Memorandum for the J-PARC E80/P92 experiment

Reply to the Minutes of the 33rd PAC

July 27, 2022

The J-PARC E80/P92 collaboration

Abstract

We reply to two issues regarding E80/P92 asked in the Minutes of the 33rd PAC held on 19 - 21 January, 2022:

- justification for the $\bar{K}NNN$ interpretation of the observed peak structure in the $K^{-4}\mathrm{He} \to \Lambda dn$ analysis, and
- clarification of the strategy for the kaonic nuclei investigation at K1.8BR.

1 J-PARC E80/P92 Experiment

The E80 experiment aims to establish the $\bar{K}NNN$ kaon-nuclear bound system with a new large solenoidal detector system (Cylindrical Detector System, CDS) at the improved (shortened) K1.8BR beam line, as a first step toward the comprehensive study of the light kaonic nuclei [1]. We will perform exclusive measurements of the production and decay of the $\bar{K}NNN$ system with $I = 0$ and $J^P = 1/2^-$ (symbolically denoted as K^-ppn) using the in-flight reaction

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

followed by the expected non-mesonic decays

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

The E80 experiment will firstly provide the mass number dependence of the binding energy, decay width, and system size of the kaonic nuclei, by comparing them from $\bar{K}N$ ($\Lambda(1405)$) to $\bar{K}NNN$. The mass number dependence will clearly reveal the $\bar{K}N$ interaction below the mass threshold.

As the phase-I experiment of E80, the P92 experiment aims at an immediate investigation into the $\bar{K}NNN$ state focusing on the $K^{-4}\mathrm{He} \to \Lambda dn$ measurement using the present setup at the K1.8BR beam line [2]. Thus, the goal of P92 is the same as a part of the E80 goal. Compare E80 with P92, E80 will enable us to perform more comprehensive study on multi-particle decay mode of $K^-ppn \to \Lambda pn$ and more detailed investigation of $K^-ppn \to \Lambda d$ with wide kinematical-acceptance coverage.

2 Reply to the Minutes of the 33rd PAC

Here we summarize replies to two issues regarding E80/P92 asked in the Minutes of the 33rd PAC.

The PAC recommends that the proponents should carefully analyze the T77 data and seek further justification for the K-NNN bound state interpretation.

At the last (33rd) PAC meeting, we reported that we observed a sub-threshold peak structure in the Λd invariant-mass spectrum using the ^{4}He target data that we required Λdn in the final state. The observed Λd invariant mass spectrum on the ^{4}He target is quite similar to the Λp invariant mass spectrum on the ^{3}He target by shifting the mass value by one nucleon mass. Thus, the formation mechanism for the sub-threshold peak structure probably relates to the one we observed in $^3\mathrm{He}(K^-, \Lambda p)n$.

An S-wave kaonic nuclear-bound state, "$\bar{K}NNN$", is expected to exist based on the $\bar{K}N$ potential evaluated from kaonic hydrogen x-ray measurements. However, as referees mentioned, the "$\Sigma^* NN$" state is also a reasonable candidate to interpret the observed signal near the K^- bound threshold. To clarify it, we investigated possible isospin-spin configurations and the coupling strength of $I_{KN} = 0$ and 1 channels, summarized in tables 1 and 2, respectively. The detailed description can be found in Ref. [3]. Using those results and the evaluated production cross-sections for these two channels from the Clebsch-Gordan coefficients and the known elementary cross sections, interpretation for the "$K^- ppn$" is a more natural candidate than "$\Sigma^{*-} pp$" in terms of the formation cross-section.

In addition, the internal structure would be explored by its decay branch. If the observed state has a "$\Sigma^* NN$" internal structure, the most natural decay process is the $\Sigma^* N \to \Lambda N'$ conversion, leaving another nucleon as a spectator. After the conversion, deuteron formation would be negligibly small, since N' must be high in energy (≈ 250 MeV). Thus, "$\Sigma^* NN$" shall dominantly decay to Λpn mode in all the non-mesonic ΛNN decay branch, instead of Λd. On the other hand, if the observed state has a "$\bar{K}NNN$" internal structure, the Λd branch would be naturally introduced from the $\bar{K}N \to \Lambda$ conversion with an off-shell $\bar{K}$ similar to a theoretical calculation in Ref [4, 5].

