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Coincidence measurement of the nonmesonic weak decay of ${}^{12}_{\Lambda}$C

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Abstract

We have measured the angular correlation of the pair nucleons np and nn emitted from the nonmesonic weak decay (NMWD) of ${}^{12}_{\Lambda}$C produced via the (π^+, K^+) reaction in coincidence measurement. The $\Lambda p \to np$ and $\Lambda n \to nn$ modes were clearly identified by measuring the back-to-back correlation of the emitted nucleon pairs which is the characteristic of two-body kinematics. From the measured nucleon pair numbers N_{nn} and N_{np}, the ratio Γ_n/Γ_p of the partial decay widths $\Gamma_n(\Lambda n \to nn)$ and $\Gamma_p(\Lambda p \to np)$ of ${}^{12}_{\Lambda}$C was extracted to be $0.51 \pm 0.13(\text{stat}) \pm 0.05(\text{syst})$; this result is almost free from the ambiguity due to the nuclear final state interaction and 3-body decay process, which were inherent in the previous results. The obtained Γ_n/Γ_p ratio of ${}^{12}_{\Lambda}$C (p-shell) is close to that of ${}^{5}_{\Lambda}$He (s-shell). The results are consistent with those of recent theoretical calculations.

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Keywords: Nonmesonic weak decay; ${}^{12}_{\Lambda}$C; $\Gamma_n(\Lambda n \to nn)/\Gamma_p(\Lambda p \to np)$

1. Introduction

A Λ bound in a nucleus decays via either mesonic weak decay, $\Lambda \to N\pi$, or nonmesonic weak decay (NMWD), $\Lambda N \to nN$. Mesonic decay is essentially similar to free Λ decay and has been studied in detail. In a nucleus a Λ can decay via an interaction with a neighbor nucleon, either a proton ($\Lambda p \to np$; Γ_p, proton-induced NMWD) or a neutron ($\Lambda n \to nn$; Γ_n, neutron-induced NMWD); this is referred to as a one-

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nucleon-induced ($1N$) NMWD process. The two-nucleon induced ($2N$) process ($\Lambda NN \to nNN$; Γ_{2N}), which is another NMWD mode, has been predicted theoretically; however, it has not yet been verified experimentally. The NMWD process has attracted considerable attention since it provides the only practical means of studying the strangeness-changing baryonic weak interaction at present [1].

Since the discovery of hypernuclei, one of the primary concerns in the study of NMWD of Λ hypernuclei has been the relative strength of the two channels of $1N$ NMWD—the ratio of the decay widths (Γ_n/Γ_p). Experimental ratios over the broad mass range of Λ hypernuclei are consistently greater than unity, thereby indicating the dominance of the neutron channel; on the other hand, the theoretical ratios are only one tenth of unity. The predominance of the proton channel in the theoretical prediction is due to the fact that the tensor term of one-pion exchange (OPE) contributing only to the proton channel is very high, and therefore, the contributions of other meson exchange terms become minor corrections. The OPE contribution is included in all model calculations for the long range contribution; hence, the Γ_n/Γ_p ratios have remained at around 0.1. This intriguing problem is referred to as the Γ_n/Γ_p puzzle.

In order to reduce the predominance of the proton-induced NMWD of the OPE model, many theoretical models for short range contribution, such as the heavy meson exchange (HME) models and the direct quark (DQ) model have been studied. All these models have been unsuccessful in increasing the Γ_n/Γ_p ratio significantly until recently. However, in recent important development, the incorrect sign in kaon exchange amplitudes was identified; the correction significantly increased the Γ_n/Γ_p values of these models [2]. Thus, the current theoretical values of the Γ_n/Γ_p ratio have increased to 0.34–0.70 for ${}^{5}_{\Lambda}\mathrm{He}$ and 0.29–0.53 for ${}^{12}_{\Lambda}\mathrm{C}$ [2–4].

Until recently experimental Γ_n/Γ_p values were extracted by fitting intranuclear cascade (INC) calculation yields to the experimental proton yields spectra. Almost all the experimental Γ_n/Γ_p ratios have been close to or greater than unity [1]. However, recent high-quality neutron yield spectra obtained by our group have made it possible to derive the Γ_n/Γ_p ratio directly by comparing the neutron yields to the corresponding proton yields; the Γ_n/Γ_p ratios obtained by this method are ~ 0.5 for ${}^{12}_{\Lambda}\mathrm{C}$ [5,6] and ~ 0.6 for ${}^{5}_{\Lambda}\mathrm{He}$ [6] agreeing well with the recent theoretical values. These ratios are significantly smaller than unity. They are the first experimental indications of the proton channel dominance ($\Lambda p \to np$) in the NMWD.

