Exclusive Measurement of the Nonmesonic Weak Decay of the ${}^{5}_{\Lambda}$He Hypernucleus

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(Received 11 September 2005; published 14 February 2006)

We performed a coincidence measurement of two nucleons emitted from the nonmesonic weak decay of ${}^{5}_{\Lambda}$He formed via the ^{6}Li(π^+, K^+) reaction. The energies of the two nucleons and the pair number distributions in the opening angle between them were measured. In both np and nn pairs, we observed a clean back-to-back correlation coming from the two-body weak reactions of $\Lambda p \to np$ and $\Lambda n \to nn$, respectively. The ratio of the nucleon pair numbers was $N_{nn}/N_{np} = 0.45 \pm 0.11(\text{stat}) \pm 0.03(\text{syst})$ in the kinematic region of $\cos\theta_{NN} < -0.8$. Since each decay mode was exclusively detected, the measured ratio should be close to the ratio of $\Gamma(\Lambda p \to np)/\Gamma(\Lambda n \to nn)$. The ratio is consistent with recent theoretical calculations based on the heavy meson and/or direct-quark exchange picture.

DOI: 10.1103/PhysRevLett.96.062301 PACS numbers: 21.80.+a, 13.30.Eg, 13.75.Ev

A free Λ hyperon decays almost totally into a pion and a nucleon, which is a mesonic weak decay process ($\Lambda \to N\pi$; $\Delta q \sim 100$ MeV$/c$). However, a Λ hyperon bound in a nucleus will eventually decay through either a mesonic or a nonmesonic weak decay (NMWD) process ($\Lambda N \to NN$; $\Delta q \sim 400$ MeV$/c$). NMWD, in which a Λ decays via a weak interaction with neighboring nucleon(s), becomes possible only inside the nucleus. The simplest and long assumed NMWD modes have been the one-nucleon ($1N$)-induced ones, namely, $\Lambda p \to np$ and $\Lambda n \to nn$, whose partial decay widths are denoted as Γ_p and Γ_n, respectively. The study of NMWD is of fundamental importance, since it provides a unique way of exploring the strangeness-changing, baryon-baryon weak interaction. In addition, the two-nucleon ($2N$)-induced NMWD ($\Lambda NN \to nNN$; Γ_{2N}) has been predicted in theoretical calculations, although its experimental identification has not yet been achieved.

There has been a long standing "puzzle" concerning the Γ_n/Γ_p ratio of NMWD of Λ hypernuclei. Until a few years ago, the experimental ratios had been reported to be close to or larger than unity, while the most naive one-pion-exchange (OPE) model with the $\Delta I = 1/2$ rule predicts very small ratios of 0.05–0.20. Other decay mechanisms beyond the OPE model have been considered to explain the large Γ_n/Γ_p ratio. The most relevant are (i) the heavy-meson-exchange (HME) mechanism in which exchanges of mesons heavier than pions (especially kaons) are considered, (ii) the direct-quark exchange (DQ) mechanism where the short range $\Lambda N \rightarrow NN$ decay is described using quark degrees of freedom, violating the $\Delta I = 1/2$ rule, and in a different context (iii) the inclusion of a two-nucleon-induced decay ($\Lambda NN \rightarrow nNN$) mechanism. Refer to the recent review article [1] for the details of various models and their results in terms of NMWD widths. It was recently found that in all previous theoretical work there had been an error in the K exchange amplitude, and its correction significantly increased theoretical values of the Γ_n/Γ_p ratio. After the correction was included, the DQ model gave 0.70 for the ratio in ${}^{5}_{\Lambda}$He [2]. The HME model calculation also predicted an increased value of up to 0.34–0.46 [3]. These calculations still underestimate the reported values of Γ_n/Γ_p ratios for light hypernuclei, although the large experimental errors (e.g., 0.93 ± 0.55 for ${}^{5}_{\Lambda}$He [4]) prevented any definite conclusion being reached. Accurate measurements of the Γ_n/Γ_p ratio are still awaited.

