

The three-body nonmesonic weak decay process of ${}_{\Lambda}^{12}\text{C}$ hypernucleus and its exclusive measurement at J-PARC (E18).

H Bhang^{1,*}, J K Ahn², S Ajimura³, K Aoki⁴, S Choi¹, T Fukuda⁵, O Hashimoto⁶, B H Kang^{1,7}, E Kim¹, J H Kim⁸, M Kim¹, S J Kim¹, T Maruta⁶, T Nagae^{4,9}, S N Nakamura⁶, H Noumi^{4,3}, S Okada^{10,11}, H Outa^{4,10}, H Park⁸, P K Saha^{4,12}, A Sakaguchi³, Y Sato⁴, M Sekimoto⁴, T Takahashi⁴, H Tamura⁶, K Tanida^{9,1}, A Toyoda⁴, K Tshoo¹, H J Yim^{1,13} and C J Yoon¹.

¹ Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea.

² Department of Physics, Pusan National University, Busan 609-735, Korea.

³ Department of Physics, Osaka University, Toyonaga 560-0043, Japan.

⁴ High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan.

⁵ Lab. of Physics, Osaka Electro Comm. University, Neyagawa 572-8530, Japan.

⁶ Department of Physics, Tohoku University, Sendai 980-8578, Japan.

⁷ Department of Nuclear Engineering, Hanyang University, Seoul 133-791, Korea.

⁸ Korea Research Institute of Standards and Science (KRISS), Daejeon 305-600, Korea.

⁹ Department of Physics, Kyoto University, Kyoto 606-8502, Japan.

¹⁰ Riken Nishina Center, Riken, Wako 351-0198, Japan.

¹¹ LNS/INFN, Frascati, Italy.

¹² Japan Atomic Energy Research Institute, Tokai 319-1195, Japan.

¹³ Korea Institute of Radiological and Medical Sciences, Seoul 139-706, Korea.

E-mail: * bhang@phy.snu.ac.kr

Abstract. In spite of the recent crucial progresses in the studies of nonmesonic weak decay (NMWD) of Λ hypernuclei, its consistent understanding is yet to be achieved. In the experimental progresses, the long standing Γ_n/Γ_p problem has finally been solved recently. And for the first time, two-nucleon induced NMWD channel has been identified experimentally and its decay width, 0.27 ± 0.13 , measured but only with a 2σ confidence level. On the other hand, the decay asymmetry remains to be understood yet and the accurate measurement of the decay width of each channel is much awaited for the consistent understanding of NMWD. In E18 of J-PARC, we are going to measure Γ_i of NMWD including Γ_{2N} with 10 % statistical uncertainties. Main concerns in E18 experiment such as the handling of the high beam intensity, the neutron background contamination in the neutron coincidence yields and the control of the trigger rates with the beam intensity as high as $10^7 \pi^+$ /spill are discussed and it is shown that they can be handled properly.

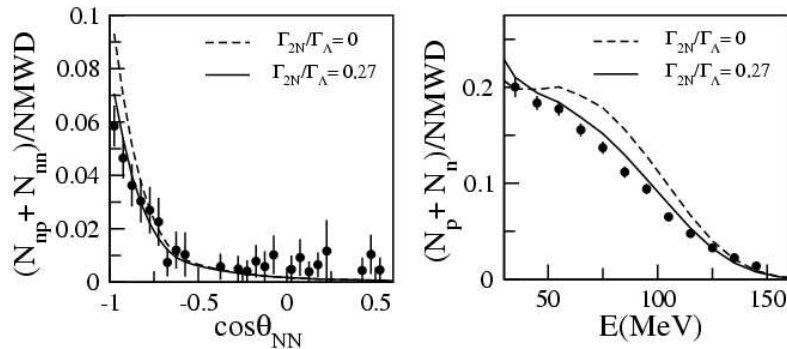


Figure 1. The two nucleon angular correlation $N_{NN}(= N_{np} + N_{nn})$ (left figure) and the normalized nucleon spectrum $N_N(= N_p + N_n)$ per NMWD in the NMWD of ^{12}C are compared with those of INC(1N) (dashed lines) and INC(1N+2N) calculation (solid lines) [1]. θ_{NN} is the opening angle of the two nucleon momenta.

