E549: Confirmation of nuclear kaonic state and search for its excited state

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Summary

E549 experiment aims at confirmation of narrow kaonic nuclear bound state with isospin T=1, which was claimed to be observed in the former E471 experiment[1], in the ^{4}He(stopped K^-,p) inclusive spectrum. In the experiment, we also measured ^{4}He(stopped K^-,nX) spectrum so as to search for the T=0 state predicted by Akaishi-Yamazaki[2]. In both of ^{4}He(stopped K^-,p) and ^{4}He(stopped K^-,nX) spectra, we drastically improved statistics and resolution of the missing mass. However we have not observed any narrow (Γ<20MeV) peak structure in the deeply bound region of the kaon.

We extended the study to search for the possible broad states attributed to the formation of kaon bound states, by investigating ΛN and Λd pairs from the stopped K^- reaction on ^{4}He. In ΛN / Λd correlation analysis, we clearly identified two- and three-nucleon K^- absorption processes, respectively. We also found additional non-mesonic reaction modes, which are hard to be explained by the simple multi-nucleon absorption picture, indicating possible exotic signals of the formation of kaon bound states.

The collaboration proposed an experiment J-PARC(E15) to search for the lightest kaonic bound state, namely K^-pp system, by measuring the missing mass in the ^{3}He(in-flight K^-,n) reaction and the invariant mass of the decay such as $K^-pp \rightarrow \Lambda p$ simultaneously. Based on the finding of the E549, YN correlation analysis is inevitable to identify broad kaon bound states.

1. Introduction

In the former experiment E471, we reported the observation of distinct peak in the ^{4}He(stopped K^-,p) spectrum, which was interpreted to be a signal of "strange tribaryon" with charge 0, strangeness −1 and isospin 1, called S^0(3115) (Mass=3117MeV/c^2, Γ<21 MeV/c^2) [1]. The goal of the original E471 proposal was the search for a deeply bound kaonic state with isospin=0, predicted by Akaishi and Yamazaki [2] in the ^{4}He(stopped K^-,n) reaction. We also obtained another candidate of the tribaryon state, S^+(3140), in the neutron spectrum, but the statistical significance was not sufficient to claim a definitite evidence for the existence [3]. Since original design of the E471 setup was optimized to measure neutron by means of TOF, the experimental resolution for protons was not satisfactory and we obtain only the upper limit for the width of S^0(3115). All the events are measured together with at least one additional charged particle detected in the coincidence arms, which is unnecessary for the proton inclusive measurement. This trigger condition made the analysis of the formation rate difficult, because of the ambiguity of the possible decay modes. Moreover, the limited momentum acceptance for protons obstructs the search for excited states.

Therefore we carried out a new experimental search with improved resolution and higher statistics by upgrading E471 experimental setup. The objective of the proton spectroscopy were (1) to confirm the S^0(3115) and determine its width and formation ratio with improved resolution by a ^{4}He(K^-,p) inclusive measurement and (2) to search for excited states of S^0(3115). For the neutron side, we also aimed at observing other candidates for tribaryon states with isopin T=0.

2. E549 experiment

The upgrade scheme of the experimental setup from E471 to E549 is shown in figure 1 schematically. In the E471 setup, we measured the timing of incoming kaon by T0 counter and outgoing particles (either neutron or proton) by NT counter, and there was no redundancy in the TOF measurement. In the E549, we newly installed proton dedicative detectors, two layers of charged particle TOF walls (PA and PB) for the ^{4}He(K^-, p) measurement with improved timing resolution. Incoming kaon timing was measured twice and outgoing proton timing was measured three times (PA/PB and NT) in E549. This redundancy of the measurement enabled us to check the consistency of the tuning parameters (ADC-slewing correction etc.) of the off-line analysis of the TOF. We also placed charged particle tracking chambers (Proton chambers in the figure) just after the target and took data with the minimum biased trigger to measure proton inclusive spectrum.