It appears that the discrepancy between the experimental and theoretical values of the Γ_n/Γ_p ratios of NMWD has been removed. However, the Γ_n/Γ_p ratios of ${}^{5}_{\Lambda}\mathrm{He}$ and ${}^{12}_{\Lambda}\mathrm{C}$ derived by comparing the nucleon yields still contain the ambiguity due to the possible contributions of $2N$ NMWD and the final state interaction (FSI) effects on the emitted nucleons. The current FSI model calculation which takes into account the $2N$ NMWD and FSI cannot reproduce the yield spectra [6,15]. Therefore, the uncertainty of the ratios due to the ambiguity could not be estimated in such single nucleon (singles) measurements. In order to remove such ambiguity experimentally, the decay channel has to be explicitly identified for each event. In order to determine each decay channel of $1N$-induced NMWD exclusively, we have performed a coincidence measurement of both $n + p$ (np pair) and $n + n$ (nn pair) pair nucleons from the NMWD of the hypernuclei, ${}^{5}_{\Lambda}\mathrm{He}$ and ${}^{12}_{\Lambda}\mathrm{C}$. Since $\Lambda N \to NN$ is a two-body process, the outgoing nucleon pairs will exhibit a clear back-to-back (*bb*) correlation with regards to their opening angle, and their energy sum distribution would exhibit a peak at around the decay Q value, ~ 155 MeV, although they are broadened due to nuclear medium effects. On the other hand, in $2N$ NMWD, three nucleons are produced in the final state and a pair of nucleons among them would exhibit neither the *bb* feature in the opening angle nor the energy sum peak at the Q value. The nucleon from $1N$ NMWD that suffered intense FSI on the way out of the residual nucleus would be deflected from the original momentum direction and lose kinetic energy, thereby degrading the *bb* kinematics characteristic of $1N$ NMWD. Therefore, by applying the event selection criteria of *bb* kinematics, we can exclusively select $1N$ NMWD events suppressing possible contributions from the $2N$ process and the events that suffered serious FSI.

Recently we have reported the Γ_n/Γ_p value of s-shell ${}^{5}_{\Lambda}\mathrm{He}$ that was determined in the two-nucleon coincidence measurement of the NMWD [7]. By applying the *bb* kinematical condition for the opening angle, we obtained the pair number ratio of nn to np pairs of $1N$ NMWD, N_{nn}/N_{np}, to be $0.45 \pm 0.11 \pm 0.03$. This ratio becomes essentially the Γ_n/Γ_p ratio when FSI is weak as in ${}^{5}_{\Lambda}\mathrm{He}$. The s-shell hypernucleus, ${}^{5}_{\Lambda}\mathrm{He}$, was selected for the first exclusive coincidence measurement, since the FSI effect for such a light hypernucleus must be small. However, the unambiguous determination of Γ_n/Γ_p for a p-shell hypernucleus also is essential in the study of baryonic weak interaction since only the p-shell hypernuclei can provide the p-wave initial state for the interaction while the s-shell ${}^{5}_{\Lambda}\mathrm{He}$ does only that of s-wave. The importance of the p-wave contribution in the NMWD in the finite nucleus has been discussed in the reference [8]. In such respect, ${}^{12}_{\Lambda}\mathrm{C}$ has been extensively studied together with ${}^{5}_{\Lambda}\mathrm{He}$. Exclusive determination is even more important for the Γ_n/Γ_p ratio of heavier p-shell hypernuclei such as ${}^{12}_{\Lambda}\mathrm{C}$ since the nucleons propagating there will suffer more intense FSI. Although ${}^{12}_{\Lambda}\mathrm{C}$ is the most extensively studied p-shell Λ hypernucleus, no unambiguous Γ_n/Γ_p ratio for it is available yet.

The values of the asymmetry parameter α_{nm} of protons from $\Lambda p \to np$ NMWD of the polarized hypernuclei were measured and reported for both ${}^{5}_{\Lambda}\mathrm{He}$ and ${}^{12}_{\Lambda}\mathrm{C}$ formed via the (π^+, K^+) reaction. Although small positive values of 0.24 ± 0.22 and $0.11 \pm 0.08 \pm 0.04$ [9,10] were observed for ${}^{5}_{\Lambda}\mathrm{He}$, a large negative value ($\alpha_{nm} \simeq -1.0 \pm 0.4$) was reported for the p-shell hypernuclei [11]. Authors indicated a possible explanation that the interaction mechanism of NMWD for short and long range could be different and therefore the initial p-state contribution in ${}^{12}_{\Lambda}\mathrm{C}$ made the difference. The theoretical predictions for the asymmetry parameter for ${}^{5}_{\Lambda}\mathrm{He}$ are about -0.7 [4,12] from both the recent heavy meson exchange (HME) and the direct quark

