π\(^0\) decay branching ratios of \(^5\Lambda\)He and \(^{12}\Lambda\)C hypernuclei

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We precisely measured π\(^0\) branching ratios of \(^5\Lambda\)He and \(^{12}\Lambda\)C hypernuclei produced via \((\pi^+, K^+)\) reaction. Using these π\(^0\) branching ratios with the π\(^-\) branching ratios and the lifetimes, we obtained the π\(^0\) decay widths and the non-mesonic weak decay widths at high statistics with the accuracy of ∼5% (stat) for both hypernuclei.

1. Introduction

It is well known that a Λ hyperon in free space decays into a nucleon associated with a pion (Γ\(_{\pi^-}\): Λ → p\(\pi^-\), Γ\(_{\pi^0}\): Λ → n\(\pi^0\)). A bound Λ in a nucleus (Λ hypernucleus) also decays via the decay process, called the mesonic weak decay of Λ hypernucleus. The relevant momentum transfer is only ∼100 MeV/c which is not necessarily enough high to exceed the Fermi momentum. The decay rate is therefore suppressed due to the Pauli blocking effect on the outgoing nucleon. Especially in light hypernuclei, it is sensitive to overlap of the Λ wave function with the nucleus. Thus, the mesonic weak decay width of light hypernuclei gives significant information to investigate Λ-nucleus potential shape.

It is believed that the folding potential between Λ and light (s-shell) nuclei has a central repulsive core, which is calculated from the commonly used YNG ΛN interaction. However, it has not been confirmed so far experimentally. For comparison of α-Λ potential, Motoba et al. calculated the mesonic decay widths of \(^5\Lambda\)He for two different potentials \([1]\). One is derived from the YNG interaction, and the other is a simply attractive potential derived from one-range-gaussian two-body interaction called “ORG”, which are
Table 1

Previous experimental results and theoretical calculations for the $^5\Lambda$He and $^{12}\Lambda$C.

|          | Refs. | $\Gamma_{tot}/\Gamma_\Lambda$ | $\Gamma_{\pi^-}/\Gamma_\Lambda$ | $\Gamma_{\pi^0}/\Gamma_\Lambda$ | $\Gamma_{nm}/\Gamma_\Lambda$ |
|----------|-------|-------------------------------|----------------------------------|----------------------------------|-------------------------------|
| $^5\Lambda$He (exp.) | 3     | 1.03±0.08                     | 0.44±0.11                        | 0.18±0.20                       | 0.41±0.14                    |
| $^5\Lambda$He (ORG)    | 1     |                               | 0.321                            | 0.177                           |                               |
| $^5\Lambda$He (YNG)    | 1     |                               | 0.393                            | 0.215                           |                               |
| $^{12}\Lambda$C (exp.)| 4, 5  | 1.14±0.08                     | 0.113±0.015                      | 0.200±0.068                     | 0.828±0.087                  |

determined to reproduce the $\Lambda$ binding energy of $^5\Lambda$He. According to their calculation, the difference in the decay widths between them is $\sim$20% as shown in Table 1. However, existent experimental data cannot distinguish the two due to the large error. In the present experiment, we precisely measured both mesonic decay widths, $\Gamma_{\pi^-}$ and $\Gamma_{\pi^0}$.

On the other hand, the bound $\Lambda$ in a nucleus can interact with a neighboring nucleon ($\Gamma_\Lambda$: $\Lambda p \rightarrow np$, $\Gamma_\Lambda$: $\Lambda n \rightarrow nn$), called the non-mesonic weak decay of $\Lambda$ hypernucleus. It gives unique opportunity to study baryon-baryon weak interaction which is hidden by strong interaction in normal nuclei. The total non-mesonic weak decay width ($\Gamma_{nm}$) is one of the most important observables for the study. It is difficult to measure the $\Gamma_{nm}$ (= $\Gamma_\Lambda p + \Gamma_\Lambda n$) directly due to experimental difficulties such as final state interaction effect. Thus, the $\Gamma_{nm}$ is usually obtained by subtracting the mesonic weak decay widths from the total decay width $\Gamma_{tot}$ (inverse of the lifetime), as $\Gamma_{nm} = \Gamma_{tot} - \Gamma_{\pi^0} - \Gamma_{\pi^-}$. Table 1 shows the latest experimental data for $^5\Lambda$He and $^{12}\Lambda$C. The errors of $\Gamma_{nm}$ for both hypernuclei mainly come from those of $\Gamma_{\pi^0}$, so that the precise measurement of $\Gamma_{\pi^0}$ is awaited.

In the present paper, we concentrate the measurement of $\pi^0$ branching ratios, and $\Gamma_{\pi^0}$s and $\Gamma_{nm}$s for $^5\Lambda$He and $^{12}\Lambda$C are derived from the $\pi^-$ branching ratios and the lifetimes.

2. Experimental Method

The present experiments (E462/E508) were performed at the K6 beam line of the KEK 12-GeV proton synchrotron (KEK-PS). Hypernuclei of $^5\Lambda$He and $^{12}\Lambda$C were produced by the $(\pi^+, K^+)$ reaction at 1.05 GeV/c on $^6\text{Li}$ and $^{12}\text{C}$ (active) targets. The hypernuclear mass spectra were calculated by reconstructing momenta of incoming $\pi^+$ and outgoing $K^+$ using the beam line spectrometer (QQDQQ) and the SKS spectrometer, respectively.

