

# 論文の内容の要旨

論文題目: Search for  $K^-pp$  bound state in the  ${}^3\text{He}(K^-, n)$  reaction at  $p_{K^-}=1$  GeV/ $c$

( $p_{K^-}=1$  GeV/ $c$  での  ${}^3\text{He}(K^-, n)$  反応による  $K^-pp$  束縛状態の探索)

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Recent theoretical studies, triggered by a pioneering work by Akaishi and Yamazaki, show that an anti-kaon can be bound in nuclei to form so-called kaonic nuclei as a consequence of strongly attractive  $\bar{K}N$  interaction in  $I = 0$  channel. Among such a new form of nuclear matter, “ $K^-pp$ ”, which is more generally expressed as  $[\bar{K} \otimes \{NN\}_{I=1}]_{I=1/2}$ , is now attracting great interest as the lightest one. Many theoretical calculations have been progressed for the  $K^-pp$  system, resulting in various binding energy and width predictions. Experimentally, candidates of the  $K^-pp$  bound state were reported by the FINUDA and the DISTO collaborations. However, the interpretation of the observed structures is still under debate, and the current experimental data is not sufficient to discriminate between a variety of conflicting interpretations.

In this situation, we are carrying out an experimental search for the  $K^-pp$  bound state at Japan Proton Accelerator Research Complex (J-PARC E15). The most important key of our experiment is the  $(K^-, n)$  reaction at 1 GeV/ $c$ . In this reaction, a fast neutron (1.2 ~ 1.4 GeV/ $c$ ) is emitted at forward angle in the formation reaction of the  $K^-pp$  state. Fast neutrons from multi-nucleon absorption reactions and hyperon decays are the possible source of the background events. However, thanks to the in-flight reaction, the former ones are expected to be substantially suppressed and the latter one to be kinematically separated. In addition, by using a liquid  ${}^3\text{He}$  target, we have more chance to reconstruct the full reaction kinematics. We developed a large acceptance detector surrounding the target to detect the  $K^-pp$  decay, such as  $K^-pp \rightarrow \Lambda p \rightarrow \pi^- pp$ .

As the first step of the J-PARC E15 experiment, a short-term data taking was

performed in May, 2013. The integrated number of kaons on the  $^3\text{He}$  target was  $5.2 \times 10^9$ , which corresponds to only  $\sim 1\%$  of the full proposal. The main purpose of this data-taking was to search for the  $K^-pp$  bound state in the neutron (semi-)inclusive spectrum, motivated by a theoretical calculation by Koike and Harada. They pointed out the possibility that a peak structure can be observed with order of 1 mb/sr cross-section in the inclusive neutron spectrum if the DISTO or the FINUDA observation was the case. Although the current statistics is too small to perform an exclusive analysis, we can carry out a (semi-)inclusive analysis of forward-going neutrons with a moderate statistics to confirm the prediction by Koike and Harada.

The experiment was performed at the K1.8BR beam line in the hadron experimental facility at J-PARC, where a new spectrometer system was designed and constructed for the present experiment. The spectrometer was composed of a beam line spectrometer, a cryogenic helium-3 target system, a cylindrical detector system (CDS), and a forward neutron detection system.

A kaon beam purified with an electro static separator was delivered to the target through the beam line spectrometer. The kaon was identified with an aerogel Cherenkov counter placed just after a Time-Zero counter (T0) and they were confirmed by the offline TOF analysis between T0 and a beam line hodoscope detector with  $\sim 7.7$  m flight length. The beam momentum was reconstructed with two sets of drift chambers and a dipole magnet sandwiched by them. A typical kaon yield at the primary proton beam intensity of 24 kW was  $1.5 \times 10^5$  per spill with a  $K/\pi$  ratio of 0.45. A spill length was  $\sim 2$  seconds with a 6-second repetition cycle. The beam momentum resolution was evaluated to be  $(2.0 \pm 0.5) \times 10^{-3}$  at 1 GeV/c by a comparison with the forward TOF spectrometer using a proton beam.

The liquid  $^3\text{He}$  target was located at the final focus point of the beam line and was surrounded by the CDS. The main components of the CDS were a cylindrical drift chamber (CDC) and a cylindrical detector hodoscope (CDH), which cover the polar angle range from 54 to 126 degrees. Momenta of charged particles were reconstructed by detecting the track curvature in the solenoid field with the CDC. A timing information of the CDH together with the measured momentum provided a particle identification. The CDH was also used as a trigger counter. A beam line drift chamber (BPC) was installed just upstream of the target to reconstruct the reaction vertex with a CDC track. In the forward-neutron analysis, the momentum reconstruction and the particle identification were not necessary, but the vertex information was essential to select the  $^3\text{He}$  and to determine the flight length of a forward-going neutron.

A forward neutron was detected with a neutron counter (NC) at a distance of  $\sim 15$  m from the target position. The NC, segmented into 16-column (horizontal)  $\times$  7-layer (depth) units, had a coverage of  $\sim 22$  msr solid angle from the target. A detection efficiency of a neutron around 1 GeV/c was evaluated to be  $23 \pm 4\%$  by an exclusive analysis of the  $^3\text{He}(K^-, nK_s^0)d$  reaction. Two scintillation counter arrays were installed

to reject charged particles at just downstream of the target system and at just upstream of the NC, while most of the beam particles were swept out from the NC acceptance with a beam sweeping magnet at downstream of the target system. In a  $1/\beta$  spectrum of the forward neutral particles detected with the NC, we successfully observed a distinct peak of the  $\gamma$ -rays. The peak position provided a reference to adjust timing offsets and time-walk effects of each NC segment, while we evaluated the momentum resolution from the peak width corresponding to 150-ps time resolution. As a consequence, the missing mass resolution of the  ${}^3\text{He}(K^-, n)X$  reaction was evaluated to be  $\sim 10 \text{ MeV}/c^2$  at around  $K^-pp$  binding threshold.

We have successfully obtained the  ${}^3\text{He}(K^-, n)X$  missing-mass distribution for the first time. It should be noted that the spectrum is under the *semi*-inclusive condition by requiring at least one charged track in the CDS to reconstruct the reaction vertex. The main feature of the spectrum is a broad peak structure just above the  $K^-pp$  binding threshold. The peak structure is a so called quasi-free peak attributed to the quasi-elastic scattering ( $K^- "n" \rightarrow K^-n$ ) and the charge-exchange reaction ( $K^- "p" \rightarrow K_s^0n$ ). There exist a bump structure toward the large missing mass region is mainly contributed by neutrons from hyperon decays. We have also observed a certain event strength below the  $K^-pp$  binding threshold as a tail of the quasi-free peak. The tail structure, which may contain some  $K^-pp$  events, was further investigated.

First, we considered experimental effects and known single-nucleon processes. The effect of the detector resolution was directly checked with a  $K_s^0$ -tagged spectrum, where the  $K_s^0 \rightarrow \pi^+\pi^-$  decay was reconstructed by the CDS. The  $K_s^0$ -tagged spectrum rises at the threshold, and has few event in the bound region. Contaminations of reactions with other materials around the target were evaluated with empty-target data. The continuous background was evaluated by an extrapolation from the unphysical region (below  $\Lambda N$  threshold). The total contribution of these three experimental effects was at most 30% of the yield of the observed tail structure. Only the single-nucleon process, which is kinematically allowed to contribute the bound region in the semi-inclusive condition, is the neutrons from  $\Sigma$  decays via  $K^- "N" \rightarrow \Sigma\pi$ ,  $\Sigma \rightarrow \pi p$ . However,  $\sim 90\%$  of their contributions can be removed by reconstructing  $\Sigma$  decays with a pion detected by the CDS. The remaining contribution, where the  $\Sigma$  reconstruction was failed, was evaluated to be approximately 5% of the tail. As a consequence, the number of the unknown excess was evaluated to be  $1462 \pm 58(\text{stat.}) \pm 122(\text{syst.})$  in a missing mass region from  $2.29 \text{ GeV}/c^2$  to  $2.37 \text{ GeV}/c^2$ , while the background was to be  $568 \pm 57(\text{stat.}) \pm 121(\text{syst.})$ . Therefore, the unknown excess is statistically significant and is robust against the systematics. Such structure just below  $K^-pp$  threshold was firstly observed by the present experiment.

Then, the possible explanations of the observed excess is discussed. Contributions from uncorrelated mesonic two-nucleon absorption and three-nucleon absorption processes were found to be substantially small. The  $\Lambda(1405)n$  branch of non-mesonic two

nucleon absorption reaction can explain the excess with a cross section as large as 5 mb/sr at  $\theta_{lab} = 0^\circ$ , which cannot be distinguished from other processes, such as the shallowly-bound  $K^-pp$  state, with the present data. In the case that the excess was fully attributed to the  $K^-pp$  formation, the cross section at  $\theta_{lab} = 0^\circ$  was evaluated to be  $(1.2\sim 1.6) \pm 0.3$  mb/sr, according to the assumed decay modes.

For the deep bound region below 2.28 GeV/ $c$  in the  ${}^3\text{He}(K^-, n)X$  missing-mass spectrum, corresponding to the  $K^-pp$  binding energy of larger than 90 MeV, upper limits of the formation cross section of the deeply-bound  $K^-pp$  state were determined to be 0.02~0.4 mb/sr at  $\theta_{lab} = 0^\circ$ . Here we assumed the widths of 20, 60 and 100 MeV $c^2$  with a decay mode of  $K^-pp \rightarrow \Lambda p$ . We found no statistically significant structure in the deep bound region claimed by the FINUDA and the DISTO groups. Also our results contradict to the theoretical calculation by Koike and Harada, where potentials are obtained from those experimental results.

In conclusion, we have searched for the  $K^-pp$  bound state by the missing-mass analysis of the  ${}^3\text{He}(K^-, n)X$  reaction at the kaon momentum of 1 GeV/ $c$ . We have found no significant structure in the deep bound region corresponding to the  $K^-pp$  binding energy of larger than 90 MeV, while a statistically significant excess just below the  $K^-pp$ , which cannot be explained neither by the experimental effects nor single-nucleon processes, has been observed.