PROCEEDINGS OF SCIENCE

Experimental studies of baryon modification in nuclei using hyperons

H. Tamura,[a,b,*] **M. Fujita,**[b] **Y. Hong,**[a] **K. Kamada,**[a] **C. Seong,**[a] **M. Ukai**[c] **and T. O. Yamamoto**[b]

[a]*Department of Physics, Tohoku University, Aoba-ku, Sendai 980-8578, Japan*
[b]*Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan*
[c]*Institute of Particle and Nuclear Science, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*

E-mail: hirokazu.tamura.a2@tohoku.ac.jp

Although the EMC effect indicates that the momentum distribution of quarks in the baryons in nuclear matter is modified from that in the free space, no clear evidence for baryon modification has been found in low energy nuclear phenomena and detailed mechanism of the modification is not understood yet. In order to challenge this problem, we plan to use Λ hyperons embedded in a nucleus.

One of the possible approaches is a measurement of Λ's β-decay rate in hypernuclei, which is expected to be significantly reduced due to structure change of baryons in the nucleus. We will measure the lifetime and the branching ratio of the β-decay of ${}^{5}_{\Lambda}\mathrm{He}$ and/or ${}^{13}_{\Lambda}\mathrm{C}$. The feasibility of this experiment is under study, in which how to suppress huge background from mesonic and nonmesonic weak decays of hypernuclei is a key point. Reliable theoretical estimates of nuclear effects and hadronic effects, including Pauli effect of nucleons, are also necessary.

The XVIth Quark Confinement and the Hadron Spectrum Conference (QCHSC24)
19-24 August, 2024
Cairns Convention Centre, Cairns, Queensland, Australia

*Speaker

PoS(QCHSC24)228

1. Nucleon modification in a nucleus?

For many years, nuclear phenomena have been described in terms of structureless nucleons, although the nucleons have substructure made of quarks and gluons together with meson clouds. The size of the nucleon is of the same order of magnitude as the inter-nucleon distance in a nucleus, and the nucleons in a nucleus are always affected by meson fields made by other nucleons. Therefore, it is natural to consider that the nucleon structure is modified in a nucleus. The EMC effect indicates that the momentum distiribution of quarks in nucleons is significantly changed in nuclear medium from those in the free space [1]. Recently, it was found that the main part of the EMC effect ($0.35 < x_B < 0.7$), where the deep inelastic cross section is reduced from that in the free space, is strongly correlated with the nucleon-nucleon short-range correlation scale factors [2]. Although this obervation provides a clue to unravel the EMC effect, the mechanism of the EMC effect has not become clear yet. In the short range correlation, when two nucleons approach in a very short distance, their quark distributuion may be changed and the nucleon structure may be modified. On the other hand, quarks in the nucleon in nuclear medium are always interacting with mesons, which leads to the conjecture that the nucleon is ”swelled” in the nucleus. Various experimental and theoretical suggestions and conjectures on ”nucleon swelling” have been made so far [3] on how and why the nucleon structure is modified in a nucleus, but nothing is clearly etablished. Actually, there has been no clear experimental evidence for the modification except for the EMC effect. In other words, the modification has not been established in low energy nuclear phenomena. It is because the effects of the nucleon modification are hindered from complicated nuclear many-body effects.

What are the suitable probes sensitive to baryon modification effects in low energy phenomena? Effects of nucleon modification in a nucleus cannot be separated from nuclear many-body effects. Thus, we propose to use a hyperon. It is a particle distinguishable from other nucleons in the nucleus and free from Pauli blocking from the others. When a Λ hyperon is produced in a nucleus, it deexcites into lower nuclear orbits and stay in the $0s$ orbit until weak decay takes place. Here, we can measure possible change of the eletromagnetic or weak properties of the Λ hyperon in the interrior of the nucleus.

We have proposed to measure the Λ's magnetic moment in a nucleus via the $B(M1)$ value of Λ's spin-flip transition in ${}^{7}_{\Lambda}\mathrm{Li}$. The experiment is apporved at J-PARC and under preparation. See Ref. [4, 5] for details. In this article, we propose another approach to investigate the baryon modification in nuclei via Λ's beta-decay rate.

2. Λ's beta-decay rate in nuclei

In the conjecture of the ”baryon swelling”, the distribution of u and d quarks are expected to be more spread in nuclear matter due to the meson field. Here, as schematically shown in Fig. 1, the distribution of the s quark in the hyperon is expected to be changed little, because the coupling of s quarks in the baryon with the meson field is considered to be much smaller than that of u and d quarks. When the weak decay of the hyperon takes place in the nucleus, it is expected that the overlap between the unchanged s quark wave fucntion and the spread u quark wave function is reduced and the weak decay probability is decreased.

However, a Λ hyperon mainly decays by emissing pions ($\Lambda \rightarrow p\pi^-/n\pi^0$) (mesonic decay) as well as via non-mesonic decay processes ($\Lambda p \rightarrow np$, $\Lambda n \rightarrow nn$). Those hadrons coming from nuclear interior are significantly affected by intra-nuclear reactions and hinder possible baryon modifiation effects. On the other hand, the β decay of Λ ($\Lambda \rightarrow pe^-\bar{\nu}_e$) is a cleaner process.

