PROCEEDINGS OF SCIENCE

Light Kaonic Nuclei at J-PARC

F. Sakuma,[a,*] T. Akaishi,[b] M. Bazzi,[c] P. Buehler,[d] A. Clozza,[c] C. Curceanu,[c] H. Fujioka,[e] C. Guaraldo,[c,†] M. Iio,[f] M. Iliescu,[c] K. Inoue,[b] S. Ishimoto,[f] K. Itahashi,[a] M. Iwasaki,[a] T. Hashimoto,[a] S. Kawasaki,[b] Y. Kimura,[g] G. Kojima,[g] Y. Ma,[a] Y. Makida,[f] S. Manti,[c] R. Murayama,[a] T. Nagae,[b] T. Nanamura,[a] H. Noumi,[b] H. Ohhata,[f] H. Ohnishi,[g] M. Oonaka,[f] K. Ozawa,[f] K. Sasaki,[f] S. Sasaki,[f] A. Scordo,[c] F. Sgaramella,[c] K. Shirotori,[b] D. Sirghi,[c] F. Sirghi,[c] N. Sumi,[f] K. Suzuki,[b] S. Suzuki,[f] K. Tanida,[h] K. Toho,[g] M. Tsuruta,[g] T. Yamaga,[f] M. Yoshida,[f] S. Okada,[i] E. Widmann[d] and J. Zmeskal[d,†] for the J-PARC E80 collaboration

[a] *RIKEN, Wako 351-0198, Japan*

[b] *Research Center for Nuclear Physics (RCNP), Osaka University, Osaka 567-0047, Japan*

[c] *Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy*

[d] *Stefan-Meyer-Institut für subatomare Physik, A-1090 Vienna, Austria*

[e] *Institute of Science Tokyo, Tokyo 152-8550, Japan*

[f] *High Energy Accelerator Research Organization (KEK), Ibaraki 305-0801, Japan*

[g] *Research Center for Accelerator and Radioisotope Science (RARIS), Tohoku University, Sendai 982-0826, Japan*

[h] *Japan Atomic Energy Agency (JAEA), Ibaraki 319-1195, Japan*

[i] *Chubu University, Aichi 487-0027, Japan*

E-mail: sakuma@ribf.riken.jp

The possible existence of deeply bound $\bar{K}$-nucleus bound states (kaonic nuclei) has been widely discussed as a consequence of the strongly attractive $\bar{K}N$ interaction in I = 0 channels. For the simplest kaonic nucleus, $\bar{K}NN$, we observed a significant peak structure that can be interpreted as the "K^-pp" bound state using the ^{3}He(K^-, N) reactions at J-PARC. To further understand the kaonic nuclei, we have proposed and prepared an experiment to precisely measure the $\bar{K}NNN$ system using the ^{4}He(K^-, N) reactions as a first step towards a comprehensive study of the light kaonic nuclei from "$\bar{K}N$" (=Λ(1405)) to "$\bar{K}NNNN$". Through the experiments and detailed theoretical calculations, we will unravel the nature of the kaonic nuclei from the changes in their properties with increasing mass number A.

QNP2024 - The 10th International Conference on Quarks and Nuclear Physics
8 – 12 July 2024
Facultat de Biologia, Universitat de Barcelona, Barcelona, Spain

*Speaker
†Deceased.

PoS(QNP2024)211

1. Introduction

The study of the $\bar{K}N$ interaction is one of the most important subjects for understanding the meson-baryon interactions in low-energy quantum chromodynamics (QCD). Extensive measurements of the anti-kaonic hydrogen atom [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 in references [5–7] and others. Theoretical calculations indicate that the kaonic nuclei can form compact systems, suggesting that high-density nuclear matter is realized in the kaonic nuclei where chiral symmetry is expected to be restored.

Among the 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 particular interest because it is the lightest $S = -1$ $\bar{K}$ nucleus and its existence is supported by many theoretical works. Despite considerable experimental efforts over the last 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 around 100 MeV in experiments measuring non-mesonic decay branches of Λp and/or $\Sigma^0 p$ in different reactions [8–10]. However, there are also contradicting reports concluding that the reactions can be understood without a bound state [11–14].