To examine the observed structure in more detail from such a point of view and to seek further justification for the "$\bar{K}NNN$" bound state interpretation, we will conduct the E80/P92 experiment. At the experiment, we will obtain further information on the binding energy, width, reaction form factor, decay branch, and production cross-section of the structure. The mass-number dependence obtained from precise determination of the binding energy, width, and reaction form factor will more firmly establish the existence of the $\bar{K}NNN$ state and $\bar{K}NN$ by comparing theoretical calculations of the light kaonic nuclei. Experimental measurements and theoretical investigations of the decay branch will also provide new insight into the observed signal's internal structure. Comparing the production cross-section between the peak structure and quasi-free process in the entire kinematical region will allow us to further the above considerations. For further confirmation, the definitive assignment of spin-parity (J^P) is a key, from spin-spin correlation study of decay products as discussed in Ref. [3].

Table 1: The internal structure of "X" via the cascade reaction $K^- + {}^4\mathrm{He} \to$ "X" $+ n$. This table is taken from Table 9 in Ref. [3].

"X"	$I(J^P)$	J_3	isospin-spin configuration of $\vert\bar{K}NNN\rangle$ or $\vert\Sigma^* NN\rangle$ of spin-up
"K^-ppn"	$0(\frac{1}{2}^-)$	$+\frac{1}{2}$	$I_{\bar{K}N} = 0 : \frac{1}{6\sqrt{2}}\Big((\bar{K}^0 n{\downarrow} - K^- p{\downarrow})\otimes\big([p,n]\otimes\{\uparrow,\uparrow\}\big) - (\bar{K}^0 n{\uparrow} - K^- p{\uparrow})\otimes\big([p,n]\otimes\{\uparrow,\downarrow\}\big)\Big)$
			$I_{\bar{K}N} = 1 : \frac{1}{6\sqrt{2}}\Big(\bar{K}^0 p{\uparrow}\otimes\{n,n\} - (\bar{K}^0 n{\uparrow} + K^- p{\uparrow})\otimes\{p,n\} + K^- n{\uparrow}\otimes\{p,p\}\Big)\otimes[\uparrow,\downarrow]$
"$\Sigma^{*-}pp$"	$0(\frac{3}{2}^+)$	$+\frac{3}{2}$	$\frac{1}{6\sqrt{2}}\Big(\Sigma^{*-}{\uparrow}^3\otimes\{p,p\} - \sqrt{2}\Sigma^{*0}{\uparrow}^3\otimes\{p,n\} + \Sigma^{*+}{\uparrow}^3\otimes\{n,n\}\Big)\otimes[\uparrow,\downarrow]$

$[A,B]$: commutator $= AB - BA$, $\{A,B\}$: anti-commutator $= AB + BA$
${\uparrow}^3$: spin $\frac{3}{2}$, $\uparrow$: spin $\frac{1}{2}$, $\Sigma^*\otimes\uparrow = N\otimes{\uparrow}^3 \equiv 0$

Table 2: The $\bar{K}N$ coupling to $I_{\bar{K}N} = 0$ channel and estimated relative yield of "X" via the cascade reaction; $K^- + {}^4\mathrm{He} \to$ "X" $+ n$ (n in the forward direction) followed by "X" $\to \Lambda d$. This table is taken from Table 10 in Ref. [3].

"X"	$I(J^P)$	$\vert\bar{K}N_{(I=0)}\vert^2$	$\vert\bar{K}N_{(I=1)}\vert^2$	$\sigma(J^P)\,/\sigma(\frac{1}{2}^-)$
"K^-ppn"	$0(\frac{1}{2}^-)$	3/6	3/6	$1^{(*)}$
"$\Sigma^{*-}pp$"	$0(\frac{3}{2}^+)$	—	—	$1/3\, \varepsilon_{P/S}\ r_{stk(\Sigma^* NN/\bar{K}NNN)}$

$^{(*)}$: normalization channel
$\varepsilon_{P/S} \equiv P(K^- N \to \bar{K}N')/S(K^- N \to \bar{K}N')$
$r_{stk(\Sigma^* NN/\bar{K}NNN)}$: the ratio of sticking probabilities between "$\Sigma^* NN$" and "$\bar{K}NNN$", including $\bar{K}N \to \Sigma(1385)$ conversion probability in ($\bar{K}NNN$)-system

The PAC also requests the proponents to clarify their strategy in combination with related experiments in which they propose to search for deeply bound kaonic states.

