— Addendum for E15 —

A staging strategy of E15 experiment with 30 kW·week operation

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Abstract

As a mile-stone of E15, which is an experimental search for the simplest kaonic nuclear system "K^-pp" ($\overline{K}$ bound with two nucleons, second simplest if $\Lambda(1405)$ is K^-p bound state), we propose to perform a first-stage production run. The aims are 1) to know the background processes in detail, 2) to evaluate the realistic beam time required to accomplish the experiment, 3) present an information of the $\overline{K}N$ interaction, and 4) expecting a hint of signal in fully reconstructed $\Lambda + p + n$ final states, at the earlier stage of the machine operation of 5 ∼10 kW range with few weeks of the running time. Since it is very important to understand the nature of the possible background processes, we will take data without requiring the forward neutron counter hit which enables us to take data at a wider coverage of the 3-body kinematical phase space. At this first-stage run, we will also collect data allowing one-proton missing events requesting a forward neutron, so as to be sensitive to the signal of E15 as much as possible. This trigger condition enhances the trigger rate substantially, and is quite meaningful to be performed at the present (or near future) proton beam intensity of ∼ 10 kW range.

Summary of the beam time requirement of the E15 first-stage run

Beamline: K1.8BR
Primary beam: ∼ 10 kW proton
Secondary beam : 1.0 GeV/c K^-
Reaction : In-flight (K^-,n)
Target : Liquid ^{3}He
Primary beam : integrated proton of 30 kW·week
Duration : more than three weeks including beam tuning for 1 GeV/c kaon

1 Introduction

An important motivation, to apply the staging strategy for E15, came from new theoretical calculation given by Koike and Harada [1, 2]. In their spectral functions of (K^-, n) reaction at 1 GeV/c, the cross section of the integrated yields of neutrons below K^-pp formation threshold could be as large as $\sim$ 3 mb/sr in the forward direction. They applied a variety of $\overline{K}N$ interactions, although the yields are almost equal over the wide range of applied interactions. They reported, in (K^-, n) reaction at 1 GeV/c, the backward recoil nature of kaon with forward neutron emission enhances the formation cross section substantially in kinematic reason, in the case of light nuclei compared to the medium-heavy target. This formation cross section is actually one $\sim$ two order of magnitude bigger than the assumption we made at the E15 proposal submission. In fact, the absolute cross section is one of the most difficult quantity to be evaluated reliably. However, it suggests the importance of multi-step accomplishment of E15 to know the order of the cross section, therefore we wish to perform the first step as early as possible. We are also motivated by the data lately published by DISTO group [8, 9], which exhibits an extremely huge peak structure in a Λp invariant-mass spectrum and a K^+ missing-mass spectrum from $pp \to \Lambda p K^+$ events. The observed peak locates at a mass $M = 2267 \pm 2$ MeV/c^2 and has a width of $\Gamma = 118 \pm 8$ MeV. If this is the kaon bound state, the K^- binding energy B_K is $\sim$ 100 MeV. The paper claims that such a large formation cross section in the pp reaction gives an evidence for the dense K^-pp state, as predicted in [11]. It implies that the Λp could be a dominant decay branch of K^-pp.

Another important fact is that it is quite important to study the reaction channels associated with two nucleons in ^{3}He(K^-, n) reaction at 1 GeV/c. Even if one select the final state to be Λpn, the forward energetic neutron could be produced not only by the formation of K^-pp state, but also by the following two processes:

- $KNN \to \Lambda N$ reaction, followed by the scattering with the spectator nucleon,
- $KNN \to \Sigma N$ reaction, followed by $\Sigma N \to \Lambda N$ conversion with the spectator.

These processes could form background components for the energy region of interest. Both processes should have two nucleon absorption reactions as a doorway, so the cross section of these processes would be small at 1 GeV/c, because of the smaller De Broglie wave length compared to the mean nucleon distance in nuclei. Actually, Osaka group data on ^{12}C(K^-, n) reaction at 1GeV/c do not have any counts at the energy region of the KNN reaction [10]. However, it is important to measure these in the early stage of the experiment also on ^{3}He target. On the other hand, it could also be interesting to know these processes to study the two-nucleon correlation at this high momentum regime, if one can observe these clearly. To accumulate these processes with a minimum trigger bias, it is preferable to take data at a weaker intensity, as of today.