2. J-PARC E15 Experiment

In such a controversial situation, we finally confirmed the existence of the K^-pp bound state using the simplest reaction of in-flight ^{3}He(K^-, N) at the J-PARC E15 experiment [15–18]. A distinct peak structure well below the mass threshold of $K^- + p + p$ was observed in the Λp invariant-mass spectrum obtained from the ^{3}He$(K^-, \Lambda p)n$ measurement as shown in Fig. 1. The simplest and most natural interpretation of this peak is K^-pp. The result obtained in the E15 experiment is experimentally robust compared to the other experiments; we measured a wide range of momentum transfer with high statistics, which allows us to clearly specify the K^{-3} He $\rightarrow \Lambda pn$ reaction using the 2-dimensional analysis on the Λp invariant mass versus the momentum transfer to the Λp system. We also performed the ^{3}He$(K^-, \pi YN)N$ measurements and successfully reproduced the πYN invariant mass and momentum transfer distributions for πYN [19], whose results indicate that mesonic decay is the dominant decay branch of $\bar{K}NN$ as predicted. The E15 experiment thus opened a new era of experimental research on the kaonic nuclei with the in-flight (K^-, N) reactions realized with the world's highest intensity kaon beam available at J-PARC.

3. J-PARC E80 Experiment

To obtain further experimental understandings of the kaonic nuclei, we have planned a series of experimental programs using the $(K^-, N/d)$ reactions on light nuclear targets. A detailed and systematic study of a range of nuclei from $\bar{K}N$ ($\Lambda(1405)$) to $\bar{K}NNNN$ will be carried out:

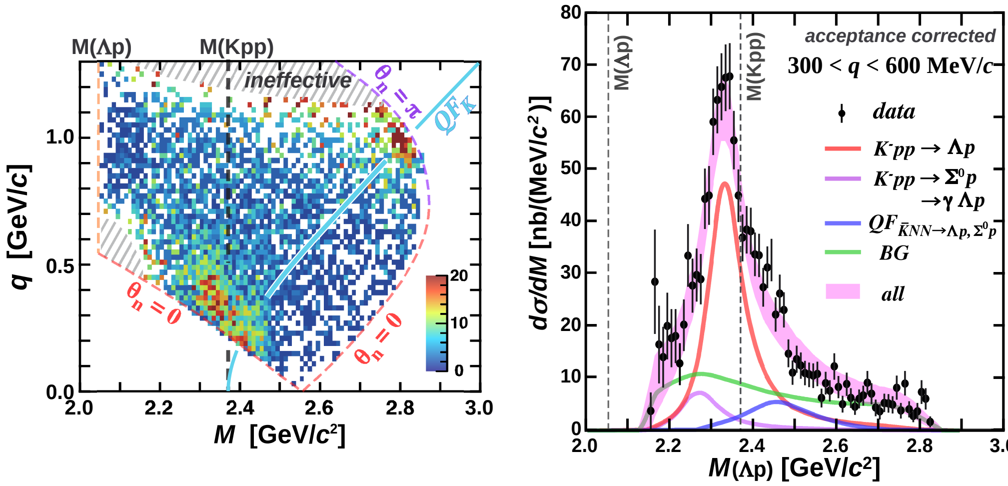

Figure 1: (left) Efficiency and acceptance corrected data over M (Λp invariant mass) and q (momentum transfer) obtained from the J-PARC E15 experiment [17, 18]. (right) Λp invariant mass in the region $0.3 < q < 0.6$ MeV/c.

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

In the series of experimental programs, we aim to determine the mass-number dependence of the binding energy, the decay width, and the decay branching ratio. Furthermore, we aim to elucidate the internal structure of the kaonic nuclei, including their spatial size, by systematically and multi-dimensionally comparing structure and reaction calculations based on detailed theoretical models with results obtained from the experiments [20]. The mass-number dependence has been calculated with several theoretical models, as summarized in Fig. 2. The calculated values of the binding energy and the decay width vary widely due to the differences in the $\bar{K}N$ interaction models, but almost all calculations show that the larger nuclei have stronger binding energies.

The J-PARC E80 experiment measures the $\bar{K}NNN$ system [25], as a first step towards a comprehensive study of the kaonic nuclei. This experiment provides for the first time the mass-number dependence of the kaonic nuclei by combining the obtained properties of the $\bar{K}NNN$ state with those of the previously reported K^-p ($\Lambda(1405)$) and K^-pp states. The dependence can reveal the $\bar{K}N$ interaction below the mass threshold and the internal structure of the kaonic nuclei with the help of detailed theoretical calculations.