Concerning the Γ_n/Γ_p ratio, most of the previous experiments measured energetic protons only and the ratio was estimated without any experimental information on neutrons and low energy protons [4–6]. Thus, the result might be much affected by missing the low energy protons caused by the rescattering process of protons inside the nucleus [final-state interaction (FSI)] and the possible existence of the two-nucleon-induced decay modes. Both of these processes may induce the quenching of energetic proton numbers above the detection threshold, thus overestimating the Γ_n/Γ_p ratio. Important progress has been made through the accurate measurement of neutron spectra from the NMWD of ${}^{12}_{\Lambda}$C (the KEK-PS E369 experiment) [7]. A neutron spectrum from the weak decay of ${}^{12}_{\Lambda}$C was measured with an order of magnitude improvement in the statistics and signal-to-background ratio compared to the results of a previous experiment [4]. This result opened a door to directly comparing the yields of neutrons to protons from the NMWD. Very recently, we reported the simultaneously measured spectra of neutrons and protons emitted from NMWD of ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C [8] with much higher statistics than those of the previous experiments [4,7]. The neutron to proton yield ratios for both hypernuclei obtained with high threshold energy (60 MeV) are approximately equal to two, which suggests a Γ_n/Γ_p ratio of about 0.5, namely, $\Lambda p \rightarrow np$ channel dominance. However, the results still contained some uncertainties due to residual FSI effects and a possible contribution from $2N$-induced NMWD.

To resolve these experimental difficulties, it is important to clearly identify the two-body decay kinematics of $\Lambda n \rightarrow nn$ and $\Lambda p \rightarrow np$. To identify these decay channels unambiguously, we have measured in coincidence two nucleons emitted back to back. Here we chose ${}^{5}_{\Lambda}$He hypernuclei because the effect of FSI is expected to be small in such light hypernuclei. The yields of pair coincidences Y_{np} and Y_{nn} can be expressed as

$$Y_{nn}(\cos\theta) = Y_{\rm hyp} b_{nm} r_n \epsilon_{nn}(\cos\theta) f_n^2, \tag{1a}$$

$$Y_{np}(\cos\theta) = Y_{\rm hyp} b_{nm} r_p \epsilon_{np}(\cos\theta) f_n f_p, \tag{1b}$$

where $Y_{\rm hyp}$, b_{nm}, and $r_{n(p)}$ are the number of ${}^{5}_{\Lambda}$He produced, the branching ratio for NMWD of ${}^{5}_{\Lambda}$He, and $\Gamma_{n(p)}/\Gamma_{nm}$, respectively. The ϵ_{np} $(=\Omega_{np}\epsilon_n\epsilon_p)$ and ϵ_{nn} $(=\Omega_{nn}\epsilon_n^2)$ are the overall efficiencies for detecting np and nn pairs including the detector acceptance, where Ω_{NN} and ϵ_N are the detector solid angle for the nucleon pair NN and the efficiency for each nucleon N, respectively. The $f_{n(p)}$ is the reduction factor due to FSI on the yield of neutrons or protons in the energy range above 30 MeV. Since the $1N$-induced NMWD is a two-body interaction and emits nucleons with much higher momentum than the nuclear Fermi momentum, one can expect that the two emitted nucleons are strongly back-to-back correlated in their opening angle θ, shown in Fig. 1, and have their energy sum $E_{\rm sum}$ close to the Q value (153 MeV) of the NMWD process, if the $1N$-induced NMWD process occurs without FSI. We were able to reject most of the events due to FSI and $2N$ processes by requiring strict conditions on the angular and energy-sum correlation. Y_{nn} and Y_{np} are proportional to r_n and r_p as shown in Eqs. (1a) and (1b).

