Recent Results and Future Prospects of Kaonic Nuclei at J-PARC

Received: 13 May 2021 / Accepted: 20 September 2021 / Published online: 14 October 2021
© The Author(s), under exclusive licence to Springer-Verlag GmbH Austria, part of Springer Nature 2021
Abstract $\bar{K}$-nuclear bound systems, kaonic nuclei, have been widely discussed as products of the strongly attractive $\bar{K}N$ interaction in $I = 0$ channels. Recently, we demonstrated that kaonic nuclei can be produced via in-flight ($\bar{K}^-, N$) reactions using the low-momentum DC kaon beam at the J-PARC E15 experiment. We observed the simplest kaonic nuclei, $\bar{K}^-pp$, having a much deeper binding energy than normal nuclei. 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 $\bar{K}NNNN$. 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.

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 [5–24]. 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 $KNN$ system with $I = 1/2$ and $J^P = 0^-$ (symbolically denoted as $K^-pp$ for the $I_c = +1/2$ 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 $\Lambda p$ and/or $\Sigma^0p$ in different reactions [25–27]. There are also contradicting reports concluding that the reactions can be understood without a bound state [28–31].

Recently, we confirmed the existence of the $K^-pp$ bound state by using the simplest reaction of in-flight $^3\text{He}(K^-, N)$ at the J-PARC E15 experiment [32–35]. A distinct peak structure was observed well below the mass threshold of $K^- + p + p$ in the $\Delta p$ invariant-mass (IM) spectrum, obtained from the $^3\text{He}(K^-, \Lambda p)n$ measurement. The simplest and most natural interpretation of this peak is $K^-pp$. This result is experimentally solid compared to previously reported results.

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 $KNNNN$ 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 $KNN$ state via $^3\text{He}(K^-, N)$ reactions,
- A search for $KNNN$ states via $^4\text{He}(K^-, N)$ reactions, as a bridge to access heavier systems, and
- An advanced search for $KNNNN$ states via the $^6\text{Li}(K^-, d)$ 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 [36], one possible approach for the measurements at J-PARC could be:

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

To ensure the measurements are systematic and precise, we are planning to construct a totally new $4\pi$ 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.

In this article, we review previous $K^-pp$ measurements at the J-PARC E15 experiment in Sect. 2 and set out what we have learned from the experimental investigations dedicated to kaonic nuclei. In Sect. 3, we present the details of the new experiment, approved as J-PARC E80, that focuses on searching for $KNNN$.

## 2 Results of the J-PARC E15 Experiment

We conducted an experimental investigation of the $K^-pp$ bound state using the simplest $\bar{K}$ induced reaction of $K^- + ^3\text{He}$, via the nucleon knock-out reaction $K^-N \to \bar{K}n$ followed by the two-nucleon absorption $\bar{K} + N N \to \bar{K}p p$. 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 $q = |p_{lab}^{K^-} - p_{lab}^n|$. 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 $\Delta pn$ final states, we observed a kinematic anomaly in the $\Delta p$ 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 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 $\Delta p$
Fig. 1 (left) Efficiency and acceptance corrected data over $IM$ ($\Lambda p$ invariant mass) and $q$ (momentum transfer). (right) $\Lambda p$ invariant mass in the region $0.3 < q < 0.6\, \text{MeV/c}$

invariant mass spectrum after the acceptance and efficiency corrections for the region $0.3 < q < 0.6\, \text{MeV/c}$ 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 reaches $\sim 50\, \text{MeV}$.

The simplest and most natural interpretation is the kaon-nuclear bound state $K^- pp$. The observed large form factor of $\sim 400\, \text{MeV/c}$, based on a simple plane wave impulse approximation (PWIA) [33–35], and the large binding energy of the $K^- pp$ state imply the formation of a fairly compact and dense system. The observed structure below the mass threshold in the $\Lambda p$ spectrum has also been 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 $^3\text{He}(K^-, \Lambda p)n$ reaction.

