Proposal for J-PARC 50 GeV Synchrotron

Phase-1 of the P75 experiment: Measurement of the formation cross section of ${}^{7}_{\Xi^-}\mathrm{H}$ in the ${}^{7}\mathrm{Li}(K^-, K^+)$ reaction

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1 Purpose of the phase-1 experiment

We submitted a proposal entitled with "Decay Pion Spectroscopy of ${}^{5}_{\Lambda\Lambda}$H Produced by Ξ-hypernuclear Decay" [1] to the 27th PAC meeting. The principle of the proposed P75 experiment is as follows:

1. production of ${}^{7}_{\Xi^-}$H in the ^{7}Li(K^-, K^+) reaction,
2. production of ${}^{5}_{\Lambda\Lambda}$H via ${}^{7}_{\Xi^-}\mathrm{H} \to {}^{5}_{\Lambda\Lambda}\mathrm{H} + 2n$ decay,
3. decay pion spectroscopy for ${}^{5}_{\Lambda\Lambda}\mathrm{H} \to {}^{5}_{\Lambda}\mathrm{He} + \pi^-$ decay.

As pointed out in the evaluation of the proposal by the PAC [2], the ${}^{5}_{\Lambda\Lambda}$H yield depends on the formation cross section of ${}^{7}_{\Xi^-}$H and the branching ratio of ${}^{7}_{\Xi^-}\mathrm{H} \to {}^{5}_{\Lambda\Lambda}\mathrm{H} + 2n$, both of which are unknown at present. We had adopted the result of a theoretical calculation for each. While we requested a 60-day beamtime for the ${}^{5}_{\Lambda\Lambda}$H production in the original proposal, we recognize the importance to take into account their uncertainties for a more realistic evaluation of the necessary beamtime.

In order to reduce the uncertainty from the experimental side, we would like to propose a phase-1 experiment to perform a missing-mass spectroscopy for ^{7}Li(K^-, K^+) reaction. The primary goal is to obtain the yield of ${}^{7}_{\Xi^-}$H by using the S-2S spectrometer, which will improve the precision of the yield prediction of ${}^{5}_{\Lambda\Lambda}$H as its decay product.

Moreover, if this phase-1 experiment is realized, it would be the second spectroscopy experiment on Ξ-hypernuclei at J-PARC, subsequent to the E70 experiment [3,4]. Although the missing-mass resolution will be worse than in the E70 experiment, which will use an active target made of scintillation fibers for energy-loss correction in the target, the first measurement of the (K^-, K^+) reaction on a lighter target than ^{12}C will serve as a guideline in planning a spectroscopy experiment on light Ξ-hypernuclei without an active target.

2 Theoretical calculations

2.1 ΞN interaction models and structure of ${}^{7}_{\Xi^-}$H

Owing to very limited experimental information on Ξ-nucleus and Ξ-nucleon interaction, several baryon-baryon interaction models have been proposed. In this proposal, we take two kinds of phenomenological interaction models (ESC04d and ND) [6] and a ΞN potential based on first-principle lattice QCD simulations by the HAL QCD collaboration [7, 9]. The ESC04d model results in a large conversion width of Ξ-hypernuclear states, because of a strong ΛΛ-ΞN-ΣΣ coupling interaction, while the conversion width is very small for the ND and HAL QCD models.

Table 1 is a summary of the calculated binding energy and width of ${}^{7}_{\Xi^-}$H as a four-body $\alpha NN\Xi^-$ system [6, 8]. While every model calculation predict a shallow bound state just below the lowest threshold of ${}^{6}\mathrm{He}_{\mathrm{g.s.}} + \Xi^-$, the width spreads over a wide range, reflecting the strength of the coupling interaction in each model. In particular, the width based on the HAL QCD potential is on the order of 10 keV, which is much smaller than that for a $NNN\Xi$ system obtained with the same HAL QCD potential [9]. Unfortunately,

Table 1: Binding energy (B) and width Γ of the $^{\;7}_{\Xi^-}$H system calculated with different ΞN interaction models. The binding energy is measured from the lowest threshold of ^{6}He(0^+) + Ξ^-. The differential cross section integrated over the bound region ($-12.64 < E_x$ [MeV] < 0) is also shown. Values in the parentheses correspond to the case of the missing-mass resolution of 3.5 MeV/c^2.

