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Development of a triple coincidence method of reaction, gamma-ray, and weak decay in the hypernuclear gamma-ray spectroscopy at J-PARC

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Abstract. To understand the mechanism of the charge symmetry breaking between ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He, we plan to measure the gamma-transition energy of ${}^{4}_{\Lambda}$H ($1^+ \to 0^+$) with a Ge detector array. For identification of the hypernucleus, we will perform triple coincidence with the reaction, γ-ray, and weak decay for the first time. We measure the pion from weak decay with a range counter. This method will enable γ-ray spectroscopy of various hyperfragments which cannot be directly produced by (K^-, π^-) or (π^+, K^+) reactions.

1 Motivations

1.1 Study of the charge symmetry breaking in the Λ-N interaction

It has been suggested that there is a sizable effect of charge symmetry breaking (CSB) in the four-body system of a Λ hyperon and nucleons (N). The mechanism of the effect is still unclear but it will provide a clue to deeper understanding the baryon-baryon interaction. Recently, our group measured the γ-ray from the ${}^{4}_{\Lambda}$He ($1^+ \to 0^+$) transition and confirmed the presence of the large CSB effect (Fig. 1 (A)) [4].

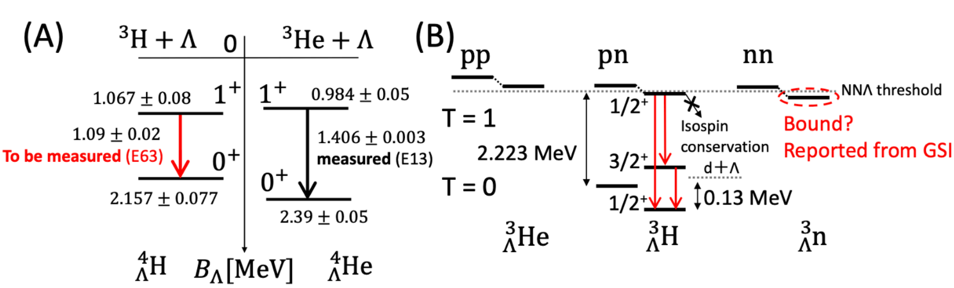

Figure 1. (A) Level schemes of γ-ray transitions of ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He. The Λ binding energy (B_Λ) of ${}^{4}_{\Lambda}$He (0^+) was measured in emulsion experiments [1] and that of ${}^{4}_{\Lambda}$H (0^+) in decay pion spectroscopy [2, 3]. (B) Level schemes of ${}^{3}_{\Lambda}$He, ${}^{3}_{\Lambda}$H, and ${}^{3}_{\Lambda}$n and possible γ-ray transitions in ${}^{3}_{\Lambda}$H.

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The transition energy of ${}^{4}_{\Lambda}$He, which we measured with germanium (Ge) detectors, has good statistics and high resolution. In contrast, the data of ${}^{4}_{\Lambda}$H measured in the 1970s and 1990s is poor in statistics and resolution. Thus, we plan to precisely measure the γ-ray energy of the ${}^{4}_{\Lambda}$H ($1^+ \rightarrow 0^+$) transition using a high-resolution Ge detector array, Hyperball-J, at J-PARC as the E63 experiment [5].

1.2 Search for excited states of hypertriton

Excited states of ${}^{3}_{\Lambda}$H are probably unbound, but there is a possibility to observe γ-rays from them (Fig. 1 (B)). If their energies are measured, we can approach two problems. One is whether the nnΛ state is bound or not. The energy of the $1/2^+$ (T=1) excited state can be very close to the NNΛ threshold. Due to the isospin conservation, the decay of ${}^{3}_{\Lambda}$H (T=1) $\rightarrow$ dΛ is suppressed and ${}^{3}_{\Lambda}$H (T=1) is expected to deexcite (partly) with γ emission. The measurement will give us important imformation on the states of ${}^{3}_{\Lambda}$H (T=1) and nnΛ. The other is related to the hypertriton lifetime puzzle. The reported values of the ${}^{3}_{\Lambda}$H binding energy are different between experiments. The energy of the excited state of $3/2^+$(T = 0) is possibly closer to the dΛ threshold than expected or lower than the dΛ threshold. In such cases, the gamma transition ($3/2^+ \rightarrow 1/2^+$) may be observed. If the energy of the transition is measured, the information helps us understand the ΛN-ΣN coupling interaction. In either case measurement of γ-rays from the simplest hypernucleus, ${}^{3}_{\Lambda}$H, is particularly important. We also plan to measure the γ-rays from ${}^{3}_{\Lambda}$H in the E63 experiment.

