Decay asymmetry in non-mesonic weak decay of light Λ-hypernuclei

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Abstract. The proton decay asymmetry, α_p^{NM}, of the polarized Λ-hypernuclei, ${}^{5}_{\Lambda}\mathrm{He}$, ${}^{12}_{\Lambda}\mathrm{C}$ and ${}^{11}_{\Lambda}\mathrm{B}$, has been investigated to understand the reaction mechanism of the non-mesonic weak-decay process. These Λ-hypernuclei were produced in the highest statistics ever via the (π^+, K^+) reaction at $1.05\,\mathrm{GeV}/c$ by using the SKS spectrometer at KEK 12 GeV PS. The results show that the α_p^{NM} are very small for these s-shell and p-shell hypernuclei.

PACS. 21.80.+a Hypernuclei – 13.30.Eg Hadronic decays – 13.75.Ev Hyperon-nucleon interactions

1 Introduction

In free space, a Λ-hyperon mainly decays through a mesonic decay process ($\Lambda \to N\pi$), in which the momentum transfer (Δq) is about $100\,\mathrm{MeV}/c$. On the other hand, the non-mesonic weak-decay process (NMWD: $\Lambda N \to nN$) becomes dominant in heavy hypernuclei because of the large momentum transfer of $\Delta q \sim 400\,\mathrm{MeV}/c$. The NMWD process is a weak-interaction process between two baryons specific to Λ-hypernuclei. While in the nucleon-nucleon case, the parity-conserving part of the weak process is masked by the strong interaction, the NMWD has the advantage that both, parity-conserving and parity-nonconserving parts can be investigated via the flavor-changing weak process.

There have been two experimental observables used to investigate the NMWD process. One is the ratio of the partial decay width between neutron-induced decay, Γ_n ($\Lambda n \to nn$), and that of proton-induced decay, Γ_p ($\Lambda p \to np$), called the Γ_n/Γ_p ratio. It is sensitive to the isospin structure of the ΛN weak interaction, because it allows only the final isospin $I_f = 1$ in neutron-induced decay, while $I_f = 0$ and 1 are allowed in proton-induced decays. The other is the asymmetry parameter of the decay proton from the NMWD process (α_p^{NM}). It is obtained from the angular distribution $W(\theta)$ of the decay particles emitted from the polarized hypernuclei, as follows:

$$W(\theta) \propto 1 + A\cos\theta = 1 + \alpha P_\Lambda \cos\theta, \qquad (1)$$

where A is the asymmetry, P_Λ denotes the polarization of a Λ-hypernucleus and θ is the emission angle of decay particles with respect to the polarization axis.

The asymmetry parameter reflects the interference between different final parity and isospin states. The $\Lambda N \to nN$ transition in s-shell hypernuclei is categorized by the six ${}^{2S+1}L_j$ amplitudes listed in table 1 [1]. Three amplitudes (a, b, f) have the final-state isospin $I_f = 1$, and the

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Table 1. Six channels of NMWD start from the ΛN relative s-states.

ΛN	NN	Amplitude	I_f	Parity conservation
$^1S_0$	$^1S_0$	a^2	1	yes
	$^3P_0$	b^2	1	no
$^3S_1$	$^3S_1$	c^2	0	yes
	$^3D_1$	d^2	0	yes
	$^1P_1$	e^2	0	no
	$^3P_1$	f^2	1	no

others (c, d, e) have $I_f = 0$. Then, the asymmetry parameter α_p^{NM} can be expressed as [2]

$$\alpha_p^{NM} = \frac{2\sqrt{3}\,\mathrm{Re}[ae^* - \frac{1}{\sqrt{3}}b(c-\sqrt{2}d)^* + f(\sqrt{2}c+d)^*]}{|a|^2+|b|^2+3(|c|^2+|d|^2+|e|^2+|f|^2)}\,. \tag{2}$$

So far, much attention has been paid to the Γ_n/Γ_p ratio both experimentally and theoretically, because early measurements suggested Γ_n/Γ_p values $\gtrsim 1$, while naive theoretical estimates based on a one-pion-exchange model gave small values of around 0.1 [3]. This large discrepancy seems to be resolved with a new measurement [4,5] and new theoretical calculations which take into account the kaon exchange etc. [6]; both are consistent with a Γ_n/Γ_p ratio in the range of $0.4 \sim 0.5$.

