LEPS in 2008-2009, a magnetic field of 2 Tesla was applied, but it should be weakened for our purpose to detect 130–135 MeV/c π^-. A hexagonal prism shaped TPC with a hexagonal bore was operated with P10 gas. In Ref. [41], a momentum resolution of 4%–25%, depending on the momentum and the polar angle, was reported.

We will investigate the performance of the TPC in detail with the aid of experts from the LEPS group, some of whom belong to the collaboration. After some test experiment using beams at SPring-8 and/or J-PARC, we will submit a Technical Design Report for PAC and FIFC. In particular, the expected momentum resolution for decay π^-'s and the fringing field, which may worsen the momentum resolution of the S-2S spectrometer, will be studied carefully. Moreover, the end-caps of

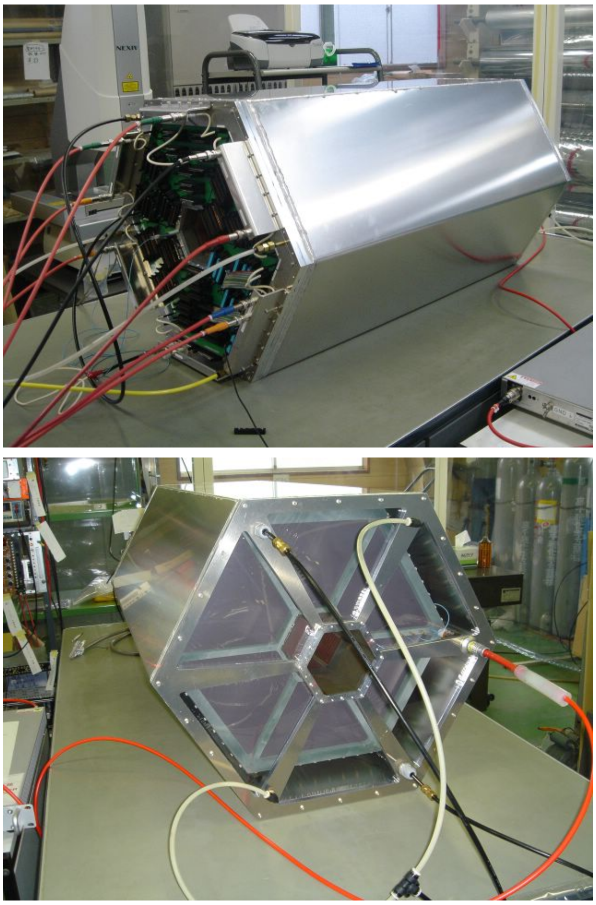

Figure 12: Photos of the TPC from the upstream (up) and the downstream (down), taken from Ref. [40].

the solenoid magnet may be replaced so as to improve the uniformity of the magnetic field inside the magnet and reduce the fringing field.

5 Yield Estimation

Integration over the bound region in Fig. 5 gives the differential cross section of $\approx$ 40 nb/sr. The K^- beam intensity and the spill cycle are assumed to be 1.3 M/spill and 4.7 sec, respectively, in accordance with the E70 proposal [2]. The integrated number of beam K^- for a 60-day beamtime will be 1.4×10^{12}. Then, when a 10 g/cm^2-thick target is used, the yield of bound ${}^{7}_{\Xi^-}\mathrm{H}$ in the (K^-, K^+) missing-mass spectrum will be $\approx$ 760. Here, the acceptance of the S-2S spectrometer is assumed to be 55 msr, and the K^+ survival rate in the S-2S spectrometer (0.4) and the efficiency (0.7) are taken into account.

Next, the number of identified ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ is estimated. If the branching ratio of ${}^{7}_{\Xi^-}\mathrm{H} \to {}^{5}_{\Lambda\Lambda}\mathrm{H} + 2n$ is 0.9, approximately 680 ${}^{5}_{\Lambda\Lambda}\mathrm{H}$'s will be produced from ${}^{7}_{\Xi^-}\mathrm{H}$ tagged in the missing-mass analysis. Among them, ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ is identified if it decays

$$ {}^{5}_{\Lambda\Lambda}\mathrm{H} \to {}^{5}_{\Lambda}\mathrm{He} + \pi^-, \tag{15} $$

$$ {}^{5}_{\Lambda}\mathrm{He} \to p + n + {}^{3}\mathrm{He}. \tag{16} $$

The branching ratio of the first decay was estimated to be $0.38/(0.38 + 0.61 + 0.31) = 0.29$ [11], and the emission probability of proton with kinetic energy larger than 15 MeV from ${}^{5}_{\Lambda}$He is $25 \pm 7\%$ [39]. Then, the number of identified ${}^{5}_{\Lambda\Lambda}$H will be $50\epsilon^2$, where ϵ denotes the detection efficiency (including the geometrical acceptance) of a single particle by the cylindrical detector system. If ϵ is set to be 0.7, approximately 25 ${}^{5}_{\Lambda\Lambda}$H will be identified.

This estimation does not include the contribution from quasi-free Ξ^- rescattering (Fig. 7). It is difficult to predict the formation probability of double-Λ compound nuclei $\left[{}^{6}_{\Lambda\Lambda}\mathrm{H}\right]^*$ per quasi-free Ξ^-, and the fragmentation probability of $\left[{}^{6}_{\Lambda\Lambda}\mathrm{H}\right]^* \to {}^{5}_{\Lambda\Lambda}\mathrm{H} + n$. Furthermore, due to various background processes such as quasi-free Ξ^- decay in flight, rescattering of $\Xi^- N \to \Xi^- N$, conversion of $\Xi^- p \to \Lambda\Lambda$, the identification of ${}^{5}_{\Lambda\Lambda}$H from quasi-free Ξ^- rescattering will be much more difficult than the case of that from Ξ-hypernuclear decay, and will require a dedicated cut condition. Therefore, a realistic yield estimation is not possible at present, but will be given in future, based on an analysis of data with a part of the beamtime allocated.

If we achieve the momentum resolution of 5% in the cylindrical detector system, the mass resolution of ${}^{5}_{\Lambda\Lambda}$H will be $\sigma = 5\,\mathrm{MeV}/c^2$. Then, we expect the statistical precision of the $\Lambda\Lambda$ bond energy to be less than 1 MeV. This precision is worse than that of ${}^{6}_{\Lambda\Lambda}$He (0.17 MeV) obtained in the NAGARA event, but better than that obtained in the MIKAGE and HIDA events [8]. As a next step beyond this proposal, we may have to develop a different spectrometer with high momentum resolution ($\lesssim$ 1%), in order to compare the difference of the $\Lambda\Lambda$ bond energy between ${}^{5}_{\Lambda\Lambda}$H and ${}^{6}_{\Lambda\Lambda}$H, which is important in revealing the role of the $\Lambda\Lambda$-ΞN mixing in double-Λ hypernuclei.

6 Beamtime Request

beam and detector commissioning 10 days

calibration measurements 7 days

- $p(\pi^+, K^+)\Sigma^+$ followed by $\Sigma^+ \to n + \pi^+$ with CH_2 target: 2 days
- $p(K^-, K^+)\Xi^-$ with CH_2 target: 2 days
- ${}^{7}\mathrm{Li}(\pi^+, K^+)$ reaction:3 days

${}^{7}\mathrm{Li}(K^-, K^+)$ reaction 60 days

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