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Femtoscopic study on the $\Lambda\Lambda$-$N\Xi$ interaction

Y. Kamiya

*CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics,
Chinese Academy of Sciences, Beijing 100190, China.
RIKEN Interdisciplinary Theoretical and Mathematical Science Program (iTHEMS),
Wako 351-0198, Japan.*

K. Sasaki

*Division of Scientific Information and Public Policy,
Center for Infectious Disease Education and Research (CiDER), Osaka University, Suita 565-0871, Japan.*

T. Fukui

RIKEN Nishina Center, Wako 351-0198, Japan.

T. Hyodo

*Department of Physics, Tokyo Metropolitan University, Hachioji 192-0397, Japan,
RIKEN Interdisciplinary Theoretical and Mathematical Science Program (iTHEMS),
Wako 351-0198, Japan.*

K. Morita

*National Institutes for Quantum and Radiological Science and Technology,
Rokkasho Fusion Institute, Rokkasho 039-3212, Japan,
RIKEN Nishina Center, Wako 351-0198, Japan.*

K. Ogata

*Research Center for Nuclear Physics, Osaka University, Ibaraki 567-0047, Japan,
Department of Physics, Osaka City University, Osaka 558-8585, Japan,
Nambu Yoichiro Institute of Theoretical and Experimental Physics, Osaka City University, Osaka 558-8585, Japan.*

A. Ohnishi

Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan.

T. Hatsuda

RIKEN Interdisciplinary Theoretical and Mathematical Science Program (iTHEMS), Wako 351-0198, Japan.

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The correlation functions of $p\Xi^-$ and $\Lambda\Lambda$ pairs from high-energy pp collisions are investigated in the coupled-channel formalism. The $N\Xi$-$\Lambda\Lambda$ coupled-channel potentials obtained in the lattice QCD calculation at almost physical quark masses are employed. The $p\Xi^-$ correlation function shows the large enhancement from the pure Coulomb case, while the $\Lambda\Lambda$ correlation function shows the moderate enhancement from the pure quantum statistics case. This agreement indicates that both the $N\Xi$ and $\Lambda\Lambda$ interactions are moderately attractive without having quasibound or bound state.

Keywords: Hyperon interaction; exotic hadrons; hadron momentum correlation.

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1. Introduction

The $S=-2$ baryon-baryon interaction is one of the most important topic for the study of exotic hadrons. The existence of the $H(uuddss)$ dibaryon state, which has $I=0$, $S=-2$ and $J^\pi=0^+$, has been discussed for a long time. Originally, the H state is predicted as the deeply bound state below the $\Lambda\Lambda$ threshold in the flavor SU(3) limit [1], while this is ruled out by the discovery of the double Λ hypernucleus [2, 3]. However, there is a probability to find the H dibaryon as a molecular state which is formed by the attractive hadron-hadron interaction. According to the $S=-2$ $N\Xi$-$\Lambda\Lambda$ coupled-channel potential obtained from the lattice QCD calculation [4], both channels show the attractive interaction, which may drive the molecular state, while the potential does not predict a bound state of $\Lambda\Lambda$ and $N\Xi$ due to the moderate attractive interaction. In order to know the fate of H state, these $N\Xi$-$\Lambda\Lambda$ interactions must be tested with the experimental observables.

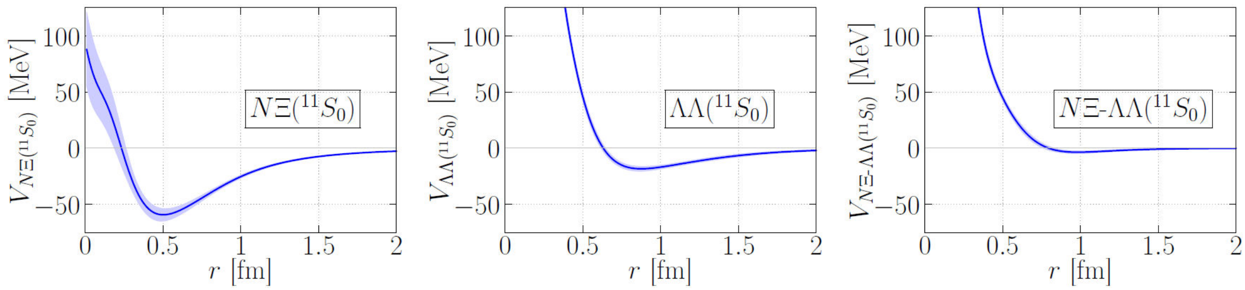

FIGURE 1. The $^{11}S_0$ coupled-channel HAL QCD potential for $t = 12$ at almost physical quark masses [4]. The colored shadow denotes the statistical error of each potential.

