Neutron energy spectra from the nonmesonic weak decay of ${}^{12}_{\Lambda}$C and ${}^{89}_{\Lambda}$Y hypernuclei

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We have measured the neutron spectra emitted in the weak decay of ${}^{12}_{\Lambda}$C and ${}^{89}_{\Lambda}$Y over the energy region above 10 MeV in the (π^+, K^+) reaction with better statistics and an improved signal-to-background ratio. The neutron yields in the nonmesonic weak decays were obtained from the spectra. By using the proton yield of ${}^{12}_{\Lambda}$C, the Γ_n/Γ_p ratio was estimated to be 0.51 ± 0.15 (stat) from the neutron-to-proton yield ratio for the first time, which suggests the Γ_n/Γ_p ratio is significantly less than unity.

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I. INTRODUCTION

The study of the weak decay properties of Λ hypernuclei is an important subject in strangeness nuclear physics. For very light hypernuclei, the mesonic decay mode (Γ_m:$\Lambda \to \pi N$, $q \sim 100$ MeV/c) is the dominant process. As the mass number increases, the nonmesonic weak decay (NMWD) which consists mainly of the two one-nucleon ($1N$) induced channels (Γ_p:$\Lambda p \to np$ and Γ_n:$\Lambda n \to nn$, $q \sim 400$ MeV/c) becomes dominant because of the Pauli blocking. In such a flavor-changing weak process, both parity-conserving and parity-violating partial widths can be measured since there is no possible contribution from the strong interaction. In the nucleon-nucleon weak interaction, in contrast, the parity-conserving partial width is masked by the overwhelming strong interaction. Thus, the NMWD plays an important role and gives us a unique opportunity for the study of baryon-baryon weak interactions.

One of the major issues in the study of the NMWD has been the large discrepancy between the experimental values and the theoretically calculated ones based on the one-boson-exchange model of the Γ_n/Γ_p ratio. The experimental results give values which are close to unity or larger [1–3], while theoretical calculations predict rather small ratios (0.1–0.5). The difficulties in understanding the Γ_n/Γ_p ratio have stimulated many theoretical approaches to solve this puzzle: the one-boson-exchange model including heavier mesons, the two-pion exchange model, and the quark model [4–7].

As for the experimental data, there have been large uncertainties mainly because Γ_n was not estimated directly from the neutron measurement, but indirectly from the proton measurement. Furthermore, the energy threshold is rather high ($30 \sim 40$ MeV) because of the thick target used to enhance the coincidence rate. Γ_n was extracted from Γ_{nm}, as $\Gamma_n = \Gamma_{nm} - \Gamma_p$, which in turn was estimated from the lifetime measurement $\Gamma_{tot} = \tau^{-1}$ subtracting the mesonic decay rate Γ_m, as $\Gamma_{nm} = \Gamma_{tot} - \Gamma_m$. Therefore, if the omitted mechanisms be-

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low the detection threshold are not properly taken into account, any proton missed from this detection threshold tends to be taken as neutron emission, which increases the Γ_n/Γ_p ratio. In this regard, there exist two important processes to be considered. One is the effect of final state interaction (FSI) on the emitted nucleons in the NMWD. FSI reduces the high-energy component and enhances the low-energy component, and becomes more important in heavier hypernuclei. The other process is the two-nucleon $(2N)$ induced process $(\Lambda NN \rightarrow NNN)$ predicted in the theoretical calculation, whose contribution was estimated as 20–30% of the free Λ width [8]. However, so far we have no experimental evidence of this $2N$ process.

Therefore, an accurate measurement of neutron over the full dynamic range is imperative. Further, we could reduce the detection energy threshold to as low as $\sim$10 MeV since neutrons suffer no energy loss in the target. It is quite important to obtain the whole energy spectral shape of the emitted neutrons in order to estimate the contribution of FSI and the $2N$ process, quantitatively. One consideration we should pay attention to is the signal-to-background (S/B) ratio in the neutron measurement when we reduce the energy threshold. Szymanski *et al.* [1] measured the neutron spectra from the NMWD of ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C in the (K^-,π^-) reaction. However, it suffered from poor statistics and a large background since a large number of π^-'s associated with the K^- beam and produced from K^- decay in flight can easily produce the background neutron through π^- absorption in the materials around the target. In this regard, the (π^+,K^+) reaction is superior to the (K^-,π^-) reaction to study the neutron yield of the NMWD. We designed the present experiment KEK-PS E369, the measurement of the neutrons in the NMWD of Λ hypernuclei using the (π^+,K^+) reaction, aiming for an order of magnitude improvement in statistics, and a similar improvement in S/B ratio keeping the detection energy threshold as low as possible.

