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Theoretical analysis on the K^{-3}He $\to \Lambda pn$ reaction for the $\bar{K}NN$ bound-state search in the J-PARC E15 experiment

Takayasu Sekihara*
Advanced Science Research Center, Japan Atomic Energy Agency, Shirakata, Tokai, Ibaraki, 319-1195, Japan
E-mail: sekihara@post.j-parc.jp

Eulogio Oset
Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Aptdo. 22085, 46071 Valencia, Spain
E-mail: oset@ific.uv.es

Angels Ramos
Departament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos, Universitat de Barcelona, Martí i Franquès 1, 08028 Barcelona, Spain
E-mail: ramos@fqa.ub.edu

We theoretically analyze the K^{-3}He $\to \Lambda pn$ reaction for the $\bar{K}NN$ bound-state search in the J-PARC E15 experiment. We find that, by detecting a fast and forward neutron in the final state, an almost on-shell $\bar{K}$ is guaranteed, which is essential to make a bound state with two nucleons from ^{3}He. Then, this almost on-shell $\bar{K}$ can bring a signal of the $\bar{K}NN$ bound state in the Λp invariant-mass spectrum, although it inevitably brings a kinematic peak above the $\bar{K}NN$ threshold as well. As a consequence, we predict two peaks across the $\bar{K}NN$ threshold in the spectrum: the lower peak coming from the $\bar{K}NN$ bound state, and the higher one originating from the kinematics.

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1. Introduction

Among various combinations of hadrons, the antikaon ($\bar{K}$) and nucleon (N) form one of the most interesting pairs. The $\bar{K}$ meson is a Nambu-Goldstone boson of the spontaneous chiral symmetry breaking of quantum chromodynamics (QCD), which constrains the $\bar{K}N$ interaction to be strongly attractive in a model independent manner. This chiral $\bar{K}N$ interaction together with its coupled channels dynamically generates the $\Lambda(1405)$ resonance [1, 2, 3, 4, 5, 6]. Recently it was shown that the $\Lambda(1405)$ resonance in chiral dynamics was indeed a $\bar{K}N$ bound state [7, 8] in terms of the compositeness [9, 10, 11].

Because the $\bar{K}N$ interaction is attractive enough to make a bound state as the $\Lambda(1405)$ resonance, we expect that there should exist bound states of $\bar{K}$ and nuclei, which are called kaonic nuclei. Motivations to study kaonic nuclei are: they are exotic states of many-body systems interacting strongly, and provide us with a test field of the $\bar{K}N$ interaction and behavior of a strange quark in finite nuclear density. For kaonic nuclei, in particular for the simplest kaonic nucleus, *i.e.*, the $\bar{K}NN$ bound state or the "K^-pp" state, many experimental searches and theoretical predictions have been performed, but even their existence is still controversial (see review in Ref. [12]).

In this line, the result from the J-PARC E15 experiment [13, 14] is very promising. In the J-PARC E15 experiment, they observed the K^{-3}He $\to \Lambda pn$ reaction with the initial kaon of momentum 1 GeV$/c$, a fast and forward neutron in the final state, and no spectator nucleon. As a result of the E15 first run, they found a peak structure near the K^-pp threshold as the black points and blue bands in Fig. 1, which could be a signal of a $\bar{K}NN$ bound state. In order to understand the reaction mechanism and to investigate how this peak is constructed, we perform a theoretical analysis on this reaction. Details of the calculations are provided in Refs. [15, 16, 17].

2. Theoretical analysis on the K^{-3}He $\to \Lambda pn$ reaction

In the J-PARC E15 experiment, they bombarded a ^{3}He target with K^-s of momentum 1 GeV$/c$