We propose a measurement of the β-decay rate of the Λ hyperon in a nucleus. The structure change of the Λ hyperon can be observed as a change of the axial charge g_A in the hyperon's β decay, since the g_A value is related to the u/d quark distribution or the structure of the pion cloud in the baryon. This effect was estimated by the quark meson coupling (QMC) model. According to Ref. [6], the g_A^Λ value of the Λ's β decay is predicted to be reduced by ~10% in the nuclear saturation density. This calculation indicates a significant (up to 20%) reduction of the β-decay rate of the Λ hyperon in the nucleus. However, it is well known that the g_A value in the neutron β-decay is quenched in nuclei (for example, see [7]). Such g_A quenching phenomena are considered to arise from nuclear many-body effects as well as hadronic effects such as meson exchange current [8]. The g_A quenching effect is measured to be 30–40% for heavy nuclei, while ~5% for light ($A \leq 4$) nuclei [7]. Thus, by using a light (s-shell) hypernucleus, we can minimize these effects. In addition, ab initio calculations for nuclear β decay are available for light nuclei. For example, the ^{6}He β-decay rate was reproduced within 2% accuracy [9]. We expect that similar ab initio calculations can be performed in near future and nuclear many-body effects and meson exchange current effects in the $g_A$value can be precisely estimated. Therefore, we propose to measure the g_A value of the $^5_\Lambda$He hypernucleus (Λ+^{4}He(0$^+$)), which has a mass number small enough but a significantly large density. Another candidate hypernucleus is $^{13}_\Lambda$C (Λ+^{12}C(0$^+$)), in which the Λ's 0s wave function is confined well inside the nucleus, It is a merit of $^{13}_\Lambda$C compared with $^5_\Lambda$He, in which the Λ's wave function is partly spread out of the nucleus, although an accurate calculation of the nuclear effects is more difficult.

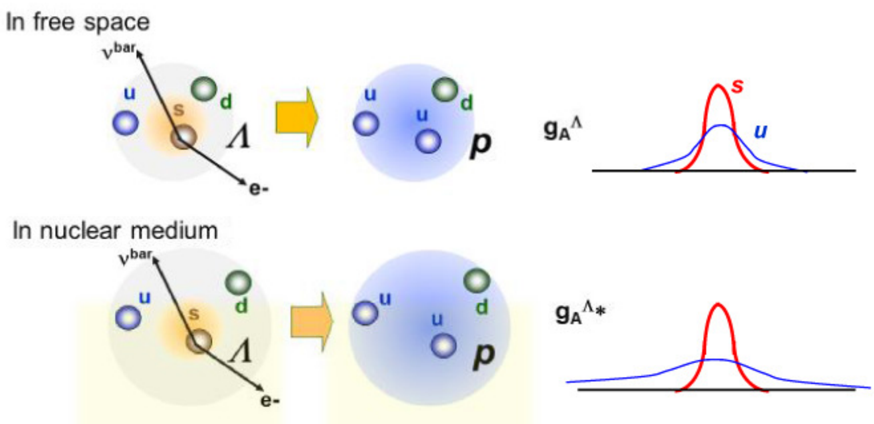

Figure 1: Illustration for possible modification of spatial distribution of quarks in nuclear matter and its effect to β decays. Distribution of u and d quarks are expected to be more spread in a nucleus but that of s quarks are less spread. Thus the overlap between the s and u quark wave functions in the hyperon β decay is expected to be decreased.

3. Principle of the experiment

We propose a precise determination of the β-decay rate Γ_β of a Λ hyperon in the ${}^{5}_{\Lambda}$He and ${}^{13}_{\Lambda}$C hypernuclei. Our goal is to measure the weak decay lifetime τ and the β-decay branching ratio B_β of these hypernuclei and to determine their β-decay rate $\Gamma_\beta = B_\beta/\tau$ with a statistical error less than 4% and a systematic error much lower than that. Provided that the β decay of a Λ in ${}^{5}_{\Lambda}$He and ${}^{13}_{\Lambda}$C does not excite the ^{4}He and ^{12}C (0^+) cores, their β decay has the same structure as the Λ's β-decay in the free space. Namely, we can assume that

$$\Gamma_\beta \propto (g_V^\Lambda)^2 \,|\int 1|^2 + (g_A^\Lambda)^2 \,|\int \sigma|^2 = (g_V^\Lambda)^2 + 3(g_A^\Lambda)^2 \sim 1 + 1.55$$

because $g_V^\Lambda = 1$ and $g_A^\Lambda = -0.718 \pm 0.015$ for the Λ in the free space, and a change of Γ_β in nuclear matter is attributed to a change of g_A^Λ since g_V^Λ is almost unchanged [6]. Since a fraction (1.55/2.55) of Γ_β comes from the axial current, Γ_β is expected to be reduced by $(1.55/2.55) \times 2 \times 10\% = 12\%$ if g_A^Λ is reduced by 10%. The proposed experiment aims at measurement of Γ_β in 4.5% accuracy, which corresponds to the accuracy of g_A of $4.5 \times (2.55/1.55)/2 = 3.7\%$.

The main difficulty of this experiment comes from a small branching ratio of the β decay of Λ, $(8.32\pm0.14)\times10^{-4}$ in free space and huge backgrounds from the other decay modes, the mesonic ($\Lambda \to p\pi^-$ and $n\pi^0$) and the non-mesonic ($\Lambda p \to np$, $\Lambda n \to nn$) weak decays. These branching ratios for ${}^{5}_{\Lambda}$He were measured at BNL and KEK, and the decay rates are given as summarized in Table 1. As shown in the table, these values are theoretically reproduced fairly well.

It is noted that the decay rate for $\Lambda \to n\gamma$, whose branching ratio in the free space is 1.75×10^{-3}, may be also changed in a nucleus due to possible change of the u, d quark distrbution, although theoretical calculation of this process is difficult. This decay mode has a larger branching ratio than the β decay and makes a peak in the γ-ray energy spectrum. Thus, we can also measure its decay rate in our proposing experiment.

In order to clearly identify the β-decay event, we employ a calorimeter covering almost 4π sr surrounding the target to select one-cluster shower events and measure the electron energy. We also install Si detectors or plastic counters as well as Lucite Cherenkov counters close to the target to identify one-charged-particle event with a fast velocity (a small dE/dx).