Concerning the α_p^{NM}, two experimental results were reported for $^{12}_{\Lambda}$C and $^{5}_{\Lambda}$He. In KEK-PS E160 experiment, a large negative α_p^{NM} of -0.9 ± 0.3 was observed for p-shell hypernuclei [7], while the α_p^{NM} of $^{5}_{\Lambda}$He studied by the KEK-PS E278 experiment, was as small as 0.24 ± 0.22 [8]. Furthermore, there existed a large difference between the measured α_p^{NM} value and theoretical values; those models which reproduced the experimental Γ_n/Γ_p ratio predict large and negative values of around $-0.6 \sim -0.7$. The contribution of relative p-states in p-shell hypernuclei is predicted to be very small theoretically. It is, therefore, expected that α_p^{NM}'s for s-shell and p-shell hypernuclei should have similar values.

There could be several effects to reduce the amplitude of the measured value. One of the effects is the final-state interaction (FSI) for nucleons emitted in the $\Lambda N \to nN$ processes. The detected proton could not be a proton directly emitted from the $\Lambda p \to np$ process, but secondary protons which experienced FSIs, thus losing the initial asymmetry information. Another effect is the possible contamination by two-nucleon–induced decay processes ($\Lambda pN \to npN$) in which the proton decay asymmetry would be very small because the emitted nucleons are assumed to be distributed in three-body phase space rather uniformly. Protons from the secondary processes or two-nucleon–induced processes should have lower energies compared to the proton produced in in the direct process. A previous measurement set a rather high detection threshold at ~ 60 MeV for protons to avoid possible contaminations of such low-energy protons. However, the ambiguity on the contaminations left a substantial systematic error.

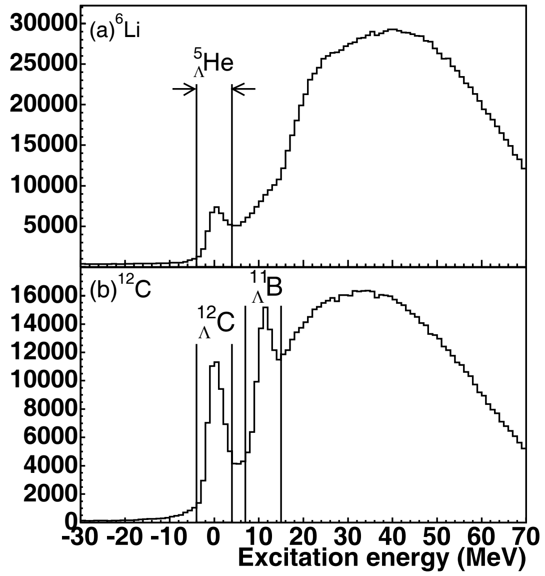

Fig. 1. The excitation energy spectra of ^{6}Li (a) and ^{12}C (b) targets.

2 Experiments

A series of experiments, E462 and E508, were carried out at the K6 beam line of the KEK 12 GeV proton synchrotron (PS) with the high-resolution and large-acceptance superconducting kaon spectrometer (SKS). Polarized Λ-hypernuclei, $^{5}_{\Lambda}$He (E462) and $^{12}_{\Lambda}$C (E508), were produced in the (π^+, K^+) reaction at 1.05 GeV/c on $^{5}_{\Lambda}$He and $^{12}_{\Lambda}$C targets. Because of the large acceptance of the SKS spectrometer, scattered kaons up to ±15° in the horizontal reaction plane were detected. The ground state of $^{6}_{\Lambda}$Li, which is proton unbound, is initially produced, and decays into $^{5}_{\Lambda}$He by emitting a proton. The excitation energy spectra shown in fig. 1 are derived from the momenta of the incoming pion and outgoing kaon.

Both, charged particles and neutral particles emitted from the weak decay of Λ-hypernuclei were detected in a newly constructed decay counter system symmetrically installed above and the below the experimental target; even coincidence measurements were possible because of the large statistics.

Each decay counter system consisted of a set of drift chambers, two sets of timing counters and a neutron counter array with six layers of plastic counters. Both charged and neutral decay particles were identified. Concerning charged particles, pions, protons and deuterons, which were observed for the first time, were clearly separated. Neutrons were well separated from gamma rays and we selected neutrons with energies from 5 MeV to 150 MeV. The details of the experimental setup and particle identification are described in ref. [9].