Thus, the E15 experiment opened a new era of experimental research on kaonic nuclei with the virtual kaon beam produced from in-flight ($K^-, N$) reactions. This has been realized by using the world’s highest intensity kaon beam available at J-PARC. However, we encountered several issues with the existing setup that made further investigations of the kaonic nuclei difficult. The new series of experiments will continue the systematic research into light kaonic nuclei using a new large acceptance detector system and the improved K1.8BR beam line.

3 New Experiment (J-PARC E80 Experiment)

For the next stage, we aim to determine the mass number dependence of the binding energy, decay width, and system size beyond $\bar{K}NN$. The mass number dependence has been calculated with several theoretical models, as summarized in Fig. 2. The values of the binding energy and decay width predicted by the models vary widely due to the differences in the $\bar{K}N$ interaction models. However, almost all the predictions show that the larger nuclei have stronger binding energies. For the width, the theoretical calculations take into account only mesonic decay channels, such as $\pi \Sigma N$ and $\pi \Lambda N$. The calculated width is expected to be larger if the models adopt non-mesonic decay channels, as demonstrated in Ref. [17].

From an experimental point of view, when the mass number is large, it becomes difficult to handle the number of particles in the final state and to deduce the physics behind the reaction. Thus, we take a step-by-step approach. 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. From the experience of E15, we have learned that reducing the number of particles in the final state is a key to removing ambiguity in interpreting the reaction process. Therefore, we focus on the $K^- ppn \rightarrow \Lambda d$ and $\Lambda pn$ decay channels in $^4\text{He}(K^-, \Lambda d/\Lambda pn)n$ reactions.
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 $K^-p$ states.

3.1 Experimental Method

To date, stopped $K^-$ reactions have mainly been used to search for the $\bar{K}NNN$ state. The KEK-PS E471/E549 collaborations measured the inclusive $^4$He($K^-_{stopped}$, $p/n$) reactions with a spectrometer dedicated to TOF measurement of protons and neutrons [38, 39]. They found no specific peak structures below the mass threshold of $M(\bar{K}NNN)$ in the missing mass spectra from the reactions. This is due to the huge background originating from the two-nucleon absorption processes, $\bar{K}NN \rightarrow YN$, and quasi-free hyperon productions and its decays, $\bar{K}N \rightarrow \pi Y$, whose production mechanisms are quite complicated. The background cannot be discriminated kinematically from the signal with small production cross section in the inclusive measurements.

Indeed, our inclusive analysis of the in-flight $^3$He($K^-, n$)X measurement showed no significant peak structures due to the huge background from quasi-free processes and the two-nucleon absorption processes [32]. By reducing the background by the exclusive measurement of $^3$He($K^-, \Lambda p)n$ and identifying all the final-state particles in a wide momentum-transfer region, the $K^-pp$ signal could be separated out. We found that the $K^-pp$ signal has a much smaller cross section ($\sim 10 \mu$b) than the quasi-free processes ($\sim 10$ mb) and is distributed up to $q \sim 600$ MeV/c [33–35].

On the other hand, there are two reports of observations of the $K^-ppn$ candidate below the mass threshold in the $\Lambda d$ invariant mass spectrum with stopped $K^-$ reactions (FINUDA) and heavy-ion collisions (FOPI). The FINUDA collaboration reported that the candidate has a binding energy of $\sim 60$ MeV and a width of $\sim 40$ MeV [40]. The candidate reported by the FOPI collaboration has a much deeper binding energy of $\sim 150$ MeV with a broader width of $\sim 100$ MeV [41]. However, because these measurements were performed only inclusively, possible contributions from multi-nucleon absorption processes and $N^*/Y^*$ decays to the peak structure cannot be excluded. Furthermore, the statistics reported were very limited and thus the results remain speculative.

Therefore, 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.

In the new experiment, we will perform exclusive measurements of the production and decay of the $K^-ppn$ state using the in-flight reaction

$$K^- + ^4\text{He} \rightarrow K^- ppm + n$$
followed by the expected no-mesonic decays

\[ K^- ppn \rightarrow \Lambda + d, \]
\[ K^- ppn \rightarrow \Lambda + p + n. \]

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

\[ K^- + ^4\text{He} \rightarrow K^- pnn + p, \]
\[ K^- pnn \rightarrow \Lambda + n + n. \]

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.

