# Letter of Intent
# for Experiment at 50-GeV PS (JPARC)

# Precise Measurement of the Nonmesonic Weak Decay of A=4, 5 Λ Hypernuclei

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## 1 Physics Motivation

### 1.1 Weak baryon-baryon interaction

The strong interaction between baryons can be studied through scattering experiments. There have been vast amount of nucleon-nucleon (NN) scattering experiments through which NN interaction has been studied in detail.[1] However, only a few data on the hyperon-nucleon (YN) scattering and almost no data on hyperon-hyperon scattering are available. Thus the study of the strong interaction among octet baryons has been carried out with the help of $SU_F(3)$ symmetry by which vast amount of NN data are related to the scare YN data.[2] Since strong interaction between the octet baryons are similar, there is a nucleus where a nucleon is replaced by a hyperon which we call a hypernucleus. Knowledge on the YN strong interaction comes from the YN scattering experiments as well as hypernuclear structure.

The situation for the weak baryon-baryon (BB) interaction is quite different. The parity violation has been only information to study weak NN interaction because its parity conserving part is completely masked by the strong interaction. Even for the study of parity violation, parity conserving strong interaction is so huge that one has to struggle with very small effect ($10^{-7} \sim 10^{-8}$).[3] Of course there is a good opportunity to observe large effect in low energy neutron scattering from specific nuclear levels.[4] In the experiment one can obtain even $\sim 10$ % effect with fairly good accuracy. However, since enhancement is due to complex mixture of the adjacent levels with opposite parity, connection of such data to weak NN interaction is rather indirect.

### 1.2 Weak decay of Λ hypernuclei

Weak YN interaction can be studied in the nonmesonic weak decay of Λ hypernuclei. The nonmesonic decay ($\Lambda n \rightarrow nn$, $\Lambda p \rightarrow np$; $\Delta q \sim 400$MeV/c) is strangeness changing YN weak process. The process has momentum transfer larger than the Fermi momentum. It thus makes the Pauli blocking effect of little importance and the process can be taken as almost two body reaction. In the decay, one can study both parity conserving and parity violating part of the weak interaction since no strong interaction can change flavor (strangeness). Meson exchange is a theoretical model that can describe the process where relevant weak $\pi\Lambda N$ vertex has been obtained by the measurement of the mesonic decay of Λ ($\Lambda \rightarrow \pi N$). This is not the case of the weak NN interaction since no experiment directly gives the weak $\pi NN$ vertex. Weak $\pi NN$

Table 1: Six amplitudes in nonmesonic decay process whose initial $\Lambda N$ system is relative $S$ states.

| Initial | Final | Matrix element | Rate | $I_f$ | Parity change |
|---|---|---|---|---|---|
| $^1S_0$ | $^1S_0$ | $a$ | $a^2$ | 1 | no |
| | $^3P_0$ | $\frac{b}{2}(\sigma_1 - \sigma_2)q$ | $b^2$ | 1 | yes |
| $^3S_1$ | $^3S_1$ | $c$ | $c^2$ | 0 | no |
| | $^3D_1$ | $\frac{d}{2\sqrt{2}}S_{12}(q)$ | $d^2$ | 0 | no |
| | $^1P_1$ | $\frac{\sqrt{3}}{2}e(\sigma_1 - \sigma_2)q$ | $e^2$ | 0 | yes |
| | $^3P_1$ | $\frac{\sqrt{6}}{4}f(\sigma_1 + \sigma_2)q$ | $f^2$ | 1 | yes |

vertex is rather constrained by the known $\pi\Lambda N$ vertex with help of $SU_F(3)$ symmetry. So far the $SU_F(3)$ symmetry with explicit breaking due to hadron masses has been successful for the strong BB interaction though almost none is known for the weak BB interaction. The nonmesonic decay gives first extension of the weak NN interaction to baryons with strangeness.