Table 1: Total and partial weak decay rates of ${}^{5}_{\Lambda}$He shown in the unit of the free Λ decay rate, Γ_Λ.

Experiment/Theory	$\Gamma_{tot}/\Gamma_\Lambda$	$\Gamma_{\pi^-}/\Gamma_\Lambda$	$\Gamma_{\pi^0}/\Gamma_\Lambda$	$\Gamma_{nm}/\Gamma_\Lambda$
Exp. (K^-,π^-), BNL [10]	1.03±0.08	0.44±0.11	0.18±0.20	0.41±0.14
Exp. (π^+,K^+), KEK [11, 12]	0.947±0.038	0.340±0.016	0.201±0.011	0.406±0.020
Theor. [13] (YNG)		0.393	0.215	
Theor. [14]		0.386	0.196	
Theor. [15]	0.966			0.358
Theor. [16] (NSC97f)			0.317	
Theor. [17]			0.43	

3.1 Production reaction of hypernuclei

The production of the hypernuclei (${}^{5}_{\Lambda}$He and ${}^{13}_{\Lambda}$C) should be clearly identified with little contamination of other processes. For this reason, the ${}^{5}_{\Lambda}$He hypernucleus will be produced via the ^{6}Li(π^+,K^+) reaction with a ^{6}Li metal target. The ground state of the ${}^{6}_{\Lambda}$Li hypernucleus produced by the ^{6}Li(π^+,K^+) reaction decays via proton emission to ${}^{5}_{\Lambda}$He(gs) (only the ground state is bound for ${}^{5}_{\Lambda}$He).

As shown in Fig. 2(a), the structure of ${}^{6}_{\Lambda}$Li hypernucleus was first studied via the (K^-,π^-) reaction [18], which revealed three-peak structure: the unbound ground state with the $(p_{3/2})_n^{-1}(s_{1/2})_\Lambda$ configuration, the ~8 MeV excited states with the $(p_{3/2})_n^{-1}(p_{3/2})_\Lambda$ configuration, and the 18 MeV excited state with $(s_{1/2})_n^{-1}(s_{1/2})_\Lambda$ configration. The second and third structures are so-called ''substitutional states'' which are populated by $\Delta L = 0$ reactions with large cross sections due to a low momentum transfer ($q < 100$ MeV/c) such as the (K^-,π^-) reaction below 1 GeV/c at forward angles. On the other hand, the ground state is produced by $\Delta L = 1$ reaction which requires a larger momentum transfer.

Previously, the weak decay of ${}^{5}_{\Lambda}$He hypernucleus was studied twice, by employing the (K^-,π^-) reaction [10] and then by the (π^+,K^+) reaction [11, 12, 20]. As shown in Fig. 2(b), the (π^+,K^+) reaction spectrum shows a clearer ^{6}Li ground state peak. One reason is that the (π^+,K^+) reaction with a momentum transfer of $q \sim 350$ MeV/c has a significant cross section for the ^{6}Li ground state ($\Delta L = 1$) but almost no cross section for the substitutional states, although the non-substitutional $n(p_{3/2}^{-1})\Lambda(p_{3/2,1/2})$ states are also produced by $\Delta L = 2$ with some production cross sections.

Therefore, in the proposed experiment for ${}^{5}_{\Lambda}$He, we will employ the (π^+,K^+) reaction at a beam momentum of 1.05 GeV/c, where the cross section for the $K^-n \rightarrow \Lambda\pi^-$ reaction is maximum. This reaction is the same as the one used in the previous ${}^{5}_{\Lambda}$He weak decay experiment at KEK [11, 12, 20]. Although the cross section for ^{6}Li(π^+,K^+)${}^{6}_{\Lambda}$Li(gs) was not measured, the yield of this reaction at 1.05 GeV/c was measured at KEK by using the same apparatus (SKS sepctrometer) as the proposed experiment. Thus, the expected yield of the proposed experiment can be reliably estimated.

On the other hand, it is desirable to produce the ${}^{13}_{\Lambda}$C hypernuclei via ^{13}C(K^-,π^-) reaction. Figure 3 shows the mass spectra of ${}^{13}_{\Lambda}$C produced by (K^-,π^-) and (π^+,K^+) reactions. Not only the two low-lying $(0s)_\Lambda$ states, $1/2^+$ and $3/2^+$, but also the ^{12}C(0^+) $\otimes$ $(0p_{1/2})_\Lambda$ and ^{12}C(0^+) $\otimes$ $(0p_{3/2})_\Lambda$ states at ~11 MeV excitation are known to be bound [23]. Therefore, when we select the two low-lying $(0s)_\Lambda$ states, no contamination of Λ-escaping events above the Λ-binding threshold is expected. Thus, in the ${}^{13}_{\Lambda}$C case, we do not have to use the (π^+,K^+) reaction in which a required intense beam may cause a difficulty in the BGO detectors.

4. Measurement of the branching ratio

We determine the branching ratio of the β decay by measuring the β-ray electron energy distributing from 0 to 163 MeV. The weak decay of ${}^{5}_{\Lambda}$He was previously studied at BNL via the (K^-,π^-) reaction and then at KEK via the (π^+,K^+) reaction. The lifetime of ${}^{5}_{\Lambda}$He was measured to be 256±21 ps [10] and 278^{+11}_{-10} ps [11] at BNL and KEK, respectively. It is almost the same as the lifetime of the free Λ of 263.2 ± 2.0 ps. The partial widths of the ${}^{5}_{\Lambda}$He weak decay were also obtained in the KEK experiment as shown in Table 1. The weak decay of ${}^{13}_{\Lambda}$C has not experimentally studied, but that of ${}^{12}_{\Lambda}$C have been studied well [12, 24, 25].

