Proton Energy Spectra in the Nonmesonic Weak Decay of ${}^{12}_{\Lambda}$C and ${}^{28}_{\Lambda}$Si Hypernuclei

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Numbers of protons per Γ hypernuclear weak decay were measured as a function of proton energy above 40 MeV, explicitly identifying production of Γ hypernuclei by the (π^+, K^+) reaction. The ratios between the neutron-stimulated to proton-stimulated nonmesonic decay widths, $\Gamma(\Lambda n \to nn)/\Gamma(\Lambda p \to np) (= \Gamma_n/\Gamma_p)$ were extracted by fitting the proton energy spectra. The present result claims that the proton yields are suppressed and the Γ_n/Γ_p ratios are close to 1 both for ${}^{12}_{\Lambda}$C and ${}^{28}_{\Lambda}$Si in contradiction to theoretical expectations based on meson exchange models.

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Nonmesonic weak decay of Λ hypernuclei plays a unique role for the investigation of the baryon-baryon weak interaction, which is not easily studied experimentally. Although a Λ hyperon decays by the mesonic weak decay process, $\Lambda \to \pi N$, in free space, the nonmesonic weak decay becomes dominant over the mesonic weak decay for Λ hypernuclei heavier than $A \approx 10$, in which the nucleon emission is blocked by the Pauli exclusion principle. The total decay width of a Λ hypernucleus is expressed as a sum of the mesonic (Γ_π) and nonmesonic ($\Gamma_{\rm nm}$) decay widths as $\Gamma_{\rm tot}(= 1/\tau) = \Gamma_\pi + \Gamma_{\rm nm}$. The nonmesonic decay process is mostly the one-nucleon ($1N$) process, $\Lambda N \to NN$, which is further divided into a proton-stimulated (Γ_p:$\Lambda p \to pn$) and neutron-stimulated (Γ_n:$\Lambda n \to nn$) processes [1]. Recently, the two-nucleon ($2N$) process, $\Lambda NN \to NNN$ has been also discussed [2,3], although its experimental evidence has yet to be shown. Thus, the nonmesonic weak decay width can be decomposed as $\Gamma_{\rm nm} = \Gamma_n + \Gamma_p(+ \Gamma_{2N})$. The ratio, Γ_n/Γ_p, between the neutron- and proton-stimulated $1N$ decay widths is known to be sensitive to the structure of the ΛN weak interaction and has been intensively investigated both experimentally and theoretically. However, it has been a puzzle that experimental Γ_n/Γ_p ratios are close to 1 or greater than 1 for ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C [4,5], while theoretical calculations based on meson exchange models imposing the $\Delta I = 1/2$ rule predict small Γ_n/Γ_p ($\ll 1$) and cannot account for the experimental ratios. There have been efforts to solve the puzzle, such as employing exchange processes of mesons heavier than pions (ρ's, kaons, etc.) and/or 2π exchange process [6–9] and direct quark exchange process [10,11] in order to take into account of the short range nature of the ΛN weak interaction and/or examine the role of the $\Delta I = 1/2$ rule. Since the pion exchange process which has a large tensor component plays an important role, isospin of final two nucleons is preferred to be 0, resulting in small Γ_n/Γ_p ratios in the meson exchange models in most of Λ hypernuclei. There is also an attempt to construct a hybrid model that takes into account a direct quark exchange process for the short range part and a meson exchange process for the longer range [12]. Although the direct quark exchange process offers larger Γ_n/Γ_p, its contribution to the total decay width seems to be much smaller than that of the meson exchange process. It was also pointed out that the proton energy spectra would be shifted toward lower energy due to the $2N$ process, suggesting that apparently greater Γ_n/Γ_p would be obtained from the experimental spectra if the $2N$ process were not considered [3]. However, none of the theoretical models can consistently describe the total decay width and Γ_n/Γ_p so far.

