Exclusive Measurement of the Non-Mesonic Weak Decay of $^5_Λ$He

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Abstract

We performed an experimental study on the Non-Mesonic Weak Decay (NMWD) width of $^5_Λ$He hypernucleus in $^6Li(\pi^+, K^+)\rightarrow n + n$ reaction in order to study the weak interaction between baryons in $Λn→NN$ process. Our aim is to measure the angular and energy correlations of two nucleon pairs ($n+n, n+p$) coming from NMWD process ($Λn→NN$) by coincidence measurement. From this information we can obtain the $Γ_n/Γ_p$ ratio without ambiguity, where $Γ_n$ is the partial decay width of $Λn→nn$ process and $Γ_p$ is that of $Λp→np$ process. In this report a very preliminary result of this coincidence analysis is shown.

1 Introduction

In the free space, $Λ$ decays dominantly associated with pions in the final state, and the branching ratio is;

$$Λ \rightarrow p + π^- + 37.8 \text{ MeV} \quad (64\%) \ (1)$$

$$Λ \rightarrow n + π^0 + 41.1 \text{ MeV} \quad (36\%) \ . \ (2)$$

In the case of $Λ$ in nucleus, $Λ$ can stimulate a nucleon and the $ΛN→NN$ decay becomes possible. Because there is no meson in the final state, it is called as Non Mesonic Weak Decay (NMWD). The main decay modes of $Λ$ hypernucleus are shown as following;

$$Γ_{tot} = \frac{1}{τ_{HY}} = \begin{cases} Γ_m &= \left\{ \begin{array}{l} Γ_{π^-} \quad Λ \rightarrow p + π^- \quad (\text{Mesonic}) \quad q=100\text{MeV}/c \\ Γ_{π^0} \quad Λ \rightarrow n + π^0 \\ Γ_p \quad Λ + "p" \rightarrow n + p \quad (\text{Non Mesonic}) \\ Γ_n \quad Λ + "n" \rightarrow n + n \quad q=400\text{MeV}/c \end{array} \right. \ (3) \end{cases}$$

where $Γ_{tot}$, $Γ_m$, and $Γ_{nm}$ stand for the total, mesonic and non-mesonic decay width of $Λ$ hypernucleus, respectively. The $Γ_{π^-}$, $Γ_{π^0}$, $Γ_p$, and $Γ_n$ are each partial decay width. Generally it is difficult to study weak interaction between two nucleons because its parity conserving part is masked by the strong interaction. The NMWD is unique tool to study
weak interaction between baryons, because this strangeness non-conserving process is purely caused by weak interaction.

Most simply, ΛN→NN reaction can be expressed as a pion re-absorption from Λ→nπ decay inside nuclei. Because one pion exchange process is tension-dominant, the final NN pair should be isospin 0 which required Γ_n close to 0. However, experimental results so far seem to indicate the large Γ_n/Γ_p ratio (~1). To solve this puzzle, the various models are considered theoretically; the heavy meson exchange model (K,η,ρ,ω,K*) [1, 2] and Direct Quark model (DQ) [1]. The DQ employs the diagram of interaction between quarks inside nucleus directly because of the large momentum transfer of this reaction (400MeV/c). However there is no satisfactory explanation at present.

The recent results of 5ΛHe NMWD width are given in Table 1. In these experiments, their setup is optimized to observe charged particles from Λ hypernuclear decay, and obtained neutron data are very limited as mentioned later. It gives extremely large error to the Γ_n/Γ_p ratio of about 60% for 5ΛHe.

