Nucleon-nucleon coincidence measurement in the non-mesonic weak decay of $^5_\Lambda$He and $^{12}_\Lambda$C hypernuclei

S. Okada\textsuperscript{a,\*}, S. Ajimura\textsuperscript{b}, K. Aoki\textsuperscript{c}, A. Bana\textsuperscript{d}, H. C. Bhang\textsuperscript{e}, T. Fukuda\textsuperscript{c,†}, O. Hashimoto\textsuperscript{f}, J. I. Hwang\textsuperscript{e}, S. Kameoka\textsuperscript{f}, B. H. Kang\textsuperscript{e}, E. H. Kim\textsuperscript{e}, J. H. Kim\textsuperscript{e}, M. J. Kim\textsuperscript{e}, T. Maruta\textsuperscript{g}, Y. Miura\textsuperscript{f}, Y. Miyake\textsuperscript{b}, T. Nagae\textsuperscript{c}, M. Nakamura\textsuperscript{g}, S. N. Nakamura\textsuperscript{f}, H. Noumi\textsuperscript{e}, Y. Okayasu\textsuperscript{f}, H. Outa\textsuperscript{c,‡}, H. Park\textsuperscript{h}, P. K. Saha\textsuperscript{c,‡}, Y. Sato\textsuperscript{c}, M. Sekimoto\textsuperscript{e}, T. Takahashi\textsuperscript{f,§}, H. Tamura\textsuperscript{f}, K. Tanida\textsuperscript{i}, A. Toyoda\textsuperscript{c}, K. Tsukada\textsuperscript{f}, T. Watanabe\textsuperscript{f}, H. J. Yim\textsuperscript{e}

\textsuperscript{a}Department of Physics, Tokyo Institute of Technology, Ookayama 152-8551, Japan
\textsuperscript{b}Department of Physics, Osaka University, Toyonaka 560-0043, Japan
\textsuperscript{c}High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan
\textsuperscript{d}Gesellschaft für Schwerionenforschung mbH (GSI), Darmstadt 64291, Germany
\textsuperscript{e}Department of Physics, Seoul National University, Seoul 151-742, Korea
\textsuperscript{f}Department of Physics, Tohoku University, Sendai 980-8578, Japan
\textsuperscript{g}Department of Physics, University of Tokyo, Hongo 113-0033, Japan
\textsuperscript{h}Korea Research Institute of Standards and Science (KRISS), Daejeon 305-600, Korea
\textsuperscript{i}RIKEN Wako Institute, RIKEN, Wako 351-0198, Japan

We have measured both yields of neutron-proton and neutron-neutron pairs emitted from the non-mesonic weak decay process of $^5_\Lambda$He and $^{12}_\Lambda$C hypernuclei produced via the $(\pi^+, K^+)$ reaction for the first time. We observed clean back-to-back correlation of the $np$- and $nn$-pairs in the coincidence spectra for both hypernuclei. The ratio of those back-to-back pair yields, $N_{nn}/N_{np}$, must be close to the ratio of neutron- and proton-induced decay widths of the decay, $\Gamma_n(A_n \rightarrow nn)/\Gamma_p(A_p \rightarrow np)$. The obtained ratios for each hypernuclei support recent calculations based on short-range interactions.

1. Introduction

The non-mesonic weak decay (NMWD) process of a $\Lambda$ hypernucleus, $\Lambda N \rightarrow nN$, gives a unique opportunity to study the weak interaction between baryons since this strangeness non-conserving process is purely attributed to the weak interaction. In the NMWD, there are two decay channels, $A p \rightarrow np$ ($\Gamma_p$) and $A n \rightarrow nn$ ($\Gamma_n$). The ratio of those decay widths, $\Gamma_n/\Gamma_p$, is an important observable used to study the isospin structure of the NMWD mechanism. For the past 40 years, there has been a longstanding puzzle that the experimental $\Gamma_n/\Gamma_p$ ratio disagrees with that of theoretical calculations based on the

*Present address: RIKEN Wako Institute, RIKEN, Wako 351-0198, Japan
†Present address: Laboratory of Physics, Osaka Electro-Communication University, 572-8530, Japan
‡Present address: Japan Atomic Energy Research Institute, Tokai 319-1195, Japan
§Present address: High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan
most natural and simplest model, the One-Pion Exchange model (OPE). In this model, the \( \Lambda N \rightarrow nN \) reaction is expressed as a pion absorption process after the \( \Lambda \rightarrow N\pi \) decay inside the nucleus. Since the OPE process is tensor-dominant and the tensor transition of the initial \( \Lambda N \) pair in the \( s \)-state requires the final \( nN \) pair to have isospin zero, the \( \Gamma_n/\Gamma_p \) ratio in the OPE process becomes close to 0. However, previous experimental results have indicated a large \( \Gamma_n/\Gamma_p \) ratio (~1) \([1, 2]\).