At the same time, the reliability of the experimental data has been often questioned since large errors are quoted for Γ_n/Γ_p, partly due to poor statistics of the coincidence spectra and also experimental difficulty of detecting neutron spectra. In addition, for light Λ hypernuclei, it is necessary to determine pionic decay widths since their contribution is large. In medium-heavy Λ hypernuclei, however, the nonmesonic decay width becomes dominant and contribution of the mesonic decay width is less than a few percent of the total decay width. Therefore, measurement of proton energy spectra readily provides a great deal of information on the nonmesonic weak decay process even without measuring that of neutrons, once the total decay widths are known. In the present paper, we report on high-quality energy spectra of protons emitted in the nonmesonic weak decay of ${}^{12}_{\Lambda}$C and ${}^{28}_{\Lambda}$Si, particularly paying attention to the derivation of absolute number of protons per weak decay, and discuss their nonmesonic decay widths.

The (π^+, K^+) reaction was used to populate Λ hypernuclei since it gives us considerably cleaner excitation spectra in the hypernuclear bound region compared with those by the (K^-, π^-) reaction. A positive pion beam of 1.06 GeV/c was delivered at the K6 beam line of KEK 12 GeV PS, irradiating natural carbon (^{12}C:99%) and silicon (^{28}Si:92%). The targets were tilted so as to maximize the thicknesses in the beam direction to be 6.4 (C) and 10.3 (Si) g/cm^2, while keeping the thicknesses seen by the coincidence detector thin enough to minimize the energy threshold. Kaons emitted from the target were detected and momentum-analyzed by the SKS spectrometer, fully utilizing the advantage of its large solid angle of 100 msr [13]. The low energy charged particles emitted in the weak decay of Λ hypernuclei were detected by two sets of coincidence counter systems installed above and below the targets. Each system consists of timing counters, tracking chambers, and 11 layers of range counters. Energies of the charged particles were derived from the range information. The measured energy region was 30–140 MeV for protons and 12–70 MeV for pions, respectively. The energy thresholds were governed by the thicknesses of the targets and the timing scintillators. Protons and pions were clearly identified by the $\Delta E - E$ information, and the pion contamination in the proton spectra was kept less than 1%. The experimental setup is the same as that for the precision measurement of hypernuclear lifetimes [14]. Details of the SKS spectrometer and the coincidence counter system are described in Ref. [13,15].

An inclusive hypernuclear mass spectrum and a proton coincidence spectrum for Si are shown as an example in Fig. 1(a), where bumps corresponding to major-shell orbitals are indicated by s_Λ, p_Λ, and d_Λ.

A proton energy spectrum per weak decay for $^{28}_{\Lambda}$Si was obtained as follows. First, the inclusive energy spectrum [Fig. 1(a)] was fitted by five Gaussians and a polynomial function representing a quasifree component as shown by the solid lines. Overall normalization and spectral energy resolution were allowed to vary, while peak positions and relative intensities among the peaks were fixed taking the values from the previous high-resolution spectrum [16]. The proton-coincidence hypernuclear-mass spectrum [Fig. 1(b)] was fitted by the same function, with the intensities of the major peaks allowed to vary but their peak positions and resolution fixed as predetermined in the fitting of the inclusive spectrum (6.3 MeV FWHM). The first two peaks of the spectrum represented nucleon bound states which eventually weak decayed from the ground state [16]. A similar procedure was taken for $^{12}_{\Lambda}$C, in which case the energy resolution was 4.8 MeV (FWHM). Numbers of measured protons in the bound region "per weak decay" are plotted as shown in Fig. 2 as a function of "experimentally measured" proton energies, $E_p^{\rm exp}$. The proton spectrum is obtained as $R_p^{\rm exp}(E_p^{\rm exp}) = Y_{\rm coin}(E_p^{\rm exp})/Y_{\rm inclusive}$, in which $Y_{\rm inclusive}$ is the number of counts for the nucleon-bound peaks in the inclusive hypernuclear-mass spectrum and $Y_{\rm coin}(E_p^{\rm exp})$ that of the corresponding proton-coincidence spectrum. Only proton spectra above 40 MeV are discussed to avoid experimental ambiguity near the detector threshold of 30 MeV.