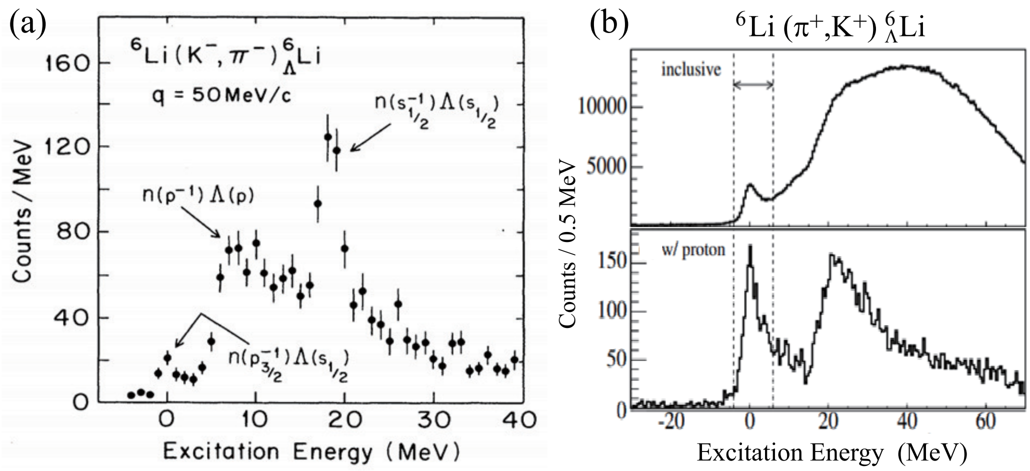

Figure 2: Excitation energy spectrum of $^{6}_{\Lambda}$Li produced by (a) (K^-,π^-) reaction [18] and by (b) (π^+,K^+) reaction [19]. Bottom figure of (b) shows a (π^+,K^+) spectrum with a proton in coincidence.

4.1 Setup

The experiment will be carried out at the K1.1 beam line, which is planned to be constructed at the J-PARC Hadron Experimental Facility. The beam line provides us with an intense and pure K^- beam as well as intense $\pi^\pm$ beams up to 1.2 GeV/c. Figure 4 shows the layout of the setup. The momentum of each π^+ or K^- beam particle is analyzed by the K1.1 beam line spectrometer, and the scattered K^+ from the ^{6}Li or ^{13}C target is idendified and momentum analyzed by employing the Superconducting Kaon Spectrometer (SKS). The production of $^{5}_{\Lambda}$He or $^{13}_{\Lambda}$C is identified from the missing mass of the ^{6}Li(π^+,K^+) or ^{13}C(K^-,π^-) reaction.

The β-decay electron is measured by a newly-developed detector system around the target. It is identified by a set of silicon (or plastic) hodoscope (TH) and Lucite Cherenkov counters (TLC) surrounding the target, and its total energy is measured by a BGO calorimeter (BGOC).

Figure 5 shows a schematic view of the setup around the target. The size of the target is ~4 cm in diameter, and ~30 cm for ^{6}Li (90%-enriched lithium metal) or ~10 cm for ^{13}C (graphite) in length (~14 g/cm^2).

At the innermost, the target is surrounded by Target Hodoscope (TH) made of silicon strip detectors or segmented plastic counters of 50 cm long along the beam direction. They measure the timing, the multiplicity, the energy loss (dE/dx), and the hit position of the charged particle(s). The target and TH are surrounded by segmented Lucite Cherenkov counters (TLC, Target Lucite Cherenkov) with the index $n \sim 1.5$ to discriminate electrons ($\beta = 1$) from weak decay pions from the nucleus ($\beta < 0.610$ for $p_\pi < 140$ MeV/c) and protons.

The target area is surrounded by a BGO calorimeter (BGOC) which measures electron energies up to 200 MeV. Optimization and detailed design of BGOC are on going. Currently, BGOC is assumed to have a thickness of 20 cm (18 radiation length) with the inner radius (distance for the center to the surface of the BGO) of 30 cm, and segmented into 225 crystal pieces with each crystal of about 7 cm × 7 cm × 20 cm. Since the counting rate for the BGO counters located around the downstream hole is expected to be higher than the operation limit in the case of the $^{5}_{\Lambda}$He experiment

