Proposal for J-PARC Experiment

Coincidence Measurement of the Weak Decay of $^{12}_{\Lambda}$C and the three-body weak interaction process.

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Abstract. We propose a comprehensive experiment of the weak decay of ${}^{12}_{\Lambda}$C in order to measure the complete set of decay observables accurately. Although there have been a few previous experiments on ${}^{12}_{\Lambda}$C including the recent coincidence measurements, KEK-PS E462 and E508, it has not yet been possible to determine the decay widths, Γ_n and Γ_p, accurately, due to the lack of experimental information on the enhanced contribution of two-nucleon (2N) induced NMWD.

In spite of the recent notable progresses achieved at BNL and KEK, a consistent understanding of weak decay of Λ hypernucleus has not yet been established. Recent results of E307 and E369 on the proton and neutron singles spectra made it possible to determine the experimental Γ_n/Γ_p ratio much smaller than unity for the first time from the direct comparison of the spectra without relying on the FSI model calculation. However, the result was still subject to the ambiguities due to the possible 2N-NMWD contribution and the FSI effect, though via second order.

In E462 and E508 experiments, we detected the decay nucleons in coincidence for the first time over a wide dynamic range of the emitted nucleons in order to exclusively identify the decay channel. The decay channels, Λn $\rightarrow$nn and Λp $\rightarrow$np, were clearly identified by requiring the back-to-back (bb) angular correlation of the eimtted nucleon pairs which is the characteristic of two-body kinematics. From the measured pair nucleon back-to-back angular correlation, $N_{nn}$and N_{np}, the Γ_n/Γ_p ratios were extracted to be 0.45±0.11±0.03 for ${}^{5}_{\Lambda}$He and 0.51±0.13±0.04 for ${}^{12}_{\Lambda}$C, almost free from the ambiguities which have been inherent in the previous results due to the effect of nuclear final state interaction and the contribution of 2N NMWD decay process. These well agreed with the recent theoretical Γ_n/Γ_p results and finally resolved the long standing discrepancy problem of Γ_n/Γ_p. In addition we have observed the significant contribution of non-back-to-back (nbb) kinematic events in the nn pair angular correlation, which should be considered as the signature of two-nucleon induced non-mesonic weak decay, the three-body weak interaction process, of ${}^{12}_{\Lambda}$C. However, the statistics were not enough to identity it clearly and to determine the decay width.

Now Γ_{2N} becomes one of the key issues in the study of NMWD. It has been predicted theoretically to be significant component of the weak decay of Λ hypernuclei, but without experimental confirmation so far. Therefore it is very important to measure its contribution accurately not only to understand its enhancing mechanism in NMWD, but also to determine the decay widths of main NMWD channels.

In this proposed experiment, we will be able to measure the contribution of the two-nucleon induced non-mesonic weak decay of ${}^{12}_{\Lambda}$C, the weak 3-body interaction process, for the first time, studying both the pair nucleon angular correlation and the triple coincidence events. The decent statistics of $\sim$100 triple coincidence events will provide the information on the 2N NMWD mechanism. Consistent understanding of them will help to remove the ambiguity due to the uncertainty of the mechanism of the 2N process. Once the Γ_{2N} is determined, we will be able to determine the widths of non-mesonic weak decay of ${}^{12}_{\Lambda}$C, such as Γ_n and Γ_p, unambiguously and accurately for the first time. We will also measure the deuteron spectrum with enough statistics and to study its origin whether they are from the weak interaction or just a pick-up process in the emission. We will reduce the uncertainty of Γ_n/Γ_p ratio from $\sim$25-30% to $\sim$10% level. Followings are the requirements for this experiment;

1. Reaction ; (π^+,K$^+$) at 1.05 GeV/c beam momentum.
2. Decay counter; Extended E462/E508 counter to 2π solid angle.
3. Beam time request (Beam current); 100 shifts ($10^7\pi$/spill)
4. Expected non-back-to-back pair numbers for 2*N_π(E508) and same target thickness; $N_{nbb}(nn)$=230(23), $N_{nbb}(np)$=360(12), $N(nnn)$=48(3) and $N(nnp)$=64(2).

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III. Physics Motivations and Previous Searches

1. Weak Decay of Λ Hypernuclei

During last decade, there have been much effort and progress to understand the weak decay interaction of Λ hypernuclei employing new dedicated spectrometers and techniques. Especially the non-mesonic weak decay (NMWD) has been one of the central concerns of these efforts.

When a Λ hyperon produced inside a nucleus via a reaction like, (π^+,K$^+$) or (K^-,π^-), the prompt emission of the particle or γ-ray (less than $\sim$ps) deexcites the nucleus to a hypernuclear ground state. It will eventually decay through a weak interaction. One of the most characteristic features of the Λ hypernuclear weak decay is that it undergoes in the nuclear medium. The π mesonic decay process which is seen in the free space is strongly suppressed in the nuclear medium by the Pauli blocking due to its small energy release. Instead, the non-mesonic weak decay (NMWD) process which involves a large energy release ($\sim$176 MeV) dominates except for very light hypernuclei.

The NMWD process in a Λ hypernucleus is basically the four Fermion weak interaction, Λ + N $\rightarrow$ N + N, and is unique in nuclear matter and hard to be realized in the free space. In this process, there is no possible contribution from the strong interaction since the strangeness is not conserved. This makes the process more interesting since both parity conserving and parity violating partial rates can be measured whereas in the weak $N+N$ interaction case, the strong interaction masks the parity conserving signal of the weak interaction.

Total weak decay width of a hypernucleus is expressed as a sum of partial widths, $\Gamma_{HY} = \frac{1}{\tau_{HY}}$ $=\Gamma_M+\Gamma_{nm}$ where τ_{HY} is a lifetime of the hypernucleus and the mesonic and nonmesonic decay widths, Γ_M and Γ_{nm}, are given as $\Gamma_M=\Gamma_{\pi^-}+\Gamma_{\pi^0}$ and $\Gamma_{nm}=\Gamma_p+\Gamma_n+\Gamma_{2N}$, respectively. Here the Γ_{π^-} and Γ_{π^0} stand for the decay width of $\Lambda \rightarrow p+\pi^-$ or $\Lambda \rightarrow n+\pi^0$ decay process inside the nucleus and Γ_p and Γ_n denote the decay width of $\Lambda p \rightarrow np$ or $\Lambda n \rightarrow nn$ NMWD process. Possible existence of two-nucleon induced MMWD mode — Γ_{2N} $= \Gamma(\Lambda NN \rightarrow NNN)$ — has been theoretically discussed by several authors, but without experimental confirmation so far. However, our latest results of angular correlation of emitted two nucleons of E508 showed significant non-back-to-back kinematic events which might be interpretted as a signature of the process, but only with a limited statistical significance.

NMWD has been extensively investigated theoretically since the first finding of Λ. Primakoff et al. already in 1953 predicted the dominance of nonmesonic weak decay process in a nucleus. The most urgent issue has been the understanding of the total decay width and the partial decay widths, Γ_n and Γ_p.

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.

In order to resolve this issue various theoretical models have been proposed. Among them the meson exchange model with ΔI=1/2 rule has been most extensively studied with a meson-exchange diagram [1, 2, 3, 4]. Those models which reproduced the total decay width (or lifetime) well have difficulties in explaining large experimental Γ_n/Γ_p ratio, even when they considered the contribution of heavier meson exchange diagrams.

The other ones are the “hybrid" type models [5, 6] which combine two interactions. The short range interaction includes both ΔI=1/2 and ΔI=3/2 components from a direct quark-quark interaction, and the long range one is one-pion exchange interaction of ΔI=1/2 rule. When they only consider the short-range quark-model based interaction, the large Γ_n/Γ_p ratio is well explained. However, it extremely underestimate the total decay width (Γ_{nm}). Thus in order to compensate the missing decay widths, the long-range part of the interaction must be taken into account. Once they reproduce the total decay widths, they can give only a little improvement on the Γ_n/Γ_p ratio. This is called as Γ_n/Γ_p -ratio “puzzle" in the field of NMWD study. However, we should keep in mind that the large Γ_n/Γ_p-ratios reported by the experiments had large uncertainties.

The measured Γ_n/Γ_p results contain large statistical uncertainties and suffered much from the possible systematic shifts coming from the assumption concerning the quantities not observed in the experiment — neutron energy spectrum and low energy shape of proton energy spectrum.

During last decade, there have been considerable efforts in the experimental study to understand the nonmesonic weak decay of Λ hypernucleus. We will explain the important progresses in the experimental studies in the following.

2. E307 Experiment — Lifetime of Heavy Hypernuclei

One of the most recent progress of NMWD study is the results of our KEK-PS E307 experiment in which lifetimes (or total decay rates) and the partial decay rates, Γ_{π^-} and Γ_p have been measured for medium heavy hypernuclei covering the wide mass number region from ${}^{12}_{\Lambda}$C to ${}^{56}_{\Lambda}$Fe. The lifetimes(or total decay rate) were measured with accuracies close to 5% error. They showed a clear mass dependence of lifetime showing a fast saturation, around 80 % of that of free Λ hyperon, with an onset already at the mass of ${}^{12}_{\Lambda}$C [7].