II. EXPERIMENT

This is the second of our series of experimental investigations with the superconducting karon spectrometer (SKS) spectrometer: so far we have reported the results on lifetimes [9] and proton energy spectra [3]. The measurement was carried out at the K6 beam line of the KEK 12-GeV PS with the (π^+,K^+) reaction at 1.05 GeV/c on ^{12}C and ^{89}Y targets, the thicknesses of which are 1.739 g/cm^2 and 2.22 g/cm^2, respectively. The hypernuclear mass spectra of ${}^{12}_{\Lambda}$C and ${}^{89}_{\Lambda}$Y were produced by reconstructing momenta and trajectories with the beam line spectrometer and the SKS spectrometer [10].

The neutral decay particles (neutron and γ) emitted from Λ hypernuclei were measured with a neutral detection system as shown in Fig. 1. It consisted of a time-zero counter T0, charged particle veto counters T1 and T2, and neutron counter arrays T3. For the neutron measurement, four sets of arrays composed of six layers of scintillators with a total thickness of 30 cm were installed 68 cm from the center of the target. Table I shows the specifications of each detector.

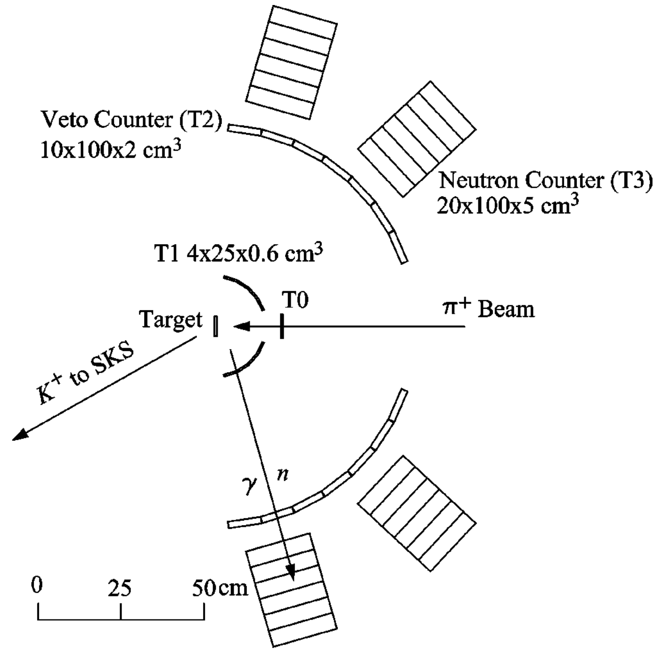

FIG. 1. Schematic view of the neutral detection system (top view) used in the neutron measurement.

III. DATA ANALYSIS

We set the gates for decay measurement in the hypernuclear mass spectra for ${}^{12}_{\Lambda}$C and ${}^{89}_{\Lambda}$Y [10] as shown in Fig. 2. These gates represent the Λ-bound regions. The particle identification of neutron and γ was performed by using the time-of-flight (TOF) technique. The neutron TOF from the decay vertex to T3 is

$$\mathrm{TOF}_n = (T_3 - T_0 - \tau_{HY}) - \mathrm{TOF}_b, \tag{1}$$

where τ_{HY} is the lifetime of Λ hypernuclei, T_3 is the timing of T3, T_0 is the time zero, and TOF_b is the TOF of the beam pion. The lifetime of ${}^{12}_{\Lambda}$C is 231$\pm$15 ps and we take the lifetime of ${}^{89}_{\Lambda}$Y as 215 ps, which is the saturated lifetime of heavy Λ hypernuclei [9]. The neutron velocity β and the neutron kinetic energy $E_n=[1/\sqrt{(1-\beta^2)}-1]m_n$ were obtained using TOF_n.

The $1/\beta$ spectra of (a) ${}^{12}_{\Lambda}$C and (b) ${}^{89}_{\Lambda}$Y are shown in Fig. 3 with 2 MeVee (MeV electron equivalent) threshold. The neutron gate corresponds to $5<E_n<150$ MeV. The neutron energy resolution is about 10 MeV (full width at half maximum) at 75 MeV. The background was estimated in the region below the γ peak and above the neutron gate in the

TABLE I. Specifications of the decay counters.