interaction model	B [MeV]	Γ [MeV]	Reference	$d\sigma/d\Omega$ [nb/sr]		Reference
ESC04d	1.80	2.64	[6]	79	(79)	[15]
ND	1.55	0.27	[6]	51	(52)	[15]
HAL (t = 11)	1.07	0.016	[8]	12	(17)	[16]
HAL (t = 12)	0.80	0.014	[8]	6.7	(11)	[16]
HAL (t = 13)	0.40	0.008	[8]	2.6	(7.1)	[16]

the missing mass resolution (approximately 3.5 MeV at FWHM) will not allow us to determine the width of $^{\;7}_{\Xi^-}$H directly.

There is no strong evidence for or against a very narrow conversion width of a Ξ hyperon in nuclear medium. If a number of twin hypernuclear events, exhibiting production and decay of a Ξ hypernucleus, are observed in the J-PARC E07 experiment [11] as well as in the KEK-PS E373 experiment [10], the mass distribution of identified Ξ hypernuclei would shed light on their decay width. Moreover, the formation probability of deeply-bound Ξ hypernuclei from Ξ^- capture in light nuclei, which may be converted into the width of the 3D level of Ξ^- atoms, the shift and width of X-ray from Ξ^- atoms [12], as well as inclusive (K^-, K^+) spectra on ^{12}C and other targets [4, 13] would be promising to further gain a detailed understanding on the strength of the $\Lambda\Lambda$-ΞN coupling. In this proposal, we treat a large-width case and a small-width case on equal footing.

The energy level of $^{\;7}_{\Xi^-}$H calculated using each interaction model is depicted in Fig. 1, together with energies of the decay thresholds. As pointed by Kumagai-Fuse and Akaishi [14], possible decay modes of $^{\;7}_{\Xi^-}$H will be limited to $^{\;\;5}_{\Lambda\Lambda}$H + 2$n$, $^4_\Lambda$H$^{(*)}$ + Λ + 2n, and ^{3}H + 2Λ + 2n, if we can ignore the decay mode of $^3_\Lambda$H + Λ + 3n and ^{2}H + 2Λ + 3n, whose energy is almost equal to the $^{\;7}_{\Xi^-}$H energy. On the other hand, if the missing mass of the ^{7}Li(K^-, K^+) reaction is above the ^{6}He(0^+) + Ξ^- threshold, a Ξ^- produced in the quasi-free (K^-, K^+) reaction can escape from the target nucleus without $\Xi^- p \to \Lambda\Lambda$ conversion. Therefore, we will gate the bound region below the ^{6}He(0^+) + Ξ^- threshold in searching for two-body decay π^- from $^{\;\;5}_{\Lambda\Lambda}$H.

2.2 Calculated spectrum of the ^{7}Li(K^-, K^+) reaction

A calculation with the DWIA framework using a coupled-channel Green's function approach is carried out by Koike and Hiyama [15, 16]. The Ξ^-–^{6}He(0^+) potential, composed of a Woods-Saxon form and a Coulomb interaction term, is prepared so as to reproduce the binding energy and width of $^{\;7}_{\Xi^-}$H in each interaction model and the Ξ^-–^{6}He(2^+) potential is assumed to be the same as the Ξ^-–^{6}He(0^+) potential. In addition, a coupling potential between the two channels with a zero-range interaction is considered. It should be noted that the incident K^- momentum was set to 1.65 GeV/c in the calculation. Taking

