Proposal for the J-PARC 30-GeV Proton Synchrotron

Proposal for the E80 Phase-I Experiment:

Investigation of the $\bar{K}NNN$ Bound State Focusing on the Λd Decay

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Abstract

We have recently observed a peak structure below the $K^-+p+p+n$ mass threshold in the Λd invariant-mass spectrum of ${}^4\text{He}(K^-, \Lambda d)n$ using the T77 data. The observed structure would be the signal of the $\bar{K}NNN$ bound state. To urgently confirm the observed structure at higher statistics with the present setup, we propose an experiment focusing on the $K^{-4}\text{He} \to \Lambda dn$ measurement as the E80 Phase-I experiment.

Summary of the E80 Phase-I Experiment

Beam Line:	K1.8BR
Primary Beam:	30 GeV, 90 kW (4.2 seconds repetition cycle)
Secondary Beam:	1.0 GeV/c K^-
Beam Intensity:	1.9×10^5 on target per pulse
Reaction:	in-flight (K^-, N)
Detectors:	present K1.8BR beam-line spectrometer and cylindrical detector system
Target:	liquid H_2 and ^{4}He
Beam Time:	1 day for calibration run with LH_2 target, and 13 days for the physics run with L^4He target
Estimated Yield:	6×10^3 Λdn final state

Contents

1 J-PARC E80 Experiment

The E80 experiment is aiming to establish the $\bar{K}NNN$ bound system as a first step toward the comprehensive study of the light kaonic nuclei [1]. We will perform an exclusive measurement of the $\bar{K}NNN$ state using the following reactions:

^{4}He$(\mathbf{K^-}, \mathbf{n})$ reaction: search for the $\bar{K}NNN$ bound state with charge +1 (symbolically denoted as K^-ppn) through Λd and Λpn decays,

^{4}He$(\mathbf{K^-}, \mathbf{p})$ reaction: search for the $\bar{K}NNN$ bound state with charge 0 (symbolically denoted as K^-pnn) through Λnn decay.

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. The E80 experiment was proposed at the 30th J-PARC PAC meeting (July, 2020) and approved as a stage-1 experiment at the 31th PAC (January, 2021).

Starting with E80, 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:

- [**$\bar{\mathbf{K}}\mathbf{N}(\mathbf{\Lambda(1405)})$**] 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,
- [**$\bar{\mathbf{K}}\mathbf{NN}$**] Investigations of the spin and parity of the $\bar{K}NN$ states via ^{3}He(K^-, N) reactions (proposed as P89 [2]),
- [**$\bar{\mathbf{K}}\mathbf{NNN}$**] A search for $\bar{K}NNN$ states via ^{4}He(K^-, N) reactions, as a bridge to access heavier systems (E80 [1] and this revised proposal),
- [**$\bar{\mathbf{K}}\mathbf{NNNN}$**] An advanced search for $\bar{K}NNNN$ states via the ^{6}Li(K^-, d) reaction, and
- [**$\bar{\mathbf{K}}\bar{\mathbf{K}}\mathbf{NN}$**] Future plan of searching for $\bar{K}\bar{K}NN$ states via $\bar{p}^3$He annihilation to access the $S = -2$ kaonic nuclei (Letter of Intent [3]).

2 Analysis of $\mathbf{K^-{}^4He \to \Lambda dn}$ Reaction at T77

We have conducted a prompt analysis on Λdn final state of $K^-{}^4$He reaction at 1 GeV/c, and found a kinematical anomaly below the mass threshold of $M(K^-ppn)$ having quite similar structure to that of Λpn final state of $K^-{}^3$He reaction. For the analysis, we utilized ^{4}He data of the T77 experiment for hypernuclear lifetime measurement of

${}^{4}_{\Lambda}$H [4]. The T77 experiment used the present cylindrical detector system (CDS). The T77 data was accumulated for 66 hours under 51 kW MR beam power corresponding to 140 kW*days.

At the experiment, incident K^- and scattered charged particles were measured with the K1.8BR beam-line spectrometer and the CDS, respectively [5]. The K^- beam was identified by time-of-flight measurement with the beam-line spectrometer, and then the beam momentum was determined with the final beam-line dipole spectrometer magnet. Particle identification and momentum determination of scattered charged particles were performed by the CDS operating in a uniform ~ 0.7 T magnetic field provided by a solenoid magnet.

