Further Theoretical Analysis on the $K^{-3}{\text{He}} \rightarrow \Lambda pn$ Reaction for the $\bar{K}NN$ Bound-State Search in the J-PARC E15 Experiment

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Based on the scenario that a $\bar{K}NN$ bound state is generated and it eventually decays into $\Lambda p$, we calculate the cross section of the $K^{-3}{\text{He}} \rightarrow \Lambda pn$ reaction, which was recently measured in the J-PARC E15 experiment. We find that the behavior of the calculated differential cross section $d^2\sigma/dM_{\Lambda p}dq_{\Lambda p}$, where $M_{\Lambda p}$ and $q_{\Lambda p}$ are the $\Lambda p$ invariant mass and momentum transfer in the ($K^-$, $n$) reaction in the laboratory frame, respectively, is consistent with the experiment. Furthermore, we can reproduce almost quantitatively the experimental data of the $\Lambda p$ invariant mass spectrum in the momentum transfer window $350 \text{ MeV}/c < q_{\Lambda p} < 650 \text{ MeV}/c$. These facts strongly suggest that the $\bar{K}NN$ bound state was indeed generated in the J-PARC E15 experiment.

KEYWORDS: $\bar{K}NN$ bound state, reaction calculation for the J-PARC E15 experiment

1. Introduction

Because the chiral $\bar{K}N$ interaction is strongly attractive and dynamically generates the $\Lambda(1405)$ [1–6], it is natural to extend the idea from the $\bar{K}N$ bound state [$\Lambda(1405)$] to the $\bar{K}NN$ bound state. The $\bar{K}NN$ bound state is a good ground to apply techniques of few-body calculations and to investigate further properties of the $\bar{K}N$ interaction. Until now a lot of effort has been put into theoretical predictions and experimental searches for the $\bar{K}NN$ bound state (see Ref. [7] for the status up to 2015).

Recently, in the J-PARC E15 experiment the cross section of the $K^{-3}{\text{He}} \rightarrow \Lambda pn$ reaction was measured and a peak structure was found in the $\Lambda p$ invariant mass spectrum around the $K^-pp$ threshold [8, 9]. One of the biggest advantages of this reaction is to put $\bar{K}$ directly into the nucleus to generate the $\bar{K}NN$ bound state. Thanks to that, we can theoretically trace the behavior of the $\bar{K}$ in the $K^{-3}{\text{He}} \rightarrow \Lambda pn$ reaction [10]. As a result, the first run data of the J-PARC E15 experiment [8] were well reproduced in the scenario that the $\bar{K}NN$ bound state is generated.

In this manuscript we perform further theoretical analysis on the $K^{-3}{\text{He}} \rightarrow \Lambda pn$ reaction measured in the J-PARC E15 experiment, in particular focusing on its second run data [9].

2. Formulation

We calculate the cross section of the $K^{-3}{\text{He}} \rightarrow \Lambda pn$ reaction in the same manner as in our previous paper [10] except for one thing: the treatment of the $\bar{K}N \rightarrow \bar{K}N$ scattering amplitude at the
first collision denoted by $T_1$. In Ref. [10] we fixed $T_1$ as a real number by using the experimental values of the $\bar{K}N \to \bar{K}N$ differential cross sections only at an initial kaon momentum 1.0 GeV/c in the laboratory frame. Namely, we neglected the Fermi motion of the nucleons and fixed the invariant mass of the first-collision $\bar{K}N, w_1$, to a unique value. In contrast, now we take into account the Fermi motion of the nucleons to evaluate $w_1$ and treat $T_1$ in a $2\times2$ matrix form in terms of the partial waves:

$$T_1(w_1, p_{\text{out}}, p_{\text{in}}) = g(w_1, p_{\text{out}}, p_{\text{in}}, x) - i h(w_1, p_{\text{out}}, p_{\text{in}}, x) \frac{(p_{\text{out}} \times p_{\text{in}}) \cdot \sigma}{p_{\text{out}} p_{\text{in}}},$$

(1)

where $p_{\text{out}}$ and $p_{\text{in}}$ are outgoing and incoming momenta of $\bar{K}$ in the $\bar{K}N$ rest frame, $p_{\text{out,in}} \equiv |p_{\text{out,in}}|$, $x \equiv p_{\text{out}} p_{\text{in}}/(p_{\text{out}} p_{\text{in}})$, $\sigma$ are the Pauli matrices acting on the baryon spinors, and $g$ and $h$ are expressed in terms of the partial-wave amplitudes $T_{L\pm}$ as

$$g(w, p_{\text{out}}, p_{\text{in}}, x) = \sum_{L=0}^{\infty} [(L + 1)T_{L+}(w, p_{\text{out}}, p_{\text{in}}) + L T_{L-}(w, p_{\text{out}}, p_{\text{in}})] P_L(x),$$

