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RECENT EXPERIMENTAL RESULTS OF WEAK DECAY OF Λ HYPERNUCLEI AND THE LONG STANDING Γ_n/Γ_p PUZZLE*

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In spite of notable progresses achieved at BNL and KEK during last decade, a consistent understanding of nonmesonic weak decay (NMWD) of Λ hypernuclei is yet to be achieved. Until recently, all the experimental data since the days of bubble chamber and emulsion showed the dominance of the neutron induced channel (Γ_n) over the proton induced one (Γ_p) in the NMWD of Λ hypernuclei, while the theoretical calculation predicted the predominance of the proton induced one. This inconsistency has been known as the famous 'Γ_n/Γ_p puzzle' and the central focus in the study of the decay mechanism of the Λ hypernuclei and the baryonic weak interaction. However, important progresses have been made recently in both the experimental and theoretical sides. In this paper, the progresses in the experimental data on NMWD will be presented. The direct comparison of the recent proton and neutron spectra showed the Γ_n/Γ_p ratio, $0.45 \sim 0.51 \pm 0.15(\text{stat.})$ much less than unity. This ratio agrees well with the recent theoretical calculations. Though this outcome seems to indicate that the famous long standing puzzle has almost been resolved, the decay asymmetry still remains to be understood.

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1. Introduction

There are two decay modes in the weak decay of Λ hypernuclei, mesonic and nonmesonic weak decay (NMWD) mode. Mesonic weak decay mode has two channels, π^- channel in which Λ decays via pπ^- and the π^0 channel where Λ via $n\pi^0$, as ($\Lambda\rightarrow p\pi^-$; Γ_{π^-}, and $n\pi^0$; Γ_{π^0}). The momentum involved in the mesonic decay is only about 100 MeV/c which is much lower than the nuclear Fermi momentum and henceforth much suppressed in the nucleus due to the Pauli blocking. On the other hand the nonmesonic weak decay (NMWD) modes in which a Λ decays via an interaction with a neighbour nucleon, either a proton or a neutron, become open in the nucleus as represented as (Λ+$p \rightarrow n + p$; Γ_p, and Λ+$n \rightarrow n + n$; Γ_n). Each emitted nucleon carries the decay momentum of about 420 MeV/c, much higher than the Fermi momentum so that it becomes the dominant decay mode in the heavy hypernuclei replacing the heavily suppressed mesonic weak decay mode.

The NMWD is via the $\Lambda N \rightarrow NN$ process, which is the strangeness changing baryon–baryon weak interaction. This NMWD process has attracted much attention during the last couple of decades, since many important issues are involved in its study. It is the main focus of this presentation. First, the crucial importance of NMWD study is that it provides the only practical means of exploring the four fermion, strangeness changing baryon–baryon weak interaction, $YN \rightarrow NN$, where Y indicates a hyperon. Second, there has been a long standing puzzle in the history of NMWD, namely the Γ_n/Γ_p ratio. Third, a pair nucleon ($2N$) induced NMWD, such as $\Lambda(NN) \rightarrow NNN$, has been predicted to be a significant component of NMWD, although it has not been identified experimentally yet. Fourth, the asymmetry, which is one of two most basic decay observables in the weak interaction study, also has been in a contradicting situation between experimental data and theoretical prediction on the asymmetry parameter, α_{NM}. It is one of the most imminent subjects of NMWD study. Finally, the final state interaction (FSI) becomes evidently an important element to understand the mechanism of NMWD. All these are crucial issues in order to understand the weak decay mechanism of Λ hypernulcei and the baryonic weak interaction.

Baryonic weak interaction has been studied mainly through parity violation phenomena in the nuclear and hadronic interaction via the meson exchange diagram (OME) which has been quite successful in explaining the parity violating phenomena in the nucleus. However, such study can prove only the parity violation component of the NN weak interaction. Furthermore, in the nuclear environment only the low momentum components are involved in the interaction. In order to understand the four baryonic weak interaction in a more universal way we need to understand also the parity conserving, the strangeness changing and higher momentum components of the weak interaction. The NMWD provides a practical means for such study of four baryonic weak interaction.