<table>
<thead>
<tr>
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<th>(Γ_p + Γ_n)/Γ_Λ</th>
<th>Γ_n/Γ_p</th>
<th>Ref.</th>
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<tr>
<td>Experimental</td>
<td>0.41 ± 0.14</td>
<td>0.93 ± 0.55</td>
<td>3</td>
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<tr>
<td>Theoretical</td>
<td></td>
<td></td>
<td></td>
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<td>π(OPE)</td>
<td>0.216</td>
<td>0.132</td>
<td>[1]</td>
</tr>
<tr>
<td>π+K</td>
<td>0.237</td>
<td>0.903</td>
<td>[1]</td>
</tr>
<tr>
<td>π+K+DQ</td>
<td>0.627</td>
<td>0.489</td>
<td>[1]</td>
</tr>
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</table>

Table 1: The recent experimental and theoretical results of non-mesonic weak decay width from 5ΛHe. FSI effects for experimental values were corrected with cascade calculation. (OPE=One Pion Exchange model, DQ=Direct Quark model)

This large error comes from the following two experimental difficulty/uncertainty: 1) There is no experimental sensitivity for the proton below 30MeV. The low energy proton is produced due to the Final State Interaction(FSI), which is not yet well understood. Therefore the number of primary n+p pair is very sensitive to the FSI, and the Γ_p might be underestimated. 2) The Γ_n is evaluated by neglecting the contribution of ΛNN→NNN decay process which is recently discussed by several authors. This process emits low energy nucleons so that it is missassigned as Λn→nn process when only energetic protons are measured. If the branching ratio of ΛNN→NNN is large, Γ_n must be overestimated in the previous experiment.

To solve the puzzle by presenting definitive number for Γ_n and Γ_p, we performed an experiment(KEK-PS E462).

2 Experimental overview

For the first time we simultaneously measured two nucleons (n+p, n+n) from decay of Λ hypernucleus. The advantage of the coincidence experiment is that we can remove both of the difficulty and uncertainty described above. The NN-pair from ΛN→NN should have back-to-back angular correlation (cosθ ~ -1), and the energy sum of NN-pair must agree
to Q-value. If we tag good event by angular and energy correlation, we can safely select the events which have the primary reaction of $\Lambda N \rightarrow NN$ without having FSI effect.

It should be noted that the $\Gamma_n/\Gamma_p$ ratio can be determined directly without any assumption as follows. If we detect neutron and proton using same counter, the numbers of np- and nn-pair, $N(n+p \text{ - back to back})$ and $N(n+n \text{ - back to back})$, can be given as:

$$N(n+p \text{ - back to back}) = N(\Lambda p \rightarrow np) \times \Omega^2 \times \epsilon_n \times \epsilon_p \times (1 - R_{FSI}) \quad (4)$$

$$N(n+n \text{ - back to back}) = N(\Lambda n \rightarrow nn) \times \Omega^2 \times \epsilon_n^2 \times (1 - R_{FSI}) \quad (5)$$

where $\Omega$ denotes the acceptance of the counter, $R_{FSI}$ stand for the reduction factor due to the FSI, and $\epsilon_n$, $\epsilon_p$ are the detection efficiency of neutron and proton, respectively. Then the ratio of $\Gamma_n/\Gamma_p$ is expressed as:

$$\frac{\Gamma_n}{\Gamma_p} \equiv \frac{N(\Lambda n \rightarrow nn)}{N(\Lambda p \rightarrow np)} = \frac{N(n+n \text{ - back to back})}{N(n+p \text{ - back to back})} \times \frac{\epsilon_p}{\epsilon_n} \quad (6)$$

In this expression, many of the factor including FSI effect cancels out. Therefore we can precisely deduce the $\Gamma_n/\Gamma_p$ only from measured numbers.

Experimentally it is preferable to have lower FSI effect, so that we used light hypernucleus, namely $^5_3\Lambda$He. We produced $^5_3\Lambda$He hypernucleus via $^6\text{Li}(\pi^+,K^+) \rightarrow$ reaction at 1.05GeV/c. In order to identify the formation of hypernucleus the missing mass is reconstructed by the momentum of incoming $\pi^+$ and that of outgoing $K^+$. Both are measured by two spectrometers 1 in front of and behind the $^6\text{Li}$ target.

The decay particles (pion, proton and neutron) are detected by plastic scintillation array as shown Fig. 1. The top and bottom coincidence arms are placed symmetrically from the target. The energy of charged particles were measured by the TOF between the T2 and T3 counters which have high resolution of $\sim$40ps and $\sim$80ps in $\sigma$, respectively. The three 30cm-thick neutron counter array 2 ($100\text{cm} \times 60\text{cm} \times 30\text{cm}$) were used as TOF counter to measure the neutron energy. For charged particle veto, T3 counter was used.