Table 2. Observed asymmetry parameter and polarization of ${}^{5}_{\Lambda}\mathrm{He}$ and ${}^{12}_{\Lambda}\mathrm{C}/{}^{11}_{\Lambda}\mathrm{B}$ (see text).

	$2 < \theta_K < 6^\circ$	$6 < \theta_K < 9^\circ$	$9 < \theta_K < 15^\circ$
${}^{5}_{\Lambda}\mathrm{He}$			
P_Λ	0.10 ± 0.05	0.27 ± 0.07	0.71 ± 0.07
α_p^{NM}		$0.07 \pm 0.08^{+0.08}_{-0.00}$	
$E_p \geq 40$		$0.09 \pm 0.08^{+0.09}_{-0.00}$	
$E_p \geq 60$		$0.12 \pm 0.08^{+0.09}_{-0.00}$	
$E_p \geq 80$		$0.03 \pm 0.12^{+0.08}_{-0.00}$	
np coin		0.31 ± 0.26	
${}^{12}_{\Lambda}\mathrm{C}/{}^{11}_{\Lambda}\mathrm{B}$			
α_p^{NM}		$-0.16 \pm 0.28^{+0.18}_{-0.00}$	

3 Result and discussion

By selecting the ground state region from -4 to 4 MeV in excitation energy as shown in fig. 1, we succeeded to detect 5.2×10^4 events of ${}^{5}_{\Lambda}\mathrm{He}$ and 6.7×10^4 events of ${}^{12}_{\Lambda}\mathrm{C}$ in their ground states. It is noted that the statistics are several times higher than that of the previous experiments.

The asymmetry, A, in eq. (1) was obtained from the up/down ratio between the yield in the up counter system, N_U, and that in the down counter system, N_D. Owing to the large acceptance of the SKS spectrometer, we can polarize the hypernucleus upwards and downwards in one setup by selecting the (π^+, K^+) scattering direction to the left or right, respectively. Thus, we can take the double ratio, R, as

$$R = \left(\frac{N_U^+ \times N_D^-}{N_U^- \times N_D^+}\right)^{\frac{1}{2}} = \frac{1 + A\cos(0+\varepsilon)}{1 + A\cos(\pi - \varepsilon)} = \frac{1 + A\eta}{1 - A\eta}, \quad (3)$$

$$\eta \equiv \cos(\varepsilon), \quad (4)$$

where $N_{U(D)}^{+(-)}$ presents the yield in the up (down) counter system at the scattering angle to the left (right). Since the decay counter systems have some finite solid angles, the average measured angle $\langle\theta\rangle$ cannot be 0 and π, and is shifted by some fraction ε which was calculated from Monte Carlo simulation. In this expression, systematic errors coming from the difference of the detection efficiencies and the acceptances between the up and down decay counter systems are canceled out. This first-order cancellation was examined in an analysis with the (π^+, pX) reaction, where X is either a proton or a pion, simultaneously obtained with the (π^+, K^+) reaction. No asymmetry is expected for protons and pions in this reaction and we confirmed it within an error of less than 0.3% for all kaon scattering angles.

Concerning the analysis of ${}^{5}_{\Lambda}\mathrm{He}$, the polarization of ${}^{5}_{\Lambda}\mathrm{He}$, P_Λ, was initially obtained as $P_\Lambda = A_\pi/\alpha_\pi^M$ from the mesonic decay process of the ground state, in which α_p^M is assumed to be almost the same as that in free space. The obtained polarizations P_Λ's are listed in table 2. It should be noticed that they are larger than the previous result [10], particularly in the large scattering angle region.

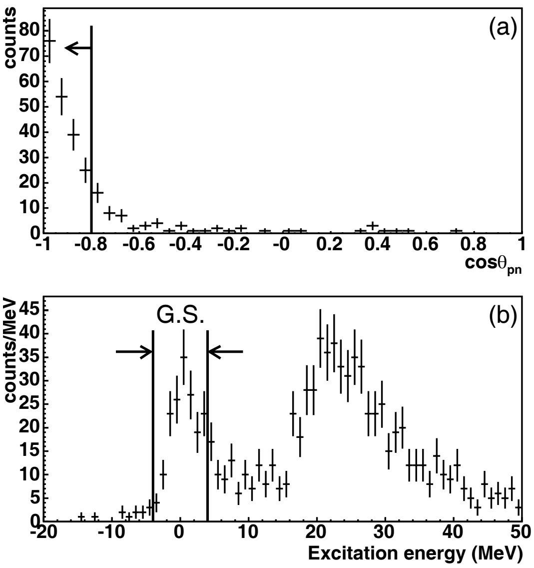

Fig. 2. (a) Opening angle distribution of a neutron and a proton from the non-mesonic decay of ${}^{5}_{\Lambda}\mathrm{He}$. Back-to-back events are clearly seen. (b) An excitation energy spectrum with the proton-neutron pair emitted in the back-to-back direction.