There has been long standing puzzle on the decay widths of NMWD, so called the Γ_n/Γ_p ratio. Most of the theoretical calculations on the NMWD have been based on one boson exchange (OBE) model in which various mesons are exchanged and $\Delta I = 1/2$ rule is adopted [1–3]. This OBE calculation is an extension, to the process $\Lambda N \to NN$, of the model which have been successfully applied to the NN parity violation weak interaction phenomena of $NN \to NN$. Until recently, essentially all these calculations predicted the predominance of the proton- over the neutron-induced NMWD while almost all the experimental results since the days of emulsion and bubble chamber showed the dominance of the neutron channel. This inconsistency has been known for a long time as the Γ_n/Γ_p puzzle and reviewed in many articles [4–6]. However, it is noted that though the experimental ratios, of the order of unity, are consistent with one another, their experimental uncertainties are too large to distinguish different models [7–9].

In order to resolve this inconsistency there have been many efforts from both experimental and theoretical sides. Since the NMWD involves a large momentum and correspondingly the short range effects become important, there have been efforts to introduce specific models for the short range part combined with that of the long range part, which is in most cases the one pion exchange model (OPE). The direct quark model and the phenomenological four fermion point interaction model are such examples [10–12]. Although the successfully enhanced Γ_n/Γ_p ratios from the direct quark model have been reported, so far the results of such model calculations exist only for s-shell hypernuclei.

Improvement of the experimental accuracy seemed very urgent. In this regards, the two experiments, E307 and E369 have been performed at KEK.

2. Experimental progress

The experiment E307 was to measure accurately the lifetimes, charged particle spectra, especially of the proton, and decay widths of a hypernuclei over a broad mass range. The experiment was done at the K6 beam line of 12 GeV KEK-PS. Λ hypernuclei were produced via (π^+, K^+) reaction with 1.05 GeV/c beam momentum, which produces clean hypernuclear mass spectrum with very low background. Scattered kaons are analysed in the SKS spectrometer which has a large acceptance solid angle, ~ 100 msr, and a short kaon flight path, ~ 4.5 m suited for decay experiments.

Decay spectrometers are placed above and below the target and its schematic view is shown in Fig. 1. It consisted of two fast timing coun-

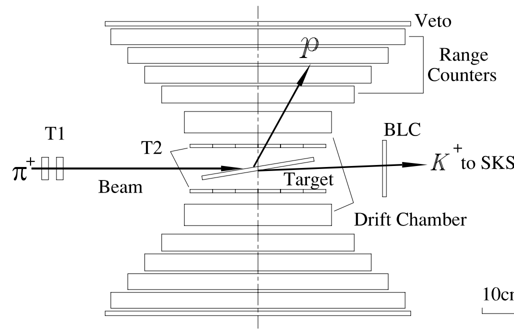

Fig. 1. The schematic view of the decay particle spectrometer used in E307 experiment for the measurement of lifetime (or decay width) and emitted proton energy spectra of Λ hypernuclei.

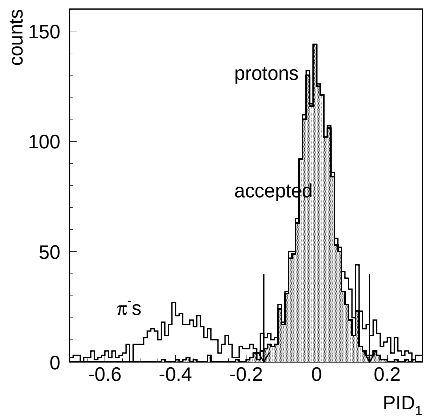

Fig. 2. The particle identification function for charged particles is shown and obtained from E (in range counter), ΔE (in T2) and the time of flight between T2 and the range counter.

ters, T1 before the target and T2 just after the target, a drift chamber and the range counter to measure the particle energy. Life time is obtained by measuring directly the production and decay time of the hypernucleus with fast plastic scintillation counters T1 and T2. A time difference between T1 and T2 was corrected for the flight time over the distances from T1 to the target (tof$_b$) and from the target to T2 (tof$_d$). Then the delay time is $dT = (T2 - \text{tof}_d) - (T1 + \text{tof}_b)$. In order to accurately determine the decay particle flight time, one has to know its velocity for which one needs accurate particle identification and energy determination. Particle identification of the charged particles was done via two methods, ΔE-range and tof-range methods. A typical projected particle identification function (PID) is shown in Fig. 2 together with the PID gate for proton; the contamination from the pion gate is minimal. The particle energy was determined by the PID and the range measurement [13].