The schematic view of the decay counter system is shown in Ref [2]. Neutral decay particles were detected by the T4 counter arrays comprising 6 layers of 5cm-thick plastic scintillators. Charged decay particles were vetoed by thin plastic scintillators installed just before T4 counter arrays. $\pi^0$ from NMWD was identified by detecting high energy $\gamma$ ray, because the energy of this $\gamma$ ray is about 70 MeV, and that from other decay process is about a few MeV. The $\gamma$ rays were separated from neutrons by means of time-of-flight technique between the start timing counter of incident beam and the T4 counter.

3. Analysis and Results

The formations of each hypernucleus were identified by gating the ground state region in the excitation energy spectra of $^6\text{Li}$ and $^{12}\text{C}$ as shown in Figure 1(a). Neutral particles from the decay were detected at T4 counter with 2 MeVee (MeV electron equivalent)
threshold. The 1/β spectrum for 12C is shown in Figure 2(a), which shows good γ/n separation. The γ gate corresponds to 0 ≤ 1/β ≤ 2. Using the yields below the γ peak (1/β < 0), the accidental background within the γ gate was estimated as good as ~ 2%.

In order to estimate the efficiency of the detector setup, the GEANT-based Monte Carlo simulation was performed. The efficiency depends on the energy of π0. We assumed mono-energetic (104.9 MeV/c) π0 for 5ΛHe (5ΛHe → π0 + 5He (g.s.)), and we used the π0 distribution for 12C given by Motoba et al. [6]. Figure 3 shows the γ energy spectra for 5ΛHe. The points with error bars are the experimental data, and the shaded one is the simulation. To select γ-ray shower clearly, we applied the multiplicity cut for the identification. Upper figure shows the spectrum with applying multiplicity M ≥ 1, and lower figure shows that for M ≥ 2. There is a low energy background in the spectrum for the M ≥ 1 condition, whereas the background disappear in that for M ≥ 2 condition. In order to remove the low energy background completely, we determined the π0 threshold. The 1/12 distribution for γ separation. The Carlo simulation was performed. The efficiency depends on the energy of c mono-energetic (104.9 MeV/π). Simulation in Figure 3(2) shows that we can count for the efficiency estimation. ε estimated to be applied in the simulation. The detection efficiency (including the detector acceptance) is clearly separated from neutron. For the efficiency estimation, the same cut condition was condition as “M ≥ 2” and “ADC sum ≥ 20 MeVee”. The 1/β spectrum applied this π0 cut condition is shown in Figure 2(b). In this figure, the γ ray from π0 decay more clearly separated from neutron. For the efficiency estimation, the same cut condition was applied in the simulation. The detection efficiency (including the detector acceptance) is estimated to be ε ~ 10.5%. The good agreement of the energy spectra between data and simulation in Figure 3(2) shows that we can count for the efficiency estimation.

Figure 1(b) shows the excitation energy of 5Li and 12C with the π0 cut condition. The π0 branching ratio is represented by bπ0 = Nπ0/Ninc/ε, where Ninc and Nπ0 are the numbers gated for the ground state regions shown in the Figure 1(a) and (b), respectively. Consequently, the π0 branching ratios for 5ΛHe and 12C were determined to be bπ0 = 0.212 ± 0.008 and 0.133 ± 0.005, respectively (statistical error only), though preliminary yet.

Γπ0s and Γnm’s for 5ΛHe and 12C were derived from our results of the lifetimes and the π− branching ratios [2] as shown in Table 2. The result of Γπ0 for 5ΛHe is located in between those of ORG- and YNG-based calculations, which is consistent with the Γπ− result [2]. It indicates that the α-Λ overlapping is larger than that of the YNG-based calculation.

The statistical errors of obtained Γnm’s for 5ΛHe and 12C were much improved as 34% → 5% for 5ΛHe and 11% → 5% for 12C. The theoretical calculations of non-mesonic weak decay are required to meet these Γnm results and our Γn/Γp results [7] simultaneously.

Table 2
Summary of present preliminary results for the 5ΛHe and 12C.

|          | Γtot/ ΓΛ | Γπ−/ ΓΛ | Γπ0/ ΓΛ | Γnm/ ΓΛ |
|----------|----------|----------|----------|----------|
| 5ΛHe     | 0.947±0.038 [2] | 0.340±0.016 [2] | 0.201±0.011 | 0.406±0.020 |
| 12C      | 1.242±0.042 [2] | 0.123±0.015 [4] | 0.165±0.008 | 0.953±0.032 |

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Figure 1. Excitation energy spectra of $^6\Lambda$Li (left figure) and $^{12}\Lambda$C (right figure). (a) for inclusive, (b) with the $\pi^0$ cut condition.

Figure 2. $1/\beta$ spectrum of neutral particle for $^{12}\Lambda$C. (a) without the $\pi^0$ cut condition, (b) with the $\pi^0$ cut condition which is layer multiplicity $M \geq 2$ and ADC sum $\geq 20$ MeVee.

Figure 3. $\gamma$ energy (ADC sum) spectra from $\pi^0$ decay of $^5\Lambda$He (point with error bar) are compared with the simulation (shaded one). (1) layer multiplicity $M \geq 1$, (2) $M \geq 2$. 