(2)

$$h(w, p_{\text{out}}, p_{\text{in}}, x) = \sum_{L=1}^{\infty} [T_{L+}(w, p_{\text{out}}, p_{\text{in}}) - T_{L-}(w, p_{\text{out}}, p_{\text{in}})] P'_L(x),$$

(3)

with the Legendre polynomials $P_L(x), P'_L(x) \equiv dP_L/dx$, and orbital angular momentum $L$.

Because the $\bar{K}N \to \bar{K}N$ scattering at the first collision takes place with bound nucleons, it is better to treat the partial-wave amplitudes $T_{L\pm}$ as functions of three independent variables $w_1, p_{\text{out}},$ and $p_{\text{in}},$ i.e., as off-shell amplitudes. We here assume that the partial-wave amplitudes depend on the momenta minimally required by the kinematics, i.e., they are proportional to $(p_{\text{out}} p_{\text{in}})^L$. Under this assumption, the partial-wave amplitudes can be easily evaluated from the on-shell ones in the formula

$$T_{L\pm}(w, p_{\text{out}}, p_{\text{in}}) = T_{L\pm}^{\text{on-shell}}(w) \left(\frac{p_{\text{out}} p_{\text{in}}}{(p_{\text{out}} p_{\text{in}})^L}\right),$$

(4)

where $p_{\text{on-shell}}(w)$ is the on-shell momentum for the $\bar{K}N$ system with the center-of-mass energy $w$. In the present study, we utilize the on-shell $\bar{K}N$ amplitudes $T_{L\pm}^{\text{on-shell}}(w)$ of Ref. [11], where the authors calculated $\bar{K}N$ amplitudes up to the $F$ wave ($L = 4$) based on a dynamical coupled-channels model with phenomenological SU(3) Lagrangians, to evaluate the amplitudes $T_{L\pm}(w, p_{\text{out}}, p_{\text{in}})$.

3. Numerical results

We now calculate the differential cross section $d^2\sigma/dM_{\Lambda p} d\cos \theta_n^{\text{cm}}$ of the $K^-\text{He} \to \Lambda pn$ reaction, where $M_{\Lambda p}$ is the $\Lambda p$ invariant mass and $\theta_n^{\text{cm}}$ is the neutron scattering angle in the global center-of-mass frame, in the scenario that a $\bar{K}NN$ bound state is formed, decaying eventually into a $\Lambda p$ pair. The formulation is the same as in the previous calculation [10] except for the $\bar{K}N \to \bar{K}N$ amplitude at the first collision, which now takes the Fermi motion into account. We then multiply $d^2\sigma/dM_{\Lambda p} d\cos \theta_n^{\text{cm}}$ by $|\partial \cos \theta_n^{\text{cm}}/\partial q_{\Lambda p}|$, where $q_{\Lambda p}$ is the momentum transfer in the ($K^-$, $n$) reaction in the laboratory frame, to obtain the differential cross section $d^2\sigma/dM_{\Lambda p} dq_{\Lambda p}$. Note that, for a fixed $M_{\Lambda p}$, the momentum transfer reaches its minimum at $\cos \theta_n^{\text{cm}} = 1$ and increases as $\cos \theta_n^{\text{cm}}$ decreases.

In Fig. 1 we show the numerical result of the differential cross section $d^2\sigma/dM_{\Lambda p} dq_{\Lambda p}$ in the $\bar{K}NN$ bound-state scenario. Here we take two options A and B for the evaluation of the energy carried by the $K$ (for the details see Ref. [10]). From Fig. 1, in both options A and B, we can see that the structure near the $K^-pp$ threshold (2.37 GeV) is generated dominantly in the lower $q_{\Lambda p}$ region, which corresponds to the condition of forward neutron scattering. In addition, we observe two trends in $d^2\sigma/dM_{\Lambda p} dq_{\Lambda p}$; one goes from $M_{\Lambda p} = 2.35$ GeV at $q_{\Lambda p} = 0.25$ GeV to the upward direction, and the other goes from the $K^-pp$ threshold at $q_{\Lambda p} = 0.2$ GeV to the upper-right direction. As discussed
in Ref. [10], the former is the signal of the \( \bar{K}NN \) bound state, and the latter is the contribution from the quasi-elastic scattering of the \( \bar{K} \) at the first collision. Interestingly, the behavior of the two trends in \( d^2\sigma/dM_{\Lambda p}dq_{\Lambda p} \) was indeed observed in the second run data of the J-PARC E15 experiment [9], and hence our result is consistent with the experimental result.