In the E80 experiment, we perform exclusive measurements of the production and decay of the K^-ppn state using the in-flight reaction

$$K^- + ^4\text{He} \quad \rightarrow \quad K^-ppn + n$$

followed by the expected non-mesonic decays

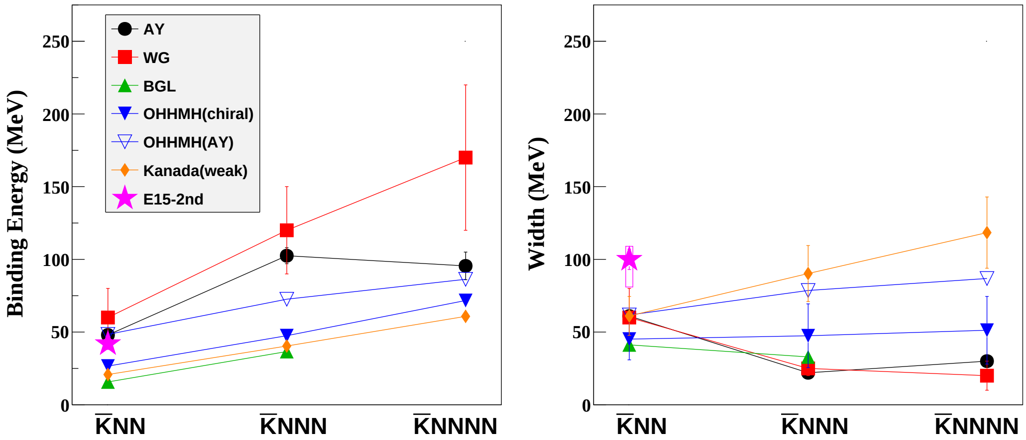

Figure 2: Summary of theoretical calculations of the kaonic nuclei from $A = 2$ to 4 in different models AY [6, 7], WG [21], BGL [22], OHHMH [23], and Kanada [24]. The result obtained from the E15 experiment is also plotted [18].

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

To maximize the $(\bar{K}, N)$ reaction rate around zero degrees, we utilize 1.0 GeV/c incident kaons. We determine the binding energy and decay width from the invariant mass reconstruction of the decays. The invariant mass must be obtained in the wide momentum transfer region in order to distinguish the bound state production from the quasi-free processes by the event kinematics, as demonstrated in the E15 analysis.

The experiment is performed in the K1.8BR area of the Hadron Experimental Facility at J-PARC. The incoming K^- beam momentum is analyzed by the beam line spectrometer. The beam kaon then collides with a liquid ^{4}He target located at the final focus point, and the particles produced from the reactions are measured with a Cylindrical Detector System (CDS) surrounding the target system. A forward or backward particle from the CDS acceptances is identified using the missing mass technique, allowing all particles from the reactions to be identified.

To achieve these systematic measurements, we are now constructing the new CDS to drastically increase the acceptance compared to the current detector system [26]. A design of the CDS is shown in Fig. 3. It consists mainly of a large superconducting solenoid magnet, a Cylindrical wire Drift Chamber (CDC), and a Cylindrical Neutron Counter (CNC). The magnet provides a uniform magnetic field of up to 1.0 T over the tracking volume by covering a large acceptance for outgoing particles from the target region. The design of the magnet is almost identical to the "detector solenoid magnet" for the COMET-I experiment [27], taking into account the experimental requirements and the feasibility of the construction. The magnet is now being manufactured at TOSHIBA with the help of the J-PARC Cryogenics Section, and will be completed in early 2025. The CDC is a cylindrical wire drift chamber containing 15 layers of anode wires. The design of the new CDC follows that of the existing CDC used for the current CDS at K1.8BR [28], except

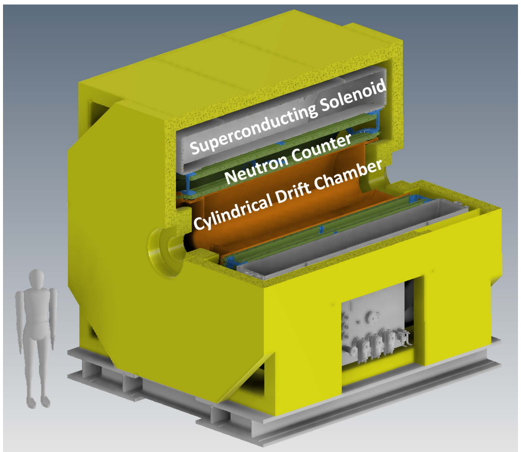

Figure 3: Design of the CDS.

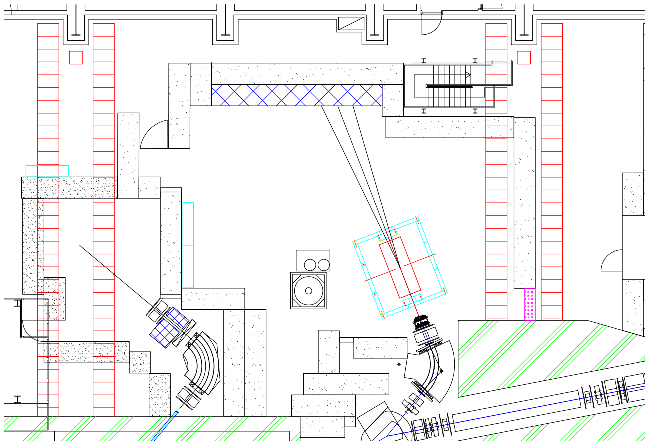

Figure 4: New layout of the K1.8BR experimental area for the E80 experiment with the future test beam line.

that the wire length is about three times longer. The CDC has been completed, and is undergoing commissioning at J-PARC. The CNC is an array of segmented plastic scintillation counters used for neutron detection. Charged particle identification and decay particle triggering are also performed on the first layer of the CNC. The CNC will be constructed in 2025, after completion of the R&D study currently underway.