Since the lifetime is the most cleanly measurable and most accurately measured weak decay observable, it is the first necessary step for a theoretical model to explain its systematics with respect to hypernuclear mass, but not a sufficient condition since the lifetime is an inclusive observable. To test a model, we need more accurate data of exclusive observables of weak decay, namely widths of each decay channel. The large Γ_n/Γ_p ratio has been repeatedly suggested in the recent data of modern counter experiments, of BNL and KEK for ${}^{11}_{\Lambda}$B and ${}^{12}_{\Lambda}$C as listed in Table 1. To shed light on the issue, the measurement of non-mesonic decay widths was extended in E307 to much heavier mass to study its systematics. The Γ_n/Γ_p ratios of E307 over the region of ${}^{12}_{\Lambda}$C to ${}^{56}_{\Lambda}$Fe were published recently [9]. The values of Γ_n/Γ_p larger than one (also given in Table. **??**) [17, 9], seemed to support the larger value of Γ_n/Γ_p ratio.

In addition, there is fundamental difficulty to extract the Γ_n/Γ_p ratio from the measured energy spectra of decay particles. It is due to the final state interaction of the outgoing decay particles and the detection energy threshold, about 40 MeV typically, which is quite high due to the energy loss in the target and the first layer of the decay counter. The missing part of the low energy region, those below 40 MeV, needs to be estimated relying on some model calculations on the final state interaction. However, such calculations are strongly model dependent and currently there are no standard method to estimate it reliably.

3. E369 Experiment — Neutron Measurement

In the previous proton experiments, 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 thresholds were rather high, $\sim$30-40 MeV. Therefore, if protons below threshold were not properly taken into account, the missing protons would tend to be taken as neutrons, thereby increasing 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 yields of high-energy component and enhances those of low-energy one. The other process is the two-nucleon (2N) induced NMWD process (ΛNN $\rightarrow$NNN), which is the interesting three-body weak interaction process, predicted to be $\sim$20% of free Λ width in the theoretical calculation [11]. However, so far we have had no experimental confirmation of this 2N process.

In the recent experiment KEK-PS E369, the decay neutron from ${}^{12}_{\Lambda}$C and ${}^{89}_{\Lambda}$Y has been successfully measured with a threshold down to 10 MeV. This was practically the first decent neutron spectra directly measured for the nuclei beyond 1*s*-shell hypernuclei [27]. Improvement in the decay neutron spectrum from that of the previous data [8] for ${}^{12}_{\Lambda}$C was twofold, both total neutron number and the signal to background ratio in the spectrum have been improved by an order of magnitude as can be seen in Fig. **??**.

TABLE 1. Recent Experimental results for the NMWD width of Λ hypernuclei. Superscripts: [a]; 1N-induced process only, [b]; 1N- and 2N-induced processes included.

	$\Gamma_{nm}/\Gamma_{\Lambda}$	$\Gamma_p/\Gamma_{\Lambda}$	$\Gamma_n/\Gamma_{\Lambda}$	Γ_n/Γ_p	Ref.
${}^{4}_{\Lambda}H$	0.17 ± 0.11				[12]
${}^{4}_{\Lambda}He$	0.17 ± 0.05	0.16 ± 0.02	$0.01^{+0.04}_{-0.01}$	$0.06^{+0.28}_{-0.06}$	[12]
${}^{4}_{\Lambda}He$		0.16 ± 0.02	0.04 ± 0.02	0.25 ± 0.13	[13]
${}^{5}_{\Lambda}\mathrm{He}$	0.41 ± 0.14	0.21 ± 0.07	0.20 ± 0.11	0.93 ± 0.55	[8]
${}^{5}_{\Lambda}\mathrm{He}$				$0.45 \pm 0.11 \pm 0.03$	[14]
${}^{11}_{\Lambda}\mathrm{B}$		$0.30 \pm 0.07^{+0.08}_{-0.04}$		$2.16 \pm 0.58^{+0.45}_{-0.95}$	[22]
${}^{11}_{\Lambda}\mathrm{B}$				$1.04^{+0.59}_{-0.48}$	[8]
${}^{12}_{\Lambda}\mathrm{C}$		$0.31 \pm 0.07^{+0.11}_{-0.04}$		$1.87 \pm 0.59^{+0.32}_{-1.00}$	[22]
${}^{12}_{\Lambda}\mathrm{C}$	1.14 ± 0.20			$1.33^{+1.12}_{-0.81}$	[8]
${}^{12}_{\Lambda}\mathrm{C}$	$0.84 \pm 0.06 \pm 0.07$			$1.17^{+0.09}_{-0.08}{}^{+0.20}_{-0.18}$	[9][a]
${}^{12}_{\Lambda}\mathrm{C}$	$0.84 \pm 0.06 \pm 0.07$			$0.96^{+0.10}_{-0.09}{}^{+0.22}_{-0.21}$	[9][b]
${}^{12}_{\Lambda}\mathrm{C}$				$0.45 - 0.51 \pm 0.15$	[27][a]
${}^{12}_{\Lambda}\mathrm{C}$				$0.51 \pm 0.13 \pm 0.04$	[15][b]
${}^{28}_{\Lambda}\mathrm{Si}$	$1.13 \pm 0.09 \pm 0.11$			$1.38^{+0.13}_{-0.11}{}^{+0.27}_{-0.25}$	[9][a]
${}^{28}_{\Lambda}\mathrm{Si}$	$1.13 \pm 0.09 \pm 0.11$			$1.18^{+0.14}_{-0.13}{}^{+0.30}_{-0.28}$	[9][b]
${}^{56}_{\Lambda}\mathrm{Fe}$	1.20 ± 0.10			$2.54^{+0.40}_{-0.46}{}^{+0.46}_{-0.67}$	[17][a]

We observed 182 neutrons with good signal-to-noise ratio of S/N=15 even when we apply very low neutron detection threshold of 2 MeV_{ee}; previous results were $\sim$22 neutrons detected with S/N-ratio $\sim$1 even when they imposed very high detection threshold at 10 MeV_{ee}. This drastic improvement of the neutron detection enabled us to analyze the yield and the energy spectrum shape of neutrons from NMWD process.

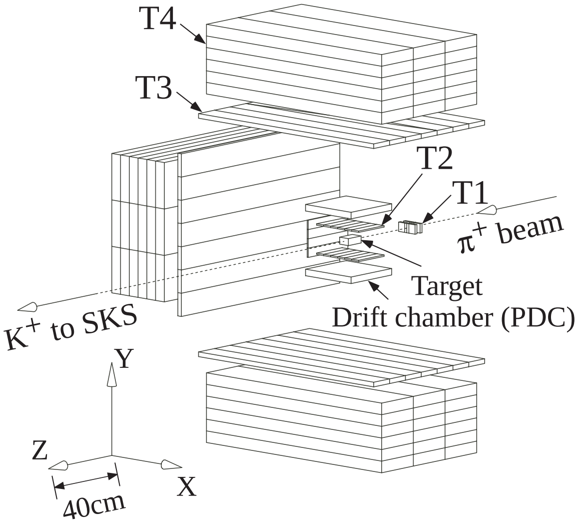

FIGURE 1. Schematics of the coincidence detectors are shown.

We now have both the neutron (preliminary) and proton spectrum in the nonmesonic weak decay of ${}^{12}_{\Lambda}$C. Since the experimental information is missing only in the low energy region. Therefore if we look at the high energy region such as that above 40 MeV where the secondary particle contribution is relatively small, we can derive Γ_n/Γ_p from the ratio of neutron number to proton number in the region, N_n/N_p. However, since the channel cross-over effect due to FSI, such as that from nn to np or from np to nn, directly contaminate the nucleon number ratio, we need to compensate for its effect, though its effect is in the second order. Neutron number per NMWD, N_n, above 40 MeV was 0.69 while that corresponding to proton spectrum 0.4 from E307. The total nucleon number N_n+N_p=1.09 that is much smaller that the INC prediction which is about 1.6. In retrospect, we now understand why we has such a long standing problem of Γ_n/Γ_p during last several decades. The strong quenching of neutron number was the source of the confusion. Then we have to understand why there are so strong quenching in the neutron number.

The details of Γ_n/Γ_p derivation from the number ratio N_n/N_p compensating the cross-over effect were explained in the reference [27]. In this FSI-model independent analysis, the Γ_n/Γ_p value was obtained 0.51±0.15 assuming no 2N-NMWD contribution. This agreed well with the recent theoretical Γ_n/Γ_p results and seemed finally resolved the long standing discrepancy problem of Γ_n/Γ_p. However, it still has some uncertainty due to the residual FSI effect and a possibly large one from 2N-NMWD process, $\Lambda NN \rightarrow nNN$, because of the assumption of no 2N-NMWD. Unfortunately, these ambiguities are inherent in all the singles measurement data and difficult to remove.