The r_n/r_p ratio, which is identical to the Γ_n/Γ_p ratio, is obtained from the ratio Y_{nn}/Y_{np} as

$$\frac{r_n}{r_p}\left(=\frac{N_{nn}}{N_{np}}\right) = \frac{\{Y_{nn}/Y_{\rm hyp}b_{nm}\epsilon_{nn}\}}{\{Y_{np}/Y_{\rm hyp}b_{nm}\epsilon_{np}\}}\,\frac{f_n f_p}{f_n^2} = \frac{Y_{nn}\Omega_{np}\epsilon_p}{Y_{np}\Omega_{nn}\epsilon_n}, \tag{2}$$

since $Y_{\rm hyp}b_{nm}$ is the total number of NMWD, and N_{nn} and N_{np} are the normalized pair yields per NMWD for a full solid angle and unit efficiency, respectively. We can assume that protons and neutrons suffer the same FSI effect

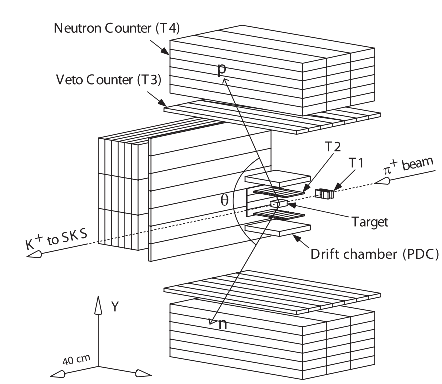

FIG. 1. Detector setup for the coincidence measurement of neutrons and protons emitted from NMWD in KEK-PS E462.

in the nucleus, i.e., $f_n = f_p$ because of the charge symmetry of the NN interaction. By taking the ratio of the nn-to-np pair yields, many systematic error sources, such as $Y_{\rm hyp}$, b_{nm}, ϵ_n, and f_n, cancel, and we do not need to know the branching ratio of the $2N$ contribution to get the Γ_n/Γ_p ratio from the pair yield ratio. In previous experiments, b_{nm} and f_n were sources of large errors in the Γ_n/Γ_p ratio. Now we directly obtain the Γ_n/Γ_p ratio from experimental quantities.

The experiment (E462) was carried out at the K6 beam line of KEK-PS using a 1.05 GeV/c π^+ beam to induce the ^{6}Li(π^+, K^+) reaction. Momenta of both the beam pion and the produced kaon were measured with $\sigma_p/p \sim 10^{-3}$ resolution using the K6 beam spectrometer and the superconducting kaon spectrometer. They were then used to reconstruct the excitation energy spectrum of the hypernucleus produced [9].

The setup detecting the particles from the weak decay of $^5_\Lambda$He is shown in Fig. 1. It has three sets of decay-particle counters, two located on the top and bottom of the target for a back-to-back coincidence measurement and one at the side to cover the solid angle for non-back-to-back events. Each of the top and bottom coincidence counter sets consists of fast timing counters (T2), a drift chamber (PDC), veto or stop timing counters (T3), and neutron counter arrays (T4). The side counter is similar but without the PDC.

Neutral particles, γ's and neutrons, were measured in T4 together with T3 as veto counters. The particle identification was done in the time-of-flight (TOF) spectra, from T1 to T4. The charged decay particles were identified by the three measured variables ΔE, TOF, and E, which denote the energy loss per unit length measured by the T2 counter, the time-of-flight between T2 and T3, and the analog-to-digital converter sum of sequentially fired counters, respectively. Protons and pions were clearly identified, and the pion contamination in the proton gate was less than 1%. The detection thresholds were $\sim$10 MeV for neutrons and $\sim$30 MeV for protons. The neutron detection efficiency of the neutron counter system, ϵ_n, was calculated by a Monte Carlo simulation with a modified version of the DEMONS [10] code, which is applicable to a multielement neutron detector and has been tested to reproduce various experimental data [7]. For charged particle analysis, only the central segments of T2 and T3 were used for more accurate determination of the acceptance and particle identification. Further details of the decay-particle counters are described in Ref. [8].