Fig. 1: Setup of the decay coincidence counter system seen from the beam down stream.

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1 The two spectrometer, beam spectrometer and SKS(Superconducting Kaon Spectrometer), are located at K6 beamline in KEK-PS.

2 The neutron counter was also used as range counter to measure the total energy of charged particles.
3 Analysis and Result

3.1 Excitation energy spectra of $^6_\Lambda$Li hypernucleus

The $^6\text{Li}(\pi^+,K^+)^6\Lambda\text{Li}$ reaction was employed to produce $^5_\Lambda$He hypernucleus. A level scheme of $^6\Lambda\text{Li}$ are shown in Fig. 2. As shown in the figure, the ground state is above the threshold of $^5_\Lambda$He+p. When the Λ produced in s-orbit, $^6_\Lambda\text{Li}$ promptly decays into $^5_\Lambda\text{He}$ with emitting a proton. In the case of producing in p-orbit, the Λ escapes from the nucleus.

The excitation energy spectrum for $^6_\Lambda\text{Li}$ are shown in the top of Fig. 3. The peak of ground state is clearly seen. Gating this ground state peak, the events from $^5_\Lambda\text{He}$ are selected. The excellent S/N ratio ($\sim$8.7) is shown in this figure comparing to the background level observed at the lower energy side of the ground state.

The gated mass spectrum is shown in the bottom of Fig. 3 by p+n back-to-back coincidence. This coincidence requires stable hypernuclear formation. It is shown that the p-substitutional state was diminished, while the s-substitutional state was enhanced as it is naturally expected.

![Fig. 2: Level scheme of $^6_\Lambda\text{Li}$ hypernucleus](image)

![Fig. 3: $^6_\Lambda\text{Li}$ excitation energy spectra. Bottom is gated by decay particles which is coincidence of decay proton and neutron.](image)

3.2 TOF spectrum for neutral particles

The $1/\beta$ (TOF) spectrum for neutral particle gated $^5_\Lambda\text{He}$ is shown in Fig. 4 whose threshold is set at 2MeVee $^3$. The peak at $\beta$=1 is from γ ray, and the neutrons are distributed in the delayed part of the spectrum. Good separation of the γ and neutron is shown.

The accidental background can be evaluated from the yield in $1/\beta$ <1 region. This background is evaluated to be less than 7% when we select the event of $2<1/\beta<10$.

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$^3$ In following all figure for neutral particle, 2MeVee threshold was used.
The energy resolution of neutron can be evaluated by the width of $\gamma$ peak in this TOF spectrum since the neutron energy is obtained by TOF method. The neutron kinetic energy scale is given at the top of the figure. The energy resolution for neutron counter is $\sim 11\text{MeV}$ in $\sigma$ at the neutron energy of $80\text{MeV}$.

3.3 Single neutron energy spectra

The present single neutron energy spectrum from $^5\Lambda\text{He}$ is shown in the top of Fig. 5. It is known that the efficiency for the neutron detection depends on the neutron energy, the energy dependence was corrected by simulation code, DEMONS(based on Cecil code [5]), in the bottom figure. We also divided by the acceptance for the solid angle and the number of inclusive events for the $^5\Lambda\text{He}$. The vertical axis directly corresponds to the number of neutrons from unit $^5\Lambda\text{He}$ decay.

It can be noted that we achieved about 150 times higher statistics for the number of neutron from NMWD than the last experiment[3], whose statistics of single neutron has only $\sim 10$.