1. Introduction

A Λ hyperon in a nucleus decays via either a mesonic or a nonmesonic weak interaction process. The mesonic weak decay process $\Lambda \rightarrow N\pi$ is strongly suppressed in the nucleus except in very light nuclei due to the low decay momentum (~ 100 MeV/c). Instead the nonmesonic weak decay (NMWD) channels $\Lambda p \rightarrow np$ (Γ_p) and $\Lambda n \rightarrow nn$ (Γ_n) emitting two energetic nucleons (~ 400 MeV/c) become open and dominant in the nuclei beyond s-shell. In addition to these one-nucleon induced(1N-) NMWD channels, we have recently confirmed and reported on the two-nucleon induced(2N-) NMWD $\Lambda NN \rightarrow nNN$ (Γ_{2N}) channel whose width $\Gamma_{2N}/\Gamma_\Lambda = 0.27 \pm 0.13$ were measured in KEK-PS E508 experiment [1].

Among the issues of NMWD, the long standing Γ_n/Γ_p inconsistency problem has recently been resolved with the newly measured values, ~ 0.5 , in the exclusive coincidence measurements at KEK-PS [2, 3]. It turned out that the previous large Γ_n/Γ_p measured values were due to the strong 3-body 2N-NMWD contribution which push the spectrum to low energy region, thereby resulting the quenching of the nucleon yields in the energy region above $E_{th}(= 30$ MeV). The Γ_{2N} value was obtained by reproducing the quenching.

On the other hand, the serious inconsistency of the asymmetry parameter, α_{nm} , among the values of experimental data ($0.07 \pm 0.08 \pm_{0.00}^{0.08}$ for $^5_\Lambda\text{He}$ and $-0.16 \pm 0.28 \pm_{0.00}^{0.18}$ for $^{12}\text{C}/^{11}\text{B}$ [4]) and theoretical calculations ($-0.6 \sim -0.7$) still remains, though the current theoretical results reproduce the widths such as Γ_n/Γ_p , Γ_n and Γ_p within the experimental uncertainties, which are quite big. In order to unravel the problem, theoretical efforts have been made to include new exchange mesons such as those of the scalar-isoscalar interactions (σ , correlated $2\pi(\sigma)$ and uncorrelated 2π meson) and the axial vector a_1 meson [5, 6, 7]. However, in order to provide more stringent guide to these theoretical calculations, it is crucial to improve the current accuracy of the experimental Γ s.

Evenif the successful resolution of Γ_n/Γ_p puzzle, the uncertainty of Γ_n/Γ_p remains quite big yet, $\sim 30\%$. The uncertainty of Γ_{2N} value obtained by reproducing the NN pair angular correlation $N_{NN}(= N_{np} + N_{nn})$ of nn and np pair in the bb 2-body kinematics region reaches to $\sim 50\%$ due to the inclusive nature of the reproduction and the limited statistics. The results of the reproduction is shown in Fig. 1. Since it is difficult to measure the widths, Γ_n and Γ_p directly, the tactics has been to derive them from Γ_{nm} , Γ_{2N} and Γ_n/Γ_p as $\Gamma_{nm} - \Gamma_{2N} = \Gamma_p(1 + \Gamma_n/\Gamma_p)$. Therefore current Γ_n and Γ_p values have big uncertainties due to not only that of Γ_n/Γ_p , but also the even larger one of Γ_{2N} .