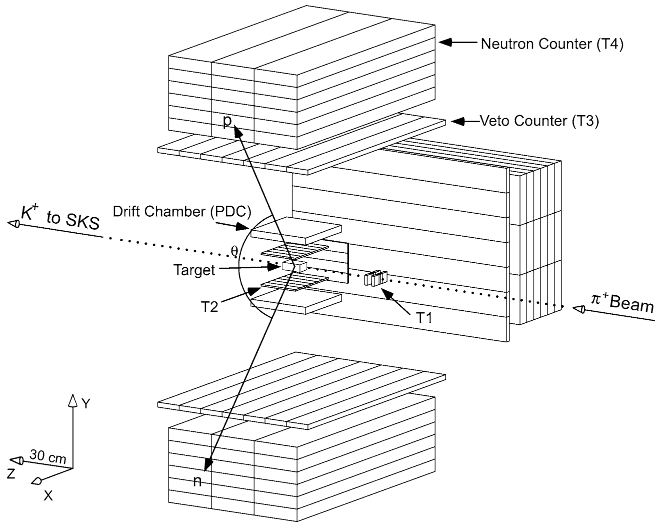

Fig. 1. Schematic view of the decay-particle detection system is shown. Each of top and bottom counter sets comprise a fast timing counter (T2), a drift chamber (PDC), veto or stop timing counter (T3) and neutron counter arrays (T4). The side set is similar; however, the PDC is absent.

(DQ) models. They significantly overestimate the magnitude of the parameter. The recent HME model prediction for α_{nm} of $^{12}_{\Lambda}$C is 0.36 that is again far off from the experimental value. The current difficulty in understanding the decay asymmetries of s- and p-shell hypernuclei implies that an accurate and unambiguous determination of Γ_n/Γ_p ratios for both s- and p-shell hypernuclei is essential for NMWD studies.

In this Letter we report the results of the two-nucleon observables measured in the coincidence experiment of the decay of $^{12}_{\Lambda}$C especially focusing on its Γ_n/Γ_p ratio.

2. Experimental setup and analysis

The experiment was carried out at the K6 beam line of 12-GeV proton synchrotron (PS) in High Energy Accelerator Research Organization (KEK). Λ hypernuclei $^{12}_{\Lambda}$C were produced via the (π^+, K^+) reaction at the beam momentum of 1.05 GeV/c on the ^{12}C target. In order to improve the vertex resolution, we used thin segmented plastic scintillators for an active ^{12}C target. Fig. 1 shows the schematic view of coincidence counters for detecting the decay product particles from the weak decay of $^{12}_{\Lambda}$C. It comprises three sets of coincidence counter-two located at the top and bottom of the target, optimized for bb coincidence events and one at the side to allow the detection of non-back-to-back events. Each of top and bottom counter sets comprise a fast timing counter (T2), a drift chamber (PDC), veto or stop timing counter (T3) and neutron counter arrays (T4). The side set is similar; however, the PDC is absent.

The inclusive $^{12}_{\Lambda}$C excitation energy spectrum derived from the momenta of incoming pion and the outgoing kaon is shown in Fig. 2(a). The two single particle Λ states ($1s$ and $1p$) are clearly identified. The $1p$ Λ state is located just above proton emission threshold; it decays into $^{11}_{\Lambda}$B by emitting a proton. Figs. 2(b) and 2(c) show the excitation energy spectra in coincidence with the emitted pair nucleons np and nn, respectively. The vertical lines show the applied gates of the decay measurement for ground state of $^{12}_{\Lambda}$C. The enhancement of the yield in the quasi-free Λ region of the nn coincidence excitation energy spectrum as compared with that of the np pairs occurs due to the emission of two neutron via the absorption of π^- from the quasi-free Λ mesonic decay.

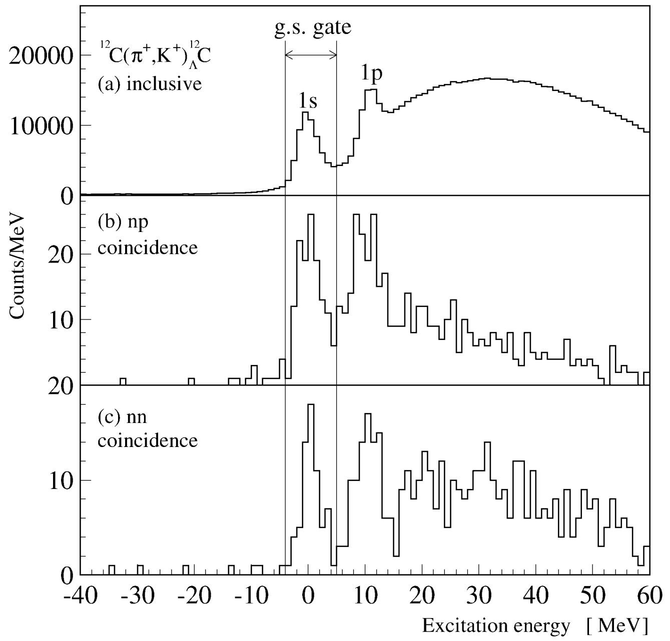

Fig. 2. Excitation energy spectra of $^{12}_{\Lambda}$C, (a) inclusive, (b) with coincidence np pairs, (c) with coincidence nn pairs, respectively. (b) and (c) case, 30 MeV energy cut condition was applied for both protons and neutrons.

