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# Search for the simplest kaonic nuclear bound state "$K^-pp$" via $^3He(K^-;n)$ reaction at J-PARC

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By embedding mesons into nuclei and studying the property change of those particles in nuclear media, one can access the physics at densities beyond standard nuclear density, e.g., in neutron star matter, as well as the origin of matter (hadron) mass, in which the standard scenario is that the hadron masses are generated by the spontaneous chiral symmetry breaking of the vacuum. In this context, one of the most interesting meson is the anti-kaon ($\bar{K}$) in the second-lightest $K$-meson group having the strange (s)-quark as a constituent quark, namely $K^-$ and $\bar{K}^0$.

The confirmation of strong attraction of the $KN$ interaction in the I = 0 channel 1,2) opens up very curious question. The $KN$ attraction is so strong that it is more natural to form a bound state between a kaon and proton. In fact, there is a well-known resonance called $\Lambda$ (1405) the mass of which is located just below the mass threshold of the kaon and proton, $M(K^-p)$; the resonance is assumed to be an exited state of a member of the $\Lambda$ hyperon, i:e:; it is an excited uds-quark baryon system. Thus, it is very natural to ask whether $\Lambda$ (1405) can be interpreted as a bound state of a kaon and proton due to the strong interaction, i:e:; $\Lambda$(1405) = "$K^-p$": If this is true, then the kaon can form a variety of nuclear bound states together with various nuclear systems. The strong $KN$ attractive interaction might help form a high-density nuclear object beyond the standard nuclear density spontaneously. It might also help the study of the in-medium property change of mesons in nuclei. Therefore, a variety of experimental studies have been conducted by a number of experimental groups to identify the simplest kaonic nuclear bound state, "$K^-pp$." The detection of the kaonic nuclear state formation is difficult from the kaon absorption at rest because the kaon mainly reacts with one of the nucleons in the mesonic channel and produces a hyperon ($\Lambda$ or $Y$ ) as $K^-N \to \pi N$, without forming a kaonic nuclear state. It can also be absorbed by two nucleons simultaneously as $K^-NN \to \Lambda N$, and this process produces huge backgrounds. The direct kaon production channel is also attempted via the $pp \to K^+ +$ "$K^-pp$" reaction. However, this channel has large ambiguity due to the presence of $N^*$(1410) resonance, which can decay strongly to $K^+\Lambda$. Obviously, no $K^-$ (nor $\bar{K}$) is generated in this reaction channel, and the channel is energetically easier to be produced compared to the $K^+K^-$-pair production. One can easily be misled by the reaction chain of $pp \to N^*(1410) + p \to (K^+\Lambda) + p$ to be a "$K^-pp$" formation signal, if one believes the $\Lambda p$ in the final state (wrong pair) is the decay product of "$K^-pp$", i:e:; $pp \to K^+ +$ "$K^-pp$" $\to K^+ + (\Lambda p)$. There are also other experimental studies to search for the kaonic bound state, but those are limited by either null results or insufficient in statistics. Therefore, there is no convincing and conclusive experimental evidence of the existence of the kaonic nuclear bound state.

We employed an entirely different approach at J-PARC K1.8BR beam-line in our experiment E15. We bombarded a $K^-$ beam on a $^3He$ target to knockout a neutron from the target nucleus at 1 GeV/c ($\sqrt{s_{KN}} \sim 1.8GeV/c^2$), i:e:; $K^- +^3 He \to K^-p_sp_s + n$ ($p_s$ denotes spectator proton). The cross section of this reaction is rather high, because of the presence of the $Y^*$ resonance near 1.8 GeV/$c^2$, which decays strongly to $KN$. There are several key advantages in this reaction channel to search for the kaonic bound state. First, the recoil kaon momentum (or momentum transfer), $q_K$, is as small as $\sim$ 200 MeV/c ($\sim p_F$ ) in this reaction; therefore, one can expect very efficient nuclear formation as $K^-p_sp_s \to$K^- pp:" Another advantage is that the presence and the commitment of $K^-$ in this channel is secured from the beginning. Still another advantage is that the two- (or multi-) nucleon absorption reaction can be expected to have a small cross section. Finally, we can cover the target region with a cylindrical detector system (CDS) to identify the final state of "K^-pp" with sensitivity to the decay process. We also placed large-volume neutron counter arrays in the forward direction 15 m away from the target system to identify neutrons in the production channel with a high missing-mass resolution of about 10 MeV/$c^2$.

The pilot run of J-PARC E15 (E151st) showed quite remarkable results. The semi-inclusive forward neutron spectrum shows a large yield below the mass threshold of M($K^-pp$) as a long tail from the quasielastic kaon scattering, implying the existence of strong $KN$ attractive interaction.3) An even more impressive spectrum was obtained in the $\Lambda p$ invariant mass spectrum of the $\Lambda pn$ final state, in which we observed an event concentration near the M($K^-pp$) threshold, and the centroid of the event concentration is well within the bound region.4) Thus, we conducted a new beam time for further study, especially focusing on the $\Lambda pn$ final state (E15$^{2nd}$).

We are still in an analysis phase, but the preliminary result is truly astonishing. As shown in Fig. 1, the event concentration near the M($K^-pp$) threshold is not a single peak structure, as we simply assumed in

our previous publication,4) but it has clear internal structures separated by the threshold energy indicated by the dashed line. First, the only reasonable explanation of the peak-structure formation below the M($K^-pp$) threshold is the kaonic nuclear bound state formation of "Kˆ-pp." Events below the threshold can be generated when virtual kaons below the rest mass are produced in a quasi-elastic (QE) reaction. The peak structure can only be formed when there exists a resonance pole below the threshold, while a smooth tail is formed below the threshold if a pole does not exist. The $\Lambda p$ pair in the final state, together with
the forward neutron, ensures that the backscattered $K^-$ interacts with the other two spectator protons. Thus, $K^-$, $\bar{K}^0$, or $\Lambda(1405)$ escaping channels are naturally suppressed substantially, in contrast to the semiinclusive missing-mass spectra of ${}^3He(K^-;n)X$.3) The peak centroid is located around ∼40 MeV, which is much deeper than that of the normal nuclear system about 10 MeV.

The existence of the structure above the threshold provides further confirmation that the structure below the threshold is actually the nuclear bound state of "$K^-pp$," in which the constituent particles do not lose their identity in the system. Generally, the peaks in a mass spectrum are isolated in the case of baryonic resonance. In contrast, nuclear-state formations are always associated with the so-called quasi-free (QF) processes in the unbound energy region, which indicate that the constituent particles can be dissolved. In this case, the structure above the threshold can be interpreted as the initial kaon backscattered at an energy above the kaon mass in the QE channel, followed by internal conversion (IC) with two spectator protons resulting in $\Lambda p$ in the final state. Thus, this successive reaction can be treated as a QF process of the ${}^3He(K^-;\Lambda p)n$ reaction channel.

To finalize the present study, we are analyzing the angular distribution of the particles in the final state, to study the form factor, spin, and parity of the observed state, and to prepare an independent analysis of the data so as to reach a confirmative result on the kaonic nuclear bound state "$K^-pp$." The peak in the
bound region would suggest that the $\sim$ on-shell $K^-$ (or $\bar{K}$) can form a nuclear bound state (Boson & Fermion hybrid system), where u- and u-quarks coexist, at-least within a time scale allowed by the width of the bound state. It is quite important and interesting to know how the hadron identity is conserved even in nuclear media.

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