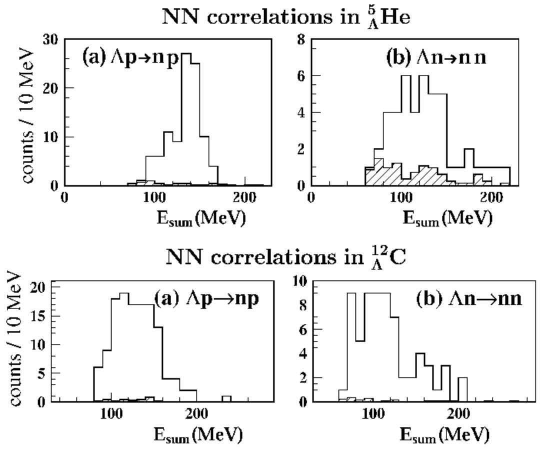

FIGURE 2. The raw energy-sum spectra of the two nucleons in the nonmesonic weak decay of ${}^{5}_{\Lambda}$He are shown in the upper figures and those of ${}^{12}_{\Lambda}$C in the lower ones. Left figures (a) are for np pairs and right ones (b) for nn pairs.The hatched area is the estimated contamination due to the π^- absorption.

4. E462 and E508-Coincidence Experiment

In order to remove such ambiguity experimentally, the decay channel has to be explicitly identified for each event. We have performed coincidence measurements of both n+p (*np* pair) and n+n (*nn* pair) pair nucleons from the NMWD of the hypernuclei, ${}^{5}_{\Lambda}$He (E462) and ${}^{12}_{\Lambda}$C(E508) at KEK-PS using the decay particle counter of Fig. 1. Since the two nucleons from the NMWD, Λn→nn and Λp→np, are emitted out with back-to-back (*bb*) kinematics, we can exclusively select 1N NMWD events by applying the event selection criteria of *bb* kinematics suppressing possible contributions from the 2N process and the events that suffered serious FSI. With the condition, we could reduce the neutron backgrounds, the effect of FSI and 2N NMWD, effectively.

Energy sum correlation: In Fig.2, the sum energy distribution of the np and nn pair nucleons in the decay of ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C are shown in the upper [14] and lower figures, [16] respectively. The hatched histograms show the estimated contamination due to the absorption of π^- from the mesonic decay which is significant in ${}^{5}_{\Lambda}$He but almost negligible in ${}^{12}_{\Lambda}$C. The amount of the contamination was estimated by referring to the π^- absorption from the mesonic decay of quasi-free Λ.

In the Figure 2(a) of ${}^{5}_{\Lambda}$He, one see the peak located at around the Q value of the process, 153 MeV, as expected. The sharp peak indicates that the effect of FSI is not severe for the nucleon in He nucleus and the one-nucleon(1N) induced decay is the major mode in the NMWD of ${}^{5}_{\Lambda}$He.

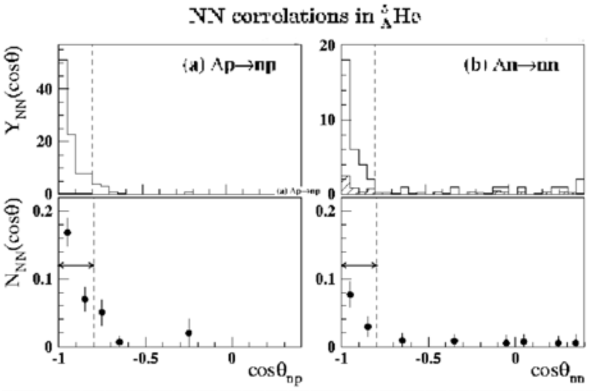

FIGURE 3. The upper figures show the pair yields, Y_{NN}, in opening angle of two nucleons, np in (a) and nn in (b), in the decay of $^{5}_{\Lambda}$He. The lower ones are the angular correlations, N_{NN}, of np, nn pairs in the weak decay of $^{5}_{\Lambda}$He normalized per NMWD and corrected for opening angle dependent efficiency. One see that the pair events are much enhanced in the back-to-back region($\cos\theta_{NN} \leq -0.8$). The hatched figure is the estimated contamination due to the π^{-} absorption.

We have a quite different energy sum distribution for nn pairs in the figure (b), Λn→nn, which has a much broader energy distribution, almost a flat distribution over 80 to 155 MeV region showing a cliff at the Q value, 152.3 MeV. This might be considered due to the effects of π^{-} absorption contamination and the contribution of the $2N$-induced NMWD. However, the π^{-} absorption contamination would not change the spectral shape since the amount of the contamination is at most a quarter of the peak and it also has a flat distribution over the region. Since FSI effect is not severe in $^{5}_{\Lambda}$He and π^{-} absorption contamination can not account for the broader structure, we consider that the broader spectral shape, namely the enhanced low energy shoulder in nn energy sum spectrum, is due to 2N NMWD contribution. Note that the back-to-back kinematic condition is not applied to these energy-sum spectra yet.

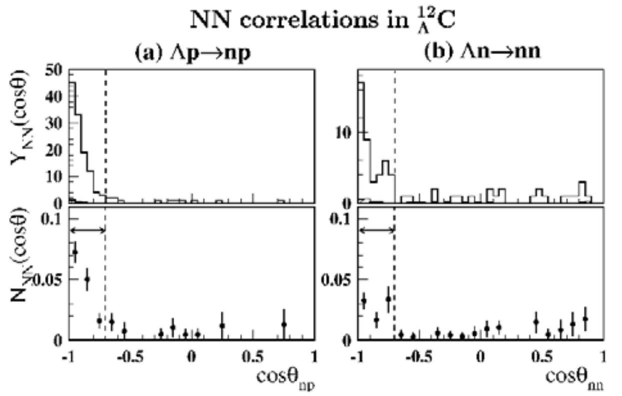

FIGURE 4. The upper figures show the pair yields, Y_{NN}, in opening angle of two nucleons, np in (a) and nn in (b), in the decay of ${}^{12}_{\Lambda}$C. The lower ones are the angular correlations, N_{NN}, of np, nn pairs in the weak decay of ${}^{12}_{\Lambda}$C normalized per NMWD and corrected for opening angle dependent efficiency. One see that the pair events are much enhanced in the back-to-back region($\cos\theta_{NN} \leq -0.7$).

The peak shape observed in ${}^{5}_{\Lambda}$He does not present anymore in the spectrum of ${}^{12}_{\Lambda}$C shown in the lower figures. Instesd it is shifted to lower energy side and broadened over the region of 100∼160 MeV due to FSI. The Q value, 156.6 MeV, can be identified in the spectrum as a cliff in the high energy side of the broadened bump. The sum energy spectrum of nn pairs in ${}^{12}_{\Lambda}$C is even further shifted to lower energy side. Note that the π^- absorption contamination in ${}^{12}_{\Lambda}$C is almost negligible. Therefore this additional shift in nn pair spectrum strongly indicates the effect of 2N NMWD as we observed in the nn spectrum of ${}^{5}_{\Lambda}$He. This supports the conjecture made with the nn pair spectrum of ${}^{5}_{\Lambda}$He that the broadening and the degrading of sum energy in nn pair would be due to 2N NMWD.

Angular correlation: Fig. 3 and Fig. 4 show the angular distributions in opening angle of two nucleons np and nn for ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C, respectively. The upper figures in Fig. 3 and Fig. 4 show the opening angle $\cos\theta$ dependence of NN coincidence pair yields, $Y_{NN}(x)$, in the NMWD of ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C. Here x denotes $cos\theta$ and NN does nn or np pairs. They were not normalized for the acceptance and efficiency yet. The lower figures in Fig. 3 and Fig. 4 show the normalized pair yields per NMWD, $N_{NN}(x)$, for full solid angle and unit efficiency. Back-to-back peaking is clearly observed and dominant in np pair angular correlations in the decay of both ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C hypernuclei. But such back-to-back kinematics is significantly moderated in nn pairs. It is still the dominat kinematics in ${}^{5}_{\Lambda}$He while it is somewhat degraded in ${}^{12}_{\Lambda}$C.

We pointed out the observation that 2N NMWD seems responsible for the broading and shifting of nn pair energy sum spectrum. The enhanced angular correlations of nn pair in non-back-to-back region over that of np pair confirm the observation.

Back to back kinematics which we observed in the two nucleon angular correlation is the clear signature of two-body final state decay and can be considered an experimental verification of the 1N-induced NMWD processes, Λp→np and Λn→nn, which have long been considered as major NMWD modes of Λ hypernuclei but without explicit experimental confirmations.

TABLE 2. 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* ($\cos\theta < -0.7$) and *non-bb* ($\cos\theta \geq -0.7$). N_{NN} values listed are the numbers simply integrated over the corresponding angular regions. Errors are statistical.

	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 *	

* due to the little acceptance

Table 2 shows the pair numbers in each opening angle region. In non-*bb* region, we observe pair events more or less uniformly distributed over all angle in $\cos\theta$ whose total number reaches ∼40 % of the total pair numbers as shown in Table 2. We consider the uniform distribution event extended even in *bb* region. Therefore, we will subtract the corresponding uniform component from the pair numbers N_{NN} of *bb* region in the following discussion of Γ_n/Γ_p of 1N NMWD.