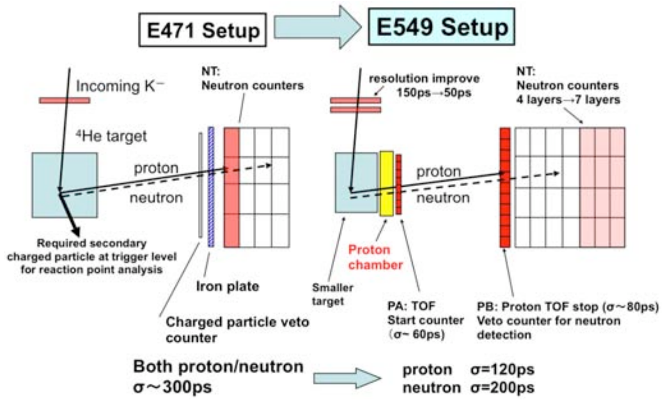

Figure 1: Improvement of the setup from E471 to E549

For the TOF calibration, we utilized so called metastable states formation of the kaonic helium atoms and the free decay of the kaon [4]. When we select the delayed charged emission events by the T0−PA TOF analysis, we can clearly select the free decay events from the prompt nuclear absorption and successive hyperon decay. Figure 2 shows the PA-PB inverse velocity (1/β) TOF spectrum of the charged particle from the stopped K^- on ^{4}He with delayed timing condition. Three peaks at 1/β=1, 1.1, 1.24 respectively correspond to electrons (mainly from K^-_{e3} decay), muons ($K_{\mu 2}$) and pions ($K_{\pi 2}$). We can estimate the TOF resolution from the width of $K_{\mu 2}$ muons to be σ =0.020 , which is consistent to the intrinsic resolution of PA (60ps) and PB (80ps). It was also consistent to the $K^+_{\mu 2}$ peak width obtained by the K^+ calibration data, demonstrating the long-term stability of the PA/PB timing offset. Since the K^- free decay fraction from the trapping in the metastable state is known to be 3.5±0.5% [5], we can also utilize the yield of this $K^-_{\mu 2}$ peak for the normalization of the ^{4}He(stopped K^-, p) missing mass spectrum.

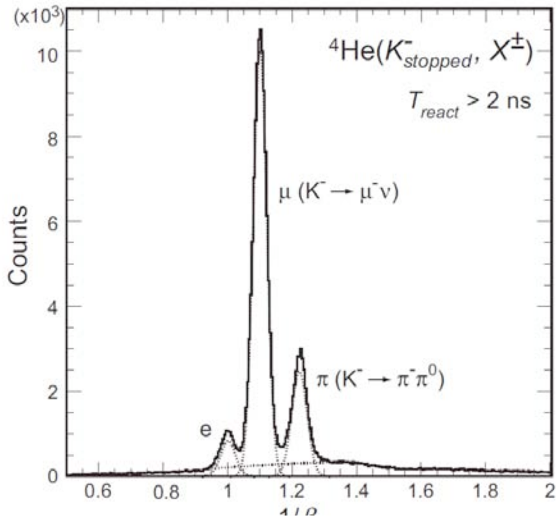

Figure 2: 1/β resolution of charged particles emitted from the free-decay of K^- trapped in the meta-stable state of kaonic ^{4}He atom

The experiment E549 was carried out at the K5 beam line in the summer of 2005. We also took data for both of ^{4}He(stopped K^-, p) and ^{4}He(stopped K^-, nX) during the period of E570 experimental runs. About 2.5 $\times 10^8$ K^-s stopped inside ^{4}He target during the E549+E570 period. Thanks to the improvement of the experimental setup of E549, the TOF resolution for protons/neutrons were respectively improved by 2/1.5 times better than the previous experiment E471. We could successfully accumulate about 20 times more statistics in ^{4}He(stopped K^-, p) inclusive spectrum (with only analyzing E549 part) and 7-8 times more statistics also in the ^{4}He(stopped K^-, p) spectrum.