Then, using these P_Λ values, α_p^{NM} was obtained from the asymmetry of proton A_p from the NMWD process of the ${}^{5}_{\Lambda}\mathrm{He}$ ground state as $\alpha_p^{NM} = A_p/P_\Lambda$. The α_p^{NM} value obtained from a weighted average was found to be 0.07 ± 0.08 for $6^\circ < |\theta_K| < 15^\circ$. The systematic error was estimated by assuming the maximum pion contamination of the protons. Since the pion asymmetry parameter has a large negative value ($\alpha_p^M = -0.642 \pm 0.013$), the contamination tends to reduce α_p^{NM}. Even by taking into account this effect, we obtained α_p^{NM} to be $0.07 \pm 0.08^{+0.08}_{-0.00}$, and confirmed with better statistical accuracy that α_p^{NM} is small and possibly slightly positive.

Up to this point, all protons detected in the decay counter systems having an energy threshold of about 30 MeV, were included in the analysis. As already discussed, there could be some protons not directly emitted from the $\Lambda p \to np$ process, which might reduce the observed asymmetry of protons. In fig. 2(a), the opening angle distribution between a proton and a neutron emitted from the ${}^{5}_{\Lambda}\mathrm{He}$ in coincidence is shown. As expected from two-body kinematics, the peak structure at $\cos\theta_{np} \sim -1$ is attributed to the proton-neutron pairs directly emitted from the $\Lambda p \to np$ process. An excitation energy spectrum with proton-neutron pairs in the back-to-back direction ($\cos\theta_{np} < -0.8$) is shown in fig. 2(b). The ground-state peak was clearly identified with very small background. The proton decay asymmetry parameter α_p^{NM} was obtained with these back-to-back coincidence events with the same procedure as for the inclusive proton events, and found to be 0.30 ± 0.26. This is the first derivation of the α_p^{NM} value for the exclusive process $\Lambda p \to np$.

The threshold-energy dependence of the α_p^{NM} values was further scrutinized by changing the proton detection energy thresholds to 40, 60, and 80 MeV (see table 2). When protons are coming from the $\Lambda p \to np$ process,

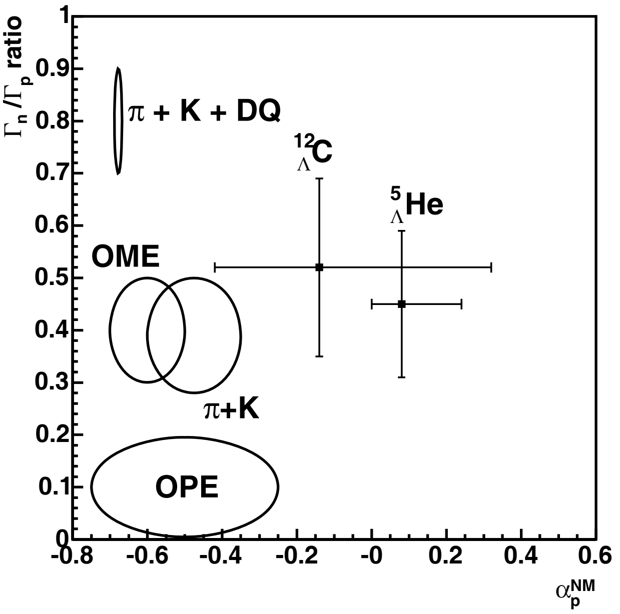

Fig. 3. Two-dimensional plot of recent theoretical calculations and our experimental results of the Γ_n/Γ_p ratio (vertical) and α_p^{NM} (horizontal).

the proton energy distribution should have a broad bump structure peaking at ~ 75 MeV. The effects of FSIs and two-nucleon induced decay mode ($\Lambda pN \to npN$) would contribute mainly at lower energies and would reduce the proton decay asymmetry. In a recent calculation by Alberico *et al.* [11], it was demonstrated that the α_p^{NM} central values can be reduced by 16% with the 30 MeV threshold, as compared to that with the 70 MeV threshold, due to the FSI effect introduced in their calculation. On the contrary, we obtained rather stable α_p^{NM} values within error level.