To access the low-energy regime of the hadron-hadron interaction, the femtoscopy, which uses the momentum correlation function $C(q)$ in the high-energy nuclear collisions, is a helpful technique [5, 6]. When the absolute value of the scattering length $|a_0|$ is comparable to or larger than the size of the hadron emitting source R, $C(q)$ shows the strong deviation from the non-interacting case. Furthermore, to investigate the source size dependence of $C(q)$ is also helpful to distinguish the existence or non-existence of bound states [7, 8].

In this proceedings, we investigate the $p\Xi^-$ and $\Lambda\Lambda$ correlation functions using the coupled-channel potentials obtained from the lattice QCD simulation by the HAL QCD collaboration [4]. To introduce the coupled-channel effect, we use the Koonin–Pratt–Lednicky–Lyuboshits–Lyuboshits (KPLLL) formula [8–11]. The results are compared with the recently obtained correlation function data [12, 13]. All the contents in this paper are based on Ref. [14].

2. $p\Xi^-$ and $\Lambda\Lambda$ correlation functions with HAL QCD potential

For the basic start point to calculate the correlation function is the Koonin-Pratt formula [9]. Its extension to the coupled-channel case is developed by Lednicky, Lyuboshits and Lyuboshits [10], which we call KPLLL formula. This formula is nowadays applied to several hadron channels [8, 11]. With this formula the correlation function $C(\boldsymbol{q})$ in the pair rest frame is given as

$$C(\boldsymbol{q}) = \int d^3r \sum_j \omega_j S_j(\boldsymbol{r}) |\Psi_j^{(-)}(\boldsymbol{q};\boldsymbol{r})|^2 \, , \tag{1}$$

where $S_j(\boldsymbol{r})$, ω_j, and q_j are the relative hadron emitting source function, the production weight factor, and the eigenmomentum in j-th channel. We assign the measured channel as channel 1, and $\boldsymbol{q} \equiv \boldsymbol{q}_1$. In this study, we use the static spherically symmetric Gaussian source function with source size R given by $S_R(r) = \exp(-r^2/4R^2)/(4\pi R^2)^{3/2}$ for all channels. In this case, the correlation function only depends on $q = |\boldsymbol{q}|$. The relative wave function $\Psi^{(-)}$ can be obtained by solving the coupled-channel Schrödinger equation with the outgoing boundary condition, where the the outgoing wave component exists only in the measured channel ($j = 1$). The Coulomb effect is introduced by adding the Coulomb potential $V_{\mathrm{C}}(r) = -\alpha/r$ to the $p\Xi^-$ diagonal component of the coupled-channel potential.

To calculate the relative wave function $\Psi^{(-)}$, we use the $N\Xi$-$\Lambda\Lambda$ coupled-channel potentials constructed by the HAL QCD collaboration [4]. As shown in Fig. 1, among the isospin-singlet spin-singlet ($^{11}S_0$) potentials, $N\Xi$ channel shows the strong attraction while the $\Lambda\Lambda$ shows the weak attraction. By solving the Schrödinger equation in charge basis, the scattering lengths are obtained as $a_0^{p\Xi^-} = -1.22 - i1.57$ fm and $a_0^{\Lambda\Lambda} = -0.78$ fm for $^{11}S_0$ $p\Xi^-$ channel and $\Lambda\Lambda$ channel, respectively. Here the scattering length is defined with $a_0 \equiv \mathcal{F}(E = E_{\mathrm{th}})$ with the scattering amplitude $\mathcal{F}$ and the threshold energy E_{th}. We also find that there is no pole corresponding to an physical state in the the $N\Xi$-$\Lambda\Lambda$ coupled-channel energy region.

The results for the $p\Xi^-$ and the $\Lambda\Lambda$ correlations with the source size $R = 1.2$ fm are shown in Fig. 2. Here we use the $N\Xi$-$\Lambda\Lambda$ coupled channel potential at $t = 12$. By solving the coupled-channel potential in the charge basis with the Coulomb potential, effects of the Coulomb potential, the coupled-channels, the threshold differences, and quantum statistics (for $\Lambda\Lambda$) are included. For simplicity, we assume the common source for all channels with $\omega_j = 1$. We can see that the $p\Xi^-$ correlation function shows the large enhancement compared to the pure Coulomb case in the low momentum region. From the result only with the $p\Xi^-$ wave function component, we find that this enhancement is originated mainly from the attractive interaction of $p\Xi^-$ channel. We also find that the contribution from $n\Xi^0$ source gives the important additional enhancement while the that from $\Lambda\Lambda$ source is negligible. The result of the $\Lambda\Lambda$ correlation function also shows the enhancement compared the case of pure quantum statistics. We also find the two cusps locating at the $p\Xi^-$ and the $n\Xi^0$ thresholds, which are enhanced by the coupled channel source contributions. However, due to the weak coupling potential of $V_{N\Xi\text{-}\Lambda\Lambda}$, both of the cusps are moderate.