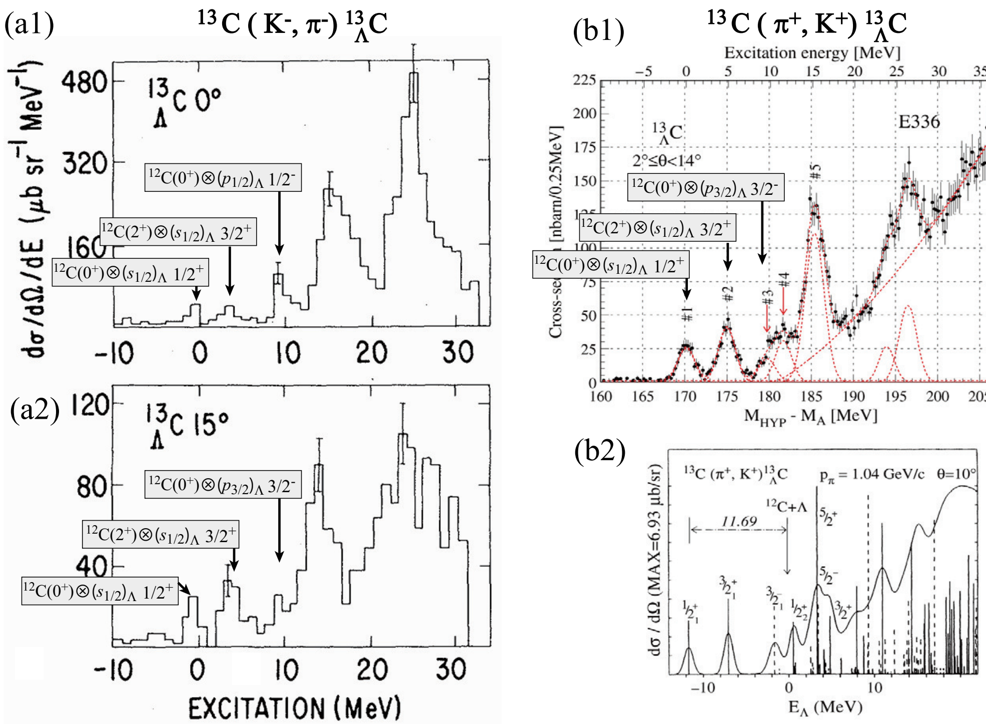

Figure 3: Excitation energy spectra of ${}^{13}_{\Lambda}$C. (a1), (a2) show spectra produced by (K^-,π^-) reaction for a scattering angle of (a1) ~ 0° and (a2) ~ 15° [21]. (b1) shows a spectrum by (π^+,K^+) reaction, comapred with a DWIA calculation (b2) in the same conditions as (b1) [22].

using the intense (~ 2×10^7 /sec) π^+ beam, we will need to replace a part of the BGO counters into faster scintillation counters.

4.2 Background suppression

We need to suppress the background events by 10^{-5}. We have studied how to suppress them via simulations using the GEANT4 code and found that the suppression by ~ 10^{-5} is achievable.

(1) π^0 from $\Lambda \to n\pi^0$ mesonic decay Most of the $\Lambda \to n\pi^0$ background events can be rejected by requiring hits in TH and TLC and a single cluster hit in BGOC. By selecting single cluster events, about 97% of the π^0 events are rejected. In most of the remaining events, one of the two photons from π^0 decay escapes from the upstream or downstream hole (~120 msr) of BGOC.

Since a photon from π^0 is converted to an e^-e^+ pair in the target or in TH with ~4% probability, 3% × 4% = 0.12% of π^0 events cannot be rejected. By multiplying the π^0 decay branching ratio of 0.20 (Table 1), this contamination has a branching ratio of 0.024%. In addition, we request the pulse height of TH to be consistent with one minimum-ionizing particle passing through the detector so that we can reject events of pair creation in the target for which the TH pulse height is twice larger. Our simulation showed that this condition suppresses the remaining π^0 events by 1/4 after correcting for the path length in TH.

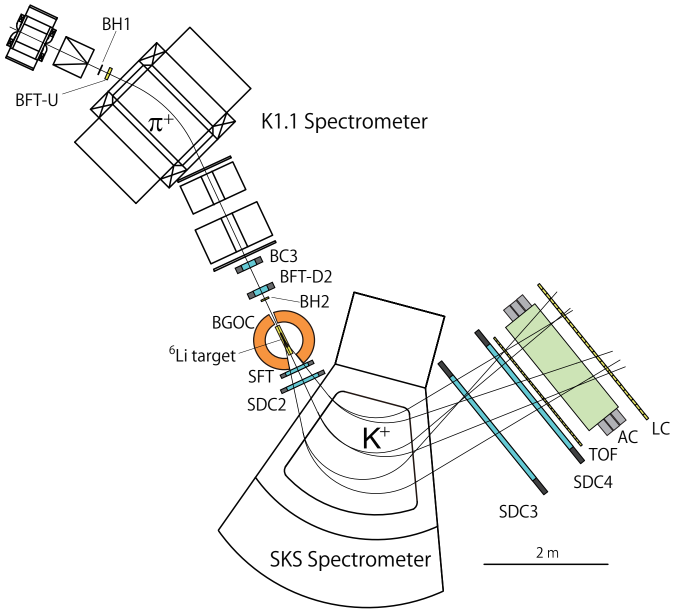

Figure 4: Setup of the proposed experiment at K1.1 beam line.

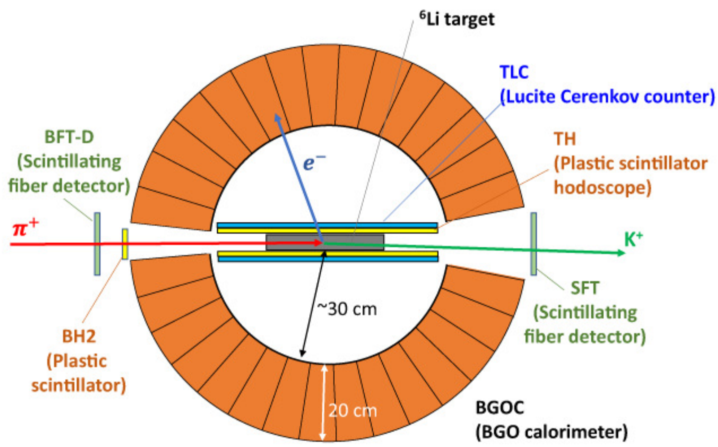

Figure 5: Setup around the target for the branching ratio measurement.

According to the simulation, the analysis described above suppresses the π^0 background down to the branching ratio of 0.007%, which corresponds to 8% of the β-decay events. On the other hand, the number of true β-decay events is also reduced to 68% through the whole analysis. Namely, the background/signal ratio is 12%. In addition, we will install photon veto counters around the entrance of the downstream spectrometer (SKS magnet) to reject a photon escaping from the downstream hole of BGOC. Thus we can supress the π^0 background down to the branching ratio of 0.0035%.

(2) π^- from $\Lambda \to p\pi^-$ mesonic decay π^- mesons emitted from the target are discriminated from electrons by use of TLC hit as well as TH pulse heigth and the number of hit clusters in BGOC.

