# WHAT MAKES THE PEAK STRUCTURE OF THE $\Lambda p$ INVARIANT-MASS SPECTRUM IN THE $K^{-3}$He $\to \Lambda pn$ REACTION?*

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Recently, a peak structure was observed near the $K^-pp$ threshold in the in-flight $^3$He$(K^-, \Lambda p)n$ reaction of the E15 experiment at J-PARC, which could be a signal of a $\bar{K}NN$ bound state. In order to investigate what is the origin of this peak, we calculate the cross section of this reaction, in particular based on the scenario that the $\bar{K}NN$ bound state is indeed generated and decays into $\Lambda p$. We find that the numerical result of the $\Lambda p$ invariant-mass spectrum in the $\bar{K}NN$ bound scenario is consistent with the J-PARC E15 data.

## 1. Introduction

We expect that there should exist kaonic nuclei, *i.e.*, bound states of antikaon ($\bar{K}$) and usual atomic nuclei, thanks to the strongly attractive interaction between $\bar{K}$ and nucleon ($N$) [1, 2]. In particular, the simplest

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kaonic nucleus $\bar{K}NN(I = 1/2)$, sometimes called $K^-pp$, has intensively attracted attention of both theoretical and experimental sides [3], but for the moment, there has been no consensus on the properties of the $\bar{K}NN$ bound state.

In this line, the result from the recent J-PARC E15 experiment [4] is very promising. They observed a peak structure near the $K^-pp$ threshold in the $\Lambda p$ invariant-mass spectrum of the in-flight ${}^3\mathrm{He}(K^-, \Lambda p)n$ reaction at the kaon momentum $k_{\mathrm{lab}} = 1$ GeV/$c$. By fitting this peak with the Breit–Wigner formula, they reported its mass $M_X = 2355^{+6}_{-8}(\mathrm{stat.}) \pm 12(\mathrm{sys.})$ MeV and width $\Gamma_X = 110^{+19}_{-17}(\mathrm{stat.}) \pm 27(\mathrm{sys.})$ MeV [4]. This could be a signal of a $\bar{K}NN$ bound state with a binding $\sim 15$ MeV from the $K^-pp$ threshold.

The task in our study is to investigate what is the origin of the peak in the J-PARC E15 experiment. In particular, we theoretically check whether or not the signal of the $\bar{K}NN$ bound state is strong enough to make a peak structure around the $K^-pp$ threshold in the reaction based on the scenario that the $\bar{K}NN$ bound state is indeed generated and decays into $\Lambda p$. In the following, we calculate the cross section of the $K^-\,{}^3\mathrm{He} \to \Lambda pn$ reaction at the kaon momentum $k_{\mathrm{lab}} = 1$ GeV/$c$. The details of the calculations are given in Ref. [5].

## 2. The cross section of the $K^-\,{}^3\mathrm{He} \to \Lambda pn$ reaction

Let us first pin down the reaction mechanism for $K^-\,{}^3\mathrm{He} \to \Lambda pn$. Because we are interested in the three-nucleon absorption of a $K^-$ with a final-state energetic neutron going to its forward direction, as in the J-PARC E15 experiment [4], we consider the diagram shown in Fig. 1. In the first step of the scattering, the initial-state $K^-$ kicks out an energetic neutron in its forward direction and a slow $\bar{K}$ plus two nucleons remain. The scattering amplitude for this first step, $K^-p \to \bar{K}^0n$ or $K^-n \to K^-n$, is fixed so as to reproduce its experimental cross section, as in Fig. 2. It is important that the cross sections of these processes have their local or global minima when the final-state neutron goes forward, i.e., $\cos\theta = -1$ in Fig. 2. Thanks to this fact, the $K^-\,{}^3\mathrm{He} \to \Lambda pn$ reaction favors the forward neutron emission compared to the middle-angle emission.

Next, the slow $\bar{K}$ after the first step propagates and is absorbed by two nucleons. This $\bar{K}$ propagator, which is expressed as $1/[(p^{\mu}_{\mathrm{prop}})^2 - m^2_K]$ with the propagating $\bar{K}$ momentum $p^{\mu}_{\mathrm{prop}}$, can make a kinematic peak structure in the cross section, as the propagating $\bar{K}$ can go almost on its mass shell, $(p^{\mu}_{\mathrm{prop}})^2 \approx m^2_K$. In terms of the $\Lambda p$ invariant mass $M_{\Lambda p}$, this peak appears around