Γ_n/Γ_p from pair number ratio: We consider the integrated pair numbers of np and nn, N_{np} and N_{nn}, in the back-to-back region ($\cos\theta \leq$ -0.8 (${}^{5}_{\Lambda}$He) and $\cos\theta \leq$ -0.7 (${}^{12}_{\Lambda}$C)) so that the possible FSI effect and 2N NMWD contribution, more or less uniformly distributed in non-back-to-back angle region, are largely rejected. The corresponding uniform-like background components are subtracted from the integrated pair numbers in the *bb* region. Then the ratio N_{nn}/N_{np} can be well approximated to Γ_n/Γ_p when FSI is weak as in the case of ${}^{5}_{\Lambda}$He. Then we obtain [14]

$$\frac{\Gamma_n}{\Gamma_p} \simeq \frac{N_{nn}}{N_{np}}({}^{5}_{\Lambda}He) = 0.45 \pm 0.11 \pm 0.03, \quad \text{for } \cos\theta \leq -0.8.$$

The corresponding pair number ratio for ${}^{12}_{\Lambda}$C is $0.53 \pm 0.12 \pm 0.04$. However, as discussed, the FSI in carbon is significant and its effect on Γ_n/Γ_p has to be corrected. Fortunately, we have observed the pair pp events (8 events) which is only possible via FSI. Since these pp pair events reflects the effects of FSI, we could use it for the correction of FSI effect on Γ_n/Γ_p ratio. How to correct was reported in the reference [**?**]Kim05). After the correction of the FSI effect, we obtain

$$\frac{\Gamma_n}{\Gamma_p}({}^{12}_{\Lambda}C) = 0.51 \pm 0.13 \pm 0.04, \quad \text{for } \cos\theta \leq -0.7.$$

Many uncertainties, like the nonmesonic decay branching ratio, FSI factors and the detection efficiencies, are cancelled out by taking the ratio so that the uncertainty becomes mainly statistical one. We point out that Γ_n/Γ_p value from N_n/N_p would show a bigger value than the real one if 2N contribution in the singles spectrum is not taken into account. It has been shown that it is really the case. Then Γ_n/Γ_p ratios of ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C are about 20-25 % bigger than those from N_{nn}/N_{np}. The difference manifested here can be considered as another indication of 2N NMWD.

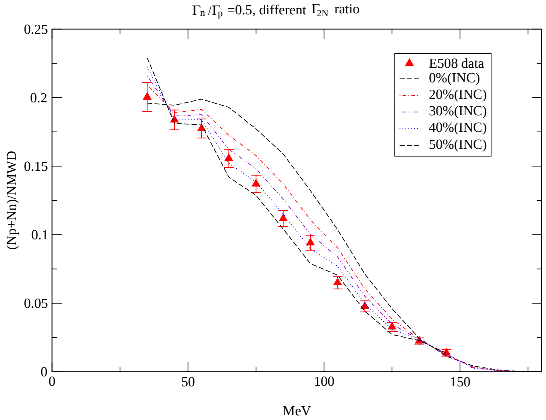

FIGURE 5. The sum spectrum of the neutron and proton yields of the decay of ${}^{12}_{\Lambda}$C, $N_n + N_p$, is compared to the INC predictions obtained with various 2N contributions, from 0 to 50 percent of $\Gamma_{\,1N}$.

Singles yields sum, $N_n + N_p$**:** As we explained in the derivation of Γ_n/Γ_p of ${}^{12}_{\Lambda}$C from the experimental N_n/N_p ratio, we pointed out the strong quenching of singles yield sum. The measured singles total yields, $N_n + N_p$, are compared with the INC yield spectra in the Fig. 5 [15] whose INC was formulated by M. Kim et al. and reported [18**?**]. The INC spectra were produced with Γ_{2N} = 0, 0.2, 0.3, 0.4 and 0.5 Γ_{nm}. Here we assumed the uniform phase space sharing kinematics for the 3 particle produced in the 2N NMWD. This would be somewhat different kinematics from that of the previous INC calculation [**?**] in which a low energy nucleon is generated from the weak Λ vertex and two energetic nucleons from the absorption of the virtual pion. Significant quenching of singles yields measured with 30-40 MeV threshold detection energy could not be explained by 1N-only INC calculation. In order to reproduce the quenching, a comparable strength of Γ_{2N} to that of Γ_{1N} was required. Please note that since the spectrum is the sum of the proton and neutron, the yield is independent of Γ_n/Γ_p ratio. Therefore the conclusion can be made irrespective of the ratio.

Pair number sum, $N_{nn} + N_{np}$**:** The total pair yield per NMWD, $N_{nn} + N_{np}$, would be one if there were no 2N NMWD contribution, but bigger than one if there were. Therefore it could show some indication on 2N NMWD contribution. For the decay of ${}^{12}_{\Lambda}$C, Fig. 6 compares the total pair number sum integrated over all the angular correlation to those of INC calculation as a function of Γ_{2N}. Though the exact Γ_{2N} strength would depend on a particular kinematic model of 2N NMWD, here we again find that the pair yield can be explained only with a significant Γ_{2N} strength confirming the observation made with the singles yield. The INC result is of the phase space sharing kinematics. Since the sum of both pair nn and np is compared, the conclusion is independent of the particular choice of a combination of initial nucleons involved in the decay process.

In summary, recently we have measured for the first time the pair nucleons in the NMWD of ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C in coincidence and determined the Γ_n/Γ_p of the NMWD for ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C accurately from the pair number ratio, N$_{nn}$/N$_{np}$, in the back-to-back kinematic region where the effects of FSI and 2N NMWD contribution are minimized.

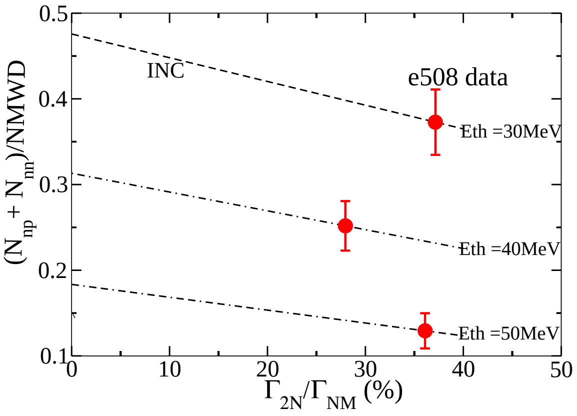

FIGURE 6. The total pair number sums of ${}^{12}_{\Lambda}$C integrated over all the angular correlation are compared to those of INC calculation as a function of Γ_{2N}.

We have clearly observed distinct peaks at the back-to-back two-body kinematic regions, the clear signature of 1N NMWD processes, and accurately determined the opening angle distributions (angular correlation) of the pair numbers.

The angular distributions of np pair are dominated by the back-to-back kinematic events for both hypernuclei while those of nn pairs show significant non-back-to-back events. This is considered a signature of 2N NMWD along with those observed in the comparison of the singles sum, N_n+N_p, and pair number sum, N_{nn}+N_{np}, to those of INC calculation. The energy sum correlation could be understood, though in a qualitative way, only when we assume a fair strength of 2N NMWD.

As we explained, we can find the experimental signatures of 2N-NMWD in many places such as the strong quenching of singles nucleon yield and coincidence pair sum yield, pair energy sum correlation and the enhancement of nn pairs in the non-bb region etc. Even if the low statistics of non-bb pairs and the uncertainty of INC calculation, its every indication points that its contribution is so significant that we can not determine other main decay widths such as Γ_n *and* Γ_p *neglecting its contribution. Only with an accurate measurement of* Γ_{2N}*, we can determine the other main decay observables. Such an enhanced contribution of the three-body weak interaction process is surprising and very interesting. It is now crucial to pin down the 2N-NMWD, not only to understand its own mechanism but also finally to determine main decay observables.*

It is astonishing to realize that after a several decade's experimental study of NMWD of Λ *hypernuclei, the recent* Γ_n/Γ_p *is almost the only quantity we now know on NMWD with confidence. We now understand what has been the source of the confusion with the* Γ_n/Γ_p *puzzle. We think we are now in the position that we can finally determine the widths of NMWD accurately in this proposed high statistics experiment.*

We propose the comprehensive experimental study of the decay of ${}^{12}_{\Lambda}$C at J-PARC. In the following we explain on the proposed experiment.

IV. Experimental Method and Layout of Experimental Setup

1. Experimental Objectives

In this proposed experiment, we measure the decay particle spectra from ${}^{12}_{\Lambda}$C over full dynamic ranges down to 20 MeV, by detecting both neutron(s) and proton in double and tripple coincidence. The basic ideas and the observables of the experiment are similar to the previous KEK-PS experiments(E508/E461). However the acceptance for double and tripple coincidence are much improved to be about 4∼8 times for double and more than 10 times for tripple coincidence higher than those of previous experiment, E508 and E462. From these much improved statistics for double and tripple coincidence measurement, the angular correlation of two nucleons from double coincidence events, the ratio of back-to-back(bb-) and non-back-to-back(nbb-) coincidence events, and also the triple coincidence measurement of $p+n+n$- or $n+n+n$-pair with reasonable statistics will make us confirm the existence of 2-nucleon induced NMWD($\Lambda NN \to NNN$) or possibly its decay width, the sign of which was seen in the previous experiment. In addition, we can determine partial decay widths of non-mesonic decay (Γ_n and Γ_p) and np ratio with much higher accuracy.