3. Results from proton/neutron inclusive spectra

For the missing mass spectroscopy of ^{4}He(stopped K^-, p) inclusive measurement, the analysis has been finished and the result was recently published in Ref.[6]. Figure 3 shows the missing mass spectrum of ^{4}He(stopped K^-, p) inclusive measurement in E549 together with the proton momentum scale and energy threshold where YNN and $Y\pi NN$ channels open. As shown in the figure, there is no distinct peak in the spectrum including the location of S^0(3115), where E471 once claim the existence of the narrow peak.

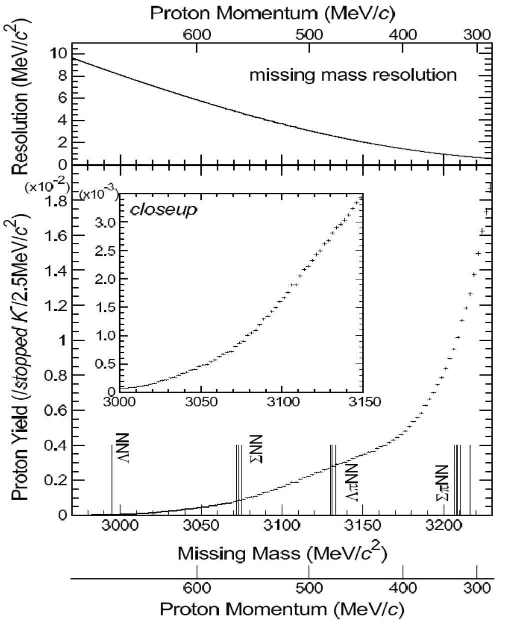

Figure 3: Missing mass spectrum from the ^{4}He(stopped K$^-$,*p*) reaction by the inclusive measurement [6]

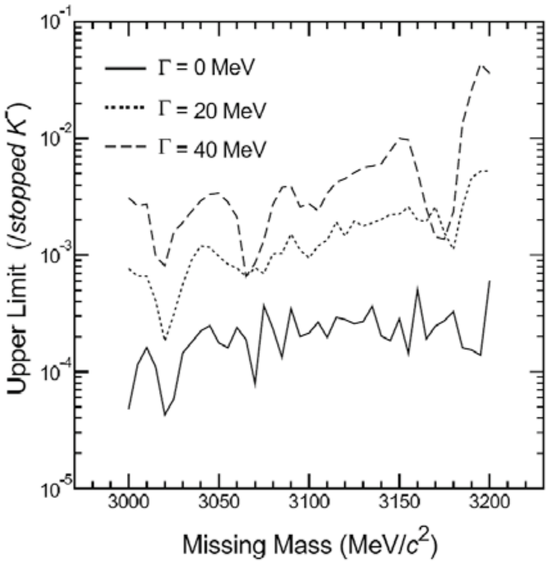

Figure 4: Upper limits of the formation branching ratio for a strange tribaryon state at the 95% C.L. as a function of the missing mass. Solid, dotted and dashed lines correspond to the assumed width of Γ =0,20 and 40MeV/c^2 states, respectively [6]

For quantifying the search results, we derived upper limits for the formation branching ratio of a tribaryon state by the fitting assuming a peak on a smooth polynomial background shape. The detail of the fitting is discussed in Ref. [6] and the obtained 95% C.L. upper limits are shown in figure 4 as a function of missing mass.

The present upper limit at mass=3115MeV/c^2, where we once claimed the observation of S^0(3115) in E471 experiment, is about 0.2%/stopped K$^-$ when we assume the width as Γ=20MeV/c^2. At the former letter paper of E471, we reported a formation branching ratio of about 1%/stopped K$^-$ [1]. This formation ratio is excluded with more than 95% C.L. in the present E549 result. We studied the reason for this discrepancy and found that the peak was an experimental artifact produced by an erroneous time correction applied for the huge proton pulse where we canot calibrate using minimum ionizing particles. The detail of the most probable reason is discussed in Ref. [7].