This large discrepancy between the OPE-model predictions and the experimental results has stimulated many theoretical studies: the heavy meson exchange model, the Direct Quark model and the two-nucleon \((2N)\) induced model \((\Lambda NN \rightarrow nNN)\). After K. Sasaki et al. pointed out an error in the sign of the kaon exchange amplitudes in 2000 \([3]\), those theoretical values of the \( \Gamma_n/\Gamma_p \) ratio have increased to the level of 0.4~0.7 \([4]\).

On the other hand, the experimental data still have large errors \((\Gamma_n/\Gamma_p = 0.93 \pm 0.55\) for \(^5_A\)He \([1]\)), and it is hard to draw a definite conclusion on the \( \Gamma_n/\Gamma_p \) ratio. When we compare the measured \( \Gamma_n/\Gamma_p \) ratio with that obtained in theoretical calculations, the most serious technical problem was a treatment of the re-scattering effect in the residual nucleus, the so-called Final State Interaction (FSI). Moreover, the possible existence of a multi-nucleon induced process has been discussed theoretically (such as \(2N\)-induced process), though there has been no experimental evidence. Several nucleon energy spectra from hypernuclear decay have been reported so far \([5, 6]\), in which it is however difficult to extract the \( \Gamma_n/\Gamma_p \) ratio without theoretical assumptions on the effects of FSI and possible multi-nucleon induced processes.

Since the \(1N\)-induced decay \("\Lambda N \rightarrow nN\"\) is two-body process, the outgoing nucleon-nucleon pair suffering no FSI effect must have about 180 degree opening angle and clear energy correlation. In the present experiment, we performed a coincident measurement of the two nucleons, \( np \) and \( nn\)-pairs, in the decay for the first time. The \(1N\)-induced processes could be clearly observed by measuring yields of the back-to-back \( np\)- and \( nn\)-pairs and confirming that the energy sums roughly correspond to their \( Q\)-values (~150 MeV). The measured yields of the coincident back-to-back \( np\)- and \( nn\)-pairs, \( Y_{np(nn)}\), are represented as \( Y_{np(nn)} = \frac{N_{np(nn)} \cdot \Omega_{np(nn)} \cdot \varepsilon_{np(nn)} \cdot (1 - R_{FSI})_{np(nn)}}{N_{np(nn)} \cdot \Omega_{np(nn)} \cdot \varepsilon_{np(nn)} \cdot (1 - R_{FSI})_{np(nn)}}\), where \( N_{np(nn)}\) are the number of back-to-back \( np(nn)\)-pair events from the decay; \( \Omega_{np(nn)} \), \( \varepsilon_{np(nn)} \) and \( (1 - R_{FSI})_{np(nn)} \) stand for decay-counter acceptances and detection efficiencies and reduction factors (due to the FSI or/and other non back-to-back processes) for the \( np(nn)\)-pair, respectively. It is noteworthy that the reduction factors are approximately canceled out with assumption of the charge symmetry, \( (1 - R_{FSI})_{np} \approx (1 - R_{FSI})_{nn} \), when we take the ratio of the \( np\)- and \( nn\)-pair yields, \( N_{nn}/N_{np} \).

In order to minimize the FSI effect, we selected a light \( s\)-shell hypernucleus, \(^5_A\)He. In \( s\)-shell hypernucleus, initial relative \( \Lambda N \) states must be \( S \) states, whereas in a \( p\)-shell hypernucleus they may be \( P \) states. To investigate the \( p\)-wave effect, we also performed the same experiment for a typical light \( p\)-shell hypernucleus, \(^{12}_A\)C.

In this Letter, we show the opening angle and the energy sum distributions of \( np\)- and \( nn\)-pairs from the NMWD of \(^5_A\)He and the \( N_{np}/N_{nn} \) ratio for both hypernuclei.
2. Experimental method

The present experiments (KEK-PS E462/E508) were carried out at the 12-GeV proton synchrotron (PS) in the High Energy Accelerator Research Organization (KEK). Hypernuclei, $^5_A$He and $^{12}_A$C, were produced via the ($\pi^+,K^+$) reaction at 1.05 GeV/c on $^6$Li and $^{12}$C targets, respectively. Since the ground state of $^6_A$Li is above the threshold of $^5_A$He + p, it promptly decays into $^5_A$He emitting a low-energy proton. The $^6$Li ($\pi^+,K^+$) $^6_A$Li reaction was therefore employed to produce $^5_A$He. The hypernuclear mass spectra were calculated by reconstructing the momenta of incoming $\pi^+$ and outgoing $K^+$ using a beam-line spectrometer composed of the QQDQQ system and the superconducting kaon spectrometer (SKS) [7], respectively.