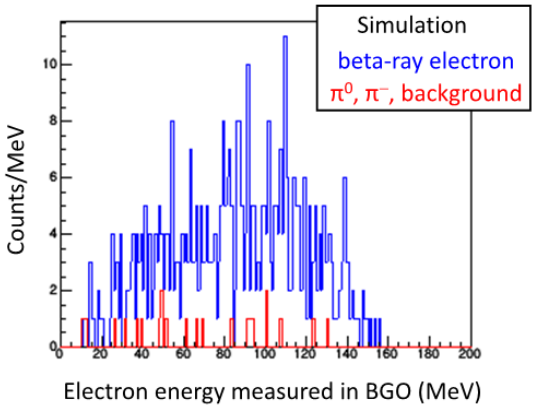

Figure 6: Simulated spectrum of the β-ray electron energy (blue) and the contaminated background events (red) after all the background rejection analysis. The number of the background events is 4% of that of the β-ray electron.

Since the pion momentum from the Λ hypernuclear weak decay distributes around 100 MeV/c and the maximun momentum is around 140 MeV/c, such pions do not emit Cherenkov light in TLC (Lucite). However, in a few per cent probablity (4.5% in the present simulation) a δ-ray is emitted in TLC, which causes misidentification of pion as electron.

Since dE/dx of the background π^- is almost twice larger than that of the β-ray electron, a TH pulse-height cut after correcting for the path length is very effective. In our simulation, almost 99.9% of the π^- background (assuming that the π^- momentum is 100 MeV/c) is rejected by applying the same TH cuts as used for the π^0 background suppression, Further suppression of π^- can be done from the number of hit clusters in BGOC, because a π^- is absorbed by a nucleus in BGO via $\pi^- pn \to nn$ in most cases and emit two or more neutrons, which increase the number of hit clusters in BGOC. The fraction of one cluster events is only 23% for π^-. In addition, by requiring the number of hit segments in BGOC, the π^- backgound is further suppressed, However, this simulation result is sensitive to the number and the energy distribution of the neutrons emitted after π^- absoprtion in BGO. We are investigating them using π^- beams injected into BGO material in order to update our simulation for the π^- absorption process.

By combining these cuts described above, the π^- background can be finally reduced to a branching ratio of 0.0004%, which corresponds to the background/signal ratio about 1%.

(3) Protons and neutrons from nonmesonic decay A proton from nonmesonic weak decay, $\Lambda p \to np$, has an energy of ~80 MeV ($\beta \sim 0.41$) at maximum. It does not emit Cherenkov light in TLC and the energy loss in TH is more than 4 times larger than that for electrons. Neutrons from nonmesonic weak decay, $\Lambda p \to np$ and $\Lambda n \to nn$, also have energies of 80 MeV or lower. A simulation showed that these processes are suppressed to less than 10^{-5} (corresponding to the background/signal ratio less than 2%) by the same cut conditions as used in (1) and (2).

PoS(QCHSC24)228

4.3 Yield and accuracy of the branching ratio

In order to measure the β-decay branching ratio within a statistical error of 4%, we need to collect more than $(1/0.04)^2 = 625$ counts of the β-decay events. To estimate the yield of ${}^5_\Lambda$He hypernuclei, we refer to the KEK E462 experiment. This experiment irradiated 2.5×10^{12} π^+ on a 3.70 g/cm^2-thick ^{6}Li metal target and obtained 45653 counts of ${}^5_\Lambda$He events employing the SKS spectrometer. Since the setup of the SKS spectrometer including detectors is almost identical, we can reliably estimate the yield of ${}^5_\Lambda$He in our experiment as shown in Table 2.

The β-decay rate is reduced due to Pauli effect because the proton from $\Lambda \to pe^-\bar{\nu}$ has a recoil momentum between 0 to 163 MeV/c, lower than the Fermi momentum. As shown in Table 1, the mesonic decay rate is reduced as $(\Gamma_{\pi^-} + \Gamma_{\pi^0})/\Gamma_\Lambda = 0.54$ in ${}^5_\Lambda$He due to Pauli effect of a proton of $\sim$100 MeV/c and the pion absorption effect. Thus we assumed the Pauli suppression factor for the β-decay proton as 0.6. For ${}^{13}_\Lambda$C, the Pauli suppression factor is assumed to be $\sim$ 0.3 from mesonic decay rates of ${}^{12}_\Lambda$C [25]. Those values will be theretically estimated later. The efficiency for β-ray electron detection, which includes various cuts in the background suppression analysis as well as the BGOC acceptance (99%), is assumed to be 0.7. In the case of ${}^{13}_\Lambda$C, we use 1.5 GeV/c K^- beam at the K1.8 beam line together with the SKS spectrometer. In the yield estimation in Table 1, we assumed 0.10 mb/sr for the cross section for the sum of the ${}^{13}_\Lambda$C$(0^+ + 2^+)$ states [21]. In both for ${}^5_\Lambda$He and ${}^{13}_\Lambda$C, we found that a statistical error less than 4% is achieved in the beam time of 1400 hours.

According to the simulation, all the background processes shown above will be sufficiently suppressed. Figure 6 shows a simulated final spectrum of single electron (β-ray) after applying all the background suppression analysis. The yield of the $beta$ ray is reduced to 68%, while the background processes are suppressed by 10^{-4}– 10^{-5} and the fraction of the remaining background events is ∼4% of the β-ray events, as shown in red in Fig. 6. Since we will be able to estimate the rejection efficiency for each background precess based on realistic simulations, the number of remaining background events in the final spectrum can be subtracted. Even if the rejection efficiency is estimated in 25% uncertainty, the systematic error of the β-ray counts coming from the background will be 1%, being much lower than the expected statistical error of 4%. It is to be noted that the $\Lambda \to n\gamma$ decay will be also clearly observed as a peak in the photon spectrum in the same

Table 2: Expected yield of ${}^5_\Lambda$He and ${}^{13}_\Lambda$C and their β-decay events for 1400 hours of beam time in the proposed experiments. The ${}^5_\Lambda$He yield is estimated in comparison with the ${}^5_\Lambda$He yield measured in KEK E462 experiment [12]. See text for details.