The analysis of ^{4}He(stopped K$^-$,*n*) spectrum is on-going and we have already reported preliminary neutron momentum spectrum [8]. The semi-inclusive momentum spectrum of neutron (with charged particle detection by top/bottom coincidence arms) for E549+E570 all the usable data are shown in Fig. 5. The TOF resolution of the neutron measurement by NT counters (in Figure 1) can be estimated by the γ-ray peak at 1/β=1 in the inverse velocity spectrum of the neutral particles. We found that we improved the 1/β resolution from σ=0.044 (E471) to σ=0.030(E549) for neutral particle measurement. We obtained neutrons with almost one-order of magnitude higher statistics, however we did not observe any narrow (Γ<20MeV/c^2) peak structure in the present ^{4}He(stopped *K*$^-$,*nX*) spectrum.

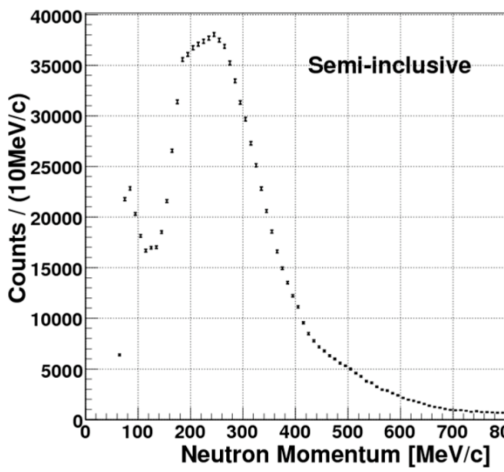

Figure 5: ***Preliminary*** ^{4}He(stopped K$^-$,*nX*) semi-inclusive momentum spectrum of E549. Statistics is 7 times higher than that of E471 and the energy resolution is 1.5 times better than E471 [8].

In order to obtain the upper limit per stopped K$^-$, we need to measure neutron spectrum with charged-pion coincidence in top and bottom coincidence arms. Our simulation tells that the pion- coincidence rate becomes lowest when the tribaryon state with isospin=0 decays to either *Λd* or *Σ*$^+$*nn* non-mesonic final state, hense the most conservative upper limit can be estimated by assuming those non-mesonic decay modes. We are finalizing the semi-inclusive neutron analysis and formation upper limits will be obtained fairly soon.

Note that in both of ^{4}He(stopped K$^-$, p) inclusive and ^{4}He(stopped K$^-$, $n\pi^{\pm}$) semi-inclusive spectra, we can obtain tight upper limits for the formation probability only for the narrow (Γ<20MeV/c^2) strange tribaryon states, whereas we have much less sensitivity for the broad structure as depicted in Fig. 4 due to the ambiguity of the background shape. When the state is as broad as Γ>40MeV/c^2, one order of looser upper limit is obtained from the fitting of the peak standing on the unknown polynomial background shape.

4. Yd correlation analysis result

The difficulty of the proton/neutron inclusive measurement in stopped K$^-$ reaction arises from the fact that momentum of nucleon emitted in the hyperon formation via K$^-$NN→YN non-mesonic reaction and that emitted from its successive decay Y→Nπ have very similar distribution. About a half of high momentum nucleon (p_N>400MeV/c) comes from the hyperon decay background. We can distinguish formation / decay nucleons when we identify hyperon (Λ, Σ) from the invariant mass reconstruction. Hyperon tagging must open the gate to identify possible existence of the relatively broad kaoninc nuclear systems.

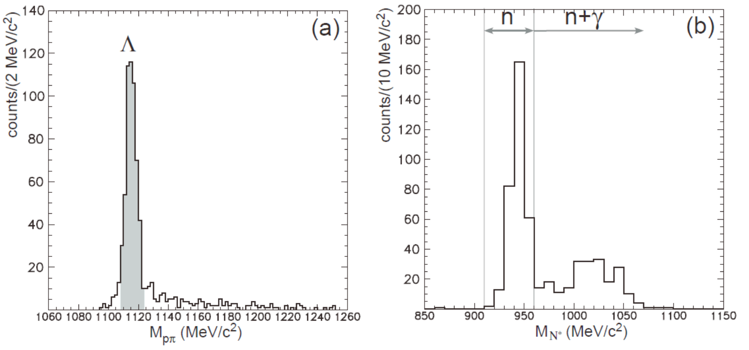

Figure 6: (a) pπ invariant mass distribution for back-to-back pd and additional charged pion detection events. (b) missing mass distribution calculated by 4-momentsa of Λ and d. Λdn final state is cleanly separated from the Σ^0($\Lambda\gamma$)dn final state.