2. Experimental Setup

The experiment will be carried out with 1.05 GeV/c π^+ beam at K1.8 beam line. By utilizing the large solid angle coverage of the SKS spectrometer system, we will identify abundant production of ${}^{12}_{\Lambda}$C in ^{12}C (π^+,K^+) reaction. Proton/neutrons and π^-/π^0 emitted from the weak decay of ${}^{12}_{\Lambda}$C will be detected by the coincidence counter system which is placed around the target region. Fig. 7 and 8 shows the proposed setup of the decay-coincidence counter system (seen from the beam downstream).

The coincidence measurement of nucleons from non-mesonic decay of ${}^{12}_{\Lambda}$C is the main subject of this experiment. The main goal of this experiment is the confirmation of the existence of 2N-induced non-mesonic decay. This could be tested with the data of the non-back-to-back(nbb-) coindence events of $n+p$- and $n+n$-pair and/or the triple coincidence of $n+n+p$ or $n+n+n$ events. These events are also observed in the previous E508 experiment. However, due to the very low statistics, one can not make clear conclusion concerning 2N-induced non-mesonic decay. Another important goal is to determine the partial decay widths of non-mesonic decay (Γ_n and Γ_p) and np ratio with high accuracy. So, the back-to-back coincidence events of $n+p$- and $n+n$-pair should have large statistics.

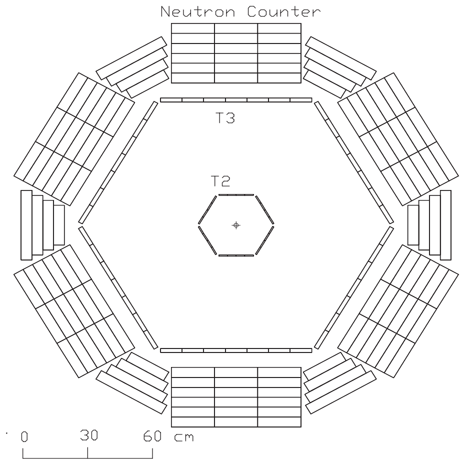

FIGURE 7. Setup of the decay-coincidence counter system seen from the beam downstream. It consists of six coincidence arm placed for top/bottom/side of the carbon target. The T2 and T3 are high-resolution TOF counters which measures the timing of charged particles. Six 30-cm-thick neutron counter array(100cm×60cm×30cm) will be used to measure the total energy of charged particles. The carbon target size is 2cm(height)×6cm(width)×8cm(in beam direction).

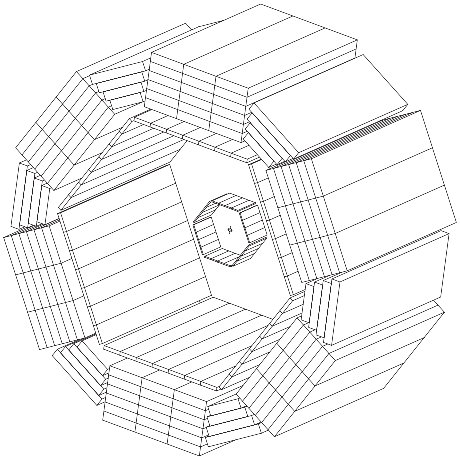

FIGURE 8. Bird-eye's view of our decay counter system.

The proposed configuration of decay spectrometer shown in Fig. 7 could satisfy both of the requirements. Also, through the series of the experiment performed at KEK-PS K6 beam line, we have long experience of the coincidence measurements of hypernuclear weak decay. Especially, because the design of the proposed decay-arm setup is similar to the experiment E462/E508 and we will use the same detector configurations, the performance of the detectors were well utilized and tested already. Also, the knowledge for the detectors from the previous experiement, we can estimate the expected results from the experiment much more realistically. *Many part($\sim$ 50 %) of the detectors could be reused from the previous experimemts.* Table 3 shows the specifications of each detector used for each decay counter system.

Timing of incoming π^+ beam is measured by the T1 counters (omitted from Fig. 7). We will install two-layers of T1 as we did in the E508 experiment. Each decay arm covers about 10% of total solid angle.

TABLE 3. Specifications of the decay counters. We will install six decay arms around the target. Specifications of the decay counters for one decay-arm. T1 counters are placed on beam and we need only one set. We will install six arms around of the target.

Name	Sensitive area (cm)	# of channel	Segmentation
T1	$9.8^{W}\times 4.0^{H}\times 1.2^{T}$	R3478S ×16	4-segments, 2-layer, 3-stage-booster
T2	$24.0^{W}\times 16.0^{H}\times 0.6^{T}$	R3478S ×8	4-segments
T3	$100.0^{W}\times 70.0^{H}\times 2.0^{T}$	R329-02 × 14	7-segments
Neutron	$100.0^{W}\times 60.0^{H}\times 30.0^{T}$	R329-02 × 36	20cm×5cm, 3×6 segments
SideNeutron	$100.0^{W}\times (20.0\sim 35.0^{H}\times 5.0^{T}$	R392-02 × 8	20cm×5cm, 4 segments

3. Charged Particle Detection

Particle identification of the charged particles emitted from the weak decay of ${}^{12}_{\Lambda}$C will be carried out by using the timing/energy information of T2/T3 and Neutron counters. The ability of PID was confirmed through the previous experiements, E462 and E508, which showed clear separation of the charged products (proton, pion and deuteron) from the carbon target as shown in Fig. 9. The contamination of pions in proton gate should be carefully avoided in order to remove the systematic errors of the proton number. Thus, the proton gate in PID was safely defined and the efficiency of the proton PID was 93.1 ± 1.0 % in E508 experiment. We expect the same performance of the charged particle PID in this proposed experiment.

The proton energy will be measured by using its range information. In the previous experiments, E462 and E508, proton ranges were estimated with the particle drift chambers (PDC). When proton stops inside the scintillator, total range of the particle can be expressed from the following equation

$$R = \left(\sum_{i=1}^{N-1} T_i \right) / \cos\theta + d, \tag{1}$$

where N and T_i denote the number of sequentially fired counters and each thickness. θ is the polar angle of the track and d is the penetration depth. Although we use 2 cm- and 5 cm-thick scintillators for T3 and neutron counters, the uncertainty of the penetration depth d will be evaluated within 10% (FWHM) of the scintillator thickness by using the mean ADC, the averaged energy deposit and the light output of the scintillator.

For the evaluation of the total range of the particle, the tracking of the decay particle is needed for the estimation of θ and d. In the previous experiment E462 and E508, PDC located between T2 and T3 was used for the tracking of the charged particles. In this proposed experiment, we don't use the drift chambers in order to increase acceptance of decay particles (See Fig. 7). However, the charged particle tracking is possible without the drift chamber. The hit positions of T2 and T3 counters take the place of those of PDC.

The hit position along the counter length is well-determined by the difference of the timing signal of PMTs on both ends. The hit position along the neutron counter length is described by $v_{eff}(t_u - t_d)/2$, where v_{eff} is the effective velocity in the scintillator and $t_{u(d)}$ is the timing of PMTs on both ends. Typical value of v_{eff} for T2 is $\sim$ 13.0 cm/ns and that for T3 is $\sim$ 14.0 cm/ns in the previous experiments (E369/E462/E508). Since timing resolutions of T2 and T3 are $\sigma_{T2} \sim$ 80 ps and $\sigma_{T3} \sim$ 100 ps, the uncertainties of the hit positions are about 1.0 cm and 1.4 cm, respectively. Because there is no way to identify the hit position along the counter width, we assume the hit position in the width center and the uncertainties 4 cm/$\sqrt{12}$ ($\sim$ 1.2 cm) and 10 cm/$\sqrt{12}$ ($\sim$ 2.9 cm) for T2 and T3, respectively. These uncertainties are sufficient to estimate the target vertex and the tracking angle, which we will show below.

The target vertex can be estimated to the intersection of the decay particle track (with T2 and T3 or PDC) and the pion beam track (with the beam particle chambers). We have checked the difference of the target vertex and the angle $\cos\theta$ in Eqn. 1 in E508 experiment between PDC tracking and T2/T3 tracking. Because X and Y vertexes are mainly determined by the beam drift chambers, the differences of the X and Y vertexes are σ = 0.41 mm and 0.24 mm, respectively. Z vertex needs the tracking information of the decay particle. The Z vertex difference is σ = 27.8 mm which is rather large compared to those of the X and Y vertexes. The $\cos\theta$ difference is σ = 0.027 which makes the proton energy difference about 2% for $\cos\theta$ = 1.