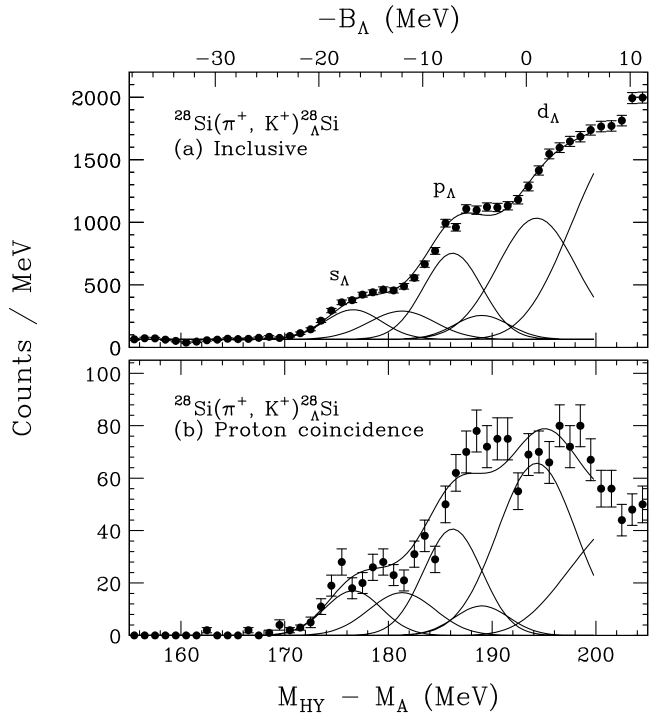

FIG. 1. Hypernuclear mass spectrum of the $^{\rm natural}$Si(π^+, K^+) reaction. (a) inclusive, (b) proton coincidence spectra.

The measured $R_p^{\rm exp}(E_p^{\rm exp})$ is related to the number of protons "per nonmesonic weak decay" coming out of the weak decay nucleus, $N_p(E_p)$, as

$$R_p^{\rm exp}(E_p^{\rm exp}) = \langle \varepsilon_{\rm coin} \Omega_{\rm coin} N_p(E_p) \rangle (1 - b_m).$$

The $N_p(E_p)$ spectrum can be calculated theoretically. The $\varepsilon_{\rm coin}$ and $\Omega_{\rm coin}$ are efficiency and solid angle of the coincidence counters, and b_m the sum of branching ratios of the charged and neutral mesonic weak decay. The solid angle, $\Omega_{\rm coin}/4\pi$, was evaluated to be 27 ± 1% by a Monte Carlo simulation and the average detection efficiency, $\varepsilon_{\rm coin}$, was found to be (84 ± 2)% for $^{12}_{\Lambda}$C and (86 ± 2)% for $^{28}_{\Lambda}$Si. Thus, about 23% of the weak decay protons were detected by the coincidence counters.

The branching ratios for negative pions were measured in the present experiment to be 9.8 ± 1.0(stat) ± 0.4(sys)% for $^{12}_{\Lambda}$C and 3.6 ± 0.8(stat) ± 0.2(sys)% for $^{28}_{\Lambda}$Si, while that of the neutral pionic decay for $^{12}_{\Lambda}$C was taken from the value reported in Ref. [17] [17.4 ± 5.7(stat) ± 0.8(sys)%]. However, since the branching ratio of the neutral pionic decay is not known for $^{28}_{\Lambda}$Si, it was calculated from the theoretical ratio, 2.3, of neutral to charged mesonic weak decay widths [18]. Thus, the branching ratios of mesonic weak decay were given to be 27.2 ± 1.0(stat) ± 5.8(sys)% for $^{12}_{\Lambda}$C and 11.9 ± 0.8(stat) ± 8.3(sys)% for $^{28}_{\Lambda}$Si.

