“K-pp”, a K-Meson Nuclear Bound State, Observed in 3He(K-, Ap)n Reactions

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We observed a distinct resonance peak in the Ap invariant-mass spectrum of 3He(K-, Ap)n, well below the mass threshold of M(K-pp). By selecting a relatively large momentum-transfer region \( q = 350 \pm 650 \) MeV/c, one can clearly separate the resonance peak from the quasi-free process, \( \overline{K} N \rightarrow \overline{K} N \) followed by the non-resonant absorption by the two spectator-nucleons \( \overline{K} N N \rightarrow LN \).

We found that the simplest fit to the observed peak gives us a Breit-Wigner pole at \( B_{Kpp} = 47 \pm 3 \) (stat.) \( ^{+3}_{-3} \) (sys.) MeV having a width \( \Gamma_{Kpp} = 115 \pm 7 \) (stat.) \( ^{+10}_{-9} \) (sys.) MeV, and the S-wave Gaussian reaction form-factor parameter \( Q_{Kpp} = 381 \pm 14 \) (stat.) \( ^{+10}_{-9} \) (sys.) MeV/c, as a new form of the nucleon bound system with strangeness – “K-pp”.

Since the prediction of the \( \pi \)-meson by Yukawa [1], there has been a long-standing question as to whether a mesonic nuclear bound state exists. Mesons are introduced as mediators between nucleons to confine them within the small space of the nucleus. They can be generated and absorbed freely in nuclei as virtual particles whose dispersion relation between energy, mass and momentum \( E^2 = m^2 + |p|^2 \) does not need to hold within the limits of the uncertainty principle. Actually, \( \exp(-mr)/r \) is the particular solution of the Klein-Gordon equation at total energy \( E = 0 \), having a point source at origin, in which \( m \) defines an interaction range of the nuclear force rather than their production energy. On the other hand, in vacuum one needs energy \( m \) to produce them. If a mesonic nuclear bound state exists, it will form a quantum state at an energy \( E_M \) below \( m \) whose binding energy \( B_M = m - E_M \). Many mesons have been examined over the past century, to see whether or not there exists a mesonic nuclear bound state below the mass threshold, but there is still no clear evidence for the existence of a nuclear bound state below the mass threshold. It is well known that the lightest pseudo-scalar meson, \( \pi \), has an S-wave repulsion with nucleons. This repulsion prevents nuclei from collapsing against the pion condensation \( (E_\pi > m_\pi) \).

What about the second-lightest meson with an \( s \)-quark, the kaon? After the long standing “kaonic hydrogen puzzle” was resolved [2–4], the strong \( \overline{K} N \) attractive interaction was established in the isospin \( I = 0 \) channel. This leads us to the natural ansatz that the \( \Lambda(1405) \) could be a \( K^{-}p \) nuclear bound state, rather than a three-quark baryonic state. Akaishi-Yamazaki predicted this kaonic
nuclear bound state by using this $\overline{K}N$ strong interaction \[5.\] The simplest kaonic nuclear system, $\overline{K}NN$, is predicted to have charge $+1$, $I = \frac{1}{2}$ and $J^P = 0^-$, with a binding energy $B_{\overline{K}pp} = 48$ MeV and a partial mesonic decay width $\Gamma_{\pi\Sigma p} = 61$ MeV \[6.\], symbolically noted as “$K^-pp$”.

Triggered by this prediction, many studies were undertaken. Theoretically, the existence of the kaonic bound states are supported, but the binding energies and the widths are widely scattered, e.g. \[7–10.\] Experimentally, there have been many searches for “$K^-pp$”, with reports of possible candidates \[11–13.\] as well as contradictory results \[14, 15.\] leaving the matter both controversial and unsettled. In general, the simple $s\overline{s}$-pair production is still not sufficient to search for the “$K^-pp$” in non-strange reaction channels. Below $K^-K^+p$ ($\sim 1930$ MeV/$c^2$), many competing channels exist, such as $K^+\Lambda$ ($\sim 1610$), $N(1710) \rightarrow K^+\Lambda$ ($\sim 1750$), etc., and they must be taken into account. These channels, in which an $s$-quark is still in a baryon without forming a $\overline{K}$, introduce ambiguity and make analysis complicated.