2 Triple coincidence of (K^-, π^-) reaction, γ-ray, and weak decay

The E63 experiment is going to be performed at the K1.1 beam area in J-PARC (Fig. 2 left) [5]. It is impossible to produce ${}^{4}_{\Lambda}$H and ${}^{3}_{\Lambda}$H directly from (K^-, π^-) or (π^+, K^+) reactions. Thus, we will produce ${}^{4}_{\Lambda}$H and ${}^{3}_{\Lambda}$H as hyperfragments from the ^{7}Li (K^-, π^-) reaction. In the reaction, highly excited states of ${}^{7}_{\Lambda}$Li are produced and decay into ${}^{4}_{\Lambda}$H, ${}^{3}_{\Lambda}$H, and other hyperfragments. We identify a K^- beam particle and a π^- scattered particle and measure their momenta with the upstream and downstream spectrometers. Using this information, we obtain the missing mass spectrum of the ^{7}Li (K^-, π^-) reaction, and then select the excited states of ${}^{7}_{\Lambda}$Li, which are expected to decay into hyperfragments such as ${}^{4}_{\Lambda}$H and ${}^{3}_{\Lambda}$H (Fig. 2 right).

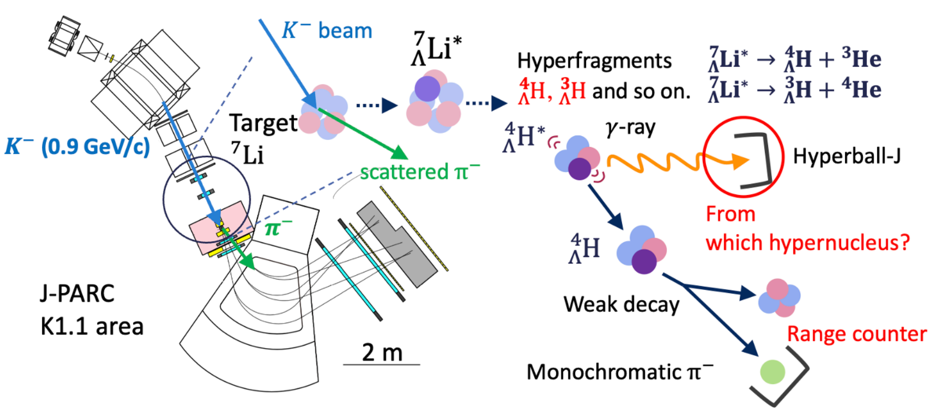

Figure 2. (Left) Experimental setup. The (K^-, π^-) reaction is identified using upstream or downstream spectorometers. (Right) The gamma-weak coincidence of ${}^{4}_{\Lambda}$H using a range counter.

When a produced hyperfragment is excited, it decays to the ground state with a γ emission. We measure the γ-rays with Hyperball-J. In this method, however, we do not know which hypernucleus emitted the γ-ray. In order to identify the hypernucleus, we measure kinetic energies of monochromatic pions from two-body weak decay of ${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$ and ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$ by a range counter (their kinetic energies are 53 MeV and 40 MeV, respectively). The branching ratios of these two-body weak decays are 50% and 27%, respectively. For identification of the hypernucleus, we will perform triple coincidence measurement for the in-flight (K^{-}, π^{-}) reaction, a γ-ray, and a weak decay pion for the first time. The requirement to the range counter system is to separate two peaks from these two monochromatic pions in the range spectrum with a confidence level of more than 3σ.

3 Range counter system

We developed a range counter system made of 24 layers of a 6 mm-thick plastic counter. We adopted a readout method using wavelength-shifting fibers and SiPMs. Scintillation photons are converted and transported in the wavelength-shifting fibers embedded in the two sides of the scintillator, and read out with SiPMs. In front of the range counter, plastic scintillator hodoscopes as a tracking device for pions (TD) are installed. Thanks to the tracking device, angular inaccuracy is removed. Figure 3 shows the range counter system which is installed inside the Hyperball-J system.