Once the kaon momentum is determined by the SKS spectrometer system, the mass of the Λ hypernucleus produced can be determined by the 2 body kinematics. Fig. 3(a) shows the inclusive mass spectrum of the produced Λ hypernucleus and the arrow indicates the mass gate for the analysis of decay particle from ${}^{12}_{\Lambda}$C(g.s.). Fig. 3(b) and (c) show the mass spectra gated to the emitted proton and pion, respectively.

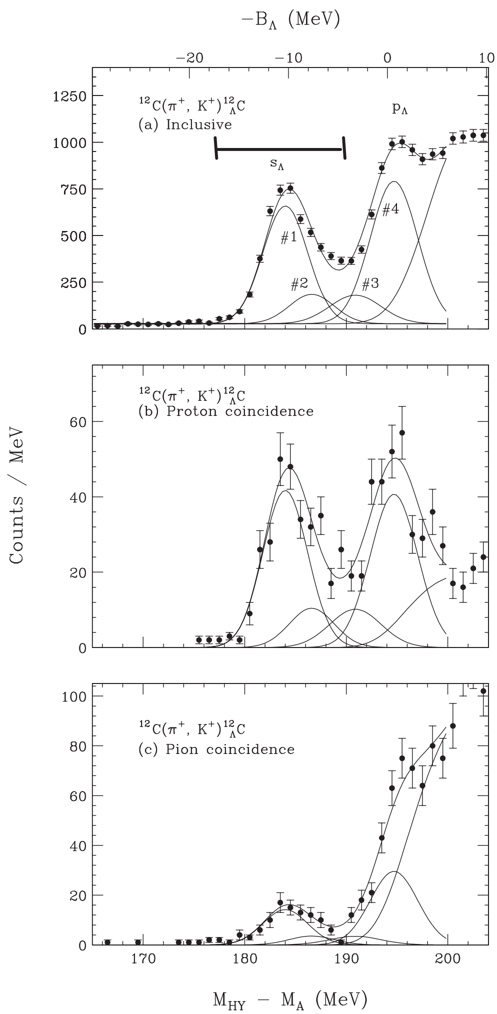

Fig. 3. (a) The inclusive mass spectrum, the mass spectra gated with (b) emitted protons and (c) emitted pions are shown for ${}^{12}_{\Lambda}$C hypernucleus.

Fig. 4 shows the delay time spectra, dT, for ${}^{12}_{\Lambda}$C, ${}^{28}_{\Lambda}$Si and ${}^{56}_{\Lambda}$Fe together with those of the prompt events of (π, pC) which is the time response of the system. This time response function shown in the dotted histogram is folded to the exponential decay function in order to fit the delay time spectra with the lifetime as a fitting parameter. The obtained lifetimes are plotted as closed circles in Fig. 5 along with the previously measured ones, *i.e.* open circles for those with the explicit identification of the hypernucleus and open squares for those without [7, 13, 16–18]. Present results of lifetimes of Λ hypernuclei revealed the systematic trend of its mass dependence with which the lifetime saturates already in the carbon mass region to a value about 80 percent of that of free Λ. Since the mesonic decays are almost forbidden for the nuclei above the carbon mass region, the saturation essentially is the behavior of the NMWD, and gives the $\Gamma_{\rm NM}$ of heavy Λ hypernuclei, at least up to Fe mass region, the value about 1.25 Γ_{Λ}.