We selected the event in which Λd are detected in CDS and missing neutron is identified by the missing mass method to identify the Λdn final state in the K^{-4}He reaction. The event consistency was examined by distance of closest approach (DCA) between the $\pi^- p$ pair for Λ decay, the kaon beam and the reconstructed Λ track, the kaon beam and the deuteron, and the Λ and the deuteron.

For the Λdn-selected events, we evaluated the invariant mass of the Λd system (IM(Λd)) and the momentum transfer to the Λd ($q_{\Lambda d}$), a synthesis momentum of Λ and d. Figure 1(left) shows the 2D event distribution on the IM(Λd) and $q_{\Lambda d}$ plane. A strong event concentration can be seen below the $K^- + p + p + n$ mass threshold $M(K^-ppn)$ at lower $q_{\Lambda d}$, which is quite similar to that of the Λpn final state in the K^{-3}He reaction shown as Fig. 1(right) [6, 7]. The Λd invariant-mass spectrum, *i.e.*, the x-axis projection of Fig. 1, is also shown in Fig. 2(left) in which a peak structure below $M(K^-ppn)$ can be seen clearly. As in the case of the $\bar{K}NN$ bound state in the Λpn final state shown as Fig. 2(right), the observed structure in the Λdn final state would be the signal of the K^-ppn bound state.

3 Staging Strategy of E80

It is urgent to confirm the observed structure focusing on the Λd decay mode at higher statistics with the present setup. At the proposal stage of E80, we assumed the cross section of the $K^-ppn \to \Lambda d$ decay branch by analogy with that of the $\bar{K}NN \to \Lambda p$ measured in E15. With the T77 data analysis, now we have demonstrated the high feasibility of the $K^-ppn \to \Lambda d$ observation at E80. Thus, we revise our E80 proposal to conduct that in a following staging plan.

Phase-I experiment:

By focusing on the $K^-ppn \to \Lambda d$ decay channel with the present setup, we will confirm the existence of the K^-ppn bound state. The binding energy, decay width, and reaction form-factor parameter will be deduced at the same data quality as it is measured in E15 for the $\bar{K}NN$ bound state.

Phase-II experiment:

We need to wait for a new 4π detector system to conduct more comprehensive

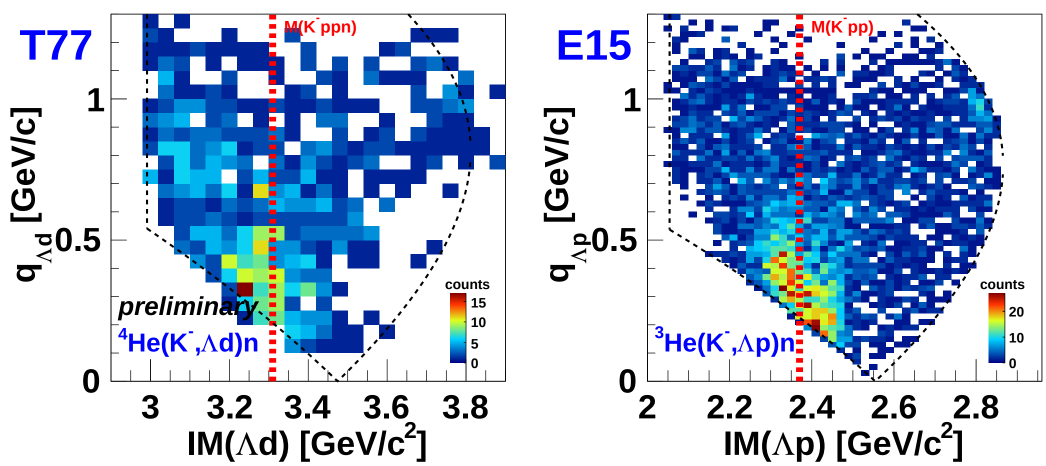

Figure 1: (left) 2D plot on the IM(Λd) and $q_{\Lambda d}$ plane for the Λdn final state obtained from ^{4}He$(K^-, \Lambda d)n$ at T77. The vertical red dotted line shows $M(K^-ppn)$, and the black dotted line is the kinematical limit of the reaction. (right) 2D plot on the IM(Λp) and $q_{\Lambda p}$ plane for the Λpn final state obtained from ^{3}He$(K^-, \Lambda p)n$ at E15 [6, 7]. Lines are similar to the left figure but for Λpn.