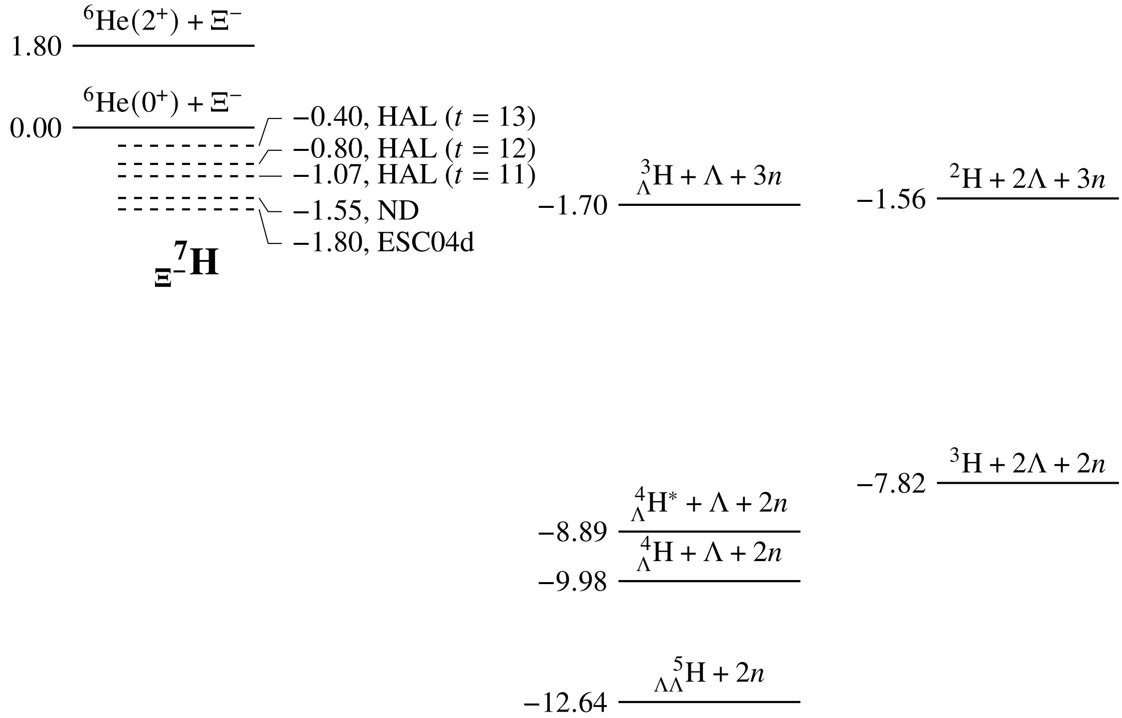


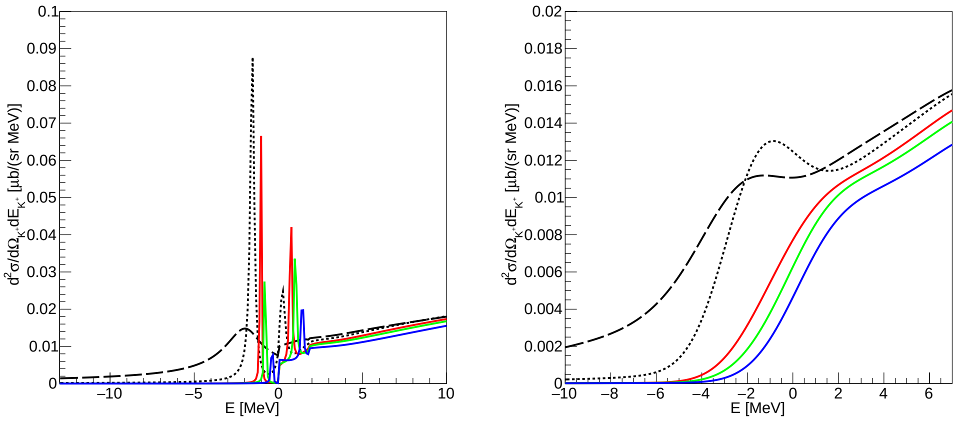
Figure 1: Calculated energy levels of $_{\Xi^-}^{7}$H (dashed line) and the relevant thresholds. The energies (in unit of MeV) are relative to the ^{6}He$(0^+) + \Xi^-$ threshold.

into account momentum dependence of the differential cross section of the elementary $K^- p \to K^+ \Xi^-$, recently measured in the E05 pilot run [4], the differential cross section of the ^{7}Li(K^-, K^+) will not be significantly different between 1.65 GeV/c and 1.8 GeV/c.

The result is shown in the left panel of Fig. 2. As expected, a peak, whose position and width are consistent with the input shown in Table 1, is seen below the ^{6}He$_{\text{g.s.}} + \Xi^-$ threshold. The differential cross section integrated over the bound region is shown in Table 1. While the ESC04d and ND model calculations yield a fairly large differential cross section, more or less similar to the result for the ^{12}C(K^-, K^+) reaction (89 ± 14 nb/sr) [17], the present calculation with the HAL-QCD potentials results in much smaller cross section than the assumption (40 nb/sr)[1] in the original proposal [1].