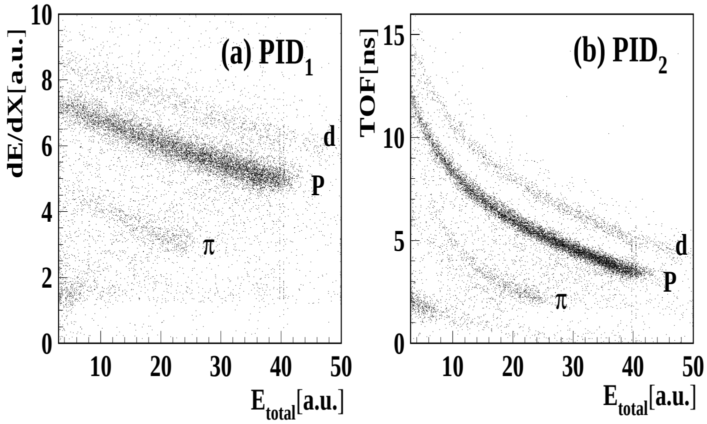

FIGURE 9. The particle identification spectra for decay products(E508 data). (a) PID $_1$ shows the E_{total} vs. dE/dX and (b) PID$_2$ shows the E_{total} vs. TOF(t2-t3) spectrum.

In E508 experiment, the proton energy uncertainty was 3.6% for the proton energy 75 MeV, which was caused by mainly the uncertainty of the penetration depth d. Thus, we can estimate that the proton energy uncertainty with T2 and T3 tracking is about 4−5%

From the crossing point of the incoming π^+ and outgoing charged particle trajectories, say K^+ and p, respectively measured by (π^+,K^+) spectrometer and decay counters, we can reconstruct the (π^+,K^+) reaction point inside carbon target. For the incoming π^+, we can assume β=1. For the charged particle detected by the coincidence-arm, we directly measured its velocity from the TOF information between T2−T3, thus we can correct both of the flight time between T1−reaction point (incoming pion flight time; $t1$) and the flight time between the reaction point−T2 (outgoing charged particle flight time; $t2$) for event-by-event basis. Then we can directly measure the difference between the π^+ injection timing and the charged particle emission timing $t_{diff.}$ from the following equation

$$t_{diff.} = T2 - T1 - t1 - t2, \tag{2}$$

where the T1 and T2 denote the hit-timing of each TOF counters. By fitting the distribution of $t_{diff.}$ with ${}^{12}_{\Lambda}$C lifetime as free parameter, we can determine the lifetime of ${}^{12}_{\Lambda}$C as we performed in the E307 and E508 experiment.

We already achieved that T1 and T2 respectively have σ =60 ps and 80 ps. A total resolution of σ=120 ps was achieved for t_{diff}, from prompt (π^+,pp) events simultaneously taken with the (π^+,K^+) data for timing calibration. The setup proposed here is essentially the same as that of E508 for the lifetime measurement, so we can safely assume that the total TOF resolution for ${}^{12}_{\Lambda}$C lifetime measurement is better than 150 ps.

Since we also measure the emission probability of protons and pions, we can determine the decay width of these charged particles (Γ_p and Γ_{π^-}) by utilizing the lifetime measured here or the previous measured lifetime.

4. Neutron Detection

Neutral particle, neutron and γ, are measured by the neutron counter arrays composed of 6 layers of 5cm-thick scintillators. The charged particles are excluded by the T3 counter veto walls installed just before the neutron counter arrays in Fig. 7. We can identify neutrons and γs by the time-of-flight (TOF) technique. It is recommended to enlarge the distance of the neutron counters from the target for better TOF resolution and neutron/γ separation. We set the distance of the neutron counters from the target 70−100 cm which is optimized for the neutron counter volume and the neutron acceptance.

The TOF from the target to the first layer of neutron array is about 2.3 ns for γ while that of fast neutron $\sim$ 150 MeV is about 4.6 ns. So the TOF difference of γ and fast neutron $\sim$ 150 MeV is about 2.3 ns. As already discussed, we have already achieved excellent TOF resolution of the neutron counters, namely, $\sigma \sim$ 200 ps resolution for $\gamma(\beta = 1)$ peak at 2 MeVee (MeV electron-equivalent light output) threshold in the KEK-PS experiment E369/E462/E508. As shown in Fig. 10, even with 2 MeVee threshold, neutron and γ is clearly separated in the TOF spectrum of neutron from the NMWD of $^{12}_{\Lambda}$C. Since the gate start timing of TDC module is set to be acceptable for events which are faster enough than γs, the accidental background can be estimated from the such fast events which are random room-background events. The yield below the γ-peak ($1/\beta < 0$) in Fig. 10 shows very low background. The accidental background within the neutron gate for $^{12}_{\Lambda}$C formation peak events in the ^{12}C (π^+,K^+) spectrum is evaluated to be $\sim$ 2%.

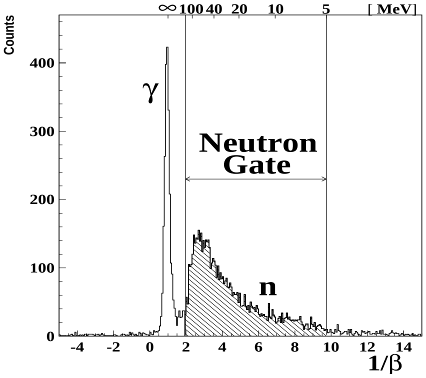

FIGURE 10. The TOF spectra of neutral particles from $^{12}_{\Lambda}$C decay (E508 data) plotted in $1/\beta$ scale to see the constant background level. Neutrons are cleanly separated from γs and the constant background level is found to be very low. Hatched region is selected as neutron events.

The TOF spectrum in Fig. 10 can be converted to the neutron energy spectrum. The neutron kinetic energy is expressed as $E_n = [1/\sqrt{(1-\beta^2)}]m_n$, where β is the neutron velocity and m_n is neutron mass. The neutron energy resolution is estimated from the resolution of γ-peak located at $\beta = 1$ in the Figure. From the TOF resolution $\sigma \sim$ 200 ps for $\gamma(\beta = 1)$ peak, neutron energy resolution is $\sigma \sim$ 3.5 MeV (FWHM) at 75 MeV of neutron energy.

The accuracy of the neutron emission angle is important because neutron energy is calculated from the flight distance and TOF. Well-localized target vertex and the hit position of the neutron counter will be used for the calculation of neutron emission angle. We can determine the hit postion of neutron along the neutron counter length by the timing difference of the PMT signal attached on both ends of the counter, the same way like the proton analysis. The effective velocity in neutron counter, v_{eff} is about 14 cm/ns and $\Delta(t_u - t_d)/2$ is less than 200 ps in E508 experiment. The amibiguity of the hit position along the neutron counter length is less than 3.6 cm, which is negligible compared to the neutron counter width, 20 cm. Therefore the angular resolution of neutron emission angle is mainly determined from the ambiguity of the hit position along the counter width direction. When we consider the largest emission angle uncertainty with the distance of the first layer from the target (75 cm), angular resolution for neutron emission angle is expected to be $\Delta \tan\theta \approx \Delta\theta = (20/75)/\sqrt{12} \sim 0.077$, which correspond to about 4 degrees. This is sufficiently good to measure the angular correlation of $n+p$- and $n+n$-pair in double coincidence.

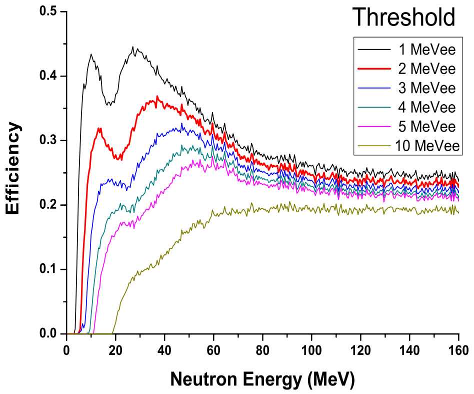

FIGURE 11. Simulated efficiencies of the 30-cm-thick neutron counter at detection thresholds of 1/2/3/5/10 MeVee for the lines from top to bottom. We will measure at 2 MeVee threshold. About 30% efficiency will be achieved for all the energy range above 10 MeV neutron kinetic energy.

It is especially important that each neutron counter array has enough neutron detection efficiency because the data statistics is most limited for the case of the $n+n$-pair back-to-back double coincidence measurement. The final detection efficiency for the case of the $n+n$-pair back-to-back double coincidence measurement is approximately proportional to a square of the thickness of the neutron counters. Figure 11 shows the simulated efficiency plots of the 30 cm-thick neutron counter arrays as a function of neutron kinetic energy. We will measure neutron with 2 MeVee detection threshold (same as that of E369/E462/E508 measurement). Then, about 30% efficiency can be achieved for all the energy range above 10 MeV neutron energy. It is also seen from the figure that the efficiency is stable at this threshold setting.

5. Angular Correlation — Acceptance for Double and Triple Coincidence

This proposed experiment is motivated from the results of KEK-PS E508. The detector configuration and the detector performances should be almost same with the case of E508. The data from E508 can provide the most realistic estimation of the angular correlations for nn and np particle pair. Fig. 12 shows the angular corelations of coincidence particle obtained from E508. We could clearly observe the enhancement in back-to-back region. This means that we can cleanly detect $n+p$ pair from the $\Lambda p \rightarrow np$ decay process even with Carbon target. In E508, we obtained 116 back-to-back ($\cos\theta < -0.7$) np coincidence event and 43 back-to-back nn coincidence events. From these events, we could obtain Γ_n, Γ_p, np values with much smaller systematic errors and the total uncertainty mainly depends on the statistical fluctuation. Also, we have obtained 12(23) non-back-to-back ($\cos\theta > -0.7$) $np(nn)$ coincidence events and 3(2) triple $nnn(nnp)$ coincidence events. These events could be due to FSI or due to 2N-induced non-mesonic decay. However, at present the statistics are not enough to distinguish the source of these events.