### 1.3 Partial decay rates of nonmesonic decay

The matrix element of the nonmesonic decay can be classified into six amplitudes[5] depending on spin, isospin and parity of the initial and final states as shown in Table 1 provided that the initial state is of relative s wave. Study of partial decay rates ($\Lambda n \to nn$, $\Lambda p \to np$) can constrain magnitude of each amplitude in terms of isospin. Phenomenological analysis of $s$-shell hypernuclei indicates the dominance of the amplitude $f$ (isospin 1 final state).[5] On the contrary, theoretical prediction based on the pion exchange implies the dominance of amplitude $d$ (isospin 0 final state) reflecting the tensor part of the potential.[6, 7] This discrepancy had existed even though heavier mesons are included in the calculation for a long time.[8, 9]

Recently KEK-PS E462[10] and E508[11] have been carried out in order to solve above discrepancy. In the experiments, all the decay particles were measured and were reconstructed the kinematics of the nonmesonic decay, in order to avoid the contribution due to the final state interaction and $\Lambda NN \to NNN$ process. Although the analysis is still in progress, the preliminary results suggest that the branching ratios ($\Gamma(\Lambda n \to nn)/\Gamma(\Lambda p \to np)$), so-called np-ratio, lie in the range of $0.5 \sim 0.7$ for ${}^5_\Lambda$He and ${}^{12}_\Lambda$C. Also the experiments tell us the importance of the effect due to the final state interaction and/or $\Lambda NN \to NNN$ process. The E462 experiment found that the effect is about 30 % of the nonmesonic decay even for ${}^5_\Lambda$He. Therefore the exclusive measurement with coincidence of all the decay particles is essential to determine the observables of the nonmesonic decay.

On the other hands, most recent calculation shows that constructive contribution of kaon exchange makes the amplitudes $f$ comparable to the amplitude $d$ and partial decay rates are now compatible with the recent experimental data, consequently.[12]

### 1.4 Weak decay of polarized Λ hypernuclei

Parity violation of the weak nonmesonic decay provides interesting quantity to investigate the spin-parity structure of the weak interaction which is the asymmetric emission of decay particle with respect to the polarization.[13] The asymmetry is due to interference between parity conserving and violating amplitudes.

The asymmetry parameter of the process is expressed in terms of six amplitudes in Table 1 as;[14]

$$\alpha_p^{NM} = \frac{2\sqrt{3}Re[-ae^* + b(c-\sqrt{2}d)^* - f(\sqrt{2}c+d)^*]}{\{a^2+b^2+3(c^2+d^2+e^2+f^2)\}}. \qquad (1)$$

Amplitudes $f$ and $d$ represent dominantly kaon and pion exchange, respectively. Therefore the asymmetry parameter is mainly determined by the last term, $f(\sqrt{2}c+d)$. However there are other two terms, $ae$ and $b(c-\sqrt{2}d)$, which come from interference between the initial $^1S_0$ and $^3S_1$ amplitudes. They were ignored in old expression[15], since the $^1S_0$ states have no asymmetry by themselves. The calculation based on the direct-quark exchange model suggests the importance of the initial $^1S_0$ states[16]. The asymmetry parameter is also sensitive to the initial $^1S_0$ states, while the decay rates (except for the nonmesonic decay of $^4_\Lambda$H and $^4_\Lambda$He) is not affected so much because of the number of quantum states of the initial $^3S_1$ states.

Quite large asymmetry parameter ($-1.3 \pm 0.4$) was observed for the nonmesonic decay of the polarized $^{12}_\Lambda$C hypernuclei by using the $^{12}$C$(\pi^+, K^+)$ reaction (KEK-PS E160).[17] It suggests equal importance of the isospin 0 and 1 amplitudes and seems to contradict to phenomenological analysis of branching ratio which suggests dominance of I=1 final state. However we have an error of 40 % for the asymmetry parameter. It is far below the accuracy that is needed for the detailed comparison with theoretical calculation. We thus have carried out a new experiment where asymmetric nonmesonic decay was observed from the weak nonmesonic decay of polarized $^5_\Lambda$He.[18]

E278 experiment was carried out at the K6 beam line of KEK-PS. The $^6$Li$(\pi^+, K^+p)^5_\Lambda$He reaction at $P_\pi = 1.05$ GeV/c was used to produce polarized $^5_\Lambda$He. The experiment demonstrated that the polarized $^5_\Lambda$He hypernucleus is really produced by the $(\pi^+, K^+)$ reaction.[19] The large asymmetry parameter and the large branching ratio of the $^5_\Lambda$He mesonic decay were essential for the polarization measurement. The observed polarization is consistent with the DWIA calculation,[20] which includes the polarization in the elementary reaction and the depolarization due to proton emission.