3. Comparison with experimental data

Finally, we compare our results with the experimental correlation data of ALICE pp collisions. The experimental correlation data contain not only the physical effect but also the

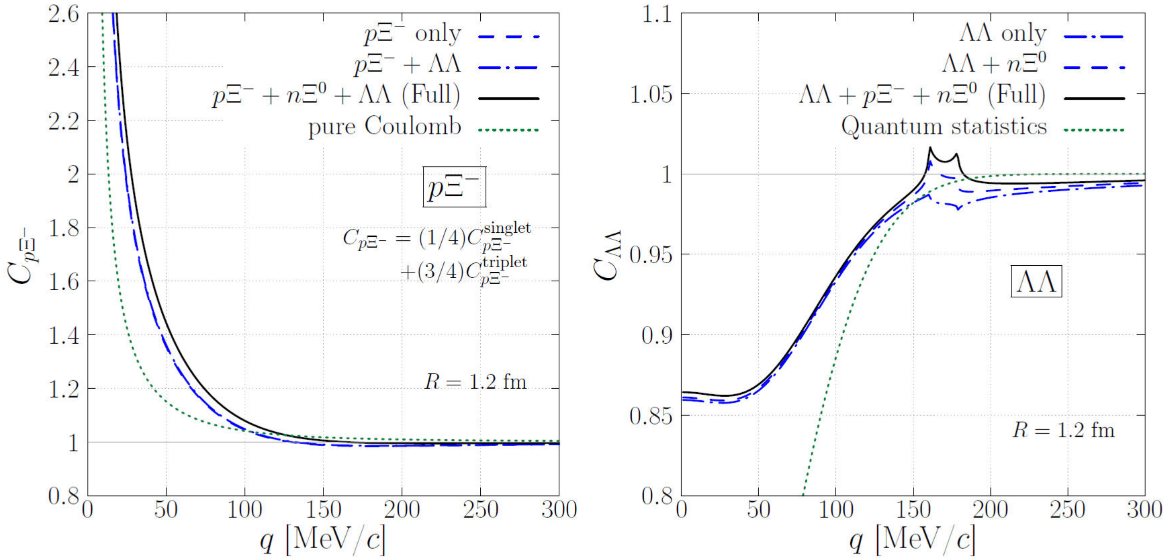

FIGURE 2. The $p\Xi^-$ (left panel) and $\Lambda\Lambda$ (right panel) correlation function and its breakdown. The dashed lines denote the correlation function calculated only with the $p\Xi^-$ or $\Lambda\Lambda$ ave function. For the $p\Xi^-$ pair, the dash-dotted line and the solid line denote the results with the contributions of $p\Xi^-$+$\Lambda\Lambda$ and $p\Xi^-$+$n\Xi^0$+$\Lambda\Lambda$ channel sources, respectively. For the $\Lambda\Lambda$ pair, the dash-dotted and the solid line denote the results with the contribution of the $\Lambda\Lambda + n\Xi^0$ and$\Lambda\Lambda + n\Xi^0 + p\Xi^-$ channel sources, respectively. The result of pure Coulomb interaction (quantum statistics) without strong interaction is shown by the dotted line for the $p\Xi^-$ ($\Lambda\Lambda$) pair.

contaminations from the particle misidentification, the feed-down effect from weak and electromagnetic decays of other particles, and the non-femtoscopic effect such as the minijet contribution. To take into account these effects, we use the following fitting function

$$C_{\text{fit}}(q) = (a + bq)(1 + \lambda(C_{\text{th}})(q) - 1), \qquad (2)$$

where λ is the pair purity probability and a and b are the experimental parameters representing the non-femtoscopic effect. The experimental data of the $p\Xi^-$ pair are obtained after the subtraction of these background so that we should take $(\lambda, a, b) = (1, 1, 0)$.

For the hadron source, we use the static Gaussian source $S_R(r)$ for all the channels. The source size R and the experimental parameters a and b for the $\Lambda\Lambda$ pair are determined by the simultaneous fitting of the $p\Xi^-$ and $\Lambda\Lambda$ correlation data. The weight factors ω_i are determined based on the simple statistical model estimation. Details of the fitting procedure is found in Ref. [14]. For the $\Lambda\Lambda$ pair, we employ the the ALICE estimation for the pair purity parameter λ as $\lambda_{pp} = 0.338$ and the parameters a and b are determined by fitting.