$$M_{\Lambda p} \approx \sqrt{\left(p^0_{\mathrm{prop}} + 2m_N\right)^2 - \boldsymbol{p}^2_{\mathrm{prop}}}, \qquad (1)$$
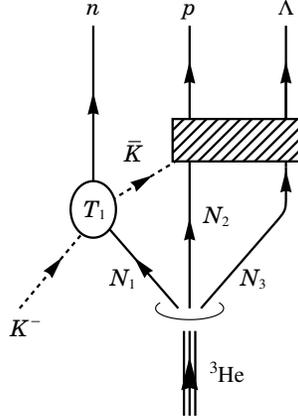
Fig. 1. Feynman diagram most relevant to the three-nucleon absorption of a $K^-$ in the $\bar{K}NN$ bound scenario [5]. We take into account the antisymmetrization for the three nucleons in $^3$He.
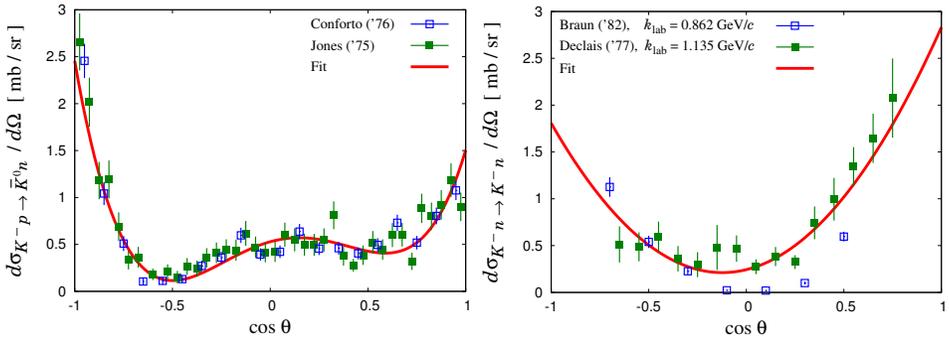


Fig. 2. Differential cross sections of the $K^- p \to \bar{K}^0 n$ (left) and $K^- n \to K^- n$ (right) reactions [5], where $\theta$ is the angle of the emerging kaon *versus* the original one. The experimental data are taken from Refs. [6, 7] at $k_{\mathrm{lab}} = 1$ GeV/$c$ for a proton target, and from Ref. [8] at $k_{\mathrm{lab}} = 1.138$ GeV/$c$ and from [9] at $k_{\mathrm{lab}} = 0.862$ GeV/$c$ for a neutron target.

where we derived this expression by neglecting the Fermi motion of two nucleons. The $\Lambda p$ invariant mass (1) depends on the scattering angle of the final-state neutron in the global center-of-mass frame of the $K^{-3}\mathrm{He} \to \Lambda p n$ reaction, $\theta_n^{\mathrm{cm}}$. At the forward neutron emission, $\theta_n^{\mathrm{cm}} = 0°$, $M_{\Lambda p}$ in Eq. (1) takes its minimum $\approx 2.40$ GeV, and it grows as $\theta_n^{\mathrm{cm}}$ becomes larger. We say that this kinematic peak structure is due to the quasi-elastic $\bar{K}$ scattering in the first step, as the propagating $\bar{K}$ can go almost on its mass shell after the first step.

Then, let us turn to the absorption process of the slow $\bar{K}$ into two nucleons, the shaded area in Fig. 1. In general, we may consider the multiple scattering of $\bar{K}$ between two nucleons before the $\bar{K}$ absorption, as shown in Fig. 3.
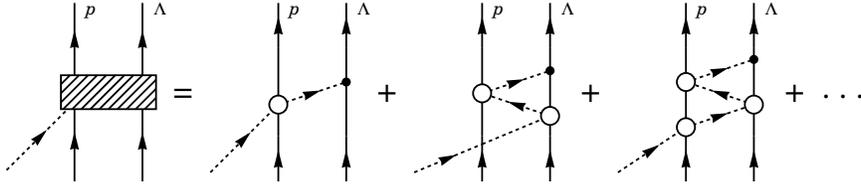


Fig. 3. Multiple kaon scattering between two nucleons [5]. Here, dashed lines and open circles represent the kaon and the $\bar{K}N \to \bar{K}N$ amplitude in the chiral unitary approach, respectively.

We note that, even if we take into account only the first term on the right-hand side of Fig. 3, there is a possibility of making a peak around the $K^- pp$ threshold in the $\Lambda p$ invariant-mass spectrum. This is because the $\Lambda(1405)$ resonance, which is generated at the open circle in Fig. 3 by the $\bar{K}N$ scattering, exists below the $\bar{K}N$ threshold and hence the invariant mass of the $\Lambda(1405)p$ system can be lower than the $K^- pp$ threshold. We call this the uncorrelated $\Lambda(1405)p$ scenario. As a result, in this scenario, we obtained the $\Lambda p$ invariant-mass spectrum with a peak at 2370 MeV [5]. Although this peak position is compatible with the experimental one at $2355^{+6}_{-8}$(stat.) $\pm$ 12(sys.) MeV within experimental errors, the mass distribution in the lower energy side clearly falls short of the data. This indicates the need to improve this scenario by considering new additional mechanisms that could bring a better agreement with data.