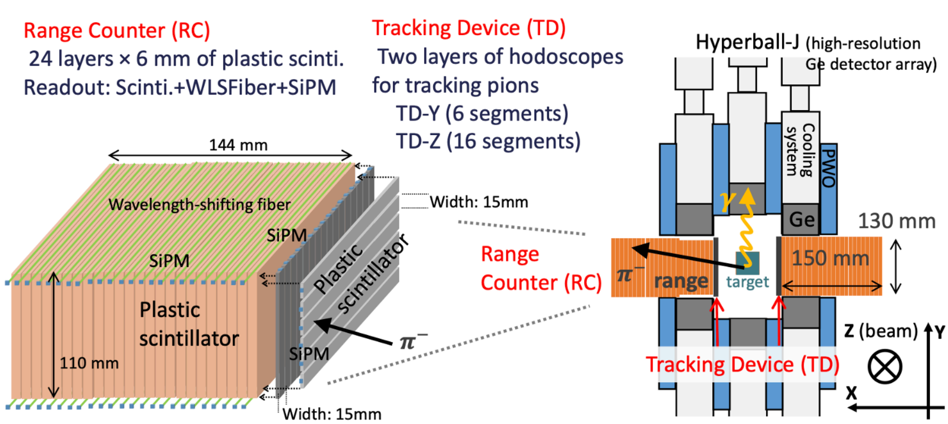

Figure 3. (Left) The range counter system, which is composed of a range counter and a tracking device. (Right) The system is installed inside the Hyperball-J.

4 Test experiment and results

We fabricated a prototype range counter made of 8 layers of a 6 mm-thick plastic counter. The total thickness of the prototype is one-third of that of the counter for the E63 experiment. We conducted an experiment at the downstream end of the J-PARC K1.8 beam line to test the prototype and evaluate its performance. The experimental setup is shown in Fig. 4 (A). Pions with momentum of 300 MeV/c were degraded down to less than 110 MeV/c to stop them in the range counter, and time of flight between two plastic hodoscope (TOF counters) located before the range counter was measured. Since the pions fly with various velocities,

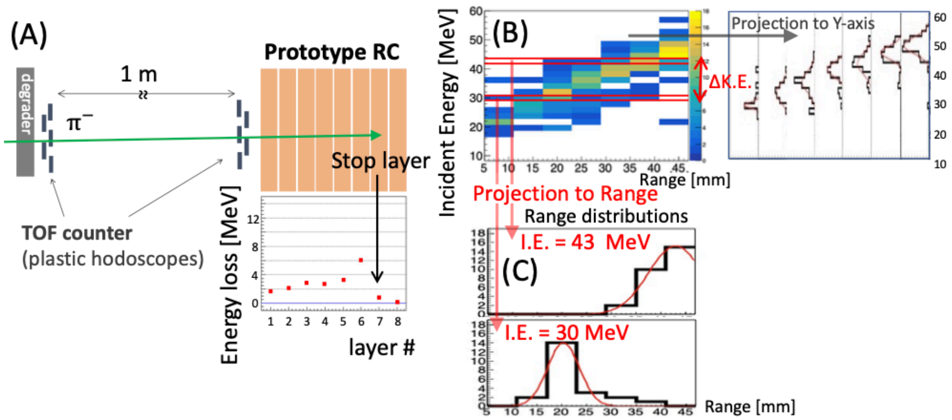

Figure 4. (A) Setup of the test experiment of a prototype range counter. The lower histogram shows the energy loss in each layer for a typical event in which a pion stopped in the prototype. (B) Correlation between incident energy and range for stop pion events. (C) Two distributions of range at energy regions around 43 and 30 MeV.

the incident energy before the range counter is not uniform. Figure 4 shows two results. First, we looked at the time of flight between TOF counters and selected slow pion events. When we plotted the energy loss in each layer of the range counter for each event, we observed Bragg curves as shown in Fig. 4 (A). In this way, we confirmed that about 300 pions stopped in the range counter. For these stop events, we plotted the correlation between the range and the incident energy (Fig. 4 (B)). We selected two energy regions around 43 MeV and 30 MeV, and then we obtained range distributions for these two regions (Fig. 4 (C)). They are found to be well separated. The difference of 43 MeV and 30 MeV (13 MeV) is equal to the difference of kinetic energies of pions from ${}^{4}_{\Lambda}$H and ${}^{3}_{\Lambda}$H. In the E63 experiment, we measure pions with higher kinetic energies than in the present test experiment, which means that the prototype can separate the pions from ${}^{4}_{\Lambda}$H and ${}^{3}_{\Lambda}$H sufficiently well.

5 Summary

We plan to measure the energy of γ-rays from ${}^{4}_{\Lambda}$H and ${}^{3}_{\Lambda}$H. For identifying the hypernucleus produced as hyperfragments, we are going to perform a triple coincidence method with a range counter which is to be newly developed. We fabricated a prototype with a thickness of one-third of the whole detector for the E63 experiment and conducted a test experiment at J-PARC using pions. As a result, we found that the prototype has the ability to measure the pion energy accurately enough in the energy region required for the E63 experiment. Based on the results, we are currently fabricating a whole set of the range counter system for the beam time coming near future.

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