The asymmetry parameter derived from the proton asymmetry and the polarization is $\alpha_p^{NM} = 0.24 \pm 0.22$.[21] The result shows that the asymmetry parameter of the nonmesonic decay has a positive sign and its magnitude is quite small compared to that obtained in E160 experiment. One expects a contribution of the relative $P$ state in the initial $\Lambda N$ system for the $p$-shell hypernuclei, although most of the decay rate comes from the initial $S$ state, according to Ref. [22]. The theoretical calculations based on the meson-exchange model estimates the asymmetry parameter to be around $-0.7$ independently of hypernuclear species. The theory prefers E160 experiment rather than E278 experiment.

Recently, E462 experiment carried out with using same reaction in E278 experiment.[10] Although the analysis is still in progress, the preliminary result suggests that the asymmetry parameter of nonmesonic decay of $^5_\Lambda$He hypernucleus is quite small and supports the E278 experiment.[23] Besides, preliminary analysis of E508 experiment shows that the asymmetry parameters for $^{12}_\Lambda$C and $^{11}_\Lambda$B are also small as $^5_\Lambda$He case. The experiment contradicts E160 result. Although the definite conclusion can not be derived from E508 experiment due to the difficulty in the determination of the hypernuclear polarization, the experiments suggest the asymmetry parameter for the nonmesonic is small as almost 0, while the theory estimates it to be around $-0.7$.

## 1.5 Importance of the precise measurement of A=4, 5 hypernuclei

As discussed above, recent experimental data on branching ratio becomes compatible with the theoretical estimation. However no theory cannot explain the asymmetry parameter. The branching ratio (or partial decay rate) is mainly determined by the initial $^3S_1$ amplitudes, because the number of quantum states of

Table 2: Allowed initial states for A=4, 5 hypernuclei

| Hypernucleus | $\Lambda n \to nn$ | $\Lambda p \to np$ |
|---|---|---|
| ${}^4_\Lambda$H | ${}^1S_0$, ${}^3S_1$ | ${}^1S_0$ |
| ${}^4_\Lambda$He | ${}^1S_0$ | ${}^1S_0$, ${}^3S_1$ |
| ${}^5_\Lambda$He | ${}^1S_0$, ${}^3S_1$ | ${}^1S_0$, ${}^3S_1$ |

the initial ${}^3S_1$ states are three times that of ${}^1S_0$ states. The contribution of the initial ${}^1S_0$ states do not affects the branching ratio so much. However the asymmetry parameter is due to interference not only among the initial ${}^3S_1$ states but also between the initial ${}^3S_1$ and ${}^1S_0$ states. The contribution of the ${}^1S_0$ states can modify the asymmetry parameter from the current theoretical estimation. Therefore the exclusive measurement of the initial ${}^1S_0$ contribution is essential to understand the nonmesonic decay.

Table 2 shows allowed initial states of the nonmesonic decay for A=4, 5 hypernuclei. Since the n-p pair in ${}^4_\Lambda$H and ${}^4_\Lambda$He forms $0^+$ state, $\Lambda n \to nn$ decay ($\Lambda p \to np$ decay) for ${}^4_\Lambda$He (${}^4_\Lambda$H) starts only from the ${}^1S_0$ states. One can determine directly the initial ${}^1S_0$ amplitudes with measurement of these decay mode.

