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Summary of the $K^{-}pp$ bound-state observation in E15 and future prospects

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Abstract. The possible existence of deeply-bound $\bar{K}$-nuclear bound states, kaonic nuclei, has been widely discussed as products of the strongly attractive $\bar{K}N$ interaction in I = 0 channels. Investigations of those exotic states will provide us unique information of the $\bar{K}N$ interaction below the threshold, which is still not fully understood so far. Recently, we observed the simplest kaonic nuclei, $\bar{K}NN$, having a much deeper binding energy than normal nuclei via in-flight (K^-, N) reactions at the J-PARC E15 experiment. For further studies, we have proposed a series of experimental programs for the systematic investigation of light kaonic nuclei, from $\bar{K}N$ ($\Lambda(1405)$) to $\bar{K}NNNN$. We will measure the $\bar{K}NNN$ ($A = 3$) system at the new experiment approved as J-PARC E80, as a first step toward a comprehensive study.

1 Introduction

The study of the $\bar{K}N$ interaction is one of the most important subjects in meson–baryon interactions in low energy quantum chromodynamics (QCD). Extensive measurements of anti-kaonic hydrogen atoms [1–3] and low-energy $\bar{K}N$ scattering [4] have revealed the strongly attractive nature of the $\bar{K}N$ interaction in the isospin I = 0 channel. Consequently, the possible existence of deeply bound kaonic nuclear states (kaonic nuclei) has been widely discussed [5–25]. Kaonic nuclei are predicted to be compact due to the strong $\bar{K}N$ attraction, suggesting that high-density nuclear matter is realized in kaonic systems.

Among kaonic nuclei, the $\bar{K}NN$ system with $I = 1/2$ and $J^P = 0^-$ (symbolically denoted as K^-pp for the $I_z = +1/2$ state) is of special interest because it is the lightest $S = -1$ $\bar{K}$ nucleus. Despite considerable experimental efforts over the past 20 years, it has been challenging to prove the existence of K^-pp. Several groups have reported observations of a K^-pp candidate with a binding energy of around 100 MeV in experiments measuring non-mesonic decay branches of Λp and/or $\Sigma^0 p$ in different reactions [26–28]. There are also contradicting reports concluding that the reactions can be understood without a bound state [29–32].

2 J-PARC E15 Experiment

We conducted an experimental investigation of the K^-pp bound state using the simplest $\bar{K}$ induced reaction of $K^- + {}^3$He, via the nucleon knock-out reaction $K^-N \to \bar{K}n$ followed by the two-nucleon absorption $\bar{K} + NN \to K^-pp$. In the experiment, we used a kaon momentum of 1 GeV/c, around which the $K^-N \to \bar{K}n$ reactions have the maximum cross section. The recoiled kaon $\bar{K}$ at a momentum q behaves as an ‘off-shell particle’ (the total energy can be lower than its intrinsic mass) within a time range allowed by the uncertainty principle. The momentum transfer q is defined as that between the incident kaon and the outgoing neutron in the laboratory frame $q = |p_{K^-}^{lab} - p_n^{lab}|$. In the reaction, we used the low-momentum back-scattered kaon as an off-shell kaon source and the residual spectator nucleons NN as an ‘actual target’ to form a K^-pp state with an energy below the intrinsic mass of $M(Kpp)$ (= $m_K + 2m_N = 2.37$ GeV/c^2).

For the Λpn final states, we observed a kinematic anomaly in the Λp invariant mass near the mass threshold of $M(Kpp)$ at $q \sim 0.4$ GeV/c [33–35]. As shown in Fig. 1 (left), we confirmed the existence of the bound state below $M(Kpp)$, whose mass centroid is independent of q, at a binding energy as deep as $\sim$ 50 MeV. The back-scattered ‘on-shell’ kaon, whose total kaon energy is above its intrinsic mass, can also be absorbed by the spectator nucleons without forming a bound state. The kinematical centroid of this quasi-free absorption