The right panel shows the spectrum smeared with a Gaussian function to account for the missing-mass resolution of 3.5 MeV/c^2. Due to the smearing, the $_{\Xi^-}^{7}$H peak will be hardly visible, even if the statistics is high enough. This is the reason why an experimental determination of the binding energy and width of $_{\Xi^-}^{7}$H is beyond the scope of the proposed phase-1 experiment. However, the differential cross section integrated over the bound region, as well as the distribution in the bound region, will help us to constrain the interaction model. To be accurate, the differential cross section integrated over the bound region in Fig. 2 (a) is not equal to that in Fig. 2 (b). Numerically, they are almost the same for the ESC04d and ND

[1]This value was obtained with the ESC04d model calculation with the $k_f = 1.055\,\text{fm}^{-1}$ case, where k_f is the Fermi momentum of nuclear matter, needed for formulating G-matrix interactions. In this proposal, k_f is fixed to be $0.9\,\text{fm}^{-1}$ according to the description in Ref. [6]. In general, a smaller k_f leads to a larger binding energy, hence a larger cross section.



(a) resolution: 0 MeV

(b) resolution: 3.5 MeV

Figure 2: Calculated inclusive spectra for the $^{7}\mathrm{Li}(K^-, K^+)$ reaction. The missing-mass resolution is assumed to be 0 MeV and 3.5 MeV (FWHM) in the left and right panels. The dashed, dotted, and solid lines corresponds to the ESC04d, ND, and HAL QCD (red: $t = 11$, green: $t = 12$, blue: $t = 13$) models, respectively.

models, while the differential cross section will be overestimated in case of the HAL QCD models due to contamination from the unbound region. As the differential cross section can be evaluated well in case it is large enough, which is one of requirements to take a step toward a phase≥2 experiment, this systematic uncertainty due to the finite resolution will not be serious from the viewpoint of the aim of the proposed phase-1 experiment.

3 Experimental Setup

The experimental setup is the same as in the E70 experiment [4] except for the target. The details of the S-2S spectrometer were described in the E70 proposal and a TDR submitted to the FIFC.

We will use a 10 g/cm^2-thick ^{7}Li target for production of $^{7}_{\Xi^-}\mathrm{H}$. Since we cannot make an event-by-event correction for energy-loss straggling without using an active target, the effect of energy-loss straggling, which is proportional to the target thickness, should be taken into consideration. Using the values in Table VI in the E70 proposal, we obtain the missing-mass resolution as 3.5 MeV$/c^2$ using the S-2S spectrometer.

4 Yield Estimation

Assuming the beam power from the main ring of 85 kW, which will be enabled thanks to a newly installed T1 target, the K^- beam intensity of 0.95 M/spill is expected. To increase the yield, the spill cycle will be shortened to 4.7 sec. Then, the integrated number of beam K^- for a 7-day beamtime will be 1.1×10^{11}, including 90% live time. 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 $\approx 1.5/(\mathrm{nb/sr})$. Namely, the expected yield of $^{7}_{\Xi^-}\mathrm{H}$ in the bound region will be approximately 115, 73, 4–17 for ESC04d, ND, HAL QCD interaction models, respectively. 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.

With this sensitivity, we will be able to determine the differential cross section in the bound region at the level of several nb/sr. This precision is sufficient enough to reduce the uncertainty of ${}^{5}_{\Lambda\Lambda}$H yield originating from ${}^{7}_{\Xi^-}$H yield. Thereby, the ${}^{5}_{\Lambda\Lambda}$H yield will be reevaluated, based on start-of-the-art calculations, such as a very recent calculation on ${}^{7}_{\Xi^-}$H decay with a statistical decay model [18], and the performance of the cylindrical detector system under preparation.

5 Beamtime Request

We request to have a 7-day beamtime soon after the E70 experiment is completed, for efficient start-up of the production run. Otherwise, we may need approximately one more week for commissioning of the beam and the spectrometer systems, and the calibration measurement with the $p(K^-, K^+)\Xi^-$ reaction.

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