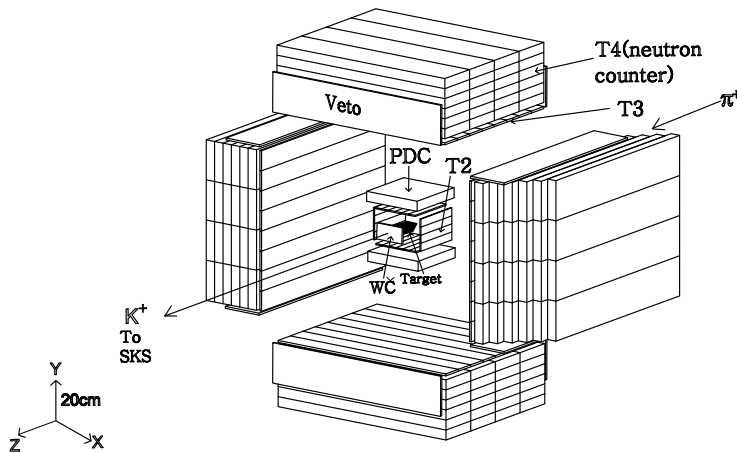


Figure 2. The decay coincidence counter system of E18. There are four coincidence counter sets; Each of the top and bottom counter sets consists of a start timing counter (T2) for charged particles, a drift chamber, a veto or stop timing counter (T3), and neutron counter (T4) arrays. The side set is similar except that the drift chamber is absent.

Therefore, it is crucial to improve the accuracy of Γ_{2N} as well as that of Γ_n/Γ_p .

In J-PARC E18 experiment, we will measure Γ_{2N} of ^{12}C with 10% statistical uncertainty measuring both the pair nucleon correlations in bb and non-bb kinematics region and the triple coincidence events with 2π solid angle decay particle detectors shown in Fig. 2 and the high intensity pion beam. At the same time we also can measure the Γ_n/Γ_p to the 10% statistical uncertainty improving the current 30% uncertainty. For such improvements, the most crucial factors are the statistics for pair coincidence in the non-bb kinematics region and the triple coincidence.

Table 1 lists the numerical pair yields Y_{NN} and the efficiency corrected normalized pair yields N_{NN} of np and nn pair at each kinematics region, bb and non-bb region where bb denotes the region of $\cos\theta_{NN} \leq -0.7$ and nbb of $-0.7 \leq \cos\theta_{NN} \leq 0.6$. The nucleon pair yields of E508 at nbb region were only 9 for np and 16 for nn. And the triple coincidence events were only 6 even if we remove the threshold condition for the kinetic energy $E_{th} \geq 30$ MeV. In order to achieve the statistical uncertainty $\sim 10\%$, we need to reach each of these yields ≥ 100 especially in nbb kinematics region.

The typical enhancement factors of the detection efficiency for proton and neutron in the E18 set up of Fig.2 are 4 and 1.8 over those of E508, respectively. Combining the enhancement factors and the pair yields of E508 of Table 1, we expect the coincidence yields to increase to $Y_{np}^{nbb} \sim 160$ and $Y_{nn}^{nbb} \sim 130$ from 9 and 16 in the nbb region, respectively and the triple coincidence events to $Y_{NNN} \sim 180$ from the 6 events of E508 when we have the total $5 \times 10^{12} \pi^+$ on the $4g/cm^2$ thickness carbon target over 80 shifts.

Table 1. Pair yields Y_{NN} and the normalized pair yields N_{NN} of np and nn pair are shown at each kinematics region from the E508 experiment. The 'bb' and 'nbb' denote the back-to-back kinematics region, $\cos\theta \leq -0.7$, and the non-back-to-back region, $-0.7 \leq \cos\theta \leq 0.6$, respectively.

Kin. region	np pair		nn pair	
	bb	nbb	bb	nbb
pair yields, Y_{NN}	116	9	43	16
pair correlation, N_{NN}	0.138 ± 0.014	0.060 ± 0.018	0.083 ± 0.014	0.083 ± 0.020