Now, we take into account all the contributions of the summation in Fig. 3. Because a $\bar{K}NN$ bound state can be generated in the full calculation of the multiple scattering in Fig. 3, we call this the $\bar{K}NN$ bound scenario. In the present approach, we employ the fixed center approximation to the Faddeev equation and obtained a resonance pole at $2354 - 36i$ MeV in the $\bar{K}NN$ scattering amplitude, which corresponds to the $\bar{K}NN$ bound state. The resulting $\Lambda p$ invariant-mass spectrum $\mathrm{d}\sigma/\mathrm{d}M_{\Lambda p}$ in the $\bar{K}NN$ bound scenario is plotted in Fig. 4 together with the experimental (E15) data and its fit in arbitrary units [4]. An important finding is that our mass spectrum is consistent with the experimental one within the present error, including the tail at the lower energy $\sim 2.3$ GeV. We also note that the total cross section in our calculation 7.6 $\mu$b is consistent with the empirical value $7 \pm 1$ $\mu$b [4].

In addition, we observe a two-peak structure below and above the $K^- pp$ threshold in the $\Lambda p$ invariant mass spectrum. We have checked that the lower peak at $\sim 2.35$ GeV is the signal of the $\bar{K}NN$ bound state, while
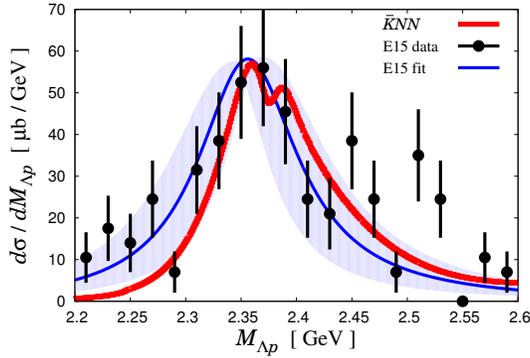
Fig. 4. Mass spectrum for the $\Lambda p$ invariant mass of the in-flight $^3\text{He}(K^-, \Lambda p)n$ reaction in the $\bar{K}NN$ bound scenario [5]. The experimental (E15) data and its fit are taken from Ref. [4] and shown in arbitrary units.

the higher peak at $\sim 2.40$ GeV comes from the quasi-elastic kaon scattering in the first step discussed around Eq. (1). One can see these origins by plotting the differential cross section $\mathrm{d}^2\sigma/\mathrm{d}M_{\Lambda p}\mathrm{d}\cos\theta_n^{\text{cm}}$ as shown in Fig. 5. In this figure, the signal of the $\bar{K}NN$ bound state stays at $\sim 2.35$ GeV independently of the neutron scattering angle $\theta_n^{\text{cm}}$. On the other hand, the higher peak in Fig. 4 originates from the band which goes from $\sim 2.4$ GeV at $\cos\theta_n^{\text{cm}} = 1$ to the lower-right direction in Fig. 5, according to Eq. (1) as the contribution from the quasi-elastic scattering of the kaon.
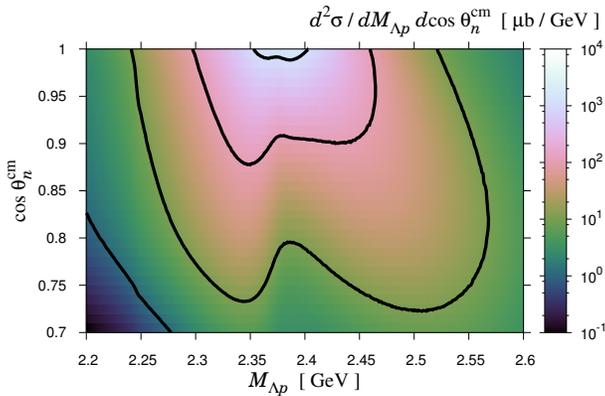


Fig. 5. Differential cross section of the in-flight $^3\text{He}(K^-, \Lambda p)n$ reaction in the $\bar{K}NN$ bound scenario [5]. Contours represent $10^3$, $10^2$, $10^1$, and $10^0$ $\mu$b/GeV, respectively.

According to all the discussions above, we can say that our results support the explanation that the E15 signal in the $^3\text{He}(K^-, \Lambda p)n$ reaction is likely a signal of the $\bar{K}NN$ bound state.

## 3. Summary and outlook

In this study, we have investigated the origin of the peak structure observed near the $K^-pp$ threshold in the $^3\text{He}(K^-, \Lambda p)n$ reaction of the J-PARC E15 experiment. The consideration of the bound $\bar{K}NN$ state brings our results of the $\Lambda p$ invariant mass spectrum, that contain uncertainties much smaller than the experimental ones, in consistency with the experimental band that accounts for the experimental errors, while our results with the uncorrelated $\Lambda(1405)p$ scenario are clearly inconsistent with this band.

Finally, we emphasize that the high statistics data are coming from the second run of the J-PARC E15 experiment [10], in which they accumulated about 30 times more data than that in the first run [4]. With these high statistics data, we will able to study more things, such as the angular dependence of the signal and the $\Lambda p/\Sigma^0 p$ branching ratio so as to conclude more clearly the existence of the $\bar{K}NN$ bound state.

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