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Study on hadron-hadron interaction with femtoscopic technique

Yuki Kamiya[1,2,*]

[1]Helmholtz Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, D-53115 Bonn, Germany
[2]RIKEN Interdisciplinary Theoretical and Mathematical Science Program (iTHEMS), Wako 351-0198, Japan

Abstract. We study the method to study the exotic hadrons using the femtoscopic correlation function in the high-energy collisions. The formula for the correlation function extended to the coupled-channel case is employed. We see that how the coupled-channel effect works for the correlation function from the different hadron emitting sources with the case of the $K^- p$ correlation function. The method is applied to the prediction for the $DD^*/D\bar{D}^*$ correlation function for the study of the $T_{cc}/X(3872)$ state.

1 Introduction

Recently, the new technique so called femtoscopy, for the hadoron-hadron interaction is beginning to be used to study hadron-hadron interaction. With this technique, we utilize the two-hadron intensity correlation in the high-energy nuclear collisions which is generated by the effect of quantum statistics and the final state interaction. This technique is originally used to investigate the detail of the hadron emitting source using the hadron pairs whose strong interaction is well known. For the study of hadron interaction, once the effective source size has been determined, the pairwise interaction of various hadron pairs can be studied by the measurement of the correlation function with the high statistics. This technique is quite useful in particular for the channel whose interaction is difficult to study through the scattering experiments, such as short-lived particles and heavy particles.

It is known that the correlation function is sensitive to the low-energy hadron interaction. Among various hadron pairs, the interesting systems to study in femtoscopy are systems related to the exotic hadrons. This is because, according to the Weinberg's weak-binding relation [1, 2], it is important to know the low-energy hadron interaction in detail in order to distinguish the nature of the near-threshold exotic states. As the XYZ states and T_{cc} state are representative, the many exotic hadron states in the heavy sector are found in the vicinity of the two-hadron threshold energies. Thus, by applying the femtoscopic study to the heavy hadron pairs, the nature of various exotic states can be investigated.

In this proceedings, we first review the recent femtoscopic study on the $\bar{K}N$ interaction. Next we discuss how we can apply the femtoscopic technique to the study of T_{cc} and $X(3872)$ states, whose nature is less known. The original contents on the study of $\bar{K}N$ (DD^* and $D\bar{D}^*$) interaction are found in Ref. [3] (Ref. [4]).

*e-mail: kamiya@hiskp.uni-bonn.de

2 Formalism

To calculate the correlation functions $C(q)$ with the coupled-channel effects, we employ the Koonin-Pratt-Lednicky-Lyuboshitz-Lyuboshitz formula (KPLLL) formula [3, 5, 6] given by

$$C(q) = \int d^3r \sum_{i=1}^{2} \omega_i S_i(r) |\Psi_i^{(-)}(q; \boldsymbol{r})|^2 , \tag{1}$$

where $\Psi^{(-)}$ is the wave function in the i-th channel written as a function of the relative coordinate r. This wave function must satisfy the outgoing boundary condition where the outgoing wave in the measured channel (channel 1) needs to be normalized. Because we consider the small momentum region, the modification of the s-wave component of the wave function is taken into account. Furthermore, $S_i(r)$ and ω_i are the normalized hadron emitting source function and its weight in i-th channel. This weight ω_i representing the ratio of the pair production yield in the i-th channel with respect to the measured channel must be determined in order to compare the theoretical models and experimental data. Due to the normalization of $C(q) = 1$ for the non-interacting case, ω_1 must be equal to unity. In general, this ratio can be written as [7]

$$\frac{\omega_j}{\omega_i} = \frac{\alpha_j}{\alpha_i} \frac{N(j_1)N(j_2)}{N(i_1)N(i_2)}, \tag{2}$$

where i_1, i_2, j_1 and j_2 are the labels of particles in each channel and α_i is the ratio of the number of particle pairs assigned to channel i among $N(i_1) \times N(i_2)$ with the number of particle i_k emitted from the hadron source $N(i_k)$. The factor α_i can be determined from the property of the channels, e.g. the spin degree and the ratio of particles. For $N(i_k)$, it is difficult to determine these values from experimental observables as we cannot directly observe the source function, however, it is reasonable to estimate it using the statistical model considering that it well reproduces hadron yields in the high-energy nuclear collisions. In this proceedings, we focus on the theoretical feature of the correlation function and we use the common Gaussian source function $S_i(r) = S_R(r) = \exp(-r^2/R^2)$ with the source size R and $\omega_i = 1$ for simplicity.

3 K^-p correlation function

First, we discuss the K^-p correlation function with the chiral SU(3) based effective potential. It is known that the detailed determination of the low-energy $\bar{K}N$ interaction and its coupling to the decay channels are very important for the study of nature of the $\Lambda(1405)$ state lying below the $\bar{K}N$ threshold energy. The scattering amplitude derived from the chiral SU(3) dynamics [8, 9] has been fitted by using an effective local $\bar{K}N$-$\pi\Sigma$-$\pi\Lambda$ coupled channels potential [10]. Solving the Schrödinger equation with the K^-p outgoing boundary condition, we obtain the squared wave functions for the KPLLL formula. The obtained wave function at $q = 50$ MeV/c and $q = 100$ MeV/c is shown in Fig. 1. We find that the wave functions in channels other than K^-p take significant values at small distances, while they are much smaller than that in K^-p at large distances. This is because of the K^-p outgoing boundary condition. From these wave functions, we can guess that contribution of the wave function components of these channels to K^-p correlation function is large for small size sources, but the K^-p wave function would be enough for large sources. Note that the coupled-channel effect contributes to the correlation function through the coupled-channel wave function $\Psi_i^{(-)}$ as well as $\Psi_{K^-p}^{(-)}$. This is because the Ψ_{K^-p} itself is affected by the channel coupling to the other channels.

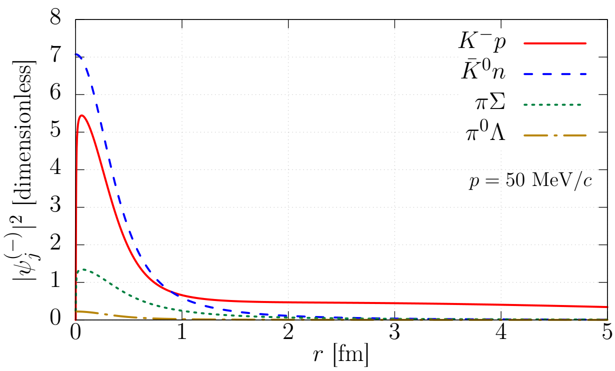

Figure 1. The square of each component of the coupled-channel wave function with $q = 50$ MeV (thin lines) and 100 MeV (thick lines). The solid, dashed, dotted, and dash-dotted line denote the K^-p, $\bar{K}^0n$, $\pi\Sigma$, and $\pi^0\Lambda$ component. For the $\pi\Sigma$ component, we show the sum of three components of $\pi^-\Sigma^+$, $\pi^0\Sigma^0$, and $\pi^+\Sigma^-$.