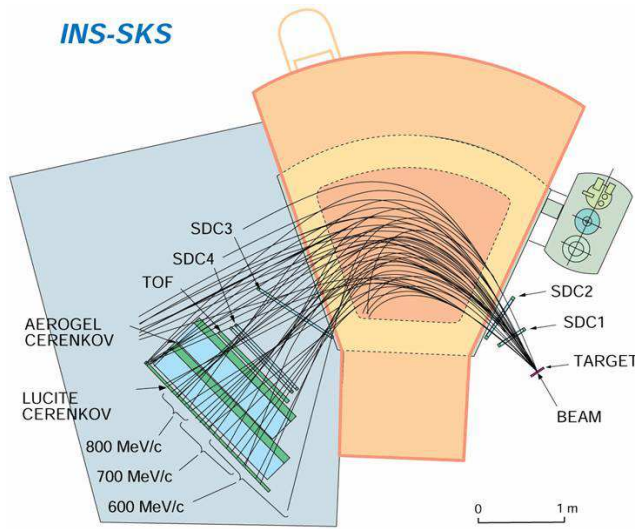


Figure 3. The schematic view of SKS. The typical momentum resolution is $\Delta p/p \sim 10^{-3}$ (FWHM) at 0.72 GeV/c and a large angular acceptance ~ 100 msr at the target focal point. Track paths of several momentum groups are shown. It is seen that the particles of the momentum above 800 MeV/c can pass the trigger condition $TOF \otimes \overline{AC} \otimes LC$.

2. Experiment

The experiment will be carried out in the K1.8 beamline of J-PARC 50 GeV Proton Synchrotron. The ^{12}C hypernucleus is produced via the (π^+, K^+) reaction at $P_{\pi^+} = 1.04$ GeV/c on ^{12}C target. The high intensity pion beam of $5 \times 10^6 \pi^+/\text{sec}$ will bombard the target so that the high rate capabilities of the beam line counter elements such as the beamline tracking chambers and hodoscopes are required.

The layout of the K1.8 beamline at J-PARC is similar to that of K6 beamline of the KEK-PS where the instantaneous beam rate has been kept below $\sim 2 \times 10^6/\text{sec}$ in order to avoid the rapidly increasing event loss due to the multi-hit events in the upstream beamline chambers. The R/D for the improved high rate tracking chambers such as MWPC and Silicon Strip Detector (SSD) are being carried out among the K1.8 user collaborations. The present requirement of $5 \times 10^6 \pi^+/\text{sec}$ which corresponds to the hit rate of the busiest wire $\sim 200\text{k}/\text{sec}$ can be met with either a MWPC (~ 1 mm wire spacing) or a drift chamber of the similar drift length.

For the detection of K^+ , we will use the standard setup of Superconducting Kaon Spectrometer (SKS) which is transferred from the K6 beamline of KEK-PS. Fig. 3 shows the layout of SKS that consists of a superconducting magnet ($B_{max} = 3\text{T}$) and the counter system for the K^+ tracking and identification. SKS has a good momentum resolution, $\Delta p/p \sim 10^{-3}$ (FWHM) at 0.72 GeV/c, and a large angular acceptance ~ 100 msr with respect to the SKS target focal point. The solid angle is reduced by $\sim 10\%$ when the vertex point moves upstream about 10 cm from the SKS target focal point. In E508, due to the crowded counter arrangement, the target was placed at ~ 10 cm upstream of SKS target focal point. Since SDC1 and SDC2 are located on the incoming beam axis, they are required high rate capabilities according to the increased beam intensity. New DCs of 1mm spacing compared to the old SDC1 and SDC2 of 5mm are being prepared.

Fig. 2 shows the decay particle counter setup of the experiment E18. There are four coincidence counter sets, two located at the top and bottom of the target and two at the left and right side. Each of the top and bottom counter sets consists of a start-timing counter (T2; 20 units) which is of 4 mm thickness and surrounding the target, a drift chamber (PDC), a veto or stop-timing counter (T3; 32 units) which is of 2 cm thickness and located right in front of the neutron counter, neutron counter arrays (T4; 96 units), and side vetos. Each of the side sets is similar to that of the top-bottom set, except that