Neutral particles, γ and neutrons, were measured using six layers of 5 cm thick plastic scintillators (T4) vetoed with T3. The particle identification (PID) of the neutrons and γ was achieved by using the flight time from the decay vertex to the fired T4 counter. The neutron and γ were well separated, and the accidental background within the neutron gate was negligible. The charged particles were identified by combining dE/dx, TOF_{23} and E_T. dE/dx denotes the energy loss per unit length measured by T_2; TOF_{23}, flight time between T_2 and T_3; and E_T, the total energy deposited in the sequentially fired counters, T_2, T_3, and T_4. Protons are well separated from pions and deutrons. The kinetic energies of neutrons and protons were calculated from the flight times and the ranges, respectively. Proton energy was corrected for the energy loss inside the target material thanks to the good vertex resolution. Further experimental details are provided in the previous report [6].

3. Results and discussion

Figs. 3(a) and 3(b) show the raw distribution of np and nn pair yields $Y_{np}(\cos\theta)$ and $Y_{nn}(\cos\theta)$ in the opening angle θ, respectively. Only the pair events of which each nucleon has an energy greater than 30 MeV are counted. The dominance of the bb peaks shown in the raw spectra is enhanced by the maximized acceptance for the coincidence back-to-back kinematic events. A total of 116 and 43 events were observed in the bb

Table 1
The yields of coincidence events Y_{np}, Y_{nn} and Y_{pp} and the normalized pair numbers per NMWD N_{np}, N_{nn} and N_{pp} are shown in the opening angle regions *bb* (back-to-back, $\cos\theta < -0.7$) and non-*bb* ($\cos\theta \geqslant -0.7$). N_{NN} values listed are the numbers simply integrated over the corresponding angular regions. The pair numbers after the subtraction of the uniform background in the *bb* region are also listed. Errors are statistical

Angular region	Y_{np}	N_{np}	Y_{nn}	N_{nn}	Y_{pp}	N_{pp}
bb	116	0.138 ± 0.014	43	0.083 ± 0.014	8	0.005 ± 0.002
non-*bb*	12	0.060 ± 0.018	23	0.083 ± 0.020	0[a]	
bb (b.g. subtracted)		0.127 ± 0.014		0.067 ± 0.015		0.005 ± 0.002

[a] Due to the little acceptance.

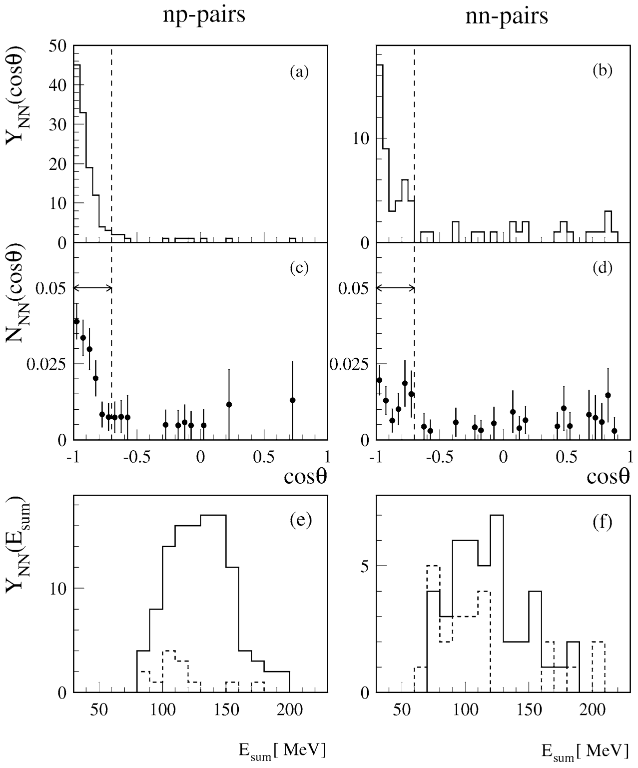

Fig. 3. The distributions of *np* and *nn* pairs are shown in the left and right figures, respectively. Top figures are the raw opening angle distribution, while middle ones are the angular correlations for the normalized pair numbers per NMWD for full solid angle and unit efficiency. The solid line of bottom ones are the pair yields in the energy sum of the two nucleons from the *bb* events indicated as the arrowed region, $\cos\theta < -0.7$. Totals of 43 and 116 events were observed for *nn* and *np* pairs in the *bb* region, respectively. Dashed lines in the bottom figures (e) and (f) indicate the energy sum spectra of the pair events in the non-*bb* region. The energy threshold was 30 MeV for both protons and neutrons.