In the previous experiment (KEK-PS E369), the result of single neutron energy spectra from $^{12}\Lambda\text{C}$ is shown in Fig. 6. The two solid lines are the theoretical calculations by Ramos[4].
assuming that $\Lambda N \to NN$ (1N-induced) and $\Lambda NN \to NNN$ (2N-induced), respectively. The vertical axis is arbitrary. In their calculation, the FSI effect is considered for both of these processes, and assumed that $\Gamma_n/\Gamma_p=1$. When only 1N-induced process is considered, it has a broad peak at the half of Q-value ($\sim 76$ MeV). The experimental result has a low energy tail instead of peaking there. This indicates that there are large $\Lambda NN \to NNN$ (2N-induced) contribution or/and larger FSI effect than the theoretical assumption. Although we were expected that the single neutron energy spectrum should have more clear peaking at Q/2 in the present experiment, because of the smaller nuclear size, yet the observed shape is very similar to the neutron spectrum of $^\Lambda_2^C$ hypernucleus. This seems to suggest the considerable contribution of $\Lambda NN \to NNN$ (2N-induced) process or/and the $^{\Lambda}_5^\Lambda$He is still heavy for FSI. There is no definitive way to reconcile which is the major reason from only single nucleon spectrum, because it is the sum of the two contributions. Hence the $\Gamma_n/\Gamma_p$ ratio previously obtained from single spectra may have larger systematic error than reported. The major advantage of the present experiment is the back-to-back coincidence as described before.

### 3.4 Coincidence analysis for n+p

The angular correlation ($\cos \theta$) of the coincidence between neutron and proton from NMWD of $^\Lambda_5^\Lambda$He ($\Lambda p \to np$) is shown in Fig. 7(top). The acceptance corrected angular correction is shown in Fig. 7(bottom). We can safely assign that the primary reaction of back-to-back event is $\Lambda N \to NN$ and two nucleons at the final state ejected without FSI.

The ratio of back-to-back and uniform components is almost 1:1. This large uniform component is consistent with single neutron energy spectrum, which suggests the large FSI effect or/and large branching ratio of $\Lambda NN \to NNN$ as the result.

The two nucleon energy sum spectrum is shown in Fig. 8, after the event selection of the back-to-back angular correlation, $\cos \theta < -0.9$. In the $\Lambda p \to np$ decay, the final state of the back-to-back event is $^\Lambda_5^\Lambda$He$\to n+p+^3H$, then the sum of the energy simply calculated as;

$$T_p + T_n = Q_0 - E_{\text{separation}} - B_\Lambda - T(^3\text{H})$$

$$= 176 - 19.8 - 3.2 - T(^3\text{H})$$

$$= 153 - T(^3\text{H}) \text{ [MeV]}$$

where $Q_0$, $E_{\text{separation}}$, $B_\Lambda$ stand for the Q-value of $\Lambda p \to np$ decay in free space, separation energy of nucleon from $\alpha$-particle and binding energy of $\Lambda$ inside the $^\Lambda_5^\Lambda$He, respectively.
Therefore the sum energy must have a peak at 153 MeV with the width due to the recoil energy of $^3\text{H}$ ($T(^3\text{H})=p_{\text{Fermi}}^2/2M$), $\sim$10 MeV. The clear peak in the energy sum spectrum shows that the back-to-back event selection works nicely to tag event which has $\Lambda\text{p}\rightarrow\text{np}$ reaction without FSI.

Fig. 8: Energy sum for pn coincidence with back-to-back angular correlation ($\cos\theta<-0.9$)

4 Summary

In order to measure the $\Gamma_n/\Gamma_p$ ratio definitively, we performed coincidence experiment of two nucleon for the first time. The single neutron energy spectrum had a low energy tail in contrast to the naive expectation of having peak at $Q/2$. This implies the existence of large FSI even in $^5\Lambda\text{He}$ and/or the large $\Lambda\text{NN}\rightarrow\text{NNN}$ (2N-induced) contribution.

According to the analysis of the np coincidence, we confirmed that the angular correlation of events from $^5\Lambda\text{He}$ was enhanced in back-to-back direction and the peak in the energy sum spectrum located at the Q-value. It shows that we can select $\Lambda\text{N}\rightarrow\text{NN}$ decay of $^5\Lambda\text{He}$ free from FSI and 2N-induced decay process.

We will have a beam time extension in this autumn, and the statistics will be improved by a factor of 4. We are expecting to report a definitive $\Gamma_n/\Gamma_p$ ratio with good accuracy in near future for the first time.

References