The fitted C_{fit} are shown in Fig. 3 with the experimental data. We obtained $R = 1.05$ fm which is consistent with that obtained by the ALICE collaboration [13]. For the $p\Xi^-$ pair, our result (solid lines) well explains the data compared to the pure Coulomb case where the strong interaction is switched off (dashed line). This implies the attractive nature of the strong $N\Xi$ interaction. For the $\Lambda\Lambda$ pair, while the uncertainty of the data is large especially for the small q region, the good agreement between our result and the data implies the attractive $\Lambda\Lambda$ interaction. In Ref. [14], the comparison with the ALICE data from pPb collisions is also shown.

4. Summary

We have studied the $p\Xi^-$ and the $\Lambda\Lambda$ correlation functions employing the coupled-channel HAL QCD potential at almost physical quark masses [4]. The large value of the scattering length of the ${}^{11}S_0$ $p\Xi^-$ channel shows the strong attractive interaction while there is no physical eigenstate corresponding to the H dibaryon. Due to the strong attractive interaction, both correlation function show the enhancement by the strong interaction, while the $N\Xi$-$\Lambda\Lambda$ coupled-channel source effect between is moderate. We find that, with the reasonable source functions parameters, our results are in good agreement with the ALICE data obtained in pp collisions [12, 13]. Then we conclude that the scenario where the H dibaryon does not exist below the $\Lambda\Lambda$ nor $N\Xi$ threshold is reasonable.

As suggested in Ref. [15], it is important to see the femtoscopic data in different collision systems. In the study of Ref. [14], our results are compared with the data from pp and pPb collisions, whose source sizes are around 1 fm. In order to confirm the non-existence of the $N\Xi$ bound state, we need the data from the larger sources, which can be obtained by the heavy ion collisions. This is because, if there is a $N\Xi$ quasibound state, a dip structure is expected for the $p\Xi^-$ correlation function at larger source sizes. Another way for the further study of $S = -2$ interaction is to measure the Ξ^--deuteron correlation [16]. The $p\Xi^-$ correlation represents the sum of the $N\Xi$ $(I, J) = (0, 0), (0, 1), (1, 0)$, and $(1, 1)$

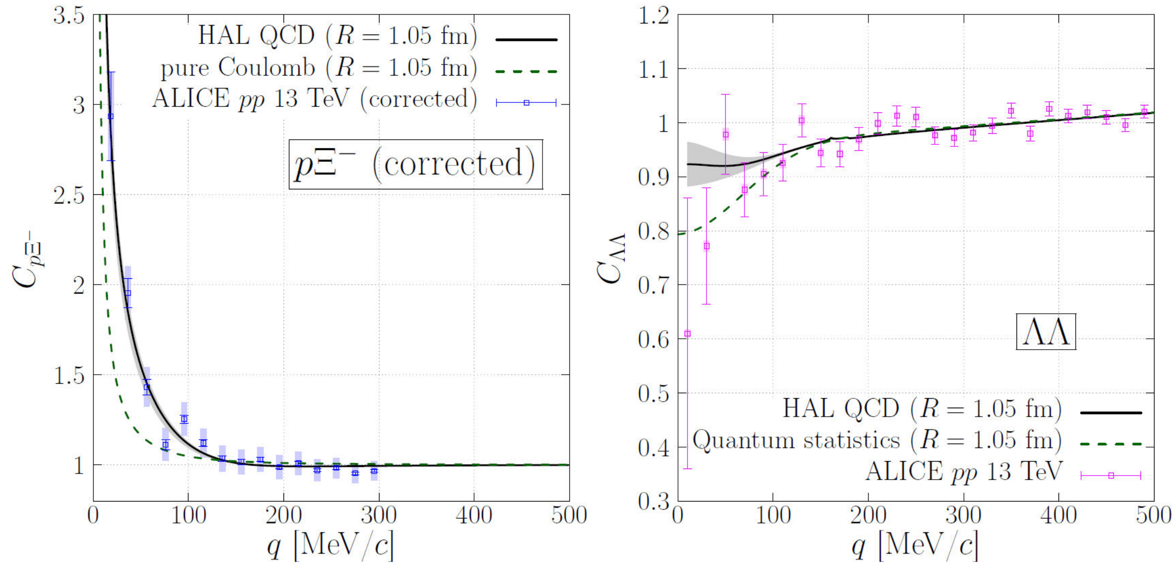

FIGURE 3. Experimental and theoretical correlation functions of the $p\Xi^-$ pairs (left panel) and the $\Lambda\Lambda$ pairs (right panel). The blank squares are the ALICE data with pp collisions at 13 TeV taken from Refs. [12, 13]. The statistical error and systematic error of data are denoted by the vertical line and the shaded bar, respectively. The solid lines are our results with the statistical and systematic uncertainties represented by the shaded region. The dashed lines show the results with only Coulomb interaction (only quantum statistics) for the $p\Xi^-$ ($\Lambda\Lambda$) correlation functions.

channels. To see the discrimination of these channels, the Ξ^--deuteron pair is a possible candidate in the future study.

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