3.2 Apparatus

We aim to produce the \( \bar{K}NNN \) state using the \( (K^-, N) \) reaction at the K1.8BR beam line, as successfully performed in the previous experiment E15; a recoiled virtual kaon \( (\bar{K}) \) generated by \( \bar{K}N \rightarrow \bar{K}N \) processes can be directly induced into residual nucleons within the strong interaction range. 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 \(^4\text{He} \) target located at the final focus point, and all the particles generated from the reactions will be identified with a cylindrical detector system (CDS) surrounding the target system. A conceptual design of the CDS is shown in Fig. 3. 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. [42].

3.3 Expected Spectrum

Figure 4 shows the expected spectra of the \( K^- ^4\text{He} \rightarrow \Lambda d n \) and \( \Lambda pnn \) final states with 100-G kaons on target, corresponding to three weeks data taking under 90-kW beam power of the J-PARC Main Ring accelerator [42]. For the \( K^- ppn \) state in the figures, we assume a similar distribution to that of \( K^- pp \) observed in E15, with a binding energy of \( \sim 50 \) MeV, a width of \( \sim 100 \) MeV, and a Gaussian form factor of \( \sim 400 \) MeV/c.
Fig. 4 Expected spectra of (top) $\Lambda d$ and (bottom) $\Lambda pn$ in the $K^-^4He \rightarrow \Lambda d + n$ and $\Lambda pn + n$ final state with 100-G kaons on target, respectively. We assume the cross section of the $K^- pn$, quasi-free, and background to be $10\mu b$, $10\mu b$, and $20\mu b$, respectively, based on the E15 results.

Fig. 5 Expected invariant-mass spectra of (left) $\Lambda d$ and (light) $\Lambda pn$ in the region $0.3 < q < 0.6 \text{ GeV/c}$, obtained from Fig. 4.
with 10 \mu b (\sigma \cdot BR). For the quasi-free process and broad background, we also used similar parameters to those obtained for the $K^{-3}\text{He} \rightarrow \Lambda pn$ final state in E15. The spectra for each process are generated using the Geant4 simulation, in which we assume the same resolution of the existing CDS to reconstruct the simulated tracks: $5.3\% \times p_t \oplus 0.5\%$ for charged particles [33] and $\sim 10\% \times p \oplus 7\%$ for a neutron.\footnote{Based on the preliminary result of $K^{-3}\text{He} \rightarrow \pi \Sigma pn$ analysis [43].}

In the assumed conditions, the bound states are clearly identified not only in the invariant mass spectra but also on the 2-dimensional plane of the momentum transfer versus the invariant mass ($q$ – $IM$) distribution, which is the most important feature of the experiment. By investigating the specific structures in the $q$ – $IM$ distribution, we can kinematically identify the signal of the bound state. Figure 5 shows a demonstration of the signal enhancement by selecting a momentum transfer of $0.3 < q < 0.6 \text{GeV}/c$. In this region, we expect the bound state to be clearly separated from the quasi-free process, as in the case of the E15 experiment shown in Fig. 1.

4 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.

Acknowledgements We are grateful to all the staff members of J-PARC/KEK/JAEA for their extensive efforts in the successful operation of the facility. This work is supported in part by MEXT Grants-in-Aid 26800158, 17K05481, 26287057, 24105003, 14102005, 18H01237, and 20K04006. Part of this work is also supported by the Ministero degli Affari Esteri e della Cooperazione Internazionale, Direzione Generale per la Promozione del Sistema Paese (MAECI), StrangeMatter project.