angular region of $\cos\theta < -0.7$ for the *np* and *nn* pair yields, respectively. The shoulder bump observed in the *bb* region of the *nn* pair can be understood as a combined result of a statistical fluctuation due to the limited statistics of *nn* pair events (total 43 counts only in the *bb* region) and the binning effect of neutron z-position analysis (refer to Fig. 1). It was revealed that the background nucleon pairs produced through the absorption of π^- from the mesonic decay of ${}^{12}_{\Lambda}\mathrm{C}$ in the materials around the target were insignificant unlike the situation in the case of ${}^{5}_{\Lambda}\mathrm{He}$ [7]. The angular resolutions for the *np* and *nn* pairs were estimated to be $\sigma_{\cos(\theta_{np})} = 0.018$ and $\sigma_{\cos(\theta_{nn})} = 0.029$ at $\cos\theta = -0.9$, respectively.

Figs. 3(c) and 3(d) show the angular correlation of pair nucleons, namely the normalized pair yields per NMWD, $N_{NN}(\cos\theta)$. $N_{NN}(\cos\theta)$ can be expressed as $N_{nn(p)}(\cos\theta) = Y_{nn(p)}(\cos\theta)/(Y_{nm} \cdot \epsilon_{nn(p)})$, where Y_{nm} and $\epsilon_{nn(p)}$ are the total number of NMWD observed and the overall efficiency for detecting two nucleons from the *nn* and *np* pairs in coincidence including the detector acceptance. Y_{nm} is obtained by multiplying the number of hypernuclei produced in the ground state of ${}^{12}_{\Lambda}\mathrm{C}$ with the NMWD branching ratio b_{nm}, which is defined as $b_{nm} = 1 - b_{\pi^-} - b_{\pi^0}$, where b_{π^-} and b_{π^0} denote the π^- and π^0 branching ratios, respectively. The accuracy of the b_{nm} value of $0.768 \pm 0.012 \pm 0.005$ has been improved drastically due to the accurate measurement of b_{π^0} in the present experiment [13] in comparison with the previous one [14]. This accurate b_{nm} value made it possible to normalize the pair yields per NMWD without introducing significant systematic errors. The measured N_{NN} angular correlation of *nn* and *np* pairs could now be directly compared with those obtained from the FSI model calculation [15]. $\epsilon_{NN}(\cos\theta)$ was calculated with energy-dependent event-by-event simulations, and it was tested to be in good agreement with the data [16]. The neutron detection efficiency was calculated by the Monte Carlo simulation code—the modified DEMONS code—which is applicable to a multi-element neutron detector and has been tested for producing various experimental data well [5]. The angular correlation of *np* pair clearly exhibits a peak at $\cos\theta \simeq -1$, thereby indicating the *bb* emission of two nucleons, which is the signature of two-body decay final state. The *bb* kinematic regions defined as $\cos\theta < -0.7$ essentially include all the events in the *bb* kinematics peak. However, although dominance of *bb* kinematics events is degraded to a certain extent in the *nn* pairs, the *bb* events continue to be a major contribution. The dominance of the *bb* kinematic events observed in both *np* and *nn* pair confirms that $1N$ NMWD, $\Lambda p \to np$ and $\Lambda n \to nn$, is the main NMWD mode of ${}^{12}_{\Lambda}\mathrm{C}$. In non-*bb* region, we observe pair events more or less uniformly distributed over all angle in $\cos\theta$ whose total number reaches $\sim 40\%$ of the total pair numbers as shown in Table 1. Table 1 shows the pair numbers in each opening angle region. We consider the uniform distribution event extended even in *bb* region. Therefore, we will subtract the corresponding component of the uniform distribution events in *bb* region from the pair numbers N_{NN} for the later discussion of $1N$ NMWD.