Experiment	${}^5_\Lambda$He(E462)	${}^5_\Lambda$He(proposed)	${}^{13}_\Lambda$C(proposed)
Number of π^+/K^- beam	2.5×10^{12}	43×10^{12}	1.2×10^{12}
^{6}Li/^{13}C target thickness	3.70 g/cm^2 (^{6}Li)	14 g/cm^2 (^{6}Li)	20 g/cm^2 (^{13}C)
${}^5_\Lambda$He/${}^{13}_\Lambda$C counts in mass spectrum	45653	2.0×10^6	4.1×10^6
BR_β		8×10^{-4}	
Pauli suppression effect		0.6	0.3
e^- detection efficiency		0.7	
β-ray counts		673	861

dataset and its branching ratio will be also determined.

5. Measurement of the lifetime

The lifetime of ${}^{5}_{\Lambda}$He and/or ${}^{13}_{\Lambda}$C will be measured separately from the branching ratio measurement employing a setup around the target optimized for the precise lifetime measurement. The lifetime of ${}^{5}_{\Lambda}$He and/or ${}^{13}_{\Lambda}$C is measured in the same ^{6}Li(π^{+},K^{+})${}^{6}_{\Lambda}$Li(gs) and/or ^{13}C(K^{-},π^{-})${}^{13}_{\Lambda}$C reactions, as the time difference between the injection of the beam particle and the emission of the weak decay products. Here, as the decay products, we use energetic protons (~30–80 MeV) from nonmesonic weak decay ($\Lambda p \to pn$) of ${}^{5}_{\Lambda}$He, because those protons give a large pulse in the timing counter, making the time resolution better than other particles. This method was used in the ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C lifetime measurement in KEK [19, 20, 24].

The timing of the beam pion and that of the decay proton emitted around the target are measured with fast-timing plastic counters, T1 placed in the beam just upstream of the target and T2L/T2R placed at both sides of the target, respectively. The time difference between them is plotted as a ‘‘decay time spectrum’’ after correcting for the π^{+} flight time from T1 to the reaction point, as well as the proton flight time from the reaction point to T2L/T2R. Here, the beam and the proton trajectories as well as the proton energy should be also measured. In addition, the decay time spectrum for the prompt reaction, ^{6}Li(π^{+}, pp), in which one proton is detected by SKS and another proton by T2L/T2R and BGOC, will be also measured and used as a response function when fitting the decay time spectrum of the hypernuclei.

The previous experiment, KEK E462, was successfully conducted by this method. This experiment achieved a lifetime precision of 4% for ${}^{5}_{\Lambda}$He and 3% for ${}^{12}_{\Lambda}$C, which was limited by statistics due to negligible systematic errors [19]. In order to achieve 2% accuracy in the proposed experiment, we will take data with four times higher statistics and with the same or better time resolution.

The target is a ^{6}Li metal plate (or a ^{13}C graphite block) of ~5 g/cm^{2} thick in the beam direction. T1 and T2L/T2R are sets of fast timing plastic counters with a time resolution of < 50 ps rms. T1 is made of 20 pieces of 2 mm-wide 50 mm-long 5 mm-thick plastic counter, each of which is read out by MPPC at both ends. T2L and T2R are made of 20 pieces of 4 mm-wide 150 mm-long 5 mm-thick plastic counter, each of which is read out via MPPC’s at both ends. In order to measure the position of the proton in the beam direction, silicon or plastic hodoscopes (THL and THR) are installed outside of T2L and T2R.

The yield of the nonmesonic proton events of ${}^{5}_{\Lambda}$He is estimated based on the KEK E462 results. By irradiating the same number of π^{+} as E462 (2.5×10^{12}), which corresponds to 120 hours of beam time for $3 \times 10^{7} \pi^{+}$/spill, we will be able to collect nonmesonic proton events of more than 4 times, which leads to twice better statistical accuracy (a relative error of 2%). In a similar way, the lifetime of ${}^{13}_{\Lambda}$C can be determined in 2% accuracy.

6. Summary

The electromagnetic and weak properties of hyperons embedded in nuclei provide us with unique means to investigate possible modification of baryons in nucler matter. In particular, the QMC model predicts a significant reduction of the Λ’s β-decay rate in nuclear matter. At J-PARC, we are planning to measure the lifetime and the branching ratio of the β decay of $^{5}_{\Lambda}$He and/or $^{13}_{\Lambda}$C and derive their β-decay rates. Feasibility of this experiment have been studied via simulations, which indicate that the β-decay rate can be determined in ~4 % accuracy in a reasonable beam time in spite of huge background from dominant hypernuclear weak decay modes. Precise theoretical estimate of the β-decay rate including nuclear effects is necessary to clarify the baryon modification.

References

[1] D. F. Geesaman, K. Saito, A. W. Thomas, *The nuclear EMC effect*, Ann. Rev. Nucl. Part. Sci. 45 (1995) 337, DOI:10.1146/annurev.ns.45.120195.002005

[2] L. B. Weinstein *et al.*, *Short Range Correlations and the EMC Effect*, Phys. Rev. Lett. 106 (2011) 052301, DOI:10.1103/PhysRevLett.106.052301

[3] R. Wang *et al.*, *Flavor-dependent EMC effect from a nucleon swelling model*, Phys. Rev. C 99 (2019) 035205 and references therein, DOI:10.1103/PhysRevC.99.035205

[4] H. Tamura, M. Ukai, T. O. Yamamoto, and T. Koike, *Study of Λ hypernuclei using hadron beams and γ-ray spectroscopy at J-PARC*, Nucl. Phys. A 881 (2012) 310, DOI:10.1016/j.nuclphysa.2012.02.013