	Active area (cm^2)	Thickness (cm)	Distance[a] (cm)	
T0	12×12	0.6	30.0	Three segments
T1	48×25	0.6	15.0	Eight segments
T2	140×100	2.0	60.0	14 Segments
T3	80×100	30.0	68.0	Four arrays with six layers

[a]Distance from the target.

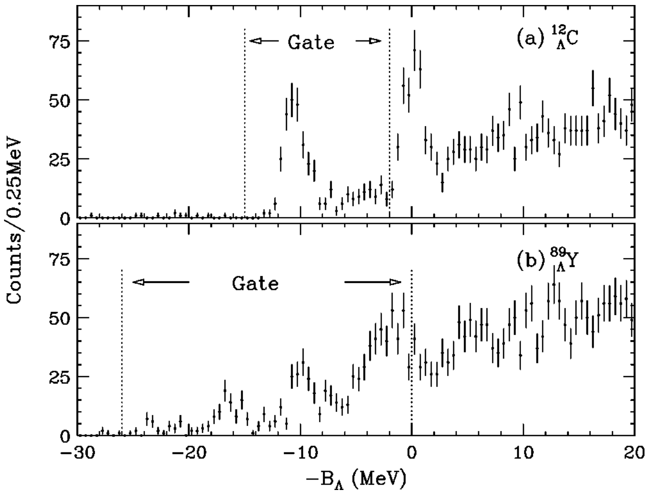

FIG. 2. Hypernuclear mass spectra as a function of Λ binding energy $-B_\Lambda$ for (a) ${}^{12}_{\Lambda}$C and (b) ${}^{89}_{\Lambda}$Y with the neutral particle coincidence.

TOF_n spectrum where the random background should be uniform. The estimated backgrounds within the neutron gate were about 2% and 3% for ${}^{12}_{\Lambda}$C and ${}^{89}_{\Lambda}$Y, respectively. The S/B ratio was greatly improved compared to the previous BNL experiment [1] [Fig. 3(c)].

The number of neutrons per NMWD, N_n, can be written as

$$N_n = Y_n/(Y_{HY} b_{nm} \varepsilon_n \Omega_n), \tag{2}$$

where Y_{HY} is the number of hypernuclei produced in the gated region and Y_n is the number of neutrons measured by T3. The acceptance of T3, Ω_n, was estimated as $(11.4\pm0.3)\%$ by GEANT-based Monte Carlo simulation.

The nonmesonic branching ratio b_{nm} for ${}^{12}_{\Lambda}$C was evaluated as 0.727 ± 0.059 from the mesonic branching ratios [11,12] and that for ${}^{89}_{\Lambda}$Y 0.996 from the theoretical ratio (See Table III in Ref. [13]). There is a non-negligible contribution

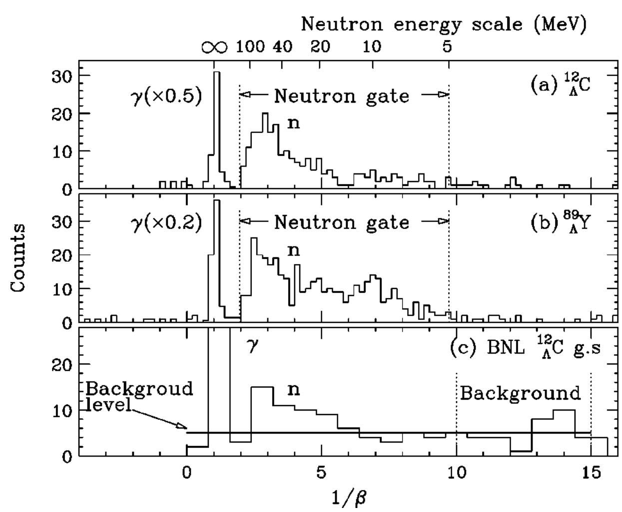

FIG. 3. $1/\beta$ spectra of (a) ${}^{12}_{\Lambda}$C and (b) ${}^{89}_{\Lambda}$Y with 2 MeVee threshold. (c) shows the previous BNL results [1] for ${}^{12}_{\Lambda}$C ground-state region with 10 MeVee threshold.