On the other hand, identifying the “$K^-pp$” signal in a $K^-$-at-rest experiment is very difficult because of the presence of strong multi-nucleon absorption channels in the primary reaction \[15, 16.\]

To overcome these difficulties, we have conducted an experimental search for “$K^-pp$” by bombarding a $^3$He target with a 1 GeV/$c$ $K^-$ beam, focusing on the neutron forward-knock-on reaction. At this momentum ($\sqrt{s} \sim 1.8$ GeV for $\overline{K}N$), the single-nucleon elastic-reaction $\overline{K}N \rightarrow \overline{K}N$ has very large cross-section, helped by the presence of $Y^*$-resonances ($m_{Y^*} \sim 1.8$ GeV/$c^2$).

The momentum transfer of the backscattered $K^-$ to the residual $^2$He$^*$ spectator can be given as $q_{KN} \equiv |q_{KN}|$, and $q_{KN} \equiv p_{Lab}^L - p_{Lab}^n$ \[18.\], where the notation marks represent that it is within the strong interaction range in a nucleus. We utilize this primary reaction as a source of low momentum virtual $\overline{K}$-mesons in the nucleus. In this reaction, the projectile itself is in fact a $K^-$, so the reaction channel is simple, and small $q_{Kn} \sim 200$ MeV/$c$ will make formation probability large.

Our first-stage experiment, J-PARC E151st, confirmed a very large cross section of $\geq 6$ mb/sr in the semi-inclusive quasi-elastic $\overline{K}N \rightarrow \overline{K}N$ channel at $cos\theta_n = 1$ above $M(\overline{K}pp)$ ($\equiv m_K + 2m_p = 2370$ MeV/$c^2$), and realized that there was a large event-excess extending from the quasi-elastic $\overline{K}$ peak to the lower mass region \[19.\] The tail reached to $\sim 100$ MeV below $M(\overline{K}pp)$, but no significant structure was observed at any location where candidates are reported to be. On the contrary, another peak-like structure was clearly observed in the $M_{miss,\Lambda p}$ spectrum of the the non-mesonic $\Lambda p$ final state (observed by the $pp\pi^-$-events) at low $q_{\Lambda p} (= q_{KN} \equiv q)$ \[20.\].

![FIG. 1. a) 2D event distribution on the $pp\pi^-$ missing mass $M_{miss,pp\pi^-}$ of the $^3$He$(K^-pp\pi^-)$ reaction, and the log likelihood $lnL$ computed from probability-density functions of simulated $\Lambda p$ events, for the events $lnL < 30$. The histogram b) is the projection onto the $M_{miss,\Lambda p\pi^-}$ axis, and c) onto $lnL$. The dashed line in a) indicates the $\Lambda p$ event selection limit, and the projections are also shown in b) and c).](image)

The centroid of the structure is located just below $M(\overline{K}pp)$, which indicates the existence of a resonance below threshold. Thus, we performed our second-stage run to verify this resonance.

In E152nd, we focused on $pp\pi^-$-events detection in our cylindrical detector system (CDS) \[21.\] at the trigger level, to improve the statistics substantially. First, we needed to determine whether the observed $pp\pi^-$ kinematics is consistent with $\Lambda p\pi^- (\Lambda \rightarrow p\pi^-)$ final state, with a single neutron missing. To realize this, we employed the log-likelihood method ($lnL$) to the events, based on the simulated probability density function. In the simulation, we generated $\Lambda p$ events proportionally to the Lorentz-invariant phase space. The $lnL$ is composed of the $p$-value for the kinematical refit to $\Lambda p$ \[22.\], a distance-of-closest-approach (DCA) for incoming $K^-$ with $p$ and $K^-$ with $\Lambda$, distance of those two vertices, and DCA of the $p\pi^-$-pair at the $\Lambda$ decay point. To be conservative, both vertices between incoming $K^-$ with $p$, and with $\Lambda$, are requested to be within the fiducial volume of the $^3$He target.

Fig. 1 shows the two-dimensional (2D) distribution of the $^3$He$(K^-pp\pi^-)$ missing mass, $M_{miss,pp\pi^-}$. A strong event concentration is seen at the bottom of Fig. 1a), which corresponds to the $\Lambda p$ final state, clearly separated from other mesonic final states. Events with a missing $\Lambda$ (thus $\Lambda p\pi^-$ final state) and all other complicated mesonic processes are on the heavier mass side. We selected $\Lambda p$ events rather tightly as indicated by the dashed curve, to analyze the event kinematics uniquely and to reduce contamination. Note that we cannot completely avoid several channels such as $\Sigma^0 p\pi^- (\rightarrow \Lambda\gamma p\pi^-)$ and $\Sigma^-pp^- (\rightarrow n\pi^-pp^-)$ in the $\Lambda p$ window.
In the $^3\text{He}(K^-, \text{pp}\pi^-)n$ reaction, there are five kinematically independent parameters, but the formation channel, $K^-+^3\text{He} \to ^4\text{K}^-\text{pp}$ $+n$, can be uniquely defined by following two parameters; $\Lambda p$ invariant mass $M_{\text{inv.} \Lambda p}$ (≡ $M$, hereafter) and the momentum transfer $q$. If a resonance exists at specific $M$, then the $M$ distribution centroid should be $q$ independent. On the other hand, the formation yield of the resonance can be a function of $q$, because the intermediate propagator reacts with the $^2\text{He}^+$ spectator at the momentum of $q$. The event distributions over $M$ and $q$ are given in Fig. 2a), and the projections onto $M$ in b), and onto $q$ in c). As shown in the figure, the momentum transfer $q \sim 200$ MeV/$c$ is achieved around the $M$ region of interest (the minimum $q$ among the search experiments performed).