The inclusive $^6_\Lambda$Li excitation energy spectrum derived from the pion and kaon momenta is shown in Fig. 2(a). Figures 2(b) and 2(c) are the spectra in coincidence with nucleon pairs np and nn, respectively. Since the ground state of $^6_\Lambda$Li is above the $^5_\Lambda$He + p threshold, it promptly decays to $^5_\Lambda$He by emitting protons of several MeV. The vertical lines show the applied gate for the measurement of the decay of $^5_\Lambda$He. The enhanced yield in the quasifree Λ region of the nn coincidence excitation spectrum over that of the np pairs is considered to be due to two-neutron emission via the absorption of π^- from mesonic decay of quasifree Λs.

In Figs. 3(a) and 3(b), the distributions of the np and nn pair yields are seen in the energy sum of the pair nucleons. In the figure, only the pair events in which each of the nucleons has an energy above 30 MeV are counted. The hatched histograms show the contamination due to the absorption of π^- emitted from the mesonic decay. The amount of contamination was estimated by referring to the π^- absorption from mesonic decay of quasifree Λ formation events. The energy-sum resolution $\sigma_{E_{\rm sum}}$ for np and nn pairs was estimated to be 12 and 16 MeV, respectively, for the typical cases. The energy resolution of a neutron deteriorates rapidly in the high energy region, while that of a proton is stable with respect to its energy. In the energy-sum spectrum of np pairs, one can see the peak located around the expected value. The sharp peak indicates that the effect of FSI is not severe and two-body $1N$ NMWD is the major process. Note that the back-to-back kinematic condition has not yet been applied to these energy-sum spectra.

The upper panels in Figs. 3(c) and 3(d) show the yields of the np and nn coincidence events Y_{np} and Y_{nn} as a function of the opening angle between the two nucleons (θ_{np} and θ_{nn}). They are not yet normalized for acceptance and efficiency. The angular resolutions were estimated to be $\sigma_{\cos(\theta_{np})} = 0.018$ and $\sigma_{\cos(\theta_{nn})} = 0.026$ at $\cos\theta = -0.9$. A total of 90 and 30 events were observed in the back-to-back angular region of $\cos\theta < -0.8$ indicated as the vertical dashed lines for the np and nn pair yields, respectively.

The lower two panels in Figs. 3(c) and 3(d) show the angular correlation of nucleon pairs, where the vertical

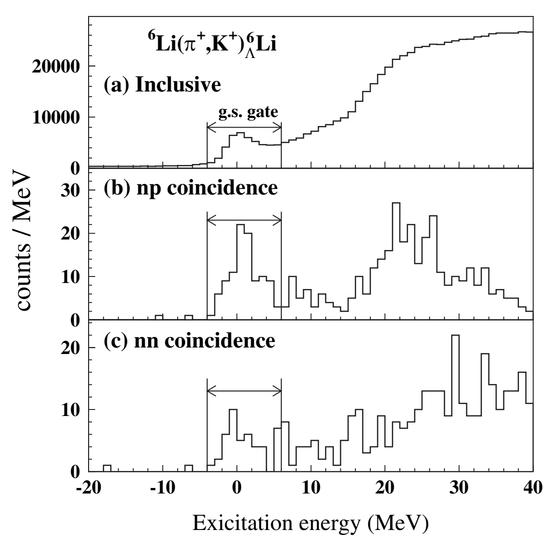

FIG. 2. The hypernuclear excitation energy spectra for $^6_\Lambda$Li for (a) inclusive, (b) np-pair coincidence, and (c) nn-pair coincidence measurements.