Particles emitted from the decays of $\Lambda$ hypernuclei were detected by the decay-particle detection system installed symmetrically in the direction to the target in order to maximize acceptance of the back-to-back event for $np$- and $nn$-pairs from the NMWD process, as shown in Ref.[8] (Fig. 1). It was composed of plastic scintillation counters and multi-wire drift chambers. The decay particles were identified by the time-of-flight and the range.

3. Analysis and Results

The ground state yields of $^5_A$He and $^{12}_A$C are, respectively, about $4.6 \times 10^4$ and $6.2 \times 10^4$ events, which were one order-of-magnitude higher than those of previous experiments. The inclusive excitation-energy spectra of $^6$Li and $^{12}_A$C are shown in Ref.[8] (Fig. 2).

For details of the neutral and charged decay particle identification, refer to Ref.[8]. In this Letter, we focus on the coincidence analysis of $np$- and $nn$-pairs from the NMWD.

Upper figures of Fig. 1 (a) and (b), show opening angle distributions of $np$- and $nn$-pairs at the energy threshold level of 30 MeV for both of proton and neutron. They seem to have clear back-to-back correlations, though these are not corrected the angular dependent acceptance. The shaded histogram shows estimated nucleon contaminations due to the pion absorption process in which $\pi^-$’s from the mesonic decay of $\Lambda$ hypernucleus are absorbed by the materials around the target. The background was estimated by assuming that the shape of the angular distribution from this $\pi^-$ absorption process is the same as that from the

Figure 1: Upper figures show opening angle distributions of $np$- and $nn$-pairs emitted from the decay of $^5_A$He: (a) and (b) are for raw yields; (c) and (d) are for yields per NMWD. Lower figures, (e) and (f), show energy sum distributions of the $np$- and $nn$-pairs.
\π^-\ decay of \Λ (\Lambda \rightarrow \pi^-p) formed via the quasi-free formation process (see Ref.[8] for the detail).

The angular distributions of middle of Fig. 1 (c) and (d), are corrected for acceptances and efficiencies for \np- and \nn-pairs, and normalized per NMWD. The estimated contamination due to the pion absorption stated above are subtracted. They still have back-to-back correlation, which indicates that the FSI effect is not so severe and 1N-induced NMWD (two body process) is the major one.

Lower figures of Fig. 1 (e) and (f), show energy sum distributions of the \np- and \nn-pairs by gating back-to-back events as shown in the upper figures (\cos \theta < -0.8). We confirmed that those energy sum distributions have broad peak around these \Q-values as expected. The shaded histogram shows estimated contaminations due to pion absorption as described above, which distributes to lower energy region.

Also for \12^A\Lambda\ C, similar distributions of the angle and energy sum of the \np- and \nn-pairs were obtained in a same way. We successfully observed \np- and \nn-pairs from the NMWD of \5^A\Lambda\He and \12^A\Lambda\ C. The ratio of the back-to-back \np- and \nn-pair yields, \nn/\np, for \5^A\Lambda\He and \12^A\Lambda\ C were obtained as

\[ \frac{\Gamma_n}{\Gamma_p} \text{(for } \5^A\Lambda\He) \sim \frac{\nn}{\np} = 0.45 \pm 0.11 \pm 0.03, \]

\[ \frac{\Gamma_n}{\Gamma_p} \text{(for } \12^A\Lambda\ C) \sim \frac{\nn}{\np} = 0.40 \pm 0.09 \text{ (preliminary)}, \]

where the quoted systematic errors mainly come from the neutron detection efficiency (\sim 6 %). They can be approximately regarded as the \Gamma_n/\Gamma_p with assumption of the charge symmetry.

It is now revealed that the \Gamma_n/\Gamma_p ratio is significantly less than unity, thus excluding the earlier claim that the ratio is close to unity [1]. On the contrary, recent theoretical calculations seem to be supportive to our results being on the increase of the ratio toward 0.5. The present results have finally given the answer to the longstanding \Gamma_n/\Gamma_p ratio puzzle, and have made a significant contribution to the study of the NMWD.

REFERENCES

1. J. J. Szymanski et al., Phys. Rev. C 43 849 (1991).
2. H. Nouni et al., Phys. Rev. C 52 2936 (1995).
3. K. Sasaki, T. Inoue and M. Oka, Nucl. Phys. A 669, 331 (2000); Nucl. Phys. A 678, 455 (2000) (E).
4. For a review, see W. M. Alberico and G. Garbarino, Phys. Rept. 369, 1 (2002).
5. O. Hashimoto et al., Phys. Rev. Lett. 88, 042503 (2002); Y. Sato et al., submitted to Phys. Rev. C; nucl-ex/0409007 (2004).
6. J. H. Kim et al., Phys. Rev. C 68, 065201 (2003).
7. T. Fukuda et al., Nucl. Instrum. and Meth. A 361, 485 (1995).
8. S. Okada et al., Phys. Lett. B 597, 249 (2004).