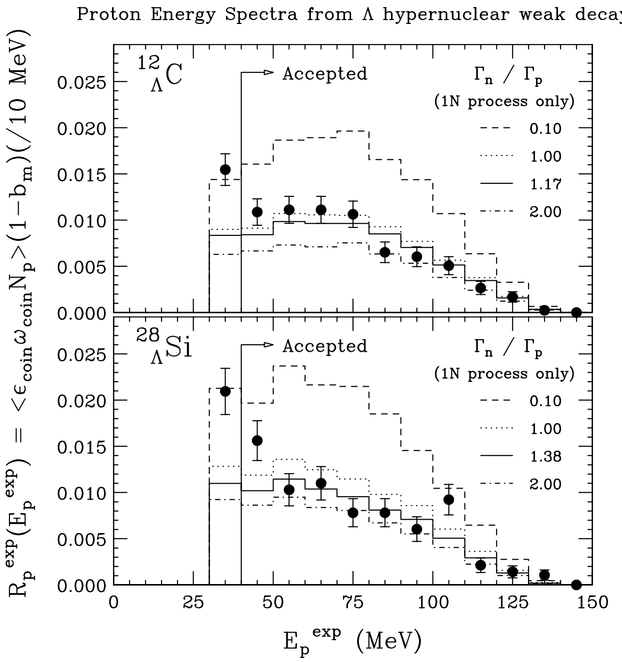

FIG. 2. Proton energy spectra measured by the coincidence counter system identifying hypernuclear bound states produced by the (π^+, K^+) reaction. The vertical axes are normalized to the number of protons per hypernuclear weak decay. Calculated spectra that took into account final state interaction, energy losses in the target and detectors, and the acceptance of the proton detectors are shown for comparison. The solid histogram represents the best fit ones.

The spectra shown in Fig. 2 fall slowly above the threshold and do not show a bump structure centered around 80 MeV, which is expected for the two-body $1N$ process. Energy loss and multiple scattering of protons in the target and the coincidence detectors are partly responsible, but they can be interpreted as needing consideration of other processes such as $\Lambda NN \rightarrow NNN$ and/or the stronger final-state interaction.

The calculated proton energy spectra were compared with the measured ones in the following way and the Γ_n/Γ_p ratios were derived. Protons and neutrons, which are originated from the weak interaction between a Λ hyperon and a nucleon with Fermi motion, subsequently undergo final state interactions, where initial numbers of weak decay protons and neutrons at the weak vertex are dependent on Γ_n/Γ_p. Some of the protons can be also converted to neutrons (and vice versa) during the cascade. Thus, proton energy spectra emerging from ${}^{12}_{\Lambda}$C and ${}^{28}_{\Lambda}$Si were modified and they were calculated with an intranuclear cascade code [19,20]. The calculations based on the essentially same code well accounted for proton spectra after pion absorption, in which protons are emitted in the similar energy region as that in the nonmesonic decay [21]. The protons to be observed by the coincidence counters are then followed by a GEANT Monte Carlo code taking into account of energy loss and multiple scattering both in the target and detectors. Those proton spectra both from the proton- and neutron-stimulated weak decay were summed incoherently according to a given Γ_n/Γ_p ratio. The calculated proton spectra "per nonmesonic weak decay" were also renormalized to "per weak decay" taking into account the branching ratios of mesonic weak decay and are shown overlaid in Fig. 2 for $\Gamma_n/\Gamma_p = 0.1$, 1.0, and 2.0. It indicates that the proton yields in the energy region above 40 MeV are considerably less than those calculated for small $\Gamma_n/\Gamma_p = 0.1$. By fitting the energy spectra with Γ_n/Γ_p as a free parameter assuming that the nonmesonic weak decay occurs through the $1N$ process only, Γ_n/Γ_p was obtained for ${}^{12}_{\Lambda}$C and ${}^{28}_{\Lambda}$Si to be $1.17^{+0.09}_{-0.08}(\text{stat})^{+0.20}_{-0.18}(\text{sys})$ and $1.38^{+0.13}_{-0.11}(\text{stat})^{+0.27}_{-0.21}(\text{sys})$ with statistical and systematic errors, respectively, as shown by a solid histogram in Fig. 2. The statistical errors came from the errors of spectral fitting while systematic errors were due to the errors of the mesonic decay widths and detection efficiencies $(\varepsilon\Omega)$ of the coincidence detectors. In addition, the spectra were also fitted considering contributions from the $2N$ process, which was calculated following the prescription of Ref. [19]. In Table I, the Γ_n/Γ_p ratios derived assuming "$1N$ only" and "$1N$ and $2N$" processes are listed. Even when the contribution of the $2N$ process is taken to be 32% and 29% of the nonmesonic weak decay width for ${}^{12}_{\Lambda}$C and ${}^{28}_{\Lambda}$Si, respectively, the lower bound of Γ_n/Γ_p still stays as large as 0.66 and 0.77 for ${}^{12}_{\Lambda}$C and ${}^{28}_{\Lambda}$Si. It is because the number of protons per weak decay is more strongly dependent on Γ_n/Γ_p in the region $0 < \Gamma_n/\Gamma_p < 1$ and the lower bound of the Γ_n/Γ_p is not very sensitive to the contribution of the $2N$ process in the region around $\Gamma_n/\Gamma_p = 1$ [19]. It is noted that stronger final-state interaction possibly lowers the Γ_n/Γ_p ratios