To our surprise, the structure near $M(Kpp)$ in Fig. 2b) cannot be represented as a single pole, as is naively assumed in [20]. There are at least two substructures. One below $M(Kpp)$ exhibits $q$-independence for the distribution centroid in $M$. Another one above $M(Kpp)$ depends on $q$ rather largely. Around the lower $q$ (larger $\cos\theta_n$) boundary, the distribution centroid shifts to the heavier $M$ side for the larger $q$ (smaller $\cos\theta_n$), suggesting its non-resonant feature, i.e., the propagator’s kinetic energy is converted to the relative kinetic energy between $\Lambda$ and $p$. Thus, the most natural interpretation would be non-resonant absorption of quasi-free ‘$K^-$’ by the $^2\text{He}^+$ spectator, $QF_{\text{F}\Lambda}$. This process can be understood as a part of the quasi-free $K^-$ reaction, in which the $K^-$ mostly escapes from the nucleus, as we published in [19]. If the ‘$K^-$’ is formed in a nuclear bound state, then one can expect ‘$K^-$’ production in ‘vacuum’ (above $M(Kpp)$) as well. Thus, there is another component, widely distributing over $q$, with a constant (between the two) for $M(Kpp)$.

This spectral substructure is in relatively good agreement with that of Sekihara-Oset-Ramos’s spectroscopic function [23] to account for the observed structure in [20]. Actually, their spectrum has two structures, namely (A) a ‘$K^-\text{pp}$’ pole below the mass threshold $M(Kpp)$ (meson bound state), and B) an ‘uncorrelated $\Lambda'p \to \Lambda p$’ resulting in $M$ above $M(Kpp)$ (corresponding to $QF_{\text{F}\Lambda}$).

Fig. 2b) is, however, very different from their predictions in many ways. Therefore, we introduce our model-functions to account for the present spectrum.

A very important and striking structure exists below $M(Kpp)$, which could be assigned as the ‘$K^-\text{pp}$’ resonance. To make the fitting function as simple as possible, let us examine the event distribution by using the same function as was applied in [20], i.e., a Cartesian product of Breit-Wigner (B.W.) for $M$, and an S-wave reaction form-factor in a Gaussian (harmonic oscillator) for $q$ as:

$$f_{\text{Kpp}}(M,q) = \frac{A_{\text{Kpp}}}{(M-M_{\text{Kpp}})^2 + (\Gamma_{\text{Kpp}}/2)^2} e^{-\left(\frac{q^2}{\sigma_{\text{Kpp}}^2}\right)},$$  \hspace{1cm} (1)

where $M_{\text{Kpp}}$ and $\Gamma_{\text{Kpp}}$ are the B.W. pole position of the spectrum and the width, $Q_{\text{Kpp}}$ is the reaction form-factor parameter, and $A_{\text{Kpp}}$ is the normalization constant. In Eq. 1, $\Lambda p n$ three-body Lorentz-invariant phase space $\rho_3(M,q)$ is omitted to treat that as a common factorial term with other components.

To fit the data, we need at least two more components. A model-function in the $QF_{\text{F}\Lambda}$ channel is introduced as follows. As described, we assume that a ‘kaon’ propagates between the two successive reactions. It consists of 1) $K^- +'n' \to K^- + n$ and 2) non-resonant ‘$K^- + \text{He}^+ \to \Lambda + p$ in the final state interaction. When the ‘$K^-$’ propagates as an on-shell particle in the spectator’s rest frame (≡ Lab.-frame), then the resulting $M$ at the momentum $q$ can be given as:

$$M_F(q) = \sqrt{4m_p^2 + m_{K^-}^2 + 4m_p\sqrt{m_{K^-}^2 + q^2}},$$  \hspace{1cm} (2)