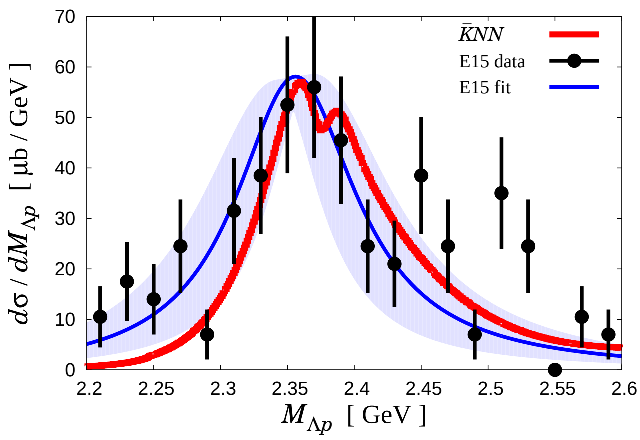
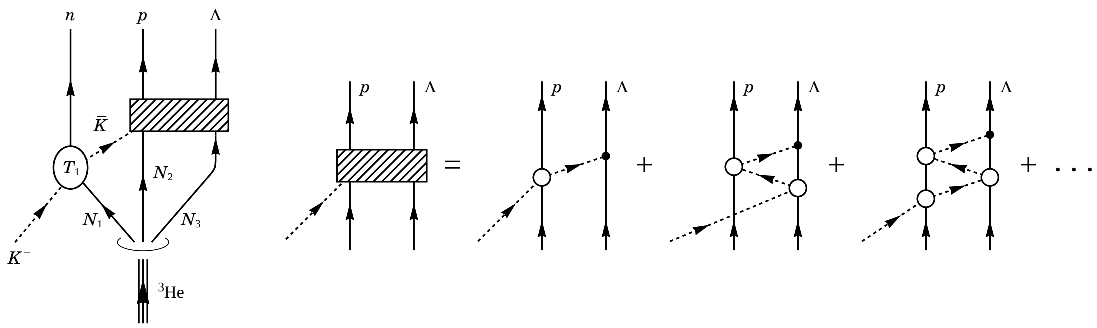


Figure 1: Λp invariant-mass spectrum of the K^{-3}He $\to \Lambda pn$ reaction [17]. Our theoretical result, shown as the thick red line, is obtained in the scenario that the $\bar{K}NN$ bound state is generated [15]. The experimental (E15) data and its fit are taken from Ref. [14] and shown in arbitrary units.



(a) (b)

Figure 2: (a) Feynman diagram most relevant to the three-nucleon absorption of an in-flight K^-, and (b) multiple $\bar{K}$ scattering and absorption [15]. In (b), the dashed lines and circles represent $\bar{K}$ and $\bar{K}N \to \bar{K}N$ amplitude, respectively.

and observed the K^{-3}He $\to \Lambda pn$ reaction with forward neutron in the final state and no spectator nucleon. This reaction can be expressed as the diagram in Fig. 2.

In the first step of the reaction, the K^- kicks out a fast and forward final-state neutron and loses its energy. The amplitude of this first collision is calculated so as to reproduce the experimental values of the cross sections of $K^- n \to K^- n$ and $K^- p \to \bar{K}^0 n$. Because both the $K^- n \to K^- n$ and $K^- p \to \bar{K}^0 n$ cross sections have their local or global minima when the final-state neutron goes forward, the K^{-3}He $\to \Lambda pn$ reaction favors the forward neutron emission compared to the middle-angle emission.

Then, the slow $\bar{K}$ after the first collision propagates and is absorbed into two nucleons from ^{3}He. An important point is that this slow $\bar{K}$ can create a kinematic peak because the propagating $\bar{K}$ can go almost on its mass shell, which largely enhances the $\bar{K}$ propagator. In order to see this effect, we calculate the differential cross section of the K^{-3}He $\to \Lambda pn$ reaction according to the Feynman diagram in Fig. 2 but neglecting the contribution from the shaded box, *i.e.*, making it unity. This means that we neglect dynamics of the slow $\bar{K}$ with two nucleons, which may generate the $\bar{K}NN$

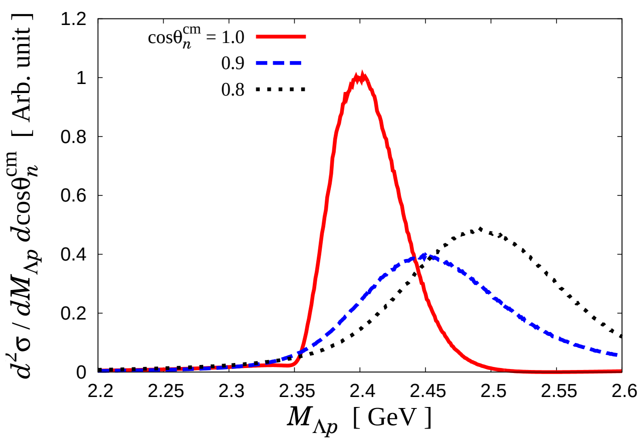


Figure 3: Differential cross section of the K^{-3}He $\to \Lambda pn$ reaction but neglecting $\bar{K}NN$ dynamics.