There is another interest in measurement ${}^1S_0$ amplitudes. If the $\Delta I = 1/2$ rule is hold in nonmesonic decay, the ratio of above to decay mode, $\Lambda p \to np$ (${}^4_\Lambda$H) and $\Lambda n \to nn$ (${}^4_\Lambda$He), is expected to be 1:2, while if $\Delta I = 3/2$ amplitude dominates we found the ratio to be 2:1. The precise measurement of these decay mode can provide an opportunity to test the $\Delta I = 1/2$ rule in the nonmesonic decay. So far the rule have been confirmed only in the free decays of hyperons and mesons.

The measurement of the asymmetry parameter for ${}^5_\Lambda$He is also important, since we can not determine each amplitude of a specific initial state from the measurement of the decay rate. So far, in the experiments on the asymmetry parameter, only the decay protons were measured to derive the asymmetry parameter. As mentioned above, the effect of the final state interaction is considerable even for ${}^5_\Lambda$He. We have to measure both of proton and neutron in order to derive unambiguous asymmetry parameter.

# 2 Proposed Experiment

## 2.1 Measurement of ${}^4_\Lambda$H decay

We use the ${}^4$He$(K^-, \pi^0)$ reaction with 0.8 GeV/$c$ $K^-$ beam from the K1.1 beamline. A high-resolution $\pi^0$ spectrometer is required to tag the production of hypernuclei. The binding energy of the ground state of ${}^4_\Lambda$H is 2 MeV. The spectrometer have to have a better energy resolution of 1.5 MeV (FWHM) at 0.7 GeV/$c$.

The decay particles are measured by the decay counter system which consists of drift chambers and stacks of plastic counters as shown in Fig. 1. The drift chambers are for tracking of the charged particles. The plastic counters are used for determine the energy of the charged particles by measuring energy deposit and range. For the neutron, the energy is determined by measuring time of flight between the plastic counters and the timing counters surrounding the experimental target. The concept of the decay counter system is same with that used in a series of the experiment to measure the nonmesonic decay at KEK-PS, where we confirmed that the particle identification can be done well. The difference is only the coverage of acceptance.

The yield of the nonmesonic decay are estimated by assuming the following conditions.