We have also proposed a new configuration of the K1.8BR beam line, as shown in Fig. 4, to achieve efficient utilization of the K^- beam at E80. With this new setup, the number of kaons available at 1 GeV/c is expected to increase by a factor of ~ 1.4 compared to the current beam line configuration with the current detector system, without deteriorating the momentum resolution of the kaon beam.

4. Summary

The possible existence of the kaonic nuclei has been extensively discussed for several decades, and finally the simplest kaonic nucleus, $\bar{K}NN$, was observed using the in-flight $^3\mathrm{He}(K^-, n)$ reactions at 1 GeV/c (J-PARC E15). For further understanding the properties of kaonic nuclei, we have proposed a new experiment, J-PARC E80, which will perform the precise measurement of kaonic nuclei focusing on the $\bar{K}NNN$ system as a first step towards a comprehensive study of the light kaonic nuclei from "$\bar{K}N$" (=$\Lambda(1405)$) to "$\bar{K}NNNN$". To achieve these systematic measurements, we are constructing a new 4π Cylindrical Detector System (CDS) that significantly improves detector acceptance. We plan to start the experiment in early 2027.

References

[1] M. Iwasaki et al.*Phys. Rev. Lett.* **78** (1997) 3067.

[2] G. Beer et al.*Phys. Rev. Lett.* **94** (2005) 212302.

[3] M. Bazzi et al.*Phys. Lett.* **B704** (2011) 113.

[4] A.D. Martin*Nucl. Phys.* **B179** (1981) 33.

[5] Y. Nogami*Phys. Lett.* **7** (1963) 288.

[6] Y. Akaishi and T. Yamazaki*Phys. Rev.* **C65** (2002) 044005.

[7] T. Yamazaki and Y. Akaishi*Phys. Lett.* **B535** (2002) 70.

[8] M. Agnello et al.*Phys. Rev. Lett.* **94** (2005) 212303.

[9] T. Yamazaki et al.*Phys. Rev. Lett.* **104** (2010) 132502.

[10] Y. Ichikawa et al.*Prog. Theor. Exp. Phys.* **2015** (2015) 021D01.

[11] O. Vázquez Doce et al.*Phys. Lett.* **B758** (2016) 134.

[12] R. Del Grande et al.*Eur. Phys. J.* **C79** (2019) 190.

[13] G. Agakishiev et al.*Phys. Lett.* **B742** (2015) 242.

[14] A.O. Tokiyasu et al.*Phys. Lett.* **B728** (2014) 616.

[15] T. Hashimoto et al.*Prog. Theor. Exp. Phys.* **2015** (2015) 061D01.

[16] Y. Sada et al.*Prog. Theor. Exp. Phys.* **2016** (2016) 051D01.

[17] S. Ajimura et al.*Phys. Lett.* **B789** (2019) 620.

[18] T. Yamaga et al.*Phys. Rev. C* **102** (2020) 044002.

[19] T. Yamaga et al.*Phys. Rev. C* **110** (2024) 014002.

[20] T. Sekihara, E. Oset and A. Ramos*Prog. Theor. Exp. Phys.* **2016** (2016) 123D03.

[21] S. Wycech and A.M. Green*Phys. Rev.* **C79** (2009) 014001.

[22] N. Barnea, A. Gal and E.Z. Liverts*Phys. Lett.* **B712** (2012) 132.

[23] S. Ohnishi, W. Horiuchi, T. Hoshino, K. Miyahara and T. Hyodo*Phys. Rev.* **C95** (2017) 065202.

[24] Y. Kanada-En'yo*Eur. Phys. J. A* **57** (2021) 185.

[25] J-PARC E80 Proposal*https://j-parc.jp/researcher/Hadron/en/pac_2007/pdf/P80_2020-10.pdf* .

[26] Technical Design Report on the E80 Experiment*http://ag.riken.jp/J-PARC/PAC/E80_TDR_2024_20240705_updated.pdf* .

[27] R. Abramishvili et al.*Prog. Theor. Phys.* **2020** (2020) 033C01.

[28] K. Agari et al.*Prog. Theor. Exp. Phys.* **2012** (2012) 02B011.