Energetic deuteron measurement is also interesting because it is never formed from the hyperon decay process. For example, we may have chance to detect charge-neutral strange dibaryon state with isospin=1/2, which is the isobaric analog state of bound K$^-$pp system[9,10], in the reaction K$^-$ ^{4}He→ $^2S^0_{T=1/2}$+d. When we measure the Λ+d in coincidence, the missing particle must be neutron. Hence we can carry out a complete exclusive measurement.

To this end, we carried out Λd–correlation analysis. Results are recently accepted for publication [11]. We observed about 10^5 energetic (p_d >500MeV/c) deuterons in E549. Fig. 6(a) demonstrates the clean Λ reconstruction, when we requires the proton + deuteron coincidence in a back-to-back direction together with an additional charged pion detection. Once the Λ is clearly identified, then we can further reconstruct the invariant mass of the missing particle. Fig. 6(b) shows the separation of Λnd and Σ^0nd final states.

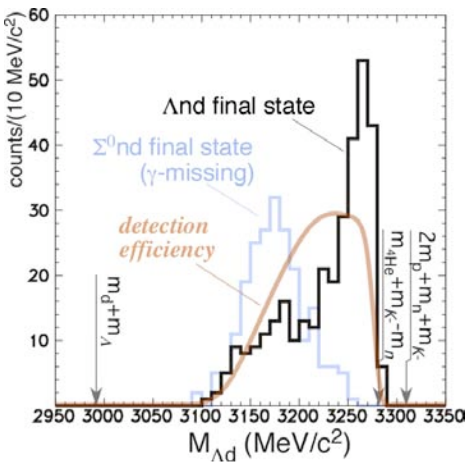

Figure 7: the Λd invariant mass of the Λnd final state.

Figure 7 shows the Λd invariant mass of the Λnd final state. Our Λd invariant mass spectrum has two components; one is the narrow peak just below the $m_{^4He}+m_{K^-}-m_n$ threshold and another is a broad component around 3100～3220 MeV/c^2. Since the momentum of the missing neutron is low and comparable to the Fermi motion, the former process can be attributed to the three-nucleon absorption process *K*$^-$ *"ppn" (n)* → *Λd (n),* where the undetected neutron is a spectator of the reaction. We also observed the similar process *K*$^-$ *"ppn" (n)* → *Σ*^{0}*d (n),* in the $\Sigma^0 dn$ final state as shown in the figure.

Similar structure of the Λd invariant mass spectrum from the stopped K$^-$ reaction on p-shell nuclear targets has been reported recently as a possible signal of kaonic nuclear bound state formation [12]. Since there exist nearly the same peak structures just below the threshold on both isospin *T=0* and *T=1* Y^0d channels, its interpretation as the formation of strange tribaryon state in Ref. [12] is very unlikely for our ^{4}He data, because one must assume two strange tribaryon state with the similar masses and widths for $^3S^+_{T=0}$ and $^3S^+_{T=1}$ states (we denote the multi-baryonic states with strangeness as $^AS^Z$ for the baryon number

A and the charge Z.).

Figure 8 shows the Λd correlation of the Λnd final state events. The momentum correlation between Λ and d of the three- nucleon absorption process is clearly seen close to the kinematical boundary with strong back-to-back correlation. On the other hand, the low mass region distributes over wide region, and the back-to-back correlation between Λ and d is weaker than that of the three-nucleon absorption process as shown in the figure. Note that we do not have sensitivity at the lower d momentum region.