- $K^-$ beam intensity: $2.2 \times 10^6$ /spill
- PS cycle: 3.4 sec

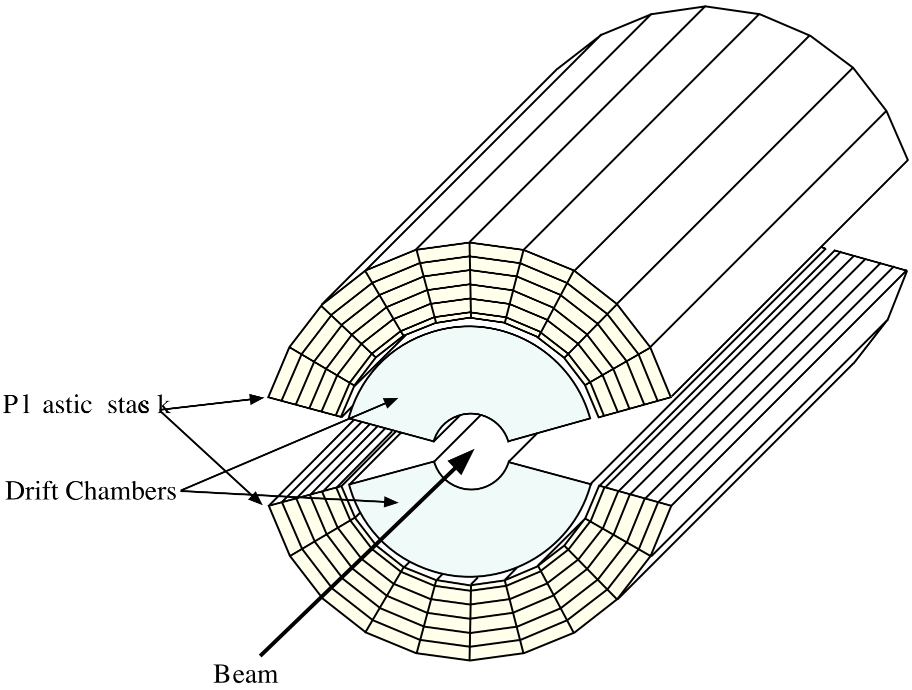


Figure 1: Conceptual design of decay counter system

- Target thickness: 1.25 $g/cm^2$
- Cross section: 0.2 $mb/sr$
- Spectrometer solid angle: 0.02 sr
- Spectrometer efficiency: 0.5
- Decay counter acceptance: 0.5
- Efficiency for decay protons: 0.8
- Efficiency for decay neutrons: 0.2
- branching ratio of $\Gamma(\Lambda n \rightarrow nn)$: 0.1
- branching ratio of $\Gamma(\Lambda p \rightarrow np)$: 0.01

We expect 2500 events for $\Lambda n \rightarrow nn$ decay and 1000 events for $\Lambda p \rightarrow np$ in 200 shifts beam time. We can achieve 3 % error even for $\Lambda p \rightarrow np$ which we have to measure, while we have only the decay rate of the nonmesonic decay ($\Gamma_{NM} = 0.17 \pm 0.11$) so far[24].

## 2.2 Measurement of ${}^4_\Lambda$He decay

We use the ${}^4$He$(K^-, \pi^-)$ reaction with 0.8 GeV/$c$ $K^-$ beam from the K1.1 beamline. We require high resolution and large acceptance spectrometer like SKS to measure scattered pions. The mass resolution should be less than 2 MeV (FWHM), since the binding energy of the ground state of ${}^{4}_{\Lambda}$H is 2.4 MeV. Decay particles are measured with the decay counter system described in the previous section.

The yield of the nonmesonic decay are estimated by assuming the following conditions.

- $K^-$ beam intensity: $2.2 \times 10^6$ /spill
- PS cycle: 3.4 sec
- Target thickness: 1.25 $g/cm^2$
- Cross section: 0.5 $mb/sr$
- Spectrometer solid angle: 0.05 sr
- Spectrometer efficiency: 0.5
- Decay counter acceptance: 0.5
- Efficiency for decay protons: 0.8
- Efficiency for decay neutrons: 0.2
- branching ratio of $\Gamma(\Lambda n \rightarrow nn)$: 0.01
- branching ratio of $\Gamma(\Lambda p \rightarrow np)$: 0.1

We expect 1100 events for $\Lambda n \rightarrow nn$ decay and 44000 events for $\Lambda p \rightarrow np$ in 200 shifts beam time. We can achieve 3 % error even for $\Lambda n \rightarrow nn$ which we have to measure, while the existing data is $\Gamma(\Lambda p \rightarrow np) = 0.16 \pm 0.02$ and $\Gamma(\Lambda n \rightarrow nn) = 0.01 \pm 0.05$[24].

## 2.3 Measurement of ${}^{5}_{\Lambda}$He decay

We use the ${}^{6}$Li$(\pi^+, K^+p)$ reaction with 1.05 GeV/$c$ $\pi^+$ beam from the K1.1 beamline. In order to measure the asymmetry parameter of the nonmesonic decay, the magnitude of produced polarization is essential. In this sense, the $(\pi^+, K^+)$ reaction is better than the $(K^+, \pi^+)$ reaction. We require high resolution and large acceptance spectrometer like SKS to measure scattered kaons. The mass resolution should be less than 2 MeV (FWHM) to separate the ground-state events from the low-lying state of ${}^{6}_{\Lambda}$Li. The coverage of the horizontal-scattering angle is essential to obtain large polarization. In E278 experiment the polarization was measured as 30 $\sim$ 40 % at 10 deg scattering angle. The coverage from $-15^\circ$ to $15^\circ$ is enough to introduce polarization. Decay particles are measured with the decay counter system described in the previous section.

The yield of the nonmesonic decay are estimated by assuming the following conditions.