2 Two new papers on K^-pp

Recently, theoretical spectral functions of forward neutron missing mass of ^{3}He(K^-, n) reaction have been reported by Koike and Harada assuming various $\overline{K}N$ interactions. Figure 1 shows two examples of their neutron spectral functions. Left panel of FIg. 1 shows a neutron spectrum for the deep potential originally reported by Akaishi and Yamazaki [3]. The right panel is that for an even deeper potential suggested by FINUDA data [4].

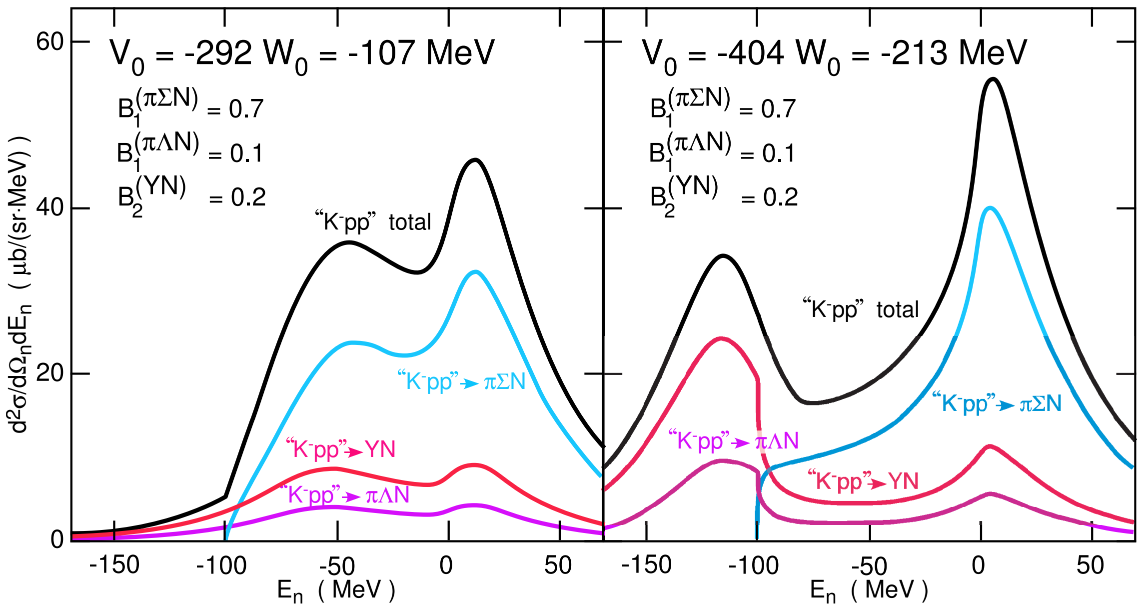

Figure 1: Calculated semi-exclusive spectra of the ^{3}He(in-flight K^-, n) reaction at p_{K^-} = 1.0 GeV/c and θ_{lab}= 0^0 for potentials (left) V_0 = -237, W_0= -128 MeV and (right) V_0 = -404, W_0= -213 MeV, measured from K^-pp threshold. Each spectrum is composed of two bumps, a bound K^-pp and a K^- quasi-free conversion ($E_n < 0$ and > 0, respectively).

As shown in the figures, there are large amount of neutron cross section at forward angle θ_{lab}= 0^0. The yield below threshold is as much as about $2 \sim 3$ mb/sr. On the contrary, we assumed the production cross section as small as 10 μb/sr in the E15 proposal [13], based on the previous works [5, 6, 7]. Koike and Harada reported that the present huge cross section is expected only for the light nuclei, such as K^-pp, while they have predicted a much smaller yield for a heavier target which is consistent with the previous works. They claimed that the large cross section results partly from the spin-isospin dependence of the intermediate K^-p state, which they properly take into account, and partly due to the momentum transfer reduction by producing a high-momentum forward neutron. This discrepancy of the production cross section of two orders of magnitude is should greatly favor the E15 experiment.