where $m_p$ and $m_{K^-}$ are the intrinsic mass of proton and kaon, respectively. The dotted line in Fig. 2a) is the $M_F(q)$. Along the line, there are two strong event concentrations observed at $\cos\theta_n = 1$ (backward ‘$K^-$’) and $\cos\theta_n = -1$ (forward ‘$K^-$’) [24]. This is consistent with quasi-elastic forward / backward peaking ‘kaon’ emission in the primary reaction [25]. To account for the distribution, we introduced $f_{QF_{\text{F}\Lambda}}(M,q)$, as two exponential distributions (for forward and backward components) with a constant (between the two) for $q$, and a Gaussian distribution around $M_F(q)$ to account for the spectator’s Fermi-motion for $M$.

There is another component, widely distributing over the kinematically allowed region of $M$ and $q$. In fact, this component was previously observed [20], in which we assumed that the yield is proportional to the $\rho_3(M,q)$. However, with the present much improved statistics,
we found that this is not as simple as we had previously assumed before. The spectrum of this component, \( f_j(M, q) \), indicates the yield suppression at heavier \( M \) and lower \( q \), as it is shown in the fit curve given in Fig. 2b) and c). Thus, we introduce a distribution similar to Eq. 1, but replace the harmonic oscillator term to allow angular momentum up to \( P \)-wave.

The \( f_j(M, q) \), representing the \( j \)-th physical process, were normalized using the common factorial functions \( \rho_3(M, q) \) and \( ppp^- \) detection efficiency \( \mathcal{E}(M, q) \), evaluated by simulation using the solid angle and momentum acceptance of CDS. Thus, one can conduct a parameter fitting over the data \( D(M, q) \) in each 2D bin by calculating the probabilities of a Poisson distribution having mean value \( \lambda_D(M, q) \) as \( P(X = D(M, q); \lambda_D(M, q)) \),

\[
\lambda_D(M, q) = \sum_j y_j \rho_3(M, q) \mathcal{E}(M, q) f_j(M, q), \tag{3}
\]

\( y_j \) are the yield of the \( j \)-th physical process. For the 2D fit, we used the maximum likelihood method again. As shown in the figure, the fit result is in good agreement with the data in a global way.

To examine whether we should introduce more sophisticated model functions, we studied the distribution of remaining three kinematical independent parameters of \( M \) and \( q \), which define the decay kinematics of \( K^-pp' \rightarrow \Lambda p \) and the \( \Lambda \rightarrow p\pi^- \) decay asymmetry. Thus, these parameters are sensitive to \( J^P \) of the reaction channels. For the \( K^-pp' \) signal, we analyzed events in the window \( q = 350 \sim 650 \text{ MeV}/c \) and \( M = 2.28 \sim 2.30 \text{ GeV}/c^2 \), where the major part of the component is located, and no severe interference is expected with \( f_{\text{BG}} \). The angular distributions are fairly flat to any of three kinematical parameters. Therefore, the angular distribution is consistent with \( S \)-wave. Thus, there is no specific reason why we need to introduce any sophisticated terms in addition to Eq. 1. In fact, a flat distribution is naturally expected if the pole’s quantum-number is \( J^P = 0^- \) [26]. We also analyzed the angular distributions for \( f_{QF_{\text{PA}}} \) and \( f_{\text{BG}} \), as well. However, again we find no specific reason.

To exhibit this \( K^-pp' \) resonance candidate, we plotted the spectrum by correcting our detector efficiency \( \mathcal{E}(M, q) \) for the events in the momentum transfer window of \( 350 < q < 650 \text{ MeV}/c \), as in Fig. 3. The acceptance correction is given by dividing data and each process by \( \mathcal{E}(M, q) \) after the 2D fitting procedure and integrating them over \( q \), to make fit values insensitive to the acceptance correction procedure. In this window, the yield of other processes is largely suppressed in contrast to the resonance, and the peak region is clearly separated from the \( QF_{\text{PA}} \) distribution, because the centroid is shifted to the heavier side according to Eq. 2. As a result, it forms a distinct peak below \( M(Kpp) \), and the yield is already clearly weakening at \( M(Kpp) \), showing the applicability of Eq. 1 to the resonance. Thus, we have established the existence of the sub-threshold resonance, \( K^-pp' \), as a part of the peak structure observed in [20], with the highly improved statistics.