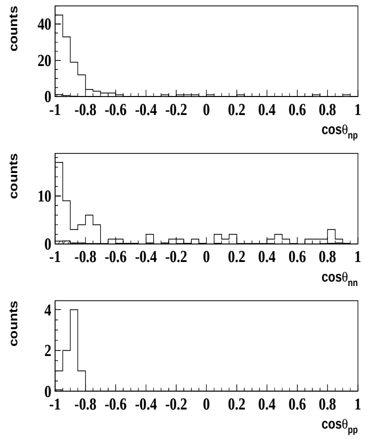

FIGURE 12. Measured $n+p$(top)-, $n+n$(middle)-, and $p+p$(bottom)-pairs are represented as a function of their opening angle distribution (E508 data).

The acceptance of the proposed setup for two-particle pair coincidence is estimated as shown in Fig. 13. The proposed experiment can promise $\sim$ 8(4) times bigger acceptance for $np(nn)$ back-to-back coincidence and $\sim$ 15(5) times bigger acceptance for $np(nn)$ non-back-to-back coincidence compared to the E508. Also, as for the triple coincidence, the proposed setup has $\sim$10 times higher acceptance compared to the previous experiment.

For the 2N-induced non-mesonic decay, E508 shows the indication from the existence of non-back-to-back events of coincidence pairs. These non-back-to-back events could be generated by FSI of 1N-induced non-mesonic decay. However, if it is the case, the ratio of back-to-back to non-back-to-back events for nn coincidence pair($(\frac{N_{bb}}{N_{nbb}})_{nn}$) and that for np coincidence pair($(\frac{N_{bb}}{N_{nbb}})_{np}$) should be similar number, *i.e.* $r = (\frac{N_{bb}}{N_{nbb}})_{np}/(\frac{N_{bb}}{N_{nbb}})_{nn} \sim 1$. The data from E508 show that $(\frac{N_{bb}}{N_{nbb}})_{nn} = 1.00 \pm 0.29$, $(\frac{N_{bb}}{N_{nbb}})_{np} = 0.43 \pm 0.14$ and the ratio is $r = 2.3 \pm 1.0$. The 1 std is about 43 % and it is not easy to make conclusion about the 2N-induced decay. Again, if we install the proposed coincidence setup and have about 2 times more pions on target than E508, we could reduce the uncertainty level down to 10 %. With this improved data, we could expect what the source of nbb events is clearly.

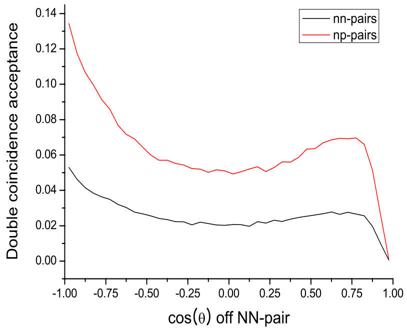

FIGURE 13. Double coincidence acceptance of the proposed setup for the two-particles pair as a function of the opening angle of two particles.

Also, we could see much more triple coincidence events with improved acceptance and the detailed study about the triple coincidence events can become possible, which can make the topic concerning 2N-induced non-mesonic decay clearer.

In addition, np was determined to be $0.51 \pm 0.14 \pm 0.04$ in E508 and the uncertainty was dominated by the statistical fluctuation, especially due to the low statistics of the nn back-to-back coincidence events (43 events corresponds to 25 % uncertainty). With the improved acceptance and about 2 times more pions on the target, we can obtain $\sim$ 350(1900) $nn(np)$ back-to-back coincidence events. This corresponds to $\sim$ 10 % uncertainty including systematic uncertainty.

6. Energy Correlation of NN-pair from $\Lambda N \to NN$ NMWD process

When we measured the energy of single nucleon from $\Lambda N \to NN$ process, the obtained spectrum is spread with more than 50 MeV width by the effect of Fermi motion. However, when we consider the sum of the energies of two-nucleons, the width becomes much narrower. When we consider the simple decay process of $^{12}_{\Lambda}\text{C} \to n + p + ^{10}\text{B}$ as an example, the relation of the energy conservation in the final state should gives the following relation for the sum of proton/neutron kinetic energy:

$$\begin{aligned} T_p + T_n &= Q_0 - E_{\text{separation}} - B(\Lambda) - T(^{10}\text{B}) \\ &= 176 - 9 - 11 - T(^{10}\text{B}) \\ &= 156 \quad [\,\text{MeV}\,], \end{aligned} \tag{3}$$

where Q_0, $E_{\text{separation}}$, B_Λ respectively stand for the Q-value of $\Lambda p \to np$ decay in free space, separation energy of nucleon from α-particle and binding energy of Λ inside the $^{12}_{\Lambda}$C .

Considering the Fermi momentum($p_{Fermi} < 270$ MeV/c), the recoil energy of ^{10}B ($T(^{3}\mathrm{H}) = p^2_{Fermi}/2M$) is found to be negligible: this is much narrower than the width of single nucleon energy spectrum ($\sim$50 MeV). So if both of the two nucleons does not suffer from rescattering from the residual nucleus, the sum of those energies must has a sharp peak at around 156 MeV with the width of $\sim$10 MeV. This relation can also be used for the clear identification of $\Lambda N \to NN$ NMWD process.

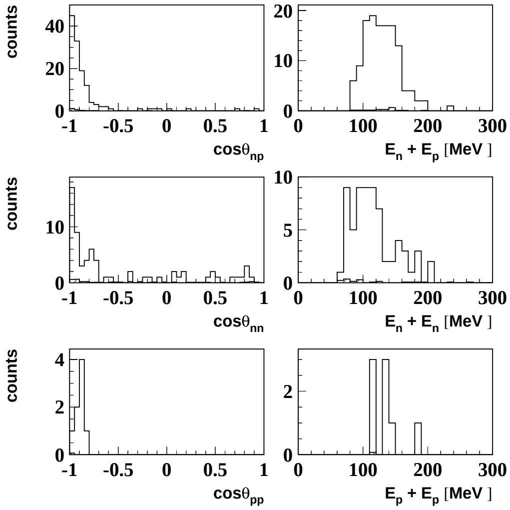

FIGURE 14. Angular (left) and energy-sum (right) distribution of two nucleons from the decay of $^{12}_{\Lambda}$C (E508 data). For *np* coincidence(top), *nn* coincidence(middle) and *pp* coincidence(bottom) are shown.

The results from E508 is shown in Fig. 14. This could be good indication that the back-to-back NN coincidence events are from the 1N-induced non-mesonic decay. The same thing could be done for triple coincidence event if we have enough statistics for triple coincidence.

V. Yield Estimations and Expected Results

1. $^{12}_{\Lambda}$C Formation Rate

In recent KEK-PS experiments (e.g. E336/E369/E419/E462/E508) at SKS, we can obtain about 8 counts for the $^{12}_{\Lambda}$C ground state when 1×10^{9} π^{+} beam hit the 1 g/cm^2-thick target and it is very stable in recent years. This $^{12}_{\Lambda}C$ formation rate is for KEK-PS K6 beam line and SKS spectrometer, but we can assume the similar beam optics and SKS acceptance at K1.8 beam line at J-PARC. And we could expect the similar fomation rate of $^{12}_{\Lambda}$C. Most recent coincidence experiment, KEK-PS E508, $\sim$ 62200 ground state of $^{12}_{\Lambda}$C was formed with 2×10^{12} pions on target, where the target thickness is 4.3 g/cm^2 for carbon. In this proposed experiment, we will use the same configuration of target(CH) shown in Fig. 15, which is the same configuration with E508. So, we can assume that we will have the same formation rate of $^{12}_{\Lambda}$C for the same number of beams on target. If we get enough statistics for coincidence events from the non-mesonic decay of $^{12}_{\Lambda}$C, we need about 2 times more hypernuclei. This means that we need about 125000 $^{12}_{\Lambda}$C's and about 2 times more pions on target, *i.e.* $4\times10^{12}\pi^{+}$ on target.

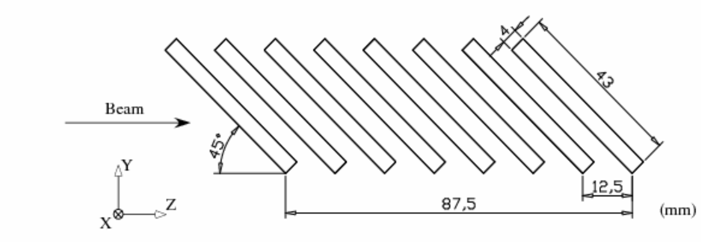

FIGURE 15. Configuration of the carbon target:eight-segmented CH target.

2. Single Coincidence Counts

The event rate of the decay products of $^{12}_{\Lambda}$C(n or p from non-mesonic decay) can be estimated from the data from E508 and the increased acceptance of proposed experiment.