In Figs. 3(e) and 3(f), the spectra of the *np* and *nn* pair yields in the NMWD of ${}^{12}_{\Lambda}\mathrm{C}$ in the *bb* region are shown in the energy sum of the two emitted nucleons. The rms energy-sum resolutions, $\sigma_{E_{\mathrm{sum}}}$, for *nn* and *np* pairs were estimated to be

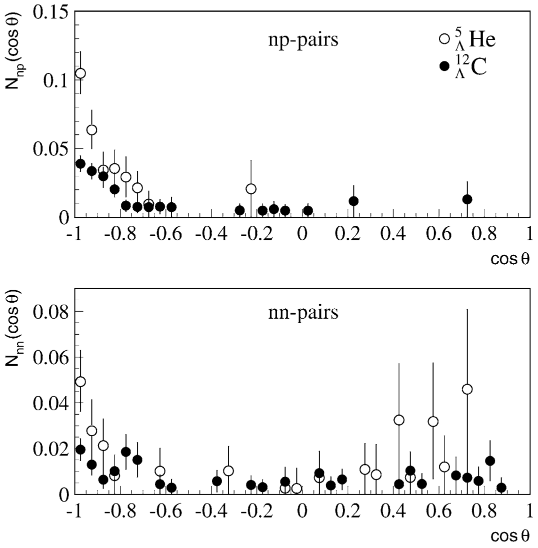

Fig. 4. *np* (top) and *nn* (bottom) pairs per NMWD of $^{12}_{\Lambda}$C (filled circle) and $^{5}_{\Lambda}$He (open circle) are represented as a function of their opening angle.

11 and 9 MeV for typical cases, such as 75 MeV nucleons, respectively. The energy-sum spectra show that the pair yields are distributed over a broad energy region from 70–80 MeV to the Q value at around 155 MeV; on the other hand, a few pair yields exist above the Q values. Those present above the Q values are considered to be due to the rapid deterioration in the neutron-energy resolution with an increase in the neutron energy. Since the energy sum spectrum of the two nucleons emitted in the two-body decay process, $\Lambda N \to NN$, would exhibit a peak at around the Q value, ~ 155 MeV, the broad energy distribution indicates that a large number of the *bb* kinematics nucleons suffered an energy loss on the way out of the residual nucleus with a mass of ~ 10. On the other hand, a dominant narrow peak around Q value was clearly visible in the *np* pair energy sum spectrum of $^{5}_{\Lambda}$He [7]. Therefore even if we consider the pair numbers confined in the *bb* region only, they include a considerable number of events that suffered FSI. We observe a similar or even more energy degraded energy-sum spectrum in *nn* pairs; however, the statistics are considerably lower.

Fig. 4 compares the angular correlations N_{np} $(\cos\theta)$ and N_{nn} $(\cos\theta)$ of $^{5}_{\Lambda}$He (open circle) [7] and $^{12}_{\Lambda}$C (filled circle). We observe dominant *bb* peaks in both $^{5}_{\Lambda}$He and $^{12}_{\Lambda}$C; this indicates that the $1N$ NMWD is the major mechanism of NMWD. By comparing the angular correlations of $^{5}_{\Lambda}$He and $^{12}_{\Lambda}$C, we observe two clear features-broadening of the *bb* peak in angular correlations and quenching of the *bb* pair numbers of $^{12}_{\Lambda}$C over those of $^{5}_{\Lambda}$He in both *np* and *nn* pairs. The total *bb* pair numbers of *np* and *nn* in $^{12}_{\Lambda}$C are reduced in comparison with those of $^{5}_{\Lambda}$He by $\sim 40\%$ and $\sim 20\%$, respectively. The features can be understood in terms of the same physics responsible for the energy degradation in the $E_{\mathrm{sum}}(^{12}_{\Lambda}\mathrm{C})$ spectra (Fig. 3(e)) in comparison with those of $^{5}_{\Lambda}$He. By considering that $2N$ theoretical branching ratio does not vary considerably with the mass number, and therefore, the relative importance of $2N$ with respect to $1N$ would be more or less the same for $^{5}_{\Lambda}$He and $^{12}_{\Lambda}$C [15], we infer that FSI is the major cause of broadening and quenching in the angular correlation and the degradation in the energy-sum spectrum. This implies that the effect of FSI on the pair numbers, even in the *bb* region, would not be negligible, and we must take it into account in order to extract Γ_n/Γ_p ratio from the pair number ratio. A significant portion ($\sim 40\%$) of the pair number is observed in the non-back-to-back region as shown in Table 1. The possible contributions in the non-back-to-back region are such as $2N$(or multinucleon)-induced NMWD events, those that suffer strong FSI, π^- absorption contamination and random coincidence events etc. However, in $^{12}_{\Lambda}$C, the contributions from the last two cases are found to be almost negligible, and the first two are considered to be the major contributions in non-back-to-back region. These non-*bb* events, whose strength reaches ~ 40 percent of NMWD, are the sources of the ambiguity in the previous results of Γ_n/Γ_p since they cannot be distinguished from $1N$ NMWD in the singles measurement. However, we can reject them by considering only the coincidence pair numbers in the *bb* region in the derivation of Γ_n/Γ_p, thereby resulting the ratio which is almost free from the ambiguity inherent in the previous results.