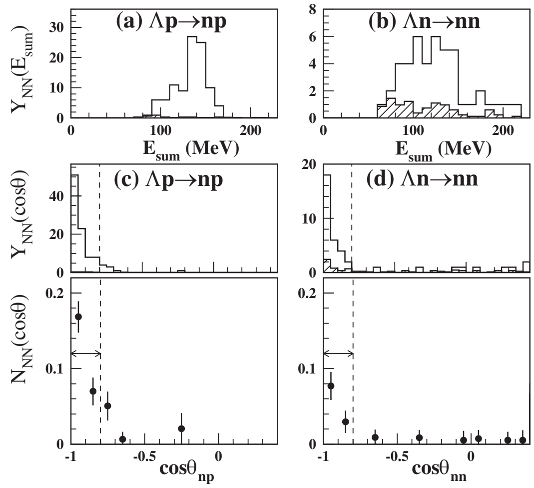

FIG. 3. (a),(b) The yields of the np and nn coincidence events Y_{np} and Y_{nn} as a function of the energy sum $E_{\rm sum}$ for the pair nucleons. The yields are not normalized for efficiency yet. (c),(d) The upper panel shows the yields of the NN coincidence events Y_{NN} plotted as a function of the opening angle between two nucleons (θ_{NN}). The lower panel depicts the normalized yields of the np and nn coincidence per NMWD.

scale is normalized for a full solid angle and unit efficiency [N_{np} and N_{nn} in Eq. (2)]. They are normalized with the simulated event-by-event efficiency $\epsilon_{NN}(\cos\theta)$. The b_{nm} value $0.429 \pm 0.012 \pm 0.005$ is derived from the π^- and π^0 branching ratios measured in the present experiment [11,12] and drastically improved from the previous 34% error [4]. This accurate b_{nm} value made it possible to normalize the pair yields per NMWD without introducing significant systematic error so that the measured N_{NN} angular correlation of nn and np pairs can be directly compared to those of the FSI model calculation [13].

Back-to-back peaking at $\cos\theta < -0.8$, which is the signature of a two-body final state, is clearly observed in the angular correlation for both np and nn pairs. This is the first clean observation of $\Lambda p \rightarrow np$ and $\Lambda n \rightarrow nn$ $1N$-induced NMWD processes.

Next we discuss the N_{nn}/N_{np} ratio in the back-to-back kinematic region ($\cos\theta < -0.8$), because the acceptance beyond there decreases rapidly. In this kinematic region, the ratio Γ_n/Γ_p simply becomes the N_{nn}/N_{np} ratio as shown in Eq. (2), assuming the same FSI on neutrons and protons. Possible differences in the FSI on neutrons and protons would not be significant due to the smallness of the FSI itself in the residual nucleus, ^{4}He or ^{4}H [13]. The similar spectral shape of the neutron and proton single spectra observed in the same experiment supports this assumption [8]. Comparing the yield of N_{nn} and N_{np} in the $\cos\theta < -0.8$ region, we obtained

$$\frac{\Gamma_n}{\Gamma_p} \simeq \frac{N_{nn}}{N_{np}} = 0.45 \pm 0.11(\text{stat}) \pm 0.03(\text{syst}). \qquad (3)$$

The systematic error of about 7% is mainly from the ambiguity of neutron detection efficiency, 6%. The Γ_n/Γ_p ratio is determined for the first time from exclusive measurement of each NMWD channel by detecting both emitted nucleons in coincidence in order to remove the ambiguities of the FSI and $2N$ NMWD contributions inherent in all the previous measurements. This ratio agrees well with the recent theoretical ratios of the direct-quark interaction and the heavy-meson-exchange models [2,3]. Although the Γ_n/Γ_p ratio is found to be smaller than previous values, it is still well above the OPE prediction. It is now clear that one needs additional shorter-range mechanisms, such as DQ and/or HME, to explain this strangeness-changing baryon-baryon weak interaction.

In summary, we have measured for the first time the energy sum and the angular correlation of two-nucleon pairs nn and np emitted in the NMWD of ${}^5_\Lambda$He. We have clearly observed a distinct nn and np back-to-back correlation coming from a one-nucleon-induced decay mode. We have determined the Γ_n/Γ_p of NMWD of ${}^5_\Lambda$He accurately and unambiguously from the pair number ratio N_{nn}/N_{np} in the back-to-back kinematics region, which is almost free from the effects of FSI and $2N$-induced NMWD contributions.

We are grateful to K. Nakamura and the KEK-PS staff for their support of our experiment and stable operation of the KEK-PS. B. H. K. and H. B. acknowledge support from Grants No. KOSEF(R01-2005-000-10050-0) and No. KRF(2003-070-C00015).

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