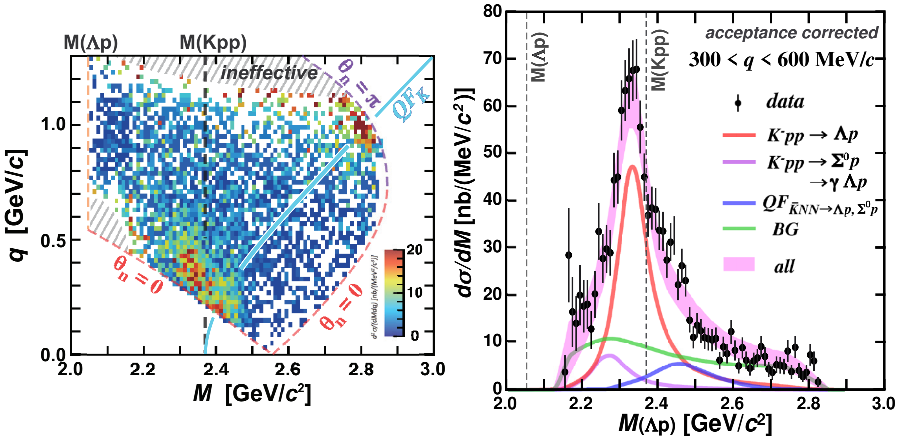

Figure 1. (left) Efficiency and acceptance corrected data over IM (Λp invariant mass) and q (momentum transfer). (right) Λp invariant mass in the region $0.3 < q < 0.6$ MeV/c.

process is plotted in the figure, denoted as QF_K. Along the line QF_K, there are two event concentration points at $\theta_n = 0$ and $\theta_n = \pi$, but both are well separated from the region of interest. Figure 1 (right) shows the Λp invariant mass spectrum for the region $0.3 < q < 0.6$ GeV/c where the $K^- pp$ bound state is dominant. A clear peak originating from $K^- pp$ can be seen below $M(Kpp)$, shown by the red line, whose binding energy, decay width, and S-wave Gaussian reaction form factor were observed to be $B_K = 42 \pm 3$ (stat.) $^{+3}_{-4}$ (syst.) MeV, $\Gamma_K = 100 \pm 7$ (stat.) $^{+19}_{-9}$ (syst.) MeV, and $Q_K = 383 \pm 11$ (stat.) $^{+4}_{-1}$ (syst.) MeV/c, respectively [35].

The observed binding energy of $B_K \sim 40$ MeV agrees with phenomenological predictions [10, 12, 13, 19, 36]. However, it should be noted that the obtained B_K is the spectral Breit-Wigner pole position, thus it might be different from the physical pole predicted by theoretical calculations. The observed decay width of $\Gamma_K \sim 100$ MeV is wider than the $\Lambda(1405) \to \pi\Sigma$ decay width of ~ 50 MeV (100%). If $\Lambda(1405)$ is the $\bar{K}N$ quasi-bound state, then it is naturally expected that the $\bar{K}NN \to \pi\Sigma N$ decay will occur in the same order as the $\Lambda(1405)$ decay, as is the case with most theoretical calculations. The $\bar{K}NN$ width obtained experimentally with the Λp decay in E15 is larger than that expected from the calculations, however, a possible increase of the width has been theoretically pointed out in Ref. [17] as follows. The inclusion of $\bar{K}$ absorption on the two nucleons (NN) in the $\bar{K}NN$ bound system increases the width by about 30 MeV from the YN decay to the total of about 80 MeV. This kinematical conditions for the $\bar{K}$ absorption process, $K^- pp \to \Lambda p$, would imply short-distance dynamics which is of importance to understand hadron interactions in medium, but remaining as an open question so far. The observed structure below the mass threshold in the Λp spectrum has also been theoretically interpreted as the $\bar{K}NN$ quasi-bound system: a theoretical calculation in Ref. [21, 37] demonstrated that the experimental spectrum can be reproduced with the $\bar{K}NN$ quasi-bound system and the quasi-free processes based on a theoretical treatment of the ^{3}He$(K^-, \Lambda p)n$ reaction. The observed large form factor of ~ 400 MeV/c, based on a simple plane wave impulse approximation (PWIA) [33–35], and the large binding energy of the $K^- pp$ state would imply the formation of a compact and dense system. However, to obtain further information on the size of the $\bar{K}NN$ system, a more realistic theoretical calculation including detailed reaction dynamics and a more detailed and systematic experimental study are essential.