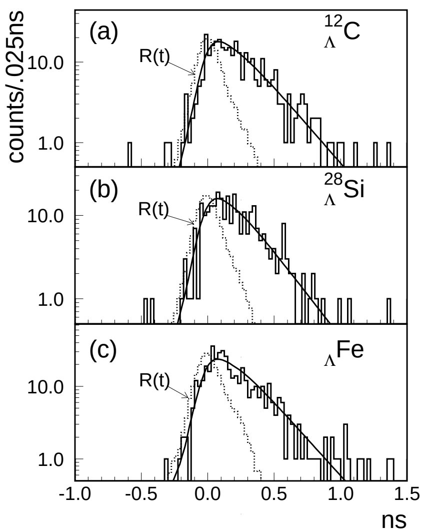

Fig. 4. The delayed time spectra of (a) ${}^{12}_{\Lambda}$C, (b) ${}^{89}_{\Lambda}$Y and (c) ${}^{56}_{\Lambda}$Fe are shown along with that of prompt (π, pC) reaction.

The measured proton energy spectra for ${}^{12}_{\Lambda}$C, ${}^{28}_{\Lambda}$Si and ${}^{56}_{\Lambda}$Fe are shown in Fig. 6 where they are compared with those of the INC (Intranuclear Cascade) calculation of Ramos *et al.* [19]. The INC calculation gives the energy of the emitted nucleon just out of the nucleus while those of the measured energy of the protons are those leaving the target. Therefore the measured energy of the proton is further degraded due to the target material. In order to match the energy scale, the shown INC spectra are those modified for the energy loss in the target material. Best fit value for Γ_n/Γ_p of ${}^{12}_{\Lambda}$C is 0.87 considering only the $1N$ NMWD, again confirming the Γ_n/Γ_p puzzle, and

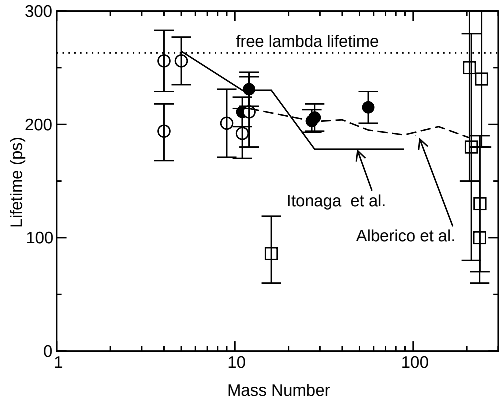

Fig. 5. Mass dependence of lifetimes of Λ hypernuclei. Open circles and squares are the previous data. Open circles are those with the explicit identifications of hypernuclei from BNL and KEK, and filled ones those from KEK-PS E307 experiment.

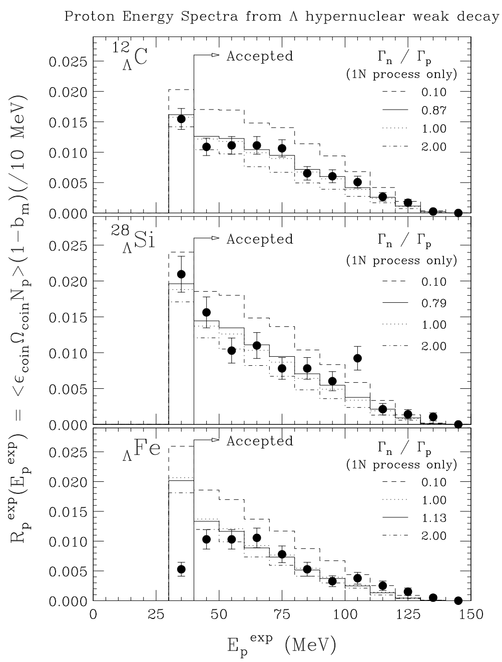

Fig. 6. The proton spectra of NMWD are shown for (a) ${}^{12}_{\Lambda}$C, (b) ${}^{28}_{\Lambda}$Si and (c) ${}^{56}_{\Lambda}$Fe. The spectra are compared with those of the INC calculation of Ramos *et al.* for 4 different Γ_n/Γ_p ratios without $2N$ NMWD contribution. The full line histogram is the best fit INC spectra.

the uncertainty of the INC is not included in the error estimation. The ratio is 0.6 when $2N$ contribution is included [19]. The ratios are smaller than unity but only within $\sim 1\sigma$ level from unity. The integrated proton number per NMWD over the energy region above 40 MeV is about 0.4. Here it was necessary to compare the proton spectra to those of INC in order to derive the Γ_n/Γ_p ratio since there are no counterpart neutron spectra. Therefore the derived result compared to INC is inevitably subjected to the uncertainty of the model calculation of the final state interaction. Unfortunately there is no standard model for the final state interaction yet and its uncertainty is not well controlled at the moment. In this sense it is very much desirable to measure the neutron spectrum for which the threshold energy can be lowered so that essentially all the emitted neutrons including the neutrons of the degraded energy due to FSI can be measured.