Among several experimental candidates of kaonic nuclear state/cluster reported so far, the DISTO data is quite remarkable in its statistics [8, 9]. Recently, data from the

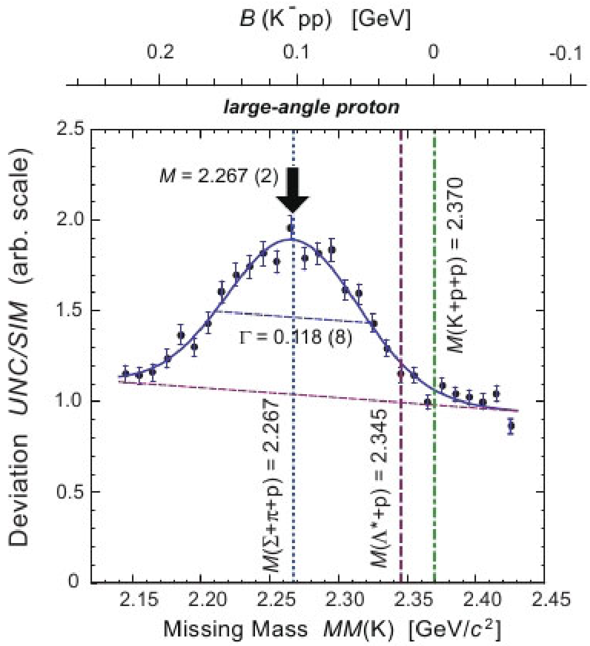

Figure 2: An experimental K^+ missing-mass deviation spectrum of $p+p \to \Lambda+K^++p$ channel observed at DISTO [?]. Large momentum transfer protons and kaons are selected by $|\cos(\theta_{CM,p})| < 0.6$ and $-0.2 < \cos(\theta_{CM,K^+}) < 0.4$.

DISTO Collaboration on the exclusive $pp \to pK^+\Lambda$ production at $T_p = 2.85$ GeV have been fully analyzed, to search for a deeply bound K^-pp $(=X)$ state. The reported spectrum is shown in Fig. 1, in which a distinct broad peak with a mass $M_X = 2265.2$ MeV/c^2 with a width of $\Gamma_X = 118.8$ MeV/c^2 is revealed.

One of the most mysterious nature of this peak structure, observed in DISTO data, is its energy. As it is indicated in the figure 2, it is located just on the $\Sigma\pi n$ threshold. Naively, it is expected that the spectral function close to the energy threshold should have structure if it can couple with the state. Since the experimental data are for exclusive $p + \Lambda + K^+$ particles, the paper is focused on $K^-pp \to \Lambda p$ decay channel. In the few body case, as it is the case, a narrow cusp structure would be the naive expectation to the spectral function, when the pole is located just on a new open-channel, while the peak structure found in DISTO is quite symmetric as it is fitted in the paper. A symmetric peak is expected only when the pole is well separated from the open channel threshold, as it is the case shown in 1, either shallower or deeper. In the present case, the spectrum is only for the Λp decay channel, where a symmetric peak structure is expected when the Λp decay is dominant and the pole comes to the $\Sigma\pi p$ threshold [12].

Another problem is that the kaon quasi-free process could not be seen in the spectrum, because the DISTO events are exclusive $p\Lambda K^+$ events, which do not include the emission of Λ^*. It should be nicer to observe a spectrum including the K^- quasi-free region. Therefore, the study of strange di-baryon / K^-pp study using different reaction channels is vitally important and urgent, at present.

2.1 Yield estimation based on KH

The yield for the K^-pp production with the expected decay such as $K^-pp \to \Lambda p \to p\pi^-p$ is estimated to be 4,500 signals in the following way.

$$Yield = N_{K^-} \times t \times d\sigma/d\Omega_{\theta=0^\circ} \times R_{K^-pp\to\Lambda p} \times r_{\Lambda\to\pi^-p} \times A \times \epsilon,$$

where

N_{K^-} : Total number of kaons.

t : Thickness of the target.

$d\sigma/d\Omega_{\theta=0^\circ}$: Differential cross section of the K^-pp production with neutron emission at $\theta = 0^\circ$.

$R_{K^-pp\to\Lambda p}$: Branching ratio of $K^-pp \to \Lambda p$.

$r_{\Lambda\to\pi^-p}$: Branching ratio of $\Lambda \to \pi^-p$.

A : Acceptance of the detector system (neutron counter + CDS).