Figure 1(b) gives the selected gates for ${}^{12}_{\Lambda}$C and ${}^{11}_{\Lambda}$B formation. There are two well-known prominent peaks at 0 MeV and 11 MeV. We selected the region of −4 MeV to 4 MeV as the ground state (${}^{12}_{\Lambda}$C) gate. The other peak of 11 MeV is interpreted as (P_n^{-1}, P_Λ) state of which by releasing a proton decay to ${}^{11}_{\Lambda}$B; the ${}^{11}_{\Lambda}$B gate was set as 7 MeV to 15 MeV.

Since the ${}^{11}_{\Lambda}$B gate is located near the Λ binding energy of 0 MeV region, the quasi-free Λ decay process is considered to leak into the ${}^{11}_{\Lambda}$B gate. The level structure and the cross-section of ${}^{12}_{\Lambda}$C were already measured precisely by the KEK-PS E369 experiment [12]. The asymmetry of ${}^{11}_{\Lambda}$B was estimated from the number of actual ${}^{11}_{\Lambda}$B inside the ${}^{11}_{\Lambda}$B gate, which was calculated by fitting the excitation energy spectrum.

The α_p^{NM}'s of ${}^{12}_{\Lambda}$C and ${}^{11}_{\Lambda}$B were obtained from the asymmetry of proton, A_p's, and P_Λ's which were estimated based on a theoretical calculation performed by Itonaga *et al.* [13], with the same procedure as for the ${}^{5}_{\Lambda}$He case. Then the averaged α_p^{NM} of both hypernuclei was obtained as $-0.16 \pm 0.28^{+0.18}_{-0.00}$ for the scattering angle of $6^\circ < |\theta_K| < 15^\circ$. This result —obtained with significantly improved statistics— contradicts the previous reported [7] large and negative value.

Figure 3 summarizes recent theoretical calculations and our experimental results [4,5]. Our Γ_n/Γ_p ratio is well reproduced by the theoretical calculations taking particularly the K exchange into account together with π, ρ, ω, etc. exchanges, or a model further including a direct quark exchange. However, they fail to reproduce the asymmetry parameter. In a recent theoretical analysis, a model —including the scalar-isoscalar meson σ with the direct quark exchange or pseudovector meson a_1— could reproduce both the Γ_n/Γ_p ratio and α_p^{NM} [14,15]. To confirm this analysis, the measurement of four body Λ-hypernuclei, ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He, is required at J-PARC facility.

4 Summary

The decay asymmetry of polarized Λ-hypernuclei, ${}^{5}_{\Lambda}$He, ${}^{12}_{\Lambda}$C and ${}^{11}_{\Lambda}$B, has been investigated to understand the reaction mechanism of the non-mesonic weak decay $\Lambda N \to nN$. These Λ-hypernuclei were produced in the highest statistics ever via the (π^+, K^+) reaction at 1.05 GeV/c by using the SKS spectrometer at KEK 12 GeV PS.

The asymmetry parameter, α_p^{NM}, of protons resulting from a non-mesonic weak decay $\Lambda p \to np$ was obtained for ${}^{5}_{\Lambda}$He with improved statistics. The α_p^{NM} for inclusive protons with $E_p \gtrsim 30$ MeV was $0.07 \pm 0.08^{+0.08}_{-0.00}$, and that for p-n coincidence events was 0.31 ± 0.26.

In the case of ${}^{12}_{\Lambda}$C and ${}^{11}_{\Lambda}$B, we found a asymmetry parameter close to zero, $-0.16 \pm 0.28^{+0.18}_{-0.00}$, which is consistent with the value for ${}^{5}_{\Lambda}$He within the statistical errors. This result contradicts a previously measured value of -0.9 ± 0.3. The present result indicates no large differences in the NMWD reaction mechanism between s-shell and p-shell Λ-hypernuclei.

In a recent theoretical analysis, a model including the scaler-isoscaler meson σ exchange with the direct quark exchange or pseudovector meson a_1 exchange could reproduce both the Γ_n/Γ_p ratio and α_p^{NM}.

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