Fig. 7 shows the schematics of the E369 setup with which neutron spectra of the weak decay of ${}^{12}_{\Lambda}$C and ${}^{89}_{\Lambda}$Y have been measured [20]. It consists of 3 fast timing counters (T0, T1 and T2) and the plastic neutron counter of 30 cm thickness (T3). A typical status of n-γ separation in the time of flight between T0 and T3 is shown in Fig. 8. A typical timing resolution was about 200 ps. Fig. 8 shows the present $1/\beta$ spectrum for ${}^{12}_{\Lambda}$C (b), ${}^{89}_{\Lambda}$Y (c) and a comparison to that of the previous BNL measurement (a) [7]. The statistics and the signal to background ratio have been greatly improved over those of the previous experiment. There were essentially no background in the neutron region and the cross talk from gamma is negligible. Total number of neutron counts was about 200.

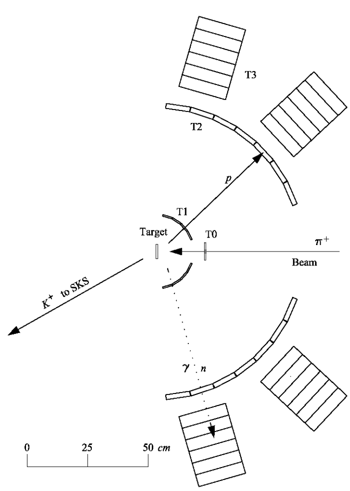

Fig. 7. The schematic view of the neutral particle detection system of the experiment E369 is shown. Neutron energy is measured with the time of flight between T0 and T3.

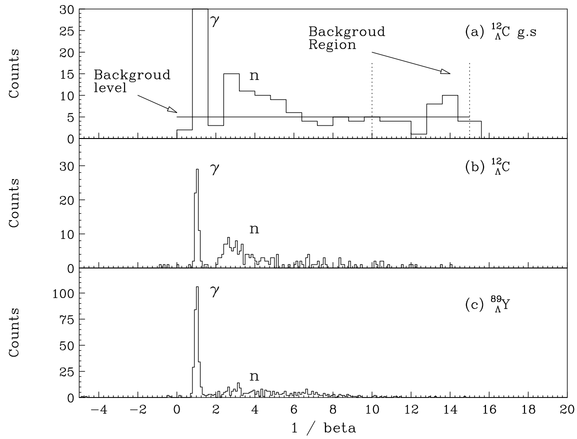

Fig. 8. $1/\beta$ spectra of (a) the previous BNL measurement [7], (b) the present measurement for $^{12}_{\Lambda}$C(g.s.) with 10 MeVee (electron-equivalent) threshold, and (c) $^{89}_{\Lambda}$Y with 2 MeVee threshold are shown.

The energy dependent efficiency of the neutron detectors was estimated using the simulation code which was based on the Demon's code and had been tested successfully for several experimental data. The efficiency corrected neutron energy spectrum converted from the $1/\beta$ spectrum is shown in Fig. 9(a) [20] and compared to the proton spectrum of E307 [9] in (b) which shows the detection threshold at about 30–40 MeV. The neutron yield is normalized per NMWD while that of proton is per weak decay. The total neutron number per NMWD above 40 MeV, N_n, is 0.86 while that of proton,