ϵ : Overall efficiency (trigger efficiency, DAQ efficiency and analysis efficiency).

According to the result of the beam tune for the K1.8BR [14], the yield of kaons per spill with 30kW operation is estimated to be 3.0×10^5 kaons/spill. Therefore, the total yield of kaons in one week is calculated to be

$$3.0\times10^5[kaons/spill]\times600[spills/hour]\times8[hours/shift]\times21[shifts] = 3.0\times10^{10}kaons.$$

The thickness of the liquid ^{3}He target is 1.4×10^{23} cm^{-2}. We take 3 mb/sr for $d\sigma/d\Omega_{\theta=0^\circ}$ from [1], [2]. $R_{K^-pp\to\Lambda p}$ is set to be 0.5 and $r_{\Lambda\to\pi^-p}$ is taken to be 0.63 from *Particle Data Group*. The acceptance of the detector system is calculated to be 5.3 msr (= $4\pi \times 0.00042$) by the Monte Carlo simulation with the assumption of isotropic decay of K^-pp. The overall efficiency is set to be 0.7. Therefore, we can collect 4,500 signals for K^-pp in one week run with 30kW·week operation.

Fig. 3 shows a simulated neutron missing-mass spectrum assuming DISTO peak structure at 3 mb/sr, under the other assumption listed above. Actually, the forward

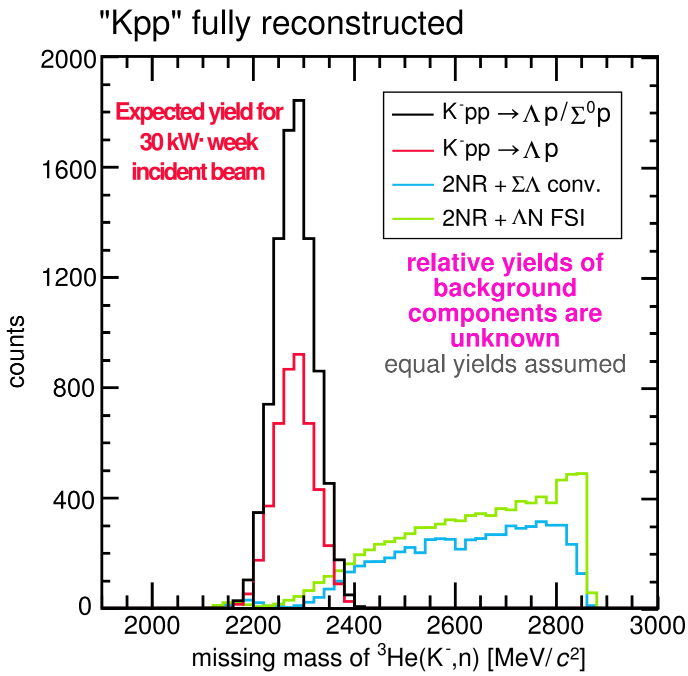

Figure 3: Simulated neutron missing mass spectrum with (red) Λp decay channel are fully reconstructed in our cylindrical spectrometer CDS, detecting forward neutron in NC arrays, in which we assumed 3 mb/sr for the production cross section located at energy and width reported by DISTO, and (black) $\Sigma^0 p$ decay channel is summed. Two background processes are also shown, namely, (blue) $\overline{K}NN \to \Sigma N$ followed by $\Sigma\Lambda$ conversion with a spectator nucleon, and (green) $\overline{K}NN \to \Sigma N$ followed by scattering with the spectator. These background processes are simulated by two step PWIA calculation. These backgrounds are not known well so the yields are arbitral (assumed to be 3 mb/sr for each process).

cross section of $2 \sim 3$ mb/r is only for the total formation rate below $K^- pp$ threshold. As it is seen in Fig. 1, when we observe the YN decay channel exclusively in CDS, which is most efficient channel to be detected by E15 apparatus, then the partial formation cross section will be reduced substantially, depending on the potential strength. The YN decay channel also strongly depends on not well known parameter of the kaon two-nucleon absorption-reaction strength, B_2^{YN}, given in reference [2]. Therefore, this estimation is rather optimistic in several way, so we cannot accomplished E15 itself within present first-stage run, although the data is vitally important to evaluate the full intensity required for E15 in reliable way. It should also be pointed out that the background will be quite small for ^{3}He(K^-, n) reaction at 1 GeV/c. Actually, Osaka group already performed performed ^{12}C(K^-, n) experiment at the same momentum, and reported background-free nature of their spectra [10] with much more simple experimental setup. The ^{3}He is much lighter than ^{12}C, so the background naturally expected to be less severe.