At E508, with 30 MeV threshold, $N_n = 3552$ and $N_p = 1579$ events for 62200 ground state $^{12}_{\Lambda}$C. With the acceptance of proposed experiment and 2 times more $^{12}_{\Lambda}$C , we can get $N_n = 3552\cdot2\cdot2 = 14200$ and $N_p = 1579\cdot4\cdot2 = 12600$. However, at E508, because we already have enough statistics for the single coincidence counts, we have no reason to discuss more about single statistics here.

3. Search for the Two-nucleon Induced NMWD Mode

From E508 experiment, we could indicate the signature of the two-nucleon induced decay process ($\Lambda NN \rightarrow NNN$). However, due to the limited statistics, we could not conclude its existence. One of the main topic of this experiment is “to make a conclusion of existence of 2N induced non-mesonic deay” and if exists, we also measure the decay width of 2N induced decay.

Basically, we have two ways to test the existence of 2N-induced non-mesonic decay as we mentioned in the previous section.

Here, we will discuss about the event rate estimation. For the ratio of back-to-back to non-back-to-back coincidence events, the event rate and the statistical error is estimated as follows :

$$\begin{array}{lcl}
N_{bb}(nn:E508) & = & 43, \quad \text{and} \quad \Delta\Omega_{bb}(nn) = 4 \\
N_{nbb}(nn:E508) & = & 23, \quad \text{and} \quad \Delta\Omega_{bb}(np) = 8 \\
N_{bb}(np:E508) & = & 116, \quad \text{and} \quad \Delta\Omega_{nbb}(nn) = 5 \\
N_{nbb}(np:E508) & = & 12, \quad \text{and} \quad \Delta\Omega_{nbb}(np) = 15 \\
\Delta N_{{}^{12}_{\Lambda}C} & = & 2 \\
N_{bb}(nn) & = & N_{bb}(nn:E508) \times \Delta\Omega_{bb}(nn) \times \Delta N_{{}^{12}_{\Lambda}C} = \mathbf{344} \\
N_{nbb}(nn) & = & N_{nbb}(nn:E508) \times \Delta\Omega_{nbb}(nn) \times \Delta N_{{}^{12}_{\Lambda}C} = \mathbf{230} \\
N_{bb}(np) & = & N_{bb}(np:E508) \times \Delta\Omega_{bb}(np) \times \Delta N_{{}^{12}_{\Lambda}C} = \mathbf{1856} \\
N_{nbb}(np) & = & N_{nbb}(np:E508) \times \Delta\Omega_{nbb}(np) \times \Delta N_{{}^{12}_{\Lambda}C} = \mathbf{360}
\end{array} \qquad (4)$$

These statistics correspond to ~ 10 % if we assume the same central value for r. So, with this error level, we could make conclusion the source of non-back-to-back coincidence events and eventually about 2N induced non-mesonic decay.

The analysis of triple coincidence events would be the tool of the study of 2N-induced non-mesonic decay. In E508, we have some triple coincidence events but it was not statisticaly meaningful number : $N_{nnn} = 3$, $N_{nnp} = 2$.*The acceptance for triple coincidence events of proposed setup is about 8 times bigger for nnn coincidence, about 16 times bigger for* nnp *events than the detector for E508. So, we expect that we would have the reasonably good data sample for triple coincidence events.*

4. Double Coincidence Counts and Γ_n/Γ_p Ratio

For the clean identification of the $\Lambda N \rightarrow NN$ NMWD process and the measurement of np ratio from E508 experiment, we will further impose the detection of both of $n+p$- or $n+n$-pairs in the back-to-back coincidence. Referring the consideration already discussed, we will impose following three conditions for the "clean" signal of $\Lambda N \rightarrow NN$ NMWD process as we do in E508 and E462:

1. Two-nuclens($n+p$ or $n+n$) are detected by the coincidence arms.
2. Opening angle(θ) of two nucleons should have back-to-back coincidence — $\cos\theta < -0.7$.
3. The sum of the kinetic energies of two nucleons should have sharp peaking at around 152 MeV.

When these conditions are satisfied, we can experimentally minimize the possible contributions to the NMWD process coming from two-nucleon induced decay process ($\Lambda NN \rightarrow NNN$) or final state interaction, etc. For the double coincidence counts of $n+p$-pair, we can estimate the number from the experience of E508 as follows:

$$\begin{aligned}
N_{np}(E508) &= 116 \\
\Delta\Omega_{np} &= 8 \\
\Delta N_{{}^{12}_{\Lambda}C} &= 2 \\
N_{np} &= N_{np}(E508) \times \Delta\Omega_{np} \times \Delta N_{{}^{12}_{\Lambda}C} = 1900
\end{aligned} \tag{5}$$

where $\Delta\Omega_{np}$ denotes the ratio of the acceptance for np back-to-back double-coincidence measurement for E508 and the proposed experiment. $\Delta N_{{}^{12}_{\Lambda}C}$ denotes the ratio of the number of ${}^{12}_{\Lambda}$Cfor E508 and the proposed experiment.

For the $n+n$-pair, the similar calculation could be performed :

$$\begin{aligned}
N_{nn}(E508) &= 43 \\
\Delta\Omega_{nn} &= 4 \\
\Delta N_{{}^{12}_{\Lambda}C} &= 2 \\
N_{nn} &= N_{nn}(E508) \times \Delta\Omega_{nn} \times \Delta N_{{}^{12}_{\Lambda}C} = 350.
\end{aligned} \tag{6}$$

With these statistics, we can estimate the error level of the proposed expeiment from that of E508. In E508, $\frac{\Gamma_n}{\Gamma_p} = 0.51 \pm 0.14 \pm 0.04$ and the statistical uncertainty dominates the total uncertainty. The statistical uncertainty of 28 % (0.14 from 0.51) corresponds to the quadratic sum of the statistical uncertainty of $\delta N_{np} \sim 12\%$ and that of $\delta N_{nn} \sim 25\%$. With the improved statistics, δN_{np} will become ~ 3 % and δN_{nn} will become ~ 8 %. Thus, the total error level of np ratio could be determined within 10 % for statistical errors.

Again, we want to stress here that the errors of np ratio determined from E462 and E508 are dominated by statistical uncertainty not by systematics and this experiment could determine the np ratio within 12% including systematic errors.

VI. Machine Time Requests

We estimated the JPARC K1.8 machine time needed for the present experiment as follows:

1. The ^{12}C (π^+,K^+) run

As discussed above, we need $4 \times 10^{12}\pi^+$ pions in total to assure enough statistics for the confirmation of 2N induced non-mesonic decay mode and also to get the enough decay-coincidence numbers($\sim$ 350) for $n+n$-paifr back-to-back double coincidence, if we have the same acceptance of SKS. However, there is a plan for the modification of SKS spectrometer which should be tuned to perform the spectrometry of S=-2 hypernuclei. So, we should consider that the acceptance of SKS for (π^+, K^+) reaction would be reduced. We assume that the reduction of SKS acceptance would be 2/3. We want to emphasize that what we need is not the net running time, but the total irradiation of π^+ (6×10^{12}).

If we assume that the spill repetition of 3.5 s and the pion intensity of $1 \times 10^7/s$, we need 72 shifts.

2. Tuning Runs

In addition to the normal ^{12}C (π^+,K^+) runs we need following runs for tuning:

i. Empty target runs: 2 shifts
In order to study the continuum background level especially in the neutron spectra, we need empty target runs. We will add (π^+,pX) calibration triggers for the purpose of in-beam calibration of decay counter system. Empty runs are also required in order to study the purity of these triggers.

ii. Beam through runs : 3 shifts
Beam through runs are required to obtain the calibration data for SKS spectrometer system. This data is used for energy loss correction/calibration inside the target and tracking chamber position alignment in the off-line analysis. We need $3-4$ times during the experiment and the full sets of beam through calibration run needs approximately 1 shift.

iii. Detector/trigger tuning: 23 shifts
We need about 10 shifts for the tuning of the decay-coincidence counters using the π^+ beam and those gain adjustment. We need to add at least two-types of in beam calibration triggers — π^+ injection, proton detected by SKS spectrometer and one or more neutral or charged particle detected by coincidence arms.

Therefore, we need 100 shifts for tuning runs.

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VIII. Budget Request for Experiment and Travel Expenses

Experimental Cost (Unit: 1000yen)

Item	Expense			Fiscal Year			
	Number	Unit Price	Sum	Year 200-			
Scintillator(BC408) for neutron/T3	950*l*	12	11,400				
Scintillator(BC408/420) for T1/T2			1,200				
2-inch PMTs (H6410)	264 (108^a)	90	14,040				
3/4-inch PMTs (R3478S)	148	90	13,320				
Light Guides (UVT)	$\sim$320	20	6,400				
BNC cables (100m)			3,000				
Lemo calbes			3,500				
Supporting frameąą			8,000				
Gas for chambers			1,800				
Carbon target			300				
Others			300				
Sum	63,260						

Table: The cost is estimated for the exact channel numbers. If we consider a safety factor, $\alpha \sim 0.1$, the cost will be $\sim$70,000. The superscript '^{a}' is to indicate the PMT numbers to be utilized with old ones of E462/E508.