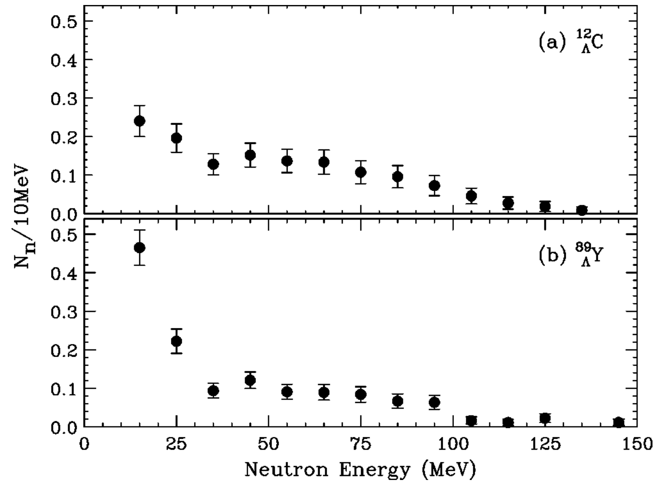

FIG. 4. Neutron energy spectra per NMWD of (a) ${}^{12}_{\Lambda}$C and (b) ${}^{89}_{\Lambda}$Y. Errors are statistical.

of the background neutrons produced through the absorption of π^- in the materials around the target emitted from mesonic decays of ${}^{12}_{\Lambda}$C. It was estimated using the yield of neutrons produced in the same way through the absorption of π^- emitted from the quasifree Λ decay ($\Lambda\rightarrow\pi^- p$). Here, we assumed that the neutron energy spectra are same. The neutron efficiency ε_n was calculated by Monte Carlo simulation DEMONS [14], which is applicable to a multielement neutron detector based on CECIL [15]. We have compared the calculations with various existing experimental results [16–19] and found that the integrated yields in the energy region above 10, 20, 30, and 40 MeV were well reproduced within 6% error level.

The neutron energy spectra per NMWD of (a) ${}^{12}_{\Lambda}$C and (b) ${}^{89}_{\Lambda}$Y are shown in Fig. 4. We should note that the two spectral shapes are very similar above 30 MeV and decline smoothly toward the high-energy end, while an enhancement in the low-energy region below 30 MeV is observed in the ${}^{89}_{\Lambda}$Y spectrum. In Table II, we summarize the number of neutrons per NMWD of ${}^{12}_{\Lambda}$C and ${}^{89}_{\Lambda}$Y in the energy region above 10, 20, 30, and 40 MeV. As the threshold energy increases, the number of neutrons per NMWD of ${}^{89}_{\Lambda}$Y becomes smaller compared to that of ${}^{12}_{\Lambda}$C. This may be interpreted as the effect of FSI.

IV. DISCUSSION

Hashimoto *et al.* [3] recently reported the energy spectra of emitted proton in the weak decay of ${}^{12}_{\Lambda}$C and ${}^{28}_{\Lambda}$Si which

TABLE II. Number of neutrons per NMWD of ${}^{12}_{\Lambda}$C and ${}^{89}_{\Lambda}$Y. Errors are statistical and systematic. Systematic errors are due to the error in neutron efficiency and that of b_{nm}.

	Number of neutrons per NMWD	
	${}^{12}_{\Lambda}$C	${}^{89}_{\Lambda}$Y
$E_n > 10$ MeV	$1.36\pm0.11\pm0.16$	$1.36\pm0.08\pm0.09$
$E_n > 20$ MeV	$1.12\pm0.10\pm0.13$	$0.89\pm0.06\pm0.06$
$E_n > 30$ MeV	$0.92\pm0.09\pm0.10$	$0.67\pm0.06\pm0.04$
$E_n > 40$ MeV	$0.80\pm0.08\pm0.09$	$0.58\pm0.05\pm0.04$

were compared to the FSI model calculations [intranuclear cascade (INC) calculations] of Ramos *et al.* [20]. The Γ_n/Γ_p ratio was obtained for ${}^{12}_{\Lambda}$C and ${}^{28}_{\Lambda}$Si to be $1.17^{+0.09+0.20}_{-0.08-0.18}$ and $1.38^{+0.13+0.27}_{-0.11-0.25}$, respectively, assuming that the NMWD occurs through the 1*N* process only. Unfortunately, the erratum of the Ref. [21] on INC calculation was reported later and the results were modified to be $0.87\pm0.09\pm0.21$ and $0.79^{+0.13+0.25}_{-0.11-0.24}$ [22] for ${}^{12}_{\Lambda}$C and ${}^{28}_{\Lambda}$Si, respectively. Since we now have both the neutron and proton spectra of ${}^{12}_{\Lambda}$C, it would be desirable to estimate Γ_n/Γ_p ratio directly from the experimental data avoiding such theoretical model dependence.