3 Study of background initiated by $\overline{K}NN$

Another motivation to perform a first-stage production run is the background study. As it is described, we are expecting that the background will be small. However, it is strongly recommended to examine the background on ^{3}He target as a part of E15 data.

In ^{3}He(K^-, n) reaction, two nucleon reaction channels (2NR), $\overline{K}NN \rightarrow YN$, could occur. As mentioned, many experimental data show that the 2NR strength drastically reduces for higher momentum region of the initial particles. Even if we assume that 2NR can happen at 1 GeV/c, these events can be clearly identified kinematically because the process associated with a spectator nucleon, when the event does not associate with final state interaction.

Relatively difficult background may form when 2NR events are followed by either $\Sigma\Lambda$ conversion or scattering with the spectator nucleon, successively as a cascade reaction. To observe these channels without having strong bias on data with E15 setup, we need to reduce the tightness of the event trigger level. As an example, expected distribution of 2NR process followed by $\Sigma\Lambda$ conversion, simulated by two step PWIA calculation, is shown in Fig. 4. As shown in the figure, most of the event will be omitted by full E15 event trigger logic, namely $\Lambda(\rightarrow p\pi^-)p$ tracks in CDS and a neutron hit in NC. It should be noted that the data gives Λpn correlation at high energy region, so it is also important if we can observe these events.

Another event example to be examined is "one proton missing from CDS". If K^- reaction produces high momentum neutron in the forward direction, so the other particle should be boosted in the backward direction. This means that the requirement of Λp track reconstruction in CDS limits the lower energy boundary for "K^-pp" events. By allowing one proton missing, we can extend the sensitivity in the low energy region, as shown in Fig 5. As shown in the figure, "fake-peak" structure appears initiated by 2NR, thus it is quite important to study these background channels.

4 Discussion and conclusion

Presently, we are preparing E15 and E17 experiments extensively, both experiments have common basic experimental apparatus, at K1.8BR. The E15 experiment "A search for deeply-bound kaonic nuclear states by in-flight ^{3}He(K^-, n) reaction" is proposed and approved at the stage when it is believed that the machine intensity will reach 100 kW power rather easily. Actually, number of approved experiments assumed full PS intensity of 9 μA proton at 30 GeV (270kW) for several weeks, which means about 1 MW·week running time. In fact, we requested two weeks of commissioning run and the 5.5 weeks of production run for E15 at K1.8BR, and got an approval as one of so