The origin of the low mass component below the invariant mass of $M_{\Lambda d}$ < 3220MeV/c^2 is still unknown and it might be a candidate of the strange multibaryonic states such as

$K^- \ {}^4He \rightarrow {}^2S^0{}_{T=1/2} + d$ or

$K^- \ {}^4He \rightarrow {}^3S^+{}_{T=0} + n; \quad {}^3S^+{}_{T=0} \rightarrow \Lambda + d.$

However, there remains possibility of the two-step schemes of the conventional processes such as Σn branch of two-nucleon absorption process followed by successive $\Sigma\ d \rightarrow \Lambda\ d$ conversion process, which will be studied with Monte Carlo simulation in a forthcoming publication.

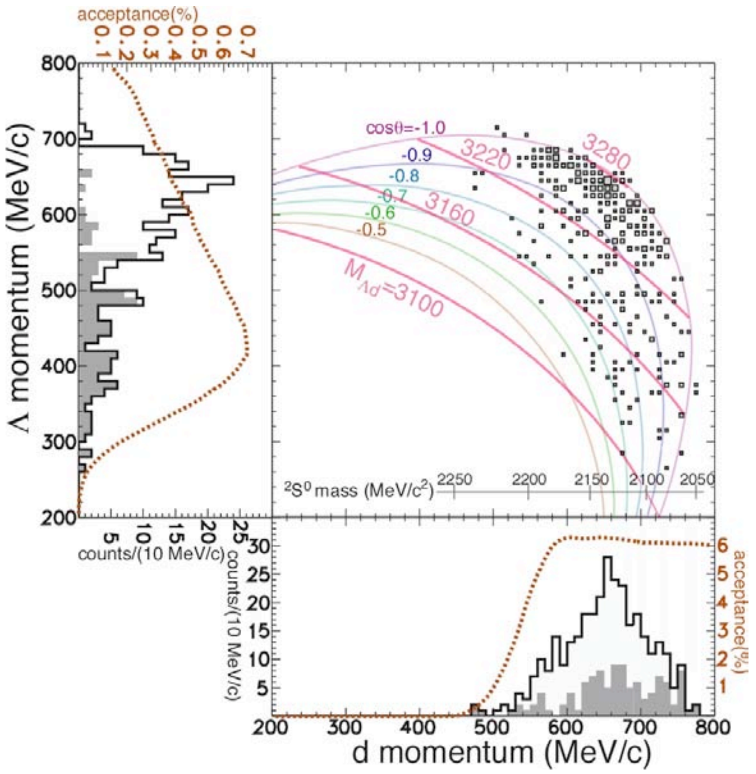

Figure 8: Correlation between Λ and d momenta for Λnd events. Kinematical constraint for invariant mass and opening angle of Λ and deuteron are overlaid. Shaded area correspond to the component with $M_{\Lambda d}$<3220MeV/c^2

5. ΛN correlation analysis result

The ΛN correlation analysis also has vital importance, because the FINUDA experimental group reported the existence of the bound state of K$^-$pp (or ${}^2S^+$ in our notation) in the Λp invariant mass spectrum[9]. Although the non-mesonic multi-nucleon absorption process are expected to be the primary source of the imaginary part of the kaon－nucleus potential in the deeply-bound region, the presently available experimental information for that process is limited to the total non-pionic absorption rate of stopped K$^-$ [13]. It is indispensable to clarify whether the two-nucleon absorption process exist as well-separable processes from the possible signatures for multibaryonic states. The two-nucleon absorption process, $K^- NN \rightarrow YN$, must be most cleanly observed when we measure back-to-back correlated YN pairs from the stopped K$^-$ reactions.

The E549 experiment has merit in the measurement of both of Λp and Λn pairs. Since we measured the momentum of both of charged and neutral particles by the TOF method using the same detectors, we can easily switch to the channels with neutron emission without paying the penalty of large loss of the energy resolution nor the change of the angular acceptance.