Thus, we would like to estimate the Γ_n/Γ_p ratio from the neutron-to-proton yield ratio in the case of ${}^{12}_{\Lambda}$C. Here, we assume the dominance of the 1*N* process ($\Lambda N \rightarrow NN$) in the nonmesonic weak decay. Then, the emitted neutron (proton) numbers per NMWD, $N_{n(p)}$, can be written as

$$N_n = (2r_n + r_p)f_n + r_p g_n, \tag{3a}$$

$$N_p = (2r_n + r_p)g_p + r_p f_p, \tag{3b}$$

where $r_n(=\Gamma_n/\Gamma_{nm})$ and $r_p(=\Gamma_p/\Gamma_{nm})$ are the fraction ratios of the neutron and proton induced channels out of the NMWD and $r_n+r_p=1$. $f_{n(p)}$ is the loss factor of neutron (proton) from the region counted due to FSI and $g_{n(p)}$ the crossover influx of neutron (proton) from proton (neutron) due to FSI. If there were no FSI, $f_{n(p)}$ would be one and $g_{n(p)}$ zero. Here, we have assumed $f_n=f_p=f$ and $g_n=g_p=g$, considering the similar spectral shapes in the energy region, say above 40 MeV, of the neutron and proton spectra, which reflect the isospin independence of the strong interaction and isospin symmetric propagating medium ${}^{12}_{\Lambda}$C. By using Eq. (3b), the Γ_n/Γ_p ratio has been estimated from proton measurements compared with some help of theoretical estimations for the factors f and g. However, the estimation would be largely affected by the uncertainty of theoretical calculations and also experimentally by the error on Γ_{nm} arising from the errors on Γ_{total} and the mesonic decay branching ratio.

Using the ratio between N_n and N_p, the Γ_n/Γ_p ratio can be written as

$$\frac{\Gamma_n}{\Gamma_p} = \frac{(N_n/N_p - 1)(1+\alpha)}{2(1-\alpha N_n/N_p)}. \tag{4}$$

It is noted that we have only one parameter, $\alpha=g/f$, to obtain the Γ_n/Γ_p ratio. Further, this method has an advantage that the ambiguity on Γ_{nm} is canceled out.

Now, we can estimate the Γ_n/Γ_p ratio from the yield ratio of neutron to proton, N_n/N_p. Unfortunately, the proton energy in Ref. [3] is only shown in the detected energy scale, which means that the energy of the emitted protons is degraded due to energy losses in the target material and other detector materials. Thus, part of low-energy protons below the detection threshold were lost from the data. In contrast, the present neutron energy is practically the emission energy of the neutron coming out of the nucleus, and the energy range is much wider than that of the proton spectrum in Ref. [3]. In order to compare the two spectra, we need to transform either the proton spectrum into the bare energy scale of neutron or neutron spectrum to the degraded energy scale of proton. It would be conceptually simpler to unfold the material effect from the proton spectrum in order to compare directly to that of neutron. However, due to the thick target used and the limited statistics of the proton spectrum in Ref. [3], it was impossible to do such an inverse transformation uniquely without knowing the whole shape of the proton energy spectrum before the energy losses. We need to rely on the spectral shapes from some model calculation, such as INC, of FSI effect on the emitted nucleons.

TABLE III. Experimental results and recent calculations of the Γ_n/Γ_p ratio for ${}^{12}_{\Lambda}$C. The "1*N* only" and "1*N* and 2*N*" stand for the processes considered to estimate the ratios.

Γ_n/Γ_p		Refs.
1*N* only	1*N* and 2*N*	
Experiment		
0.51 ± 0.15 (stat)		Present (α=0.11)
0.45 ± 0.14 (stat)		Present (α=0.076)
$1.33^{+1.12}_{-0.81}$		Szymanski *et al.* [1]
$1.87\pm0.59^{+0.32}_{-1.00}$		Noumi *et al.* [2]
$1.17^{+0.09+0.20}_{-0.08-0.18}$	$0.96^{+0.10+0.22}_{-0.09-0.21}$	Hashimoto *et al.* [3]
$0.87\pm0.09\pm0.21$	$0.60^{+0.11+0.23}_{-0.09-0.21}$	Sato *et al.* [22]
Theory		
0.288∼0.341		Parreño and Ramos [4]
0.53		Jido *et al.* [5]
0.368		Itonaga *et al.* [6]