Based on the successful measurement of the $\bar{K}NN$ by the E15 experiment, we have proposed the systematic investigation to search for the kaonic nuclei with more than two nucleons, such as the $\bar{K}NNN$, $\bar{K}NNNN$, and so forth. The E80 experiment is the first step experiment focusing on the $\bar{K}NNN$. Recently, even with limited statistics, we observed a similar structure on the Λd invariant mass spectrum in the $^4\mathrm{He}(K^-, \Lambda d)n$ reaction data, from a by-product of the E73 experiment test data as described avobe. Because final state particles in the $^4\mathrm{He}(K^-, \Lambda d)n$ reaction are charged particles, and the E73 experimental setup is already operational, we decided to submit a new proposal to focus on the Λd decay from the $\bar{K}NNN$ state using the existing setup. It is the P92 experiment.

This April, we successfully obtained a large research grant, "Grant-In-Aid for Specially Promoted Research by MEXT (FY2022-26)." The main detector components for the E80 experiment will be constructed with the grant, *i.e.*, the new CDS which is composed of the superconducting solenoid magnet, the cylindrical drift-wire chamber (CDC), and the first layer of the cylindrical neutron counter (CNC) *. The schedule for the E80 preparation is shown in Fig. 1. The new CDS construction will be completed in the first half of the FY2025. Therefore, the E80 experiment will be ready to start in late FY2025, which is described in the E80 TDR submitted for this 34th PAC and discussed at the FIFC in June 2022.

The current plan is that we would like to concentrate all our efforts on the early realization of the E80 experiment with the new CDS. However, to maximize the physics outcome from our project, we would like to maintain the possible realization of the P92 proposal in case unforeseen circumstances arise such as significant delays in the new CDS construction due to the COVID-19 pandemic and/or the Ukrainian war.

Determining the J^P of the kaonic nuclei is the next direction. After E80, we aim to measure the J^P of $\bar{K}NN$, which has already been proposed as the P89 experiment [6]. For this purpose, we are making efforts to install the polarimeter composed of the CNC and a tracker system surrounding the CNC.

*The rest of the CNC will be built with budgets from other sources that we are currently trying to acquire.

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<tr><td>SC Solenoid</td><td colspan="2">Design</td><td colspan="2">Purchase (SC Wire)</td><td colspan="7">Construction</td><td colspan="3">Installation & Test</td><td rowspan="3">Integration</td><td rowspan="3">Commissioning</td><td rowspan="3">Physics Run</td><td colspan="3" rowspan="3">Analysis & Pblication</td></tr>
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Figure 1: Schedule of the preparation for the E80 experiment taken from the E80 TDR.

References

[1] Proposal for J-PARC, 2020, ”Systematic investigation of the light kaonic nuclei: via the in-flight ^{4}He(K^-, N) reactions” *http://j-parc.jp/researcher/Hadron/en/pac_2007/pdf/P80_2020-10.pdf* .

[2] Proposal for J-PARC, 2021, ”Proposal for the E80 Phase-I Experiment: Investigation of the $\bar{K}NNN$ Bound State Focusing on the Λd Decay” *http://j-parc.jp/researcher/Hadron/en/pac_2201/pdf/P92_2022-05.pdf* .

[3] M. Iwasaki, ”Nuclear Physics Handbook, Section 9: Kaonic Nuclei from the Experimental Viewpoint”, will be published in Elsevier.

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

[5] T. Sekihara, E. Oset, and A. Ramos *JPS Conf. Proc.* **26** (2019) 023009.

[6] Proposal for J-PARC, 2021, ”Investigation of fundamental properties of the $\bar{K}NN$ state” *http://j-parc.jp/researcher/Hadron/en/pac_2107/pdf/P89_2021-09.pdf* .