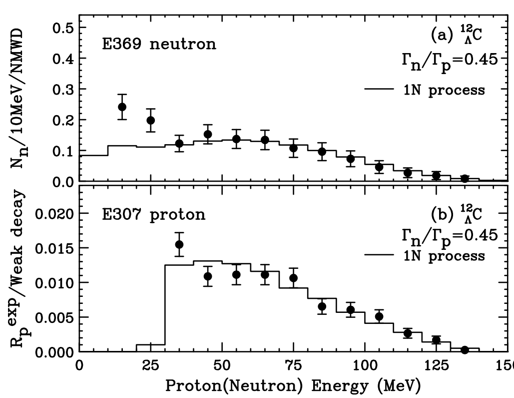

Fig. 9. The neutron energy spectrum of NMWD of $^{12}_{\Lambda}$C is shown in (a) along with that of proton in (b). Yield numbers are normalized per NMWD. Errors are statistical.

N_p, 0.40. We note that above the detection threshold the spectral shapes of the two spectra are rather similar, what indicates the similar nature of the final state interaction on proton and neutron. This can be understood from the isospin independence of the strong interaction and the isospin-symmetric propagating medium.

However, the neutron spectrum has to be corrected for the neutron background originating from the π^- absorption. This correction was done comparing the quasifree pion gated and neutron gated mass spectra, and the amount of the π^- absorption contamination estimated is shown in Fig. 10. After the correction, N_n became 0.80.

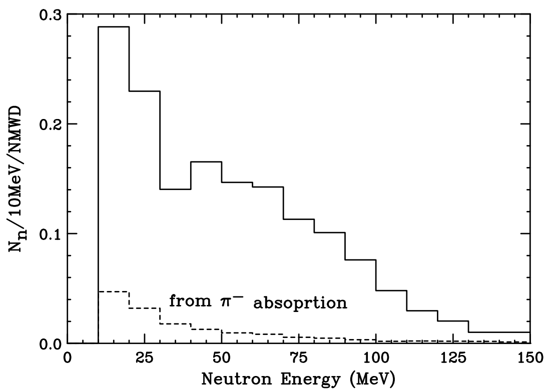

Fig. 10. The left neutron spectrum shown in histogram here is compared to that of the contamination due to the π^- absorption.

Since the proton spectrum exists only in the energy region above 30–40 MeV, we have to compare the two spectra there. Such direct comparison in the high energy region is further justified considering (1) that a proton and a neutron carry the same kinetic energy from weak vertex point, (2) that they are essentially identical particles and undergo the same FSI through the propagation out of the nucleus, and (3) that the effect due to the secondary cross talk contribution is minimized in the high energy region. However, we note that the neutron and proton spectra shown in Fig. 9 are in the measured energy scale which means that the neutron energy is close to the energy emitted from the nucleus, but that of proton is further degraded passing through the target material. Therefore, we need to unify the energy scale of the two spectra. We transformed the neutron spectrum into the energy scale of the proton. After the transformation, N_n became 0.69 and we now can directly compare this with N_p=0.40.

3. Direct estimation of Γ_n/Γ_p from the proton and neutron spectra

We may estimate the ratio assuming that NMWD process is mainly $1N$ process, namely $\Gamma_n + \Gamma_p = \Gamma_{\rm NM}$ or $r_n + r_p = 1$, where $r_{n(p)}$ is $\Gamma_n(\Gamma_p)/\Gamma_{\rm NM}$, respectively. Then the ratio of the neutron number to proton number per NMWD can be expressed as

$$\frac{N_n}{N_p} = \frac{2 - r_p + r_p\beta}{(2 - r_p)\beta + r_p} = \frac{0.69}{0.40} = 1.73\,, \tag{1}$$

where β is the ratio of the secondary cross talk contribution to that of primary nucleon such as an emitted neutron originated from a primary proton or *vice versa*. Here it was assumed that a proton and a neutron experience the same final state interaction due to the isospin independence of the strong interaction and the isospin-symmetric propagating medium. The β value is estimated with INC calculations over the energy region above 40 MeV where the secondary cross talk contribution is as small as one tenth of the primary one. β values adopted are 0.11 extracted from the INC calculation of Ramos *et al.* [21] and 0.076 from that we have formulated [22]. Then,