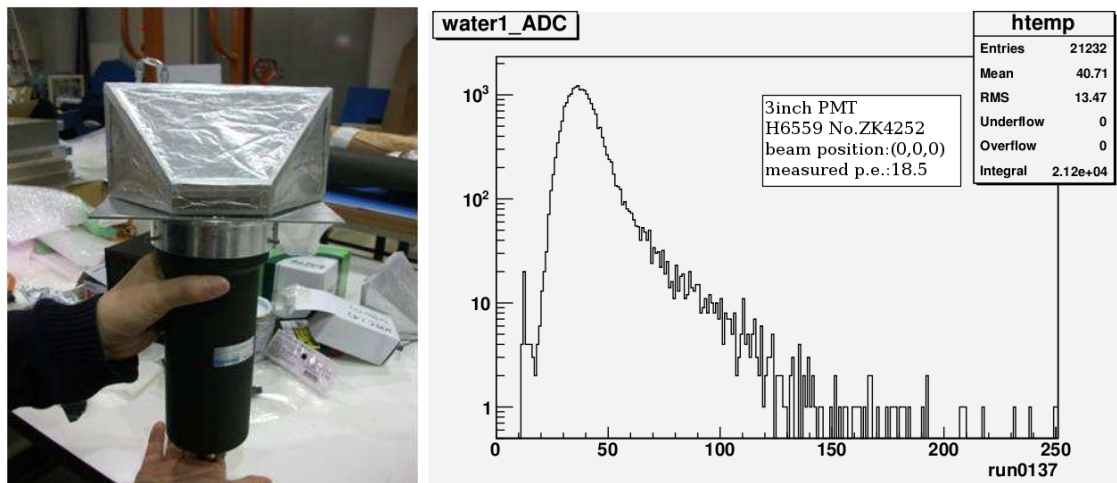


Figure 4. The test module of the water Cherenkov counter is shown in the left figure. The observed ADC spectrum for $\beta=1$ particles in the right figure is explained in the text.

the drift chamber is absent. The left neutron counter arrays are gradually pushed toward upstream due to the space conflict with the wall of SKS spectrometer. For the protons (or pions) to the side counters, the tracking is made with T2 and T3 counters. From the results of E508, the vertex resolutions of the side counter events obtained with the hodoscopes T2 and T3 were $\sigma_x = 1.4(0.8)mm$, $\sigma_y = 2.5(2.5)mm$ and $\sigma_z = 42.4(31.2)mm$ where the values in the parenthesis are those tracked with PDC. The degradation of the vertex resolution of the side counter is considered acceptable.

The random neutron background in E508 experiment was estimated to be about 2 % of the real events in $1/\beta$ spectrum. In E18, the overall enhancement factor for neutron yield is $\sim 4.5 (= 1.8(\text{neutron detector volume}) \times 2.5(\text{beam current}))$ times that of E508. Therefore the expected random background yields of nn coincidence events would increase by the factor $(1.8 \times 2.5)^2$ factor assuming the neutron background proportional to the beam intensity while the nn pair yields by $1.8^2 \times 2.5$ so that the background to signal ratio of nn pair yields increases to 5 % from 2%. Therefore, the background to signal ratio of nn events in the nbb region would increase to $\sim 8\%$. When the beam rate is increased by a factor 2, the random background ratio in the nn coincidence yields also increases by two times to $\sim 16\%$ of the nn yields at nbb region so that the uncertainty due to the random background would be comparable to that of the statistical one, which is not acceptable. Similarly the beam micro-structure would increase the random background ratio in the nn pair yields. Therefore, it is crucial to keep the instantaneous beam rate under $5 \times 10^6/sec$ all the time.

3. Trigger

We plan to use the kaon trigger scheme combining the SKS downstream counters ($TOF \cdot \overline{AC} \cdot LC$) and the upstream proton veto trigger counter, the water Cherenkov counter placed right after the target. Since the beam rate of E18 experiment is 2-5 times higher than E508, where the hardware trigger rate for (π^+, K^+) event (for all events) was 150/spill (270/spill) for $3.5 \times 10^6 \pi^+/spill$, our total trigger rate could reach $10^3/spill$, which we can not handle within the current TKO data acquisition system.