Next, we would like to derive the Γ_n/Γ_p ratio from the pair number ratio, N_{nn}/N_{np}, of the *bb* region. If neither Γ_{2N} contribution nor FSI existed, the ratio of N_{nn}/N_{np} would become Γ_n/Γ_p. However, as discussed, the effects of FSI still remain in the pair numbers of $^{12}_{\Lambda}$C. The most harmful effect of FSI is the channel crossover such as that from *nn* to *np* or from *np* to *nn*. It directly contaminates the pair number ratio. We observed 8 *pp* pair coincidence events in the *bb* region, which are possible only via the FSI process. A neutron in the *np* pair emitted at the vertex is converted into a proton via the nuclear interaction on the way out of the nucleus, thereby registering as a *pp* coincidence event. Therefore, they represent the channel crossover information of FSI on the nucleons emitted. Table 1 shows N_{pp} yields—the normalized *pp* pair numbers per NMWD. We will utilize N_{pp} for the correction of the FSI crossover effect on Γ_n/Γ_p ratio. The pair numbers in the *bb* region $N_{nn}(bb)$, $N_{np}(bb)$ and $N_{pp}(bb)$ can be expressed as

$$\begin{aligned}
N_{nn}(bb) &= r_n f_n^2 p + r_p f_n g_n q, \\
N_{np}(bb) &= r_p f_n f_p p + 2 r_n f_n g_p q, \\
N_{pp}(bb) &= r_p f_p g_p q + r_n g_p^2 q', \qquad (1)
\end{aligned}$$

where $r_n (= \Gamma_n/\Gamma_{nm})$ and $r_p (= \Gamma_p/\Gamma_{nm})$ are the fractions of neutron and proton induced channels out of the NMWD. $f_{n(p)}$ is the loss factor of neutrons (protons) from the energy region of interest due to FSI and $g_{n(p)}$ is the resulting crossover influx factor of neutrons (protons) from protons (neutrons) channel. The first terms of N_{nn} and N_{np} represent the pair numbers emitted out of the nucleus that maintain the channel starting at the initial weak vertex point. The second terms represent the pair numbers that cross the channel and end in a channel different from the starting one. p, q, and q' are the loss factors from the *bb* angular region of the original and channel crossing pairs; however, their actual values are not required in the following derivation. Instead, they are replaced with the observed *pp* pair numbers. If there were no FSI effects, $f_{n(p)}$ and $g_{n(p)}$ would be one and zero, respectively. We put $f_n = f_p = f$ and $g_n =$

$g_p = g$ by considering the charge symmetry of a strong interaction. A similar shape of proton and neutron spectrum obtained from the present experiment [6] supports this approximation. A simple simulation reveals that the g^2 term in Eq. (1) is less than 1 percent of the noncrossing terms and can therefore be neglected. Then, the second terms of $N_{nn}(bb)$ and $N_{np}(bb)$ of Eq. (1) are replaced by $N_{pp}(bb)$ and the $r_n/r_p (= x = \Gamma_n/\Gamma_p)$ ratio can be expressed in terms of pair numbers only as follows:

$$2N_{pp}(bb)x^2 - N_{np}(bb)x + N_{nn}(bb) - N_{pp}(bb) = 0,$$
$$\frac{\Gamma_n}{\Gamma_p} = x = 0.51 \pm 0.13 \pm 0.05. \tag{2}$$

The $N_{NN}(bb)$ numbers are the integrated pair numbers in the bb region after the subtraction of the background, which is assumed to be uniformly distributed in all $\cos\theta$ as we pointed out in the discussion of Figs. 3(c) and 3(d). The value of the constant background was determined by χ^2 fitting. The ratio of the raw pair numbers simply integrated over the bb region 0.60 ± 0.12 becomes 0.53 ± 0.13 after the subtraction of the uniform background. The obtained Γ_n/Γ_p ratio $0.51 \pm 0.13 \pm 0.05$ in the Eq. (2) is only 4 percent reduced from the pair number ratio $N_{nn}(bb)/N_{np}(bb)$. This is surprising considering that we observed the strong FSI effect both in the energy-sum spectra and in the angular correlations. However, the small correction can be understood considering that $N_{nn}/N_{np} \sim 1/2$ and hence the crossover pair numbers from nn to np and from np to nn are almost balanced, and therefore, the crossover-influx and -outflux due to FSI cancel each other. The systematic errors mainly originate from the uncertainties of the neutron detection efficiency (6%) and the pp pair acceptance (4%). Many sources of uncertainty such as b_{nm}, f_n and detection efficiencies are canceled out by taking the ratio [7].