$$\frac{\Gamma_n}{\Gamma_p} = \frac{1 - r_p}{r_p} = 0.45 \sim 0.51, \tag{2}$$

for β=0.076$\sim$0.11. We now have obtained the Γ_n/Γ_p ratio significantly smaller than unity directly comparing the measured neutron and proton numbers without relying on INC calculation except the estimation of the second order effect. Direct comparison of the experimental yield numbers remove the dependence on INC calculation on FSI which is conveniently used but can not be considered as a standard model. Then the statistical error, 0.14, became the major one in Γ_n/Γ_p. The error due to the estimation of β was not included, and instead the ratios were given for two available values of β. The Γ_n/Γ_p ratio with $\beta = 0.11$, which is about 50 percent bigger than $\beta = 0.076$, was 0.51 which is only 11 percent bigger than 0.45. This is because INC calculation is used only for the second order correction of Γ_n/Γ_p ratio in this estimation. The difference of the two ratios might be considered as a theoretical uncertainty of the estimated ratio. This is the first experimental result showing the dominance of the proton channel in NMWD. However, we note here that ambiguities due to the final state interaction in the estimation of β and the neglection of $2N$ induced NMWD in our estimation of Γ_n/Γ_p still require further studies.

The current status of the Γ_n/Γ_p ratio is shown in the Table I. Relatively recent theoretical values are in the upper box and experimental ones in the lower box. There have been important development in the theoretical calculations which significantly increased the value of the ratio. The direct quark interaction model calculation produced the ratio for ${}^{5}_{\Lambda}$He 0.70 [14]. The extensive meson exchange model calculatios of Jido *et al.* and the correlated two pion exchange model of Itonaga *et al.* also were able to reproduce the increased value for the ratio reaching to 0.57 [3, 15]. It seems that as far as Γ_n/Γ_p ratio is concerned, new experimental and theoretical values on Γ_n/Γ_p ratio well agree with each other.

TABLE I

The previous and current measurements and calculations on Γ_n/Γ_p.

Γ_n/Γ_p	${}^{5}_{\Lambda}$He	${}^{12}_{\Lambda}$C
Parrenho *et al.* [2]	~ 0.07	~ 0.07
Sasao *et al.* [14]	0.70	
Jido *et al.* [15]	0.53	0.53
Itonaga *et al.* [3]		0.57
BNL	0.93±0.55	1.33± 1.12/0.81 [7]
KEK		1.87± 0.91/1.59 [8]
KEK		0.87± 0.09± 0.21(1N only) [19]
		0.60± 0.11± 0.23(1N & 2N) [19]
KEK		**(0.45-0.51)± 0.15 [20]**

4. Discussion

We have obtained the Γ_n/Γ_p ratio, $0.45 \sim 0.51$, directly comparing N_n and N_p assuming NMWD of $1N$ process only. Since the shapes in the low energy region of the neutron and proton spectra are not quite the same due to the different amount of the recoil contribution, we focused only on the high energy region, say above 40 MeV, where the cross over recoil contribution was estimated only $\sim 1/10$ of the primary. Considering the assumption and the correction we adopted, this derivation leaves some ambiguities due to the $2N$ NMWD contribution and treatment of the final state interaction. Therefore, it would be very important to confirm this first small experimental Γ_n/Γ_p ratio. In this regard, it would be desirable to measure each decay channel of NMWD exclusively in order to reduce the ambiguities due to FSI and the $2N$ components. As far as FSI is concerned, ${}^{5}_{\Lambda}$He which is of the least FSI would be the best hypernucleus for such experiment. Also an experimental identification of $2N$ NMWD is now necessary in order to extract the Γ_n/Γ_p ratio accurately. In this regards, KEK-PS E462 and E508 have been performed for exclusive measurement of the decay of s-shell ${}^5_\Lambda$He and p-shell ${}^{12}_\Lambda$C.