With the trigger logic $TOF \cdot \overline{AC} \cdot LC$, only a few percent of the (π^+, K^+) trigger

events were actually fired by K^+ event in E508 and most of them were due to the mis-identification of protons. It was partly due to the high energy protons above 850 MeV/c, the threshold for protons of the Lucite Cerenkov radiation, and partly due to the scintillation of the wavelength shifter (WS) material doped (~ 10 ppm) in Lucite Cerenkov (LC) counter. In order to remove the high energy protons and the WS scintillation events, we place a water Cerenkov (WC) counter of $n=1.33$ right after the target with which the threshold momenta are 0.55 and 1.06 GeV/c for kaon and proton, respectively.

Therefore the real (π^+, K^+) events, whose typical K^+ momenta ~ 720 MeV/c in the (π^+, K^+) reaction at 1.04 GeV/c pion beam momentum are well above the threshold 550 MeV/c, are safe. Since the protons above 1.06 GeV/c definitely can not pass through SKS, essentially all the protons and the WS scintillation events will be rejected when the trigger logic include the water Cerenkov counter as $WC \cdot BEAM \cdot TOF \cdot \overline{AC} \cdot LC$. With the improved trigger efficiency of K^+ events we will be able to handle much higher (π^+, K^+) trigger rates with $\sim 10^7$ /spill(2 sec) pion beam.

In order to check the efficiency of kaon trigger, we have tested a simple water Cerenkov counter (Fig. 4) of a demension $1 \times 8 \times 15$ cm³ viewed with a 3 inch PMT (Hamamatsu H6559UVB) using the positron beam of ≤ 450 MeV/c at LNS of Tohoku University. The average photo-electron number for $\beta=1$ particles was ~ 18.5 as shown in Fig.4 (right side), with which we expect ~ 7 photoelectrons for ~ 720 MeV/c kaon beam and the efficiency high enough. Overall we conclude that an efficient water Cerenkov counter can be implemented in the (π^+, K^+) trigger logic so that most of the proton events can be removed and the kaon event ratio in the (π^+, K^+) trigger will be drastically improved.

4. Summary

In spite of the recent crucial progresses in the studies of NMWD, its consistent understanding is yet to be achieved. We now understand the composition of the decay channels of NMWD and are in the position to measure its branching ratios accurately. In E18 of J-PARC, we plan to measure Γ_i of NMWD including Γ_{2N} with 10 % statistical uncertainties. Main concerns in E18 experiment are the handling of the high beam intensity, the neutron background contamination in the neutron coincidence yields and the control of the trigger rate. We need to keep the instantaneous beam intensity in the level of $\sim 5 \times 10^6 \pi^+$ /sec and to remove the beam micro-structure in order to maintain the neutron background contribution less than ~ 10 percent of the coincidence yields. We have shown that an efficient water Cerenkov counter can be implemented in the (π^+, K^+) trigger logic to reduce the false proton trigger rate so that the π^+ beam as high as 5×10^6 /sec can be handled even with the old TKO box data acquisition system.

We are grateful to the KEK-PS staff for the support of our experiments and for the stable operation of KEK-PS. H.B. acknowledges the support from the WCU program of NRF and from KOSEF (Grant No. R01-2007-000-11714-0).

References

- [1] M.J. Kim *et al.*, *Phys. Rev. Lett.* **103** 182502(2009) and *Eur. Phys. J. A* **33** 259(2007).
- [2] B. H. Kang *et al.*, *Phys. Rev. Lett.* **96** 062301(2006) and *Phys. Lett. B* **597** 249(2004).
- [3] M. J. Kim *et al.*, *Phys. Lett. B* **641** 28(2006) and *Phys. Rev. C* **68** 065201(2003).
- [4] T. Maruta *et al.*, *Eur. Phys. J. A* **33** 255(2007).
- [5] K. Sasaki, M. Izaki and M. Oka, *Phys. Rev. C* **71** 035502(2005).
- [6] C. Chumilas, G. Garbarino, A. Parreno and A. Ramos, *Phys. Lett B* **657** 180(2007).
- [7] K. Itonaga, T. Motoba, T. Ueda and Th.A. Rijken, *Phys. Rev. C* **77** 044605(2008).