[5] H. Tamura, M. Ukai *et al.*, *Gamma-Ray Spectroscopy of Light Λ Hypernuclei II*, J-PARC E63 proposal (2016),
https://j-parc.jp/researcher/Hadron/en/pac_1601/pdf/P63_2016-2.pdf

[6] P. A. M. Guichon, A.W. Thomas, *Lambda beta-decay in-medium*, Phys. Lett. B 773 (2017) 332, DOI:10.1016/j.physletb.2017.08.052

[7] W. T. Chou *et al.*, *Gamow-Teller beta-decay rates for $A \leq 18$ nuclei*, Phys. Rev. C 47 (1993) 163, DOI:10.1103/PhysRevC.47.163

[8] F. C. Khanna, I. S. Towner, H. C. Lee, *Quenching of Axial Vector Coupling Constant in the beta Decay of Finite Nuclei*, Nucl. Phys. A 305 (1978) 349, DOI:10.1016/0375-9474(78)90343-3

[9] S. Vaintraub, N. Barnea, D. Gazit, *He-6 beta-decay rate and the suppression of the axial constant in nuclear matter*, Phys. Rev. C 79 (2009) 065501, DOI:10.1103/PhysRevC.79.065501

[10] J. J. Szymanski *et al.*, *Nonleptonic weak decay of $^{5}_{\Lambda}He$ and $^{12}_{\Lambda}C$*, Phys. Rev. C 43 (1991) 849, DOI:10.1103/PhysRevC.43.849

[11] S. Kameoka *et al.*, *Measurement of the π^{-} decay width of $^{5}_{\Lambda}He$*, Nucl. Phys. A 754 (2005) 173c, DOI:10.1016/j.nuclphysa.2005.03.016

[12] S. Okada *et al.*, *Neutron and proton energy spectra from the non-mesonic weak decays of $^{5}_{\Lambda}He$ and $^{12}_{\Lambda}C$*, Phys. Lett. B 597 (2004) 249, DOI:10.1016/j.physletb.2004.07.031; *π^{0} decay branching ratios of $^{5}_{\Lambda}He$ and $^{12}_{\Lambda}C$ hypernuclei*, Nucl. Phys. A 754 (2005) 178c, DOI:10.1016/j.nuclphysa.2005.02.128

[13] T. Motoba, H. Bandō, T. Fukuda, J. Žofka, *Continuum pion spectra in the weak decays of $^{4}_{\Lambda}H$, $^{5}_{\Lambda}He$ and $^{6}_{\Lambda\Lambda}He$*, Nucl. Phys. A 534 (1991) 597, DOI:10.1016/0375-9474(91)90463-G

[14] I. Kumagai-Fuse, S. Okabe, Y. Akaishi, *Pionic decay spectra of few body Λ hypernuclei*, Phys. Rev. C 54 (1996) 2843, DOI:10.1103/PhysRevC.54.2843

PoS(QCHSC24)228

[15] K. Itonaga, T. Motoba, *Hypernuclear weak decays*, Prog. Theor. Phys. Suppl. 185 (2010) 252, DOI:10.1143/PTPS.185.252

[16] A. Parreno, A. Ramos, *Final state interactions in hypernuclear decay*, Phys. Rev. C 65 (2001) 015204, DOI:10.1103/PhysRevC.65.015204

[17] C. Barbero, C. De Conti, A. P. Galeao, F. Krmpotic, *Kinematical and nonlocality effects on the nonmesonic weak hypernuclear decay*, Nucl. Phys. A 726 (2003) 267, DOI:10.1016/S0375-9474(03)01620-8

[18] R. Bertini *et al.*, *Neutron Hole States in* $^{6}_{\Lambda}$*Li,* $^{7}_{\Lambda}$*Li,* $^{9}_{\Lambda}$*Be, and* $^{12}_{\Lambda}$*C Hypernuclei*, Nucl. Phys. A 368 (1981) 365, DOI:10.1016/0375-9474(81)90761-2

[19] S. Kameoka, *Study of mesonic decay of* $^{5}_{\Lambda}$*He and* $^{12}_{\Lambda}$*C*, Ph.D thesis, Tohoku University (2005).

[20] B. H. Kang *et al.*, *Exclusive Measurement of the Nonmesonic Weak Decay of* $^{5}_{\Lambda}$*He Hypernucleus*, Phys. Rev. Lett. 96 (2006) 062301, DOI:10.1103/PhysRevLett.96.062301

[21] M. May *et al.*, *Observation of Levels in* $^{13}_{\Lambda}$*C,* $^{14}_{\Lambda}$*N, and* $^{18}_{\Lambda}$*O Hypernuclei*. Phys. Rev. Lett. 47 (1981) 1106, DOI:10.1103/PhysRevLett.47.1106

[22] O. Hashimoto and H. Tamura, *Spectroscopy of* Λ *hypernuclei*, Prog. Part. Nucl. Phys. 57 (2006) 564, DOI:10.1016/j.ppnp.2005.07.001

[23] S. Ajimura *et al.*, *Observation of Spin-Orbit Splitting in* Λ *Single-Particle States*, Phys. Rev. Lett. 86 (2001) 4255, DOI:10.1103/PhysRevLett.86.4255

[24] M. Kim *et al.*, *Three-Body Nonmesonic Weak Decay of the* $^{12}_{\Lambda}$*C Hypernucleus*, Phys. Rev. Lett. 103 (2009) 182502, DOI:10.1103/PhysRevLett.103.182502

[25] H. Bhang *et al.*, *The Weak Decay Widths of* Λ *Hypernuclei*, J. Korean Physical Society 59 (2011) 1461, DOI:10.3938/jkps.59.1461

PoS(QCHSC24)228