- $\pi^+$ beam intensity: $1 \times 10^7$ /spill
- PS cycle: 3.4 sec
- Target thickness: 4 $g/cm^2$
- Cross section: 0.005 $mb/sr$
- Spectrometer solid angle: 0.03 sr
- Spectrometer efficiency: 0.5

- Kaon survival rate: 0.5
- Decay counter acceptance: 0.5
- Efficiency for decay protons: 0.8
- Efficiency for decay neutrons: 0.2
- branching ratio of $\Gamma(\Lambda p \to np)$: 0.2

We expect 4000 events for $\Lambda p \to np$ decay in 200 shifts beam time. We can achieve 4 % error for the asymmetry parameter, while the E278 result has 20 % error.

# 3 Summary

We propose experiments to study the nonmesonic decay of A=4, 5 $\Lambda$ hypernuclei. Key observables are:

- decay rate of $\Lambda n \to nn$ of ${}^{4}_{\Lambda}$He
- decay rate of $\Lambda p \to np$ of ${}^{4}_{\Lambda}$H
- asymmetry parameter respect to the polarization of $\Lambda$ for $\Lambda p \to np$ of ${}^{5}_{\Lambda}$He

So far the exsisting accelerator facility cannot provide enough intense beam for above purpose. The coming 50 GeV machine will be unique facility since it provides high intense and pure secondary beam. Purity of the secondary beam is crucial for the expriment using the $(K^-, \pi^-)$ and $(K^-, \pi^0)$ reactions.

E462/E508 experiments found that we have to measure all the decay particles in order to derive the observables of the nonmesnic decay unambiguously. The proposed experiments are suffered from low detection efficiency for decay neutron(s) and from small decay rate ($\sim 0.01$ of free $\Lambda$ decay). High intense beam at 50 GeV machine can overcome this difficulty.

# References


[1] J.J. de Swart, T.A. Rijken, P.M. Maessen and R.G. Timmermans, Nuovo Ciment **102A** (1989) 203, and references therein.

[2] T.A. Rijken, P.M. Maessen and J.J. de Swart, Nucl. Phys. A **547** (1992) 245c.

[3] E.G. Adelberger and W.C. Haxton, Ann. Rev. of Nucl. Sci. **35** 501 (1985).

[4] A. Masaike, Proc. IV Int. Symp. on Weak and Electromagnetic Interaction in Nulcie(WEIN'95), June 1995, Osaka, World Sci. (1995) 20.

[5] M.M. Block and R.H. Dalitz, Phys. Rev. Lett. **11** (1963) 96.

[6] B.H.J. McKellar and B.F. Gibson, Phys. Rev. C **30** (1984) 322.

[7] K. Takeuchi, H. Takaki and H. Bando, Prog. Theor. Phys. **73** (1985) 841.

[8] J. dubach, Nucl. Phys. A **450** (1986) 71c.

[9] A. Parreño, A. Ramos, and C. Bennhold, Phys. Rev. C **56** (1997) 339, and references therein.

[10] H. Outa *et al.*, KEK-PS E462 proposal.

[11] H. Bhang *et al.*, KEK-PS E508 proposal.

[12] A. Parreño and A. Ramos, Phys. Rev. C **65** (2001) 015204.

[13] T. Kishimoto, KEK **83-6** (1983) 51, unpublished.

[14] H. Nabetani *et al.*, Phys. Rev. C **60** (1999) 017001.

[15] H. Bando, T. Motoba and J. Zofka, Int. J. Mod. Phys. Vol. **5** (1990) 4021.

[16] K. Sasaki *et al.*, nucl-th/0204057 (2002).

[17] S. Ajimura *et al.*, Phys. Lett. B **282** (1992) 293.

[18] T. Kishimoto *et al.*, KEK-PS E278 proposal.

[19] S. Ajimura *et al.*, Phys. Rev. Lett. **80** (1998) 3471.

[20] K. Itonaga, T. Motoba, O. Richter and M. Sotona, Phys. Rev. C **49** (1994) 1045.

[21] S. Ajimura *et al.*, Phys. Rev. Lett. **84** (2000) 4052.

[22] C. Bennhold and A. Ramos, Phys. Rev. C **45** (1992) 3017.

[23] H. Outa *et al.*, private communication.

[24] H. Outa *et al.*, Nucl. Phys. A **639** (1998) 251c.