Next we integrate the differential cross section \( d^2\sigma/dM_{\Lambda p}dq_{\Lambda p} \) to obtain the invariant mass spectrum \( d\sigma/dM_{\Lambda p} \), which is shown in Fig. 2. When we take into account the whole region of the momentum transfer, we obtain lines “Full” in Fig. 2. In this case, we observe a two-peak structure around the \( K^-pp \) threshold as we found in Ref. [10]; the peak below (above) the \( K^-pp \) threshold originates from the \( \bar{K}NN \) bound state (quasi-elastic scattering of the \( \bar{K} \) at the first collision). Then, we restrict the momentum transfer to the region \( 350 \text{ MeV} < q_{\Lambda p} < 650 \text{ MeV} \), as done in the experimental analysis [9], where they aimed at reducing the kinematic peak above the \( K^-pp \) threshold corresponding to the quasi-elastic \( \bar{K} \) scattering. Our mass spectrum with the momentum-transfer cut is plotted as lines “Cut” in Fig. 2. With this cut, only the peak for the signal of the \( \bar{K}NN \) bound state survives. In this sense, our result supports the validity of the experimental cut of the momentum transfer.

Finally, we compare the calculated invariant mass spectrum \( d\sigma/dM_{\Lambda p} \) in the momentum transfer window \( 350 \text{ MeV} < q_{\Lambda p} < 650 \text{ MeV} \) with the experimental one in the same window. The result is shown in Fig. 3. As for the experimental data, we subtract the background contribution in the analysis of the experiment [9], because we do not take into account background but rather the generation of the \( \bar{K}NN \) bound state. From Fig. 3, in both options A and B, we can see that our calculation reproduces almost quantitatively the experimental data of the \( \Lambda p \) invariant mass spectrum with the momentum transfer cut throughout a wide range of the \( \Lambda p \) invariant mass. The consistent behavior of the mass

**Fig. 1.** Differential cross section for the \( K^{-3}\text{He} \rightarrow \Lambda pn \) reaction in option A (left) and B (right).

**Fig. 2.** Invariant mass spectrum \( d\sigma/dM_{\Lambda p} \) for the \( K^{-3}\text{He} \rightarrow \Lambda pn \) reaction in options A and B. In the “Cut” case we restrict the momentum transfer to the region \( 350 \text{ MeV}/c < q_{\Lambda p} < 650 \text{ MeV}/c \).
spectrum strongly suggests that the $\bar{K}NN$ bound state was indeed generated in the J-PARC E15 experiment.

4. Summary

In this manuscript we have investigated the origin of the peak structure of the $\Lambda p$ invariant mass spectrum near the $K^-pp$ threshold in the $K^-{^3}He \rightarrow \Lambda pn$ reaction, which was recently observed in the J-PARC E15 experiment. For this purpose, we have calculated the cross section of the $K^-{^3}He \rightarrow \Lambda pn$ reaction and $\Lambda p$ invariant mass spectrum based on the scenario that a $\bar{K}NN$ bound state is generated and it eventually decays into $\Lambda p$. As a result, we have found that the behavior of the calculated differential cross section $d^2\sigma/dM_{\Lambda p}dq_{\Lambda p}$ is entirely consistent with the experimental data. In particular, the peak for the quasi-elastic scattering of the $\bar{K}$ at the first collision in the $\Lambda p$ invariant mass spectrum, which exists above the $K^-pp$ threshold, is highly suppressed when we restrict the momentum transfer to the region $350 \text{ MeV}/c < q_{\Lambda p} < 650 \text{ MeV}/c$, as done in the experimental analysis [9]; with this cut only the peak for the $\bar{K}NN$ bound state below the $K^-pp$ threshold survives. Furthermore, throughout a wide range of the $\Lambda p$ invariant mass, our calculation reproduces almost quantitatively the experimental mass spectrum with the momentum transfer cut. These findings strongly suggest that the $\bar{K}NN$ bound state was indeed generated in the J-PARC E15 experiment.

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