The present result determined with the pair nucleon number ratio N_{nn}/N_{np} is in good agreement with the recent theoretical results based on heavy meson exchange (HME) model calculations [3,4]. It finally resolved the longstanding Γ_n/Γ_p ratio puzzle without ambiguity by removing the effect of FSI self-consistently and by rejecting non-bb events applying bb kinematic condition. It is quite accidental that the present result is close to that of the previous singles measurement which were determined only by assuming the nonexistence of $2N$ (or multi-nucleon induced) NMWD [5]. However, we have pointed out that there exist a significant amount ($\sim 40\%$ of the total) of non-bb events, which probably are the candidates of them. The present Γ_n/Γ_p ratio of ${}^{12}_{\Lambda}$C is in good agreement with that of the previous exclusive measurement of ${}^{5}_{\Lambda}$He ($0.45 \pm 0.11 \pm 0.03$), which indicates that the NMWD mechanism of s-shell (${}^{5}_{\Lambda}$He) and p-shell (${}^{12}_{\Lambda}$C) hypernuclei are rather similar. Though the Γ_n/Γ_p ratio determined from the ratio of pair numbers N_{nn}/N_{np} agrees well with those of the theoretical predictions [4,15], there remain discrepancies between the pair numbers N_{NN} of our measurement and those of the theoretical calculation [15]: the pair numbers for bb events and non-bb events, and the significant quenching of pair numbers of ${}^{12}_{\Lambda}$C compared with those of ${}^{5}_{\Lambda}$He. For example, the observed pair number of bb events is about half of the prediction while that of non-bb events is only a fraction.

4. Conclusion

We have measured, for the first time, the angular correlation $N_{NN}(\cos\theta)$ of the pair nucleons np and nn from the NMWD of ${}^{12}_{\Lambda}$C in coincidence measurement. We have exclusively identified the dominant $1N$ NMWD process, $\Lambda p \to np$ and $\Lambda n \to nn$, by requiring the bb angular correlation of the two emitted pair nucleons, which is the characteristic of two-body decay. Then we have obtained the Γ_n/Γ_p ratio from the ratio of pair numbers N_{nn}/N_{np} of $1N$ NMWD in which most of the non-bb events are excluded and FSI effects have been corrected using the simultaneously measured pp pair events. Therefore, the present Γ_n/Γ_p result is almost free from the ambiguities due to $2N$ (or multinucleon induced) NMWD contribution and the FSI effects which were inherent in the previous results obtained with singles spectra.

The obtained Γ_n/Γ_p ratio of $0.51 \pm 0.13 \pm 0.05$ is in good agreement with the recent theoretical results calculated based on HME models. This has finally resolved the long standing Γ_n/Γ_p ratio puzzle unambiguously. This ratio is very close to that of the previous exclusive measurement of ${}^{5}_{\Lambda}$He, thereby indicating the decay mechanisms of s-shell (${}^{5}_{\Lambda}$He) and p-shell (${}^{12}_{\Lambda}$C) hypernuclei are rather similar. Moreover, we have obtained the pair number yields in the non-back-to-back kinematics region, which would provide information on the possible $2N$ NMWD contribution.

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References

[1] W.M. Alberico, G. Garbarino, Phys. Rep. 369 (2002) 1, and references therein.
[2] K. Sasaki, T. Inoue, M. Oka, Nucl. Phys. A 669 (2000) 331;
K. Sasaki, T. Inoue, M. Oka, Nucl. Phys. A 678 (2000) 455.
[3] D. Jido, E. Oset, J.E. Palomer, Nucl. Phys. A 694 (2001) 525.
[4] A. Parreno, A. Ramos, Phys. Rev. C 65 (2001) 015204.
[5] J.H. Kim, et al., Phys. Rev. C 68 (2003) 065201.
[6] S. Okada, et al., Phys. Lett. B 597 (2004) 249.
[7] B.H. Kang, et al., Phys. Rev. Lett. 96 (2006) 062301.
[8] C. Bennhold, A. Ramos, Phys. Rev. C 45 (1992) 3017.
[9] S. Ajimura, et al., Phys. Rev. Lett. 84 (2000) 4052.
[10] T. Maruta, et al., Nucl. Phys. A 754 (2005) 168c, nucl-ex/0509016.
[11] S. Ajimura, et al., Phys. Lett. B 282 (1992) 293.
[12] K. Sasaki, T. Inoue, M. Oka, Nucl. Phys. A 691 (2001) 201.
[13] S. Okada, et al., Nucl. Phys. A 754 (2005) 178.
[14] A. Sakaguchi, et al., Phys. Rev. C 43 (1991) 73.
[15] G. Garbarino, A. Parreño, A. Ramos, Phys. Rev. C 69 (2004) 054603.
[16] B.H. Kang, Ph. D. Thesis, Seoul National University, 2004, p. 132.