To reach the final fit value, we conducted the fitting procedure in this \( q \)-window with same procedure as was given in Eq. 3 by fixing parameters other than \( K^-pp' \) (peak fitting), and iterated this together with the global fit by fixing \( K^-pp' \) parameters except for its yield (background evaluation) until the procedure converged. The \( S \)-wave parameters obtained were; the mass eigenvalue \( M_{Kpp} = 2324 \pm 3 \text{ (stat.)} \pm 6 \text{ (sys.)} \text{ MeV}/c^2 \) (i. e. \( B_{Kpp} = M(Kpp) - M_{Kpp} = 47 \pm 3 \text{ (stat.)} \pm 6 \text{ (sys.)} \text{ MeV} \)), the width \( \Gamma_{Kpp} = 115 \pm 7 \text{ (stat.)} \pm 10 \text{ (sys.)} \text{ MeV} \), and the reaction form-factor parameter \( Q_{Kpp} = 381 \pm 14 \text{ (stat.)} \pm 5 \text{ (sys.)} \text{ MeV}/c \). The \( q \)-integrated \( K^-pp' \) formation yield below the threshold going to the \( \Lambda p \) decay channel is evaluated to be \( \sigma_{Kpp} \cdot B_{\Lambda p} = 15 \pm 1 \text{ (stat.)} \pm 3 \text{ (sys.)} \text{ mb} \) (for \( M < M(Kpp) \)) [27].

We evaluated the systematic errors caused by the spectrometer magnetic field strength calibrated by invariant masses of \( \Lambda \) and \( K^0 \) decay, binning effect of the spectrum, and the contamination effects of the other final states (\( \Sigma^0 pn \) and \( \Sigma^- pp \)) to the \( \Lambda pn \) window. To be conservative, the effects to the fit values are added linearly. Due to page limitation, more detailed analysis will be given in a full paper forthcoming shortly.

The \( B_{Kpp} \sim 50 \text{ MeV} \) is much deeper than our first publication. This is because the previous assumption of single pole structure is not valid. It is also much deeper than chiral-symmetry-based theoretical predictions. The \( B_{Kpp} \sim 110 \text{ MeV} \) is rather wide. On the other hand, it should be similar to that of \( \Lambda(1405) \rightarrow \Sigma \pi \), if \( K^-pp' \) decays like \( \Lambda(1405)^+p \rightarrow \Sigma \pi p \). Thus, the observed large width indicates that the non-mesonic \( YN \) channels would
be the major decay mode of the “K−pp” resonance. Interestingly, the observed Q_{Kpp} ∼ 400 MeV/c is very large compared to other normal nuclear resonances, which implies the formation of a very compact (∼ 0.5 fm) system referring to b ∼ 200 MeV/c·fm. The compactness of the system is also supported by the large B_{Kpp}. However, the present Q_{Kpp} can be strongly affected by the primary KN → KN reaction in the formation process, so one needs more study to evaluate the static form-factor parameter of “K−pp” to deduce its size (or nuclear density) more quantitatively.

The “K−pp” formation yield of ∼ 15 µb observed in the Δp decay channel might be a bit weak in view of ∼ 1 mb/sr (M < M(Δpp)) of the semi-inclusive 3He(K−, n) reaction at cosθn = 1 and pK− = 1 GeV/c, reported in the previous paper [19]. Although, the quasi-free K is very forward peaked process so it is not excessive. It would also be reasonable in view of the small spatial size (this also implies a small cross section) of the system, as implied by Q_{Kpp}. Actually, if one compares this with the yield of Q_{FKA}, the “K−pp” has an even larger yield. On the other hand, we also reported in the previous paper that the formation upper limit of the resonance (assuming that it decays to Δp (100 %)) is ∼ 120 µb/sr where “K−pp” is observed. By taking account of the angular distribution of the present peak of ∼ 0.7 sr, the present yield is consistent.

The determination of the internal physical structure of “K−pp” is not easy. The most natural and simplest interpretation is, however, a kaonic nuclear bound state; a system composed of a K−-meson and two protons with J^P = 0^−, i.e. a highly excited novel form of nucleus with a strange-meson. Because it locates just below the M(Δpp), efficiently formed at lower q, much larger width than that of Λ(1405), and the spectral shape is adjacent to quasi-free K processes (and thus Q_{FKA}) above M(Δpp), these facts indicate that the mesonic degree-of-freedom still holds in the observed “K−pp” system.

In another forthcoming paper, we will describe the analysis of the mesonic final state focusing on π^±Σ^±pn (Λ^∗pn) to reveal a role of Λ^∗ in the “K−pp” formation process and thus to answer the longstanding question of whether the mesonic nuclear bound state exists in a more comprehensive manner. In parallel to the experimental studies, further theoretical studies are also required for the universal understanding of the internal structure of the observed resonance.

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