In this discussion, we would like to take the maximum advantage of the availability of both spectra of proton and neutron in order to avoid the model dependence on the conclusion. What we need is just one number, N_n/N_p, the ratio of the integrated neutron-to-proton numbers per NMWD in the same dynamic range. Therefore we degrade the energy of neutrons as if they were protons, we can adjust the energy scale same as the proton energy scale in Ref. [3], and take account of the same detection condition. Then, the neutron number per NMWD over 40 MeV in the degraded energy scale became 0.69 ± 0.08 (stat) which is to be compared with the corresponding proton number 0.40 ± 0.02 (stat) [3]. Thus, we have obtained the N_n/N_p ratio in a common energy threshold to be 1.73 ± 0.22 (stat), although we could not tell the threshold energy explicitly.

In order to determine the Γ_n/Γ_p ratio, we need to know α. It is about 0.11 which we adopted from the FSI calculation on the proton energy spectrum by Ramos [23]. Then, the Γ_n/Γ_p ratio is obtained to be 0.51 ± 0.15 (stat) from Eq. (4). In order to see the effect of α magnitude on the Γ_n/Γ_p ratio, we obtained the ratio of 0.45 ± 0.14 (stat) with a different α, 0.076, estimated from the INC calculation [24]. We note that a 30% decrease of α changes the ratio by 0.06 which is much smaller than the current statistical uncertainty of 0.15. Table III summarizes the present result of the Γ_n/Γ_p ratio along with the recent theoretical calculations.

This is the first experimental result suggesting the dominance of the proton channel over the neutron channel in the NMWD of Λ hypernucleus. Recent theoretical calculations

TABLE IV. List of the data points of the neutron energy per NMWD of ${}^{12}_{\Lambda}$C and ${}^{89}_{\Lambda}$Y as shown in Fig. 4. The quoted values of E_n show the centers of the bins and the errors are statistical.

E_n (MeV)	Number of neutrons per NMWD ${}^{12}_{\Lambda}$C	${}^{89}_{\Lambda}$Y
15	0.24±0.04	0.46±0.05
25	0.20±0.04	0.22±0.03
35	0.13±0.03	0.09±0.02
45	0.15±0.03	0.12±0.02
55	0.14±0.03	0.09±0.02
65	0.13±0.03	0.09±0.02
75	0.11±0.03	0.08±0.02
85	0.10±0.03	0.07±0.02
95	0.07±0.03	0.06±0.02
105	0.05±0.02	0.02±0.01
115	0.03±0.02	0.01±0.01
125	0.02±0.01	0.02±0.01
135	0.01±0.01	
145	–	0.01±0.01

[4–6] on the NMWD reported greatly increased values of the Γ_n/Γ_p ratio reaching 0.5 and now agree reasonably well with our measured result of proton dominance. We note that the Γ_n/Γ_p ratio rederived from the proton spectrum comparing with the recently corrected INC calculation [21] also showed a value smaller than unity, namely, 0.87±0.09±0.21 [22].

However, we note that the low-energy portion of the spectra has not been well reproduced in the existing theoretical calculations. Further conclusive determination of the ratio Γ_n/Γ_p requires further studies on the FSI effect and the contribution from the 2N process. In the experimental side, coincidence measurements of the two emitted nucleons ($n+p/n+n$) would provide very useful information. In fact, such experiments are now in progress at KEK [25,26].

V. SUMMARY

We have measured the neutron spectra emitted in the weak decay of ${}^{12}_{\Lambda}$C and ${}^{89}_{\Lambda}$Y with better statistics and an improved signal-to-background ratio. Such improvement of the neutron spectrum and the recent accurate measurement of the proton spectrum [3] made it possible to estimate the Γ_n/Γ_p ratio to be 0.51±0.15 (stat), from the neutron-to-proton yield ratio of 1.73±0.22 (stat). It suggests that the Γ_n/Γ_p ratio of NMWD is significantly less than unity.

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APPENDIX

Table IV is the list of the data points of the neutron energy spectra per NMWD of ${}^{12}_{\Lambda}$C and ${}^{89}_{\Lambda}$Y as shown in Fig. 4. The quoted values of E_n show the centers of the bins and the errors are statistical.

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