References

1. M. Iwasaki et al., Phys. Rev. Lett. 78, 3067 (1997)
2. G. Beer et al., Phys. Rev. Lett. 94, 212302 (2005)
3. M. Bazzi et al., Phys. Lett. B 704, 113 (2011)
4. A.D. Martin, Nucl. Phys. B 179, 33 (1981)
5. Y. Nogami, Phys. Lett. 7, 288 (1963)
6. Y. Akaishi, T. Yamazaki, Phys. Rev. C 65, 044005 (2002)
7. T. Yamazaki, Y. Akaishi, Phys. Lett. B 535, 70 (2002)
8. N.V. Shevchenko, A. Gal, J. Mares, Phys. Rev. Lett. 98, 082301 (2007)
9. N.V. Shevchenko, A. Gal, J. Mares, J. Revai, Phys. Rev. C 76, 044004 (2007)
10. Y. Ikeda, T. Sato, Phys. Rev. C 76, 035203 (2007)
11. A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A 804, 197 (2008)
12. Y. Ikeda, T. Sato, Phys. Rev. C 79, 035201 (2009)
13. S. Wycech, A.M. Green, Phys. Rev. C 79, 014001 (2009)
14. A. Doté, T. Hyodo, W. Weise, Phys. Rev. C 79, 014003 (2009)
15. Y. Ikeda, H. Kamano, T. Sato, Prog. Theor. Phys. 124, 533 (2010)
16. N. Barnea, A. Gal, E.Z. Liverts, Phys. Lett. B 712, 132 (2012)
17. M. Bayar, E. Oset, Phys. Rev. C 88, 044003 (2013)
18. S. Maeda, Y. Akaishi, T. Yamazaki, Proc. Jpn. Acad. B89, 410 (2013)
19. J. Révai, N.V. Shevchenko, Phys. Rev. C 90, 034004 (2014)
20. A. Doté, T. Inoue, T. Myo, Prog. Theor. Exp. Phys. 2015, 043D02 (2015)
21. T. Sekihara, E. Oset, A. Ramos, Prog. Theor. Exp. Phys. 2016, 123D03 (2016)
22. S. Ohnishi et al., Phys. Rev. C 95, 065202 (2017)
23. A. Doté, T. Inoue, T. Myo, Phys. Rev. C 95, 062201 (2017)
24. A. Doté, T. Inoue, T. Myo, Phys. Lett. B 784, 405 (2018)
25. M. Agnello et al., Phys. Rev. Lett. 94, 212303 (2005)
26. T. Yamazaki et al., Phys. Rev. Lett. 104, 132502 (2010)
27. Y. Ichikawa, et al., Prog. Theor. Exp. Phys. 2015, 021D01 (2015)
28. O. Vzquez Doce, et al., Phys. Lett. B758, 134 (2016)
29. R. Del Grande et al., Eur. Phys. J. C 79, 190 (2019)
30. G. Agakishiev et al., Phys. Lett. B 742, 242 (2015)
31. A.O. Tokiyasu et al., Phys. Lett. B 728, 616 (2014)
32. T. Hashimoto, et al., Prog. Theor. Exp. Phys. 2015, 061D01 (2015)
33. Y. Sada, et al., Prog. Theor. Exp. Phys. 2016, 051D01 (2016)
34. S. Ajimura et al., Phys. Lett. B 789, 620 (2019)
35. T. Yamaga et al., Phys. Rev. C 102, 044002 (2020)
36. Letter of Intent for J-PARC, Double Anti-kaon Production in Nuclei by Stopped Anti-proton Annihilation (2009). http://j-parc.jp/researcher/Hadron/en/Proposal_e.html
37. T. Sekihara, E. Oset, A. Ramos, J.P.S. Conf. Proc. 26, 023009 (2019)
38. M. Sato et al., Phys. Lett. B 659, 107 (2008)
39. H. Yim et al., Phys. Lett. B 688, 43 (2010)
40. M. Agnello et al., Phys. Lett. B 654, 80 (2007)
41. N. Herrmann, et al., in Proceedings of the EXA05 Conference. ISBN 3-7001-3616-1, 73 (2005)
42. Proposal for J-PARC, Systematic investigation of the light kaonic nuclei (2020). http://j-parc.jp/researcher/Hadron/en/Proposal_e.html
43. F. Sakuma et al., AIP Conf. Proc. 2249, 020005 (2020)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.