Asymmetry is another important issue in NMWD study. There have been two measurements for the asymmetry parameter, $\alpha_{\rm NM}$, for the decay of ${}^5_\Lambda$He and ${}^{12}_\Lambda$C whose values are very different as shown in Table II. $\alpha_{\rm NM}$ of ${}^5_\Lambda$He is close to zero while that of ${}^{12}_\Lambda$C(g.s.) is, -1.3 ± 0.4. Furthermore, until recently, theoretical predictions for $\alpha_{\rm NM}$, for ${}^5_\Lambda$He and ${}^{12}_\Lambda$C, were about $-0.2 \sim -0.4$ and did not agree with either of this experimental values. It is quite urgent to resolve this inconsistency of the asymmetry parameter together with that of the Γ_n/Γ_p ratio. The long standing inconsistency between the experimental and the theoretical values of the Γ_n/Γ_p ratio seems to be resolved in the recent development in that the reduced experimental ratio as explained in the previous section and the greatly enhanced recent theoretical ratios [15] finally reached to the values around 0.5. The recent theoretical development finally reproduced the experimental Γ_n/Γ_p ratio successfully on one hand, but on the other hand the prediction of the same theory on $\alpha_{\rm NM}$ seems to deviate further away as shown in Table II. The two KEK-PS experiments, E462 and E508, were performed to resolve

TABLE II

The previous and current measurements and calculations on $\alpha_{\rm NM}$.

$\alpha_{\rm NM}$	${}^5_\Lambda$He	${}^{11}_\Lambda$B	${}^{12}_\Lambda$C
previous theory	-0.273	-0.391	$-0.238 \sim -0.316$
E160			-1.3 ± 0.4 [23]
E278	0.24 ± 0.22 [24]		
current theory	$\mathbf{-0.33 \sim -0.68}$ [14]		$\mathbf{-0.73}$ [25]
E462	$\mathbf{0.09 \pm 0.08}$ **(prel.)** [26]		
E508			$\mathbf{-0.12 \pm 0.24}$ **(prel.)** [26]

these current problems of NMWD. In the experiments the spectra of decay particles, both charged and neutral particles, of ${}^5_\Lambda$He and ${}^{12}_\Lambda$C, have been measured in coincidence.

From these accurate spectra it is expected to be able to resolve the problems of the decay widths of NMWD and $\alpha_{\rm NM}$. Currently, the data taking runs have been completed and their analysis are in progress. Preliminary results of decay asymmetry for ${}^5_\Lambda$He and ${}^{12}_\Lambda$C obtained from the single proton spectra showed that both $\alpha_{\rm NM}({}^5_\Lambda\text{He})$ and $\alpha_{\rm NM}({}^{12}_\Lambda\text{C})$ are small and close to zero, 0.09 ± 0.08 and -0.12 ± 0.24, respectively. These results confirm the previously measured $\alpha_{\rm NM} = 0.24 \pm 0.22$ for ${}^{5}_{\Lambda}$He, but contradicting $\alpha_{\rm NM} = -1.3 \pm 0.4$ for ${}^{12}_{\Lambda}$C.

5. Summary

In summary, the recent experimental results of the weak decay of light Λ hypernuclei has been reviewed especially focusing on the long standing Γ_n/Γ_p puzzle. It was found from E307 experiment that the mass dependence of the measured lifetime showed a saturation to a value about 80 percent of that of free Λ. Since the mesonic decay width is strongly suppressed at heavy mass hypernuclei, this saturated lifetime essentially gives the nonmesonic weak decay width of heavy hypernuclei such as ${}^{28}_{\Lambda}$Si and ${}^{56}_{\Lambda}$Fe. The Γ_n/Γ_p derived from the proton spectra of ${}^{12}_{\Lambda}$C, ${}^{28}_{\Lambda}$Si, and ${}^{56}_{\Lambda}$Fe were close to or somewhat smaller than unity, but only with the large error bars due to the uncertain FSI and the high energy threshold in the charged particle measurements. In E369 the neutron spectrum for ${}^{12}_{\Lambda}$C has been accurately measured with drastically improved statistics and signal to background ratio. The direct comparison of the proton and the neutron spectra gave $\Gamma_n/\Gamma_p = (0.45 - 0.51) \pm 0.15$, the first experimental value much smaller than unity. This result agrees well with the recent theoretical results on the ratio finally resolving the long standing puzzle. However, there still remains the issue of the asymmetry parameter which shows a serious inconsistency between experimental and theoretical values and requires further studies.

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