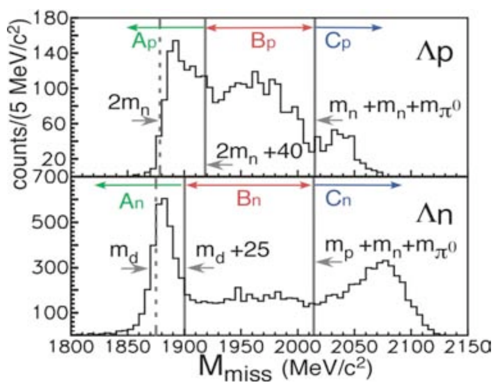

Figure 9: Missing mass spectra for both of the Λp and the Λn back-to-back coincidence events with three divided zones [14].

The Λp and Λn correlation analysis has been accomplished very recently and we submitted the results to PRL (cf. Ref. [14] for the detail). Figure 8 shows the missing mass spectra of Λp and Λn back-to-back correlated pairs ($\cos\theta < -0.6$) from stopped K$^-$ on ^{4}He target. In E549 experiment, we observed about 3,000/10,000 pairs for Λp / Λn, respectively. As shown in divided zones in the figure, we found three different components in the missing mass spectrum. Both A and B components are below the pion production threshold, thus these must be attributed to the non-mesonic hyperon production processes. On the other hand, the C components will be associated with pion having back-to-back ΛN in the final state. These events can be formed by the chain reaction of $K^- N \rightarrow \pi\ \Sigma$ and $\Sigma N \rightarrow \Lambda\ N$. The correlation between the ΛN invariant mass $M_{\Lambda N}$ and the total 3-momentum $P_{\Lambda N}$ are shown in Fig. 10 together with the classification introduced in Fig. 9.