TABLE I. Γ_n/Γ_p ratios measured for ${}^{12}_{\Lambda}$C and ${}^{28}_{\Lambda}$Si are compared with previous data and recent calculations. The extracted Γ_n/Γ_p ratios in the column "$1N$ only" assumed no $2N$ process in fitting the proton energy spectra. Those in the column "$1N$ and $2N$" were obtained taking the ratio between the decay width of the $2N$ process (Γ_2) and that of nonmesonic weak decay (Γ_{nm}) as given in parentheses. See text for details.

	Γ_n/Γ_p "$1N$ only"	Γ_n/Γ_p "$1N$ and $2N$"	Refs.
		Experiment	
${}^{12}_{\Lambda}$C	$1.17^{+0.09+0.20}_{-0.08-0.18}$	$0.96^{+0.10+0.22}_{-0.09-0.21}$ $(\Gamma_2/\Gamma_{\text{nm}} = 0.32)$	Present
${}^{28}_{\Lambda}$Si	$1.38^{+0.13+0.27}_{-0.11-0.25}$	$1.18^{+0.14+0.30}_{-0.13-0.28}$ $(\Gamma_2/\Gamma_{\text{nm}} = 0.29)$	Present
${}^{12}_{\Lambda}$C	$1.33^{+1.12}_{-0.81}$		[4]
	$1.87 \pm 0.59^{+0.32}_{-1.00}$		[5]
		Theory	
${}^{12}_{\Lambda}$C	0.31		[23]
	0.53		[9]
	0.288–0.341		[22]
${}^{28}_{\Lambda}$Si	0.34		[23]

since an energy spectrum can be shifted toward the lower energy side and beyond the proton energy threshold of the present measurement. The energy spectra in the lower energy region are subject to further theoretical and experimental investigations.

The obtained Γ_n/Γ_p ratio for ${}^{12}_{\Lambda}C$ is consistent with those reported previously [4,5], but the quality of the data has been greatly improved. For ${}^{28}_{\Lambda}Si$, the Γ_n/Γ_p ratio has been for the first time measured and was found to be near unity as in the case of ${}^{12}_{\Lambda}C$. In Table I, the Γ_n/Γ_p ratios predicted by various models are also given. Although the total decay widths are reasonably well reproduced by those models, the experimental Γ_n/Γ_p ratios are not accounted for by any theoretical calculations presently available.

In summary, energy spectra of protons emitted in the nonmesonic weak decay of ${}^{12}_{\Lambda}C$ and ${}^{28}_{\Lambda}Si$ were measured by the (π^+, K^+) reaction with special attention to the normalization per weak decay. The measured proton spectra above 40 MeV per weak decay were compared with those calculated based on a meson-exchange model, applying an intranuclear cascade code and a GEANT simulation for the coincidence detector response. The Γ_n/Γ_p ratios were derived assuming the $1N$ process alone, and also including the $2N$ process in addition. The present high-quality proton-energy spectra show $\Gamma_n \approx \Gamma_p$ not only for ${}^{12}_{\Lambda}C$ but also ${}^{28}_{\Lambda}Si$ even when a sizable contribution of the $2N$ process is considered. The puzzle of large Γ_n/Γ_p ratios remains, being contradictory to most of the available theoretical models which predict small ratios. Spectral distortion due to the final-state interaction and contribution of the $2N$ process will be further issues to be studied experimentally and theoretically. In this regard, measurements of neutron energy spectra as well as correlation of pair nucleons in the nonmesonic weak decay have been conducted recently and the analyses are underway [24,25]. Those data together with the present proton energy spectra are expected to further reveal the nonmesonic weak decay process, providing clearer information on the contribution of the $2N$ process and the degree of the final state interaction.

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