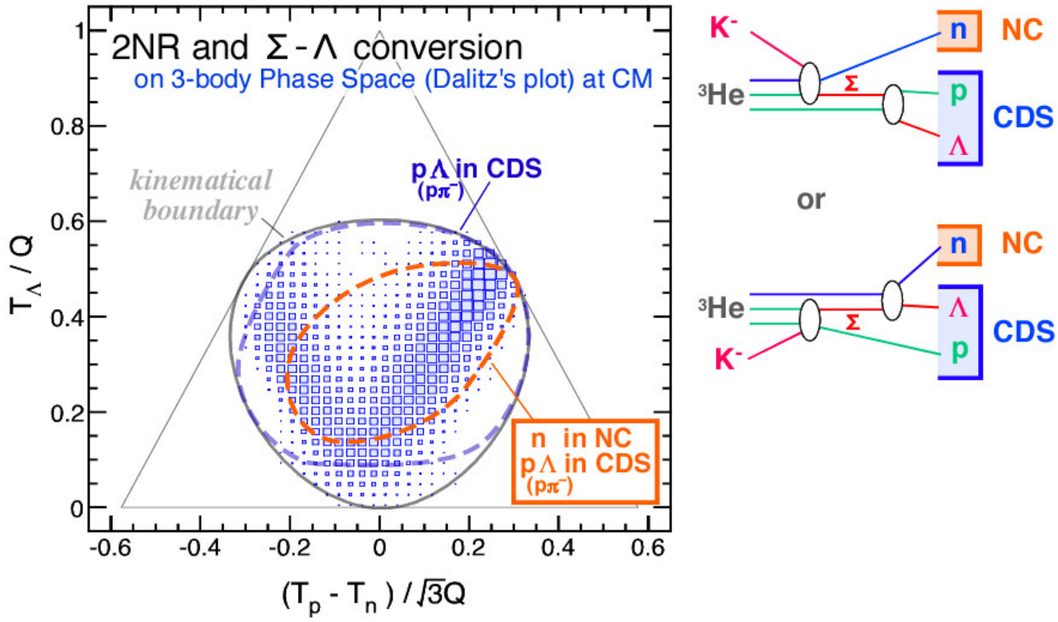

Figure 4: Simulated event distribution of 2NR process followed by $\Sigma\Lambda$ conversion on $pn\Lambda$ Dalitz's plot at CM, for without requesting a neutron hit in NC array. Black circle is the kinematical boundary, blue dashed line is the rough acceptance boundary for Λp in CDS without NC coincidence, and orange dashed line is that for E15 trigger (Λp in CDS and neutron hit in NC).

called *Day-One* experiments. On the other hand, 1 MW·week production run is still a way to go to realize in short term, in spite of all the hard work of the J-PARC machine stuff. At present, the proton beam power is at around 3 kW and the duty factor of about 20%.

It seems that the machine can improve the beam power rather easily compared to the improvement on the duty factor. In this situation, the performance of pion incident experiments are quite limited compared to that of kaon, because of the high multiplicity in the beamline tracker. In the kaon incident experiments, this difficulty does not tangible up to 100 kW, because kaons are about two orders of magnitude rare particles than pions. Thanks to the kaon separated beam optics, most of the time structure of the slow extracted beam will be killed at the DC separator.

At this stage, we wish to perform first-stage production run of E15 with 30 kW·week integral proton beam. We believe that this integral intensity can be achievable even in the latter half of the next year at J-PARC K1.8BR. If the production cross section is as large as ∼mb/sr at 0 dgree, as it is reported by Koike and Harada, there is a good chance to observe a signal with the first-stage production run. We will also perform a detailed background study by loosing E15 trigger condition. To accumulate minimum bias data with this condition, present kaon yield is preferable rather than

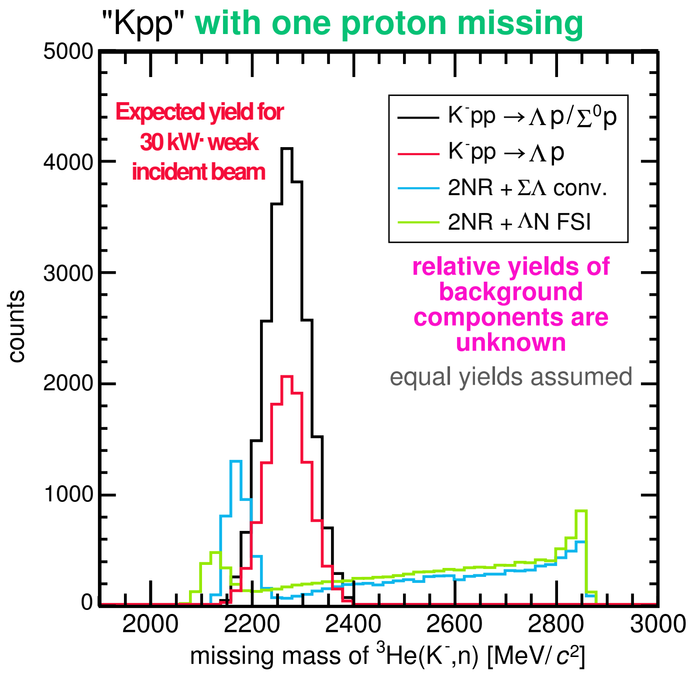

Figure 5: Simulated neutron missing mass spectrum allowing one proton missing from CDS. Histograms are same as in Fig. 3. It is shown that the acceptance increased by factor two (vertical scale), and the acceptance limit at low energy side is extended by allowing one proton missing.

the full intensity of the J-PARC. This data might give information of three-body force of Λpn as well. We wish to run E15 first-stage production run as soon as possible after the accomplishment of E17.

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