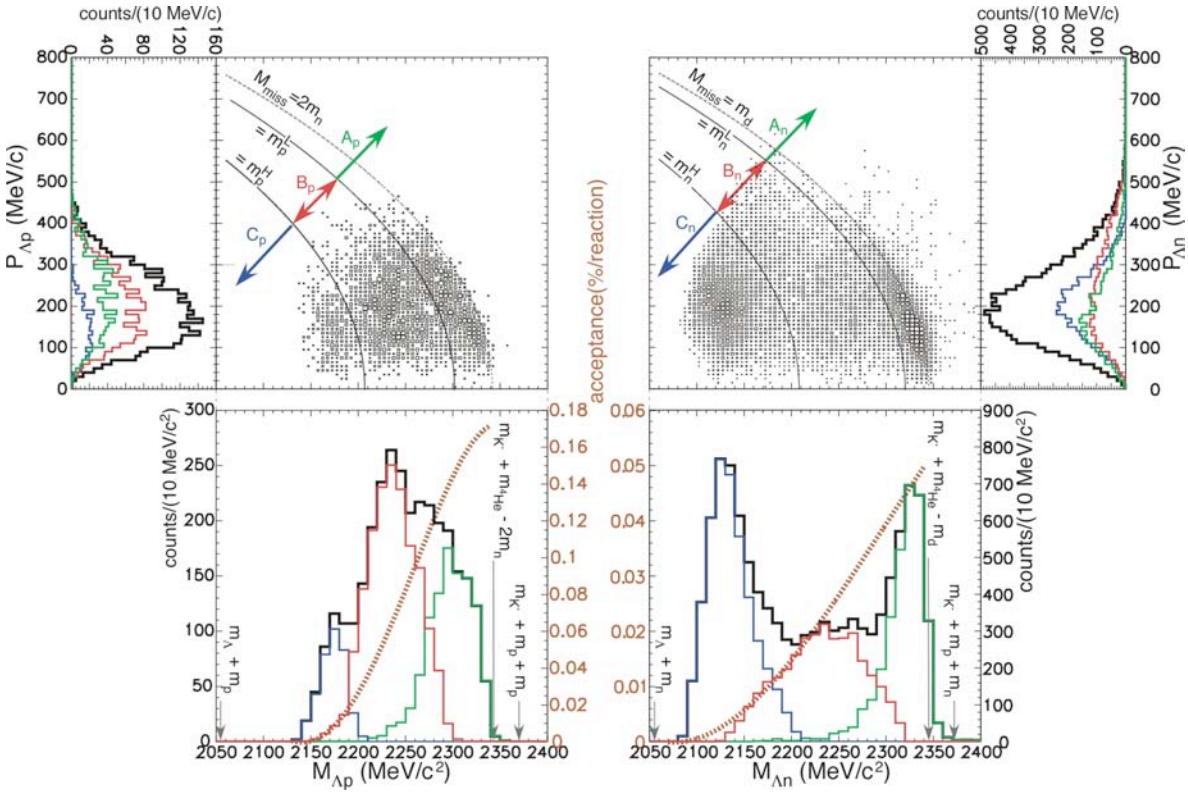

Figure 10: Correlation of ΛN invariant mass and the 3-momenta for both of back-to-back correlated Λp and Λp pairs. The regions A_N,B_N,C_N respectively correspond to the division given in Fig. 8 [14].

In both of $\Lambda p/\Lambda n$ pairs in the region A, the back-to-back ΛN pairs share most of the Q-value. Therefore events in region A come from the two-nucleon absorption process. The existence of the process is established experimentally for the first time. The observed invariant mass widths are consistent with the broadening effect caused by the Fermi motion. The reaction branching ratios to A_p and A_n processes are about 0.2 and 2% of stopped K-, respectively. The small ratio of the branch of Br(A_p) /Br(A_n) indicates the dominant contribution of deuteron-like "pn"-pairs in the K- two-nucleon absorption. The sum of Br(A_p) +Br(A_n) account only 20% of the total ΛNNN branching ratio (11.7 ± 2.4%) in Ref. [13]. Thus the non-mesonic Λ production predominantly occurs via the unassigned component B_N, which is also the candidate process for the broad strange multibaryon states either

$K^-\ {}^4He \rightarrow {}^2S^{0/+} + (NN) :\ {}^2S^{0/+} \rightarrow \Lambda N$ or

$K^-\ {}^4He \rightarrow {}^3S^{0/+} + (N) :\ {}^3S^{0/+} \rightarrow \Lambda NN,$

however we cannot rule out the possibility of some of the multistep conventional processes also for this case. The detailed discussion is given in Ref. [14].

6. J-PARC experiment E15

Presently there are many theoretical calculations on this system and most of them predict the bound kaonic system with relatively broad widths of 50MeV/c^2 or more. On the other hand, what we learned from the results of E549 experiment are:

(1) In the invariant mass spectroscopy, an exclusive measurement is important to remove the ambiguity.

(2) Broad states are hard to be identified only by the missing mass spectroscopy.

(3) Even with the light target with A=4, there remains ambiguity of the identification between strange dibaryon and tribaryon formation. The experiment must be done with lightest available nuclear target.

(4) Stopped K^- reaction may not the ideal reaction because nucleons from the non-pionic milti-nucleon hyperon formation and the successive hyperon decay particles have similar momenta.

To overcome these experimental difficulties, we are preparing a new experiment E15 at J-PARC K1.8BR beam line. The experiment aim at the observation of the lightest kaonic nuclear system —K^-pp— in the ^{3}He(in-flight K^-,n) reaction. Since this formation reaction has unique kinematics that the momentum of emitted neutron is even higher than the incident K^- momentum and the kaonic nuclear system is moving backwards in the laboratory frame, we can distinguish whether a measured nucleon comes from the kaon nucleus formation or from its decay. In the in-flight condition, milti-nucleon absorption channels are also separated in momenta, and the yield of the channels themselves will be substantially suppressed. The experiment must have a capability to identify the state in both the formation stage (in missing mass spectroscopy) and the decay stage (in invariant mass spectroscopy). If the sizable portion of the K^-pp bound states decay into *e.g.* Λp, $\Sigma^+\pi^-p$ *etc.*, we can detect all the decay products by the cylindrical spectrometer system(CDS). Preparation of the experiment is now in progress.

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