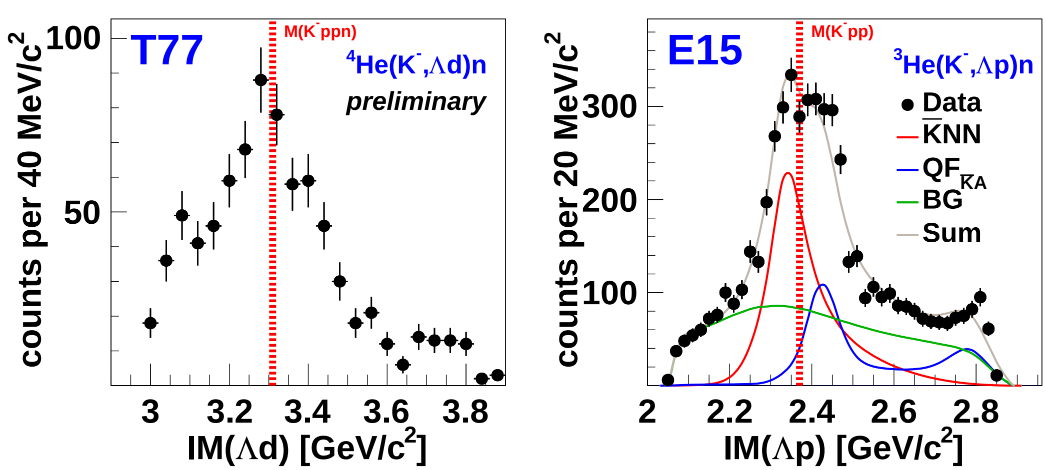

Figure 2: (left) Invariant-mass spectrum of Λd (x-axis projection of the Fig. 1(left)). (right) Invariant-mass spectrum of Λp (x-axis projection of the Fig. 1(right)) together with the decompositions of the fit result by considering the three physics processes: the $\bar{K}NN$ bound state, the non-mesonic quasi-free kaon absorption process ($QF_{\bar{K}A}$), and a broad distribution covering the whole kinematically allowed region of the Λpn final state (BG) [6, 7].

study on multi-particle decay mode such as $K^-ppn \to \Lambda pn$ and $K^-pnn \to \Lambda nn$, what we described in the original E80 proposal. Based on results of the Phase-I experiment, we will submit the TDR in which detailed design of the new 4π detector system and revised beam-time plan will be presented.

4 Beam-Time Request for the Phase-I Experiment

To establish the K^-ppn state, we need $\sim$ 6,000 events of the $K^{-4}\text{He} \to \Lambda dn$ reaction, which is the same statistical quality as it is measured in E15 for the $K^{-3}\text{He} \to \Lambda pn$ reaction. We have observed $\sim$ 800 events of Λdn final state with 140 kW*days beam time at T77, so that we need $\sim$ 1,050 kW*days beam time for the E80 Phase-I experiment. When we assume 90 kW primary beam power and 90 % up-time ratio of accelerator, it corresponds to the beam time of 13 days.

We would like to perform the E80 Phase-I experiment after the MR long shutdown conducted in 2021-22. Apparatus for the Phase-I has already been ready and well commissioned so far. We will also perform H_2 run for a day with liquid H_2 target to confirm the spectrometer performance under the high-intensity operation.

References

[1] Proposal for J-PARC, 2020, "Systematic investigation of the light kaonic nuclei: via the in-flight $^4\text{He}(K^-, N)$ reactions" *http://j-parc.jp/researcher/Hadron/en/Proposal_e.html* .

[2] Proposal for J-PARC, 2021, "Investigation of fundamental properties of the $\bar{K}NN$ state" *http://j-parc.jp/researcher/Hadron/en/Proposal_e.html* .

[3] Letter of Intent for J-PARC, 2009, "Double Anti-kaon Production in Nuclei by Stopped Anti-proton Annihilation" *http://j-parc.jp/researcher/Hadron/en/Proposal_e.html* .

[4] Test Beam Proposal for J-PARC, 2020, "Feasibility study for $^3_\Lambda\text{H}$ mesonic weak decay lifetime measurement with $^4\text{He}(K, \pi^0)^4_\Lambda\text{H}$ reaction" *http://j-parc.jp/researcher/Hadron/en/Proposal_e.html* .

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

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

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