bound state. The result is shown in Fig. 3. As one can see, even if we do not have $\bar{K}NN$ dynamics, we obtain a peak structure whose peak position is just above the $\bar{K}NN$ threshold $= 2.37$ GeV. The peak position shifts upward as the neutron angle becomes larger, which can be explained by the kinematics of the quasi-elastic kaon scattering in the first collision.

Now let us take into account $\bar{K}NN$ dynamics and transition $\bar{K}NN \to \Lambda p$. Because all the three particles, $\bar{K}$ and two nucleons, are slow in the present reaction mechanism, the multiple $\bar{K}$ scattering as in Fig. 2(b) should be essential in general. Actually, if we truncate the scattering in Fig. 2(b) up to the first term in the right-hand side [uncorrelated $\Lambda(1405)p$ scenario], we cannot reproduce the behavior of the lower tail ~ 2.3 GeV in the experimental Λp invariant-mass spectrum [15]. In this study, we calculate the multiple $\bar{K}$ scattering in the so-called fixed center approximation [18, 19]. By including the two-nucleon absorption width for $\bar{K}$ in a phenomenological way, we obtain a $\bar{K}NN$ bound state with its pole position at $2354 - 36i$ MeV [15]. This multiple $\bar{K}$ scattering creates the peak structure in the Λp invariant-mass spectrum as the red thick line in Fig. 1. Our mass spectrum is consistent with the experimental one within the present error. An interesting finding is that we predict two peaks across the $\bar{K}NN$ threshold in the spectrum. The lower peak comes from the $\bar{K}NN$ bound state, which reproduces the tail at the lower energy ~ 2.3 GeV qualitatively well. This means that our spectrum supports the explanation that the E15 signal in the ${}^{3}\text{He}(K^{-}, \Lambda p)n$ reaction is indeed a signal of the $\bar{K}NN$ bound state. On the other hand, the higher peak originates from the kinematics, *i.e.*, from the almost on-shell $\bar{K}$ denoted in Fig. 3. Because using almost on-shell $\bar{K}$ is essential to make a $\bar{K}NN$ bound state in this reaction, this inevitably brings a kinematic peak above the $\bar{K}NN$ threshold in the physical mass spectrum.

3. Summary

We expect that kaonic nuclei should exist owing to the strongly attractive interaction between antikaon and nucleon. Even the existence of kaonic nuclei is still controversial, but a peak structure which could be a signal of the simplest kaonic nucleus, the $\bar{K}NN$ bound state, was recently found in the in-flight ${}^{3}\text{He}(K^{-}, \Lambda p)n$ reaction in the J-PARC E15 experiment.

In order to understand the mechanism of the reaction, we theoretically analyzed the reaction observed in the J-PARC E15 experiment. We found that, by detecting a fast and forward neutron in the final-state, an almost on-shell $\bar{K}$ is guaranteed, which is essential to make a bound state with two nucleons from ^{3}He. This almost on-shell $\bar{K}$ can bring a signal of the $\bar{K}NN$ bound state in the Λp invariant-mass spectrum, although it inevitably brings a kinematic peak above the $\bar{K}NN$ threshold as well. As a consequence, we predicted two peaks across the $\bar{K}NN$ threshold in the spectrum: the lower peak coming from the $\bar{K}NN$ bound state, and the higher one originating from the kinematics.

We finally note that the predicted two-peak structure is indeed implied by the data of the E15 second run, where 30 times more statistics of the same reaction are accumulated [20]. This will support more strongly that the E15 signal in the ${}^{3}\text{He}(K^{-}, \Lambda p)n$ reaction is indeed a signal of the $\bar{K}NN$ bound state.

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