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Production of light Ξ-hypernuclei, $^{7}_{\Xi}$H

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Abstract. A light Ξ hypernucleus, $^{7}_{\Xi}$H, is expected to be bound. Furthermore, it is pointed out that $^{7}_{\Xi}$H will decay into $^{5}_{\Lambda\Lambda}$H with a large branching ratio. We plan to study the ^{7}Li(K^-, K^+) reaction to investigate the $^{7}_{\Xi}$H system and to evaluate the experimental feasibility to perform decay pion spectroscopy of $^{5}_{\Lambda\Lambda}$H in future.

1 Introduction

Experimental studies of double strange hypernuclei — Ξ hypernuclei and double-Λ hypernuclei — are one of important subjects in J-PARC. In particular, with the advent of a high-resolution magnetic spectrometer S-2S, high-resolution spectroscopy of $^{12}_{\Xi}$Be, which can be produced with the ^{12}C(K^-, K^+) reaction, will be realized as the J-PARC E70 experiment in the near future [1, 2]. As detailed properties of spin- and isospin-dependent Ξ-nucleon interaction are not well-known at present, the structure of light Ξ hypernuclei, to be explored with the S-2S spectrometer, is considered to be important in revealing the nature of Ξ-nucleon interaction [3].

We plan to investigate $^{7}_{\Xi}$H produced by the ^{7}Li(K^-, K^+) reaction [4]. The (K^-, K^+) reaction on nuclear targets other than ^{12}C has not been attempted, whereas the aforementioned $^{12}_{\Xi}$Be had been studied in the BNL-AGS E885 experiment [5] and is to be investigated with a much better resolution in the forthcoming J-PARC E70 experiment. The physics motivation to investigate experimentally the $^{7}_{\Xi}$H system, is twohold. The first is to gain some insight into the Ξ-nucleus and Ξ-nucleon interactions through the formation spectrum in the reaction, as is the case with single-Λ hypernuclei. The second is the relevance to double-Λ hypernuclei; formation of $^{5}_{\Lambda\Lambda}$H from $^{7}_{\Xi}$H, owing to the $\Xi N \to \Lambda\Lambda$ conversion, is plausible [6].

A proposal of an experiment, being afterward referred to as the P75 experiment, to determine the mass of $^{5}_{\Lambda\Lambda}$H by means of decay pion spectroscopy, was submitted to J-PARC in 2018 [7]. As the first phase of the P75 experiment, we will measure the formation spectrum of the ^{7}Li$(K^-, K^+)\,^{7}_{\Xi}$H reaction and derive the formation cross section of $^{7}_{\Xi}$H. The proposal of the phase-1 experiment, submitted in 2019, can be found in Ref. [4].

2 Very light Ξ hypernuclei — $^{7}_{\Xi}$H

The level structure is expected to be simple, because the ^{6}He core is an even-even nucleus. The existence of a bound state of $^{7}_{\Xi}$H is supported by various theoretical calculations [8–10]. Hiyama *et al.* [8] calculated the binding energy and width of $^{7}_{\Xi}$H with a four-body cluster

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model, in which three types of ΞN interaction models, ESC04d, ND and HAL QCD, were adopted. Whereas the ESC04d interaction results in a moderately large decay width, the decay width could be narrower than 1 MeV in case of the other two interactions. In particular, the decay width for the HAL QCD interaction could be of the order of 10 keV [9], because of a small coupling between ΞN and $\Lambda\Lambda$ predicted by the HAL QCD calculation [11]. A calculation by H. Le *et al.* with the chiral effective field theory led to the decay width of 0.2 MeV [10]. On the contrary, the binding energy is less model-dependent; it would lie around 2–3 MeV below the $\Xi^- + {}^6$He threshold. Moreover, ${}^{7}_{\Xi}$H is expected to be close to the onset of Ξ binding. While the existence of bound states of $NNN\Xi$ systems are suggested by recent theoretical calculations [10, 12], production in the ${}^4\mathrm{He}(K^-, K^{0/+})$ reactions are challenging from an experimental point of view.

For these reasons, ^{7}Li will be one of the most suited target candidates for populating Ξ hypernuclei after a high-resolution spectroscopy of ${}^{12}_{\Xi}$Be with a ^{12}C target is performed. According to a calculation on the ${}^7\mathrm{Li}(K^-, K^+)$ reaction [13, 14], the formation cross section is expected to be several tens of nb/sr, which is more or less similar to that for ${}^{12}_{\Xi}$Be derived in the BNL-AGS E885 experiment [5].

3 J-PARC E75 phase-1 experiment

The experiment will be performed at the K1.8 beamline at J-PARC, similar to the E70 experiment [1, 2]. The S-2S spectrometer will be utilized for missing-mass spectroscopy of the ${}^7\mathrm{Li}(K^-, K^+)$ reaction. The missing-mass resolution is expected to be 3.5 MeV (FWHM) if a lithium target with the mass thickness of 10 g/cm^2 is used. According to formation cross sections with various inputs for the ΞN interaction [13, 14], the yield in the bound region below the $\Xi^- + {}^6$He threshold is estimated 56–104 for one-week beamtime [4].

4 Toward production of double-Λ hypernuclei — ${}^{5}_{\Lambda\Lambda}$H

Another noteworthy feature of ${}^{7}_{\Xi}$H is that kinematically allowed decay modes are limited: (i) ${}^{5}_{\Lambda\Lambda}\mathrm{H} + 2n$, (ii) ${}^{4}_{\Lambda}\mathrm{H} + \Lambda + 2n$, (iii) ${}^{4}_{\Lambda}\mathrm{H}^* + \Lambda + 2n$, and (iv) ${}^3\mathrm{H} + 2\Lambda + 2n$ [6]. It is because the released energy of $\Xi^- p \to \Lambda\Lambda$ is largely canceled by the proton separation energy of ^{6}He, which is the core of ${}^{7}_{\Xi}$H.

If the branching ratio into the decay mode (i) is sufficiently large, ${}^{5}_{\Lambda\Lambda}$H can be exclusively produced as a decay particle of ${}^{7}_{\Xi}$H. Theoretically, it is calculated to be $\sim 90\%$ [6] or 40–60% with the remaining part being the decay modes (ii) and (iii) [15]. This feature is in contrast to the Ξ^- capture in nuclear emulsion, resulting in production of double-Λ hypernuclei with mass numbers ranging from 5 to 18.

The P75 experiment [7] will attempt to produce ${}^{5}_{\Lambda\Lambda}$H via production and decay of ${}^{7}_{\Xi}$H. Not only for confirmation of ${}^{5}_{\Lambda\Lambda}$H production but also for determination of its mass, a decay pion from two-body decay, ${}^{5}_{\Lambda\Lambda}\mathrm{H} \to {}^{5}_{\Lambda}\mathrm{He} + \pi^-$, which should have a discrete momentum, will be momentum analyzed. The technique to determine the mass of the parent hypernucleus is called decay pion spectroscopy, and is established for single-Λ hypernuclei, especially ${}^{4}_{\Lambda}$H decaying into ${}^4\mathrm{He} + \pi^-$ [16]. For this purpose, a cylindrical detector system, equipped with a time projection chamber and timing counters etc., is being developed.

5 Conclusion and Outlook

The E75 phase-1 experiment which will be performed in series with the E70 experiment will provide the first experimental data on ${}^{7}_{\Xi}$H. It would provide further information on Ξ-nucleus and Ξ-nucleon interactions. Moreover, it will be the first step toward exclusive production of ${}_{\Lambda\Lambda}^{5}\mathrm{H}$. If the P75 experiment is realized, it may open a new era of double-Λ hypernuclear physics; the properties of ${}_{\Lambda\Lambda}^{5}\mathrm{H}$, such as the lifetime and the weak decay modes, may be assessed in a counter experiment. By using a different nuclear target, e.g. ${}^{9}\mathrm{Be}$ and ${}^{10}\mathrm{B}$, other light double-Λ hypernuclei may be produced in a similar way.

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