3 Systematic Investigation of Light Kaonic Nuclei at J-PARC

To obtain further detailed information on kaonic nuclei, we have planned a series of experimental programs using the $(K^-, N/d)$ reaction on light nuclear targets. The programs will enable a detailed study of a range of nuclei from $\bar{K}N$ ($\Lambda(1405)$) to $\bar{K}NNNN$ using the world's highest intensity low-momentum kaon beam at J-PARC. The programs comprise:

- Precise measurements of the $\Lambda(1405)$ state in a large momentum transfer region via the $d(K^-, n)$ reaction, to experimentally clarify whether it is a baryonic state or a $\bar{K}N$ molecular state,
- Investigations of the spin and parity of the $\bar{K}NN$ state via $^3\mathrm{He}(K^-, N)$ reactions,
- A search for $\bar{K}NNN$ states via $^4\mathrm{He}(K^-, N)$ reactions, as a bridge to access heavier systems, and
- An advanced search for $\bar{K}NNNN$ states via the $^6\mathrm{Li}(K^-, d)$ reaction.

In parallel to these studies, we also intend to access the $S = -2$ kaonic nuclei, such as the theoretically predicted K^-K^-pp state. The $S = -2$ system could allow us to access even higher density systems than the $S = -1$ kaonic nuclei. As described in our Letter of Intent [38], one possible approach for the measurements at J-PARC could be:

- Searching for $\bar{K}\bar{K}NN$ states via $\bar{p}^3\mathrm{He}$ annihilation.

To ensure the measurements are systematic and precise, we are planning to construct a totally new 4π spectrometer to measure all the particles involved in the reactions and to reconstruct their formation and decay exclusively. The spectrometer is designed to be highly versatile so that all the experiments can be performed simply by changing the target materials. In addition, for more efficient use of the high-intensity kaon beam, we have proposed shortening the existing K1.8BR beam line for a larger kaon yield without deteriorating the momentum resolution of the kaon beam.

4 J-PARC E80 Experiment

In the new experiment, J-PARC E80, we aim to measure the $\bar{K}NNN$ ($A = 3$) system as a first step toward a comprehensive study. The key to the experimental search is to adopt a simple reaction and to measure it exclusively. Adopting a simple reaction, such as in-flight $\bar{K}$ induced reactions with light target nuclei, enables us to specify the reaction channel using the momentum-transfer dependence. Exclusive measurements are crucial for distinguishing small and broad signals from the large and widely distributed quasi-free and multi-nucleon absorption background.

We will perform exclusive measurements of the production and decay of the K^-ppn state using the in-flight reaction

$$K^- +^4 \mathrm{He} \quad \to \quad K^-ppn + n$$

followed by the expected no-mesonic decays

$$\begin{aligned} K^-ppn &\quad \to \quad \Lambda + d, \\ K^-ppn &\quad \to \quad \Lambda + p + n. \end{aligned}$$

We aim to determine the binding energy and width from the invariant mass reconstruction of the decays. The invariant mass will be obtained as a function of the momentum transfer to distinguish the bound-state production from the quasi-free processes and multi-nucleon absorption processes by the event kinematics as demonstrated in the E15 analysis. In the

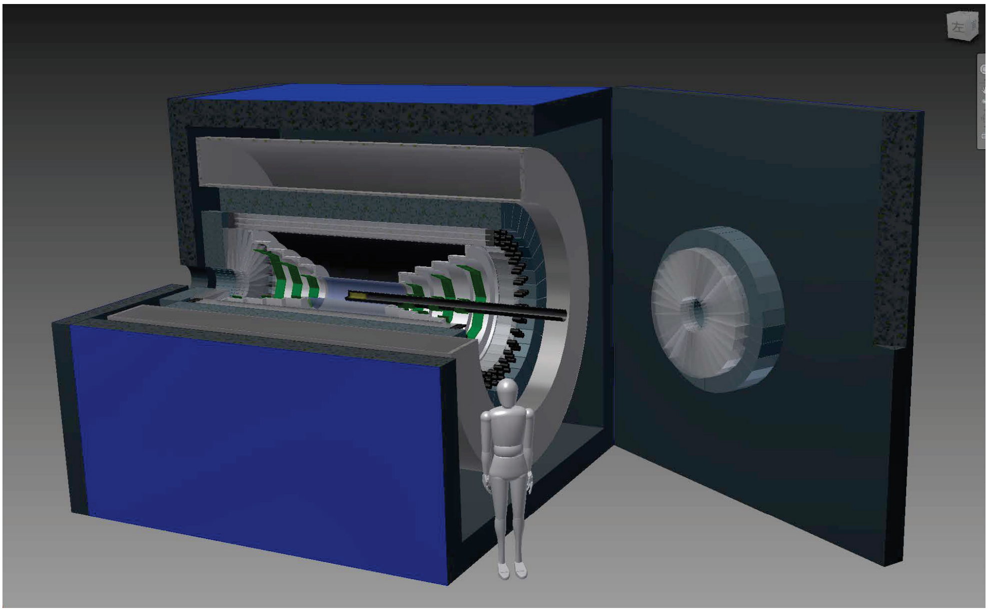

Figure 2. Conceptual design of the CDS.

$K^- + {}^4$He reaction, it is possible to measure the isospin partner of K^-ppn, *i.e.*, the K^-pnn state via

$$\begin{aligned} K^- +^4 \mathrm{He} &\rightarrow K^-pnn + p, \\ K^-pnn &\rightarrow \Lambda + n + n. \end{aligned}$$

Comparing the properties of the isospin partners is of special importance for investigating the internal composition of the kaonic nuclei. On the other hand, the measurement is challenging, because two-neutron detection is required to identify the K^-pnn decay.

We will utilize 1.0 GeV/c incident kaons to maximize the $\bar{K}N$ reaction rate at around zero degrees. The incoming K^- beam will be identified and its momentum analyzed by the beam-line spectrometer. The beam kaon will irradiate a liquid ^{4}He target located at the final focus point, and all the particles generated from the reactions will be identified with a newly constructed cylindrical detector system (CDS) surrounding the target system. A conceptual design of the CDS is shown in Fig. 2. It is mainly composed of a large superconducting solenoid magnet, a cylindrical wire drift chamber, and a cylindrical neutron detector. The kaonic nuclei will then be identified via invariant-mass reconstruction of the decay particles. By detecting the nucleon coming from the initial (K^-, N) reaction, or by identifying it with the missing mass technique, we will realize exclusive measurement of the kaonic nuclei. The details of the apparatus used for the experiment can be found in Ref. [39].

The new experiment will provide the mass number dependence of the kaonic nuclei for the first time. The dependence can more clearly reveal the $\bar{K}N$ interaction below the mass threshold, by comparing the obtained properties of the $\bar{K}NNN$ state with those of the already reported K^-p ($\Lambda(1405)$) and K^-pp states.

5 Summary

We demonstrated that kaonic nuclei can be produced via in-flight (K^-, N) reactions using the low-momentum DC kaon beam at the J-PARC E15 experiment. We observed that the simplest kaonic nuclei, K^-pp, has a much deeper binding energy than normal nuclei. We also found that the large form factor obtained in a PWIA analysis implies the possible formation of a compact and dense system. For the next stage, we have proposed a series of experimental programs for the systematic investigation of light kaonic nuclei, from $\bar{K}N$ ($\Lambda(1405)$) to $\bar{K}NNNN$. Through the experiments, we will determine the features of kaonic nuclei depending on the mass number A, *i.e.*, nuclear density, which is related to spontaneous and explicit chiral symmetry breaking in QCD. In the new experiment approved as J-PARC E80 we will measure the $\bar{K}NNN$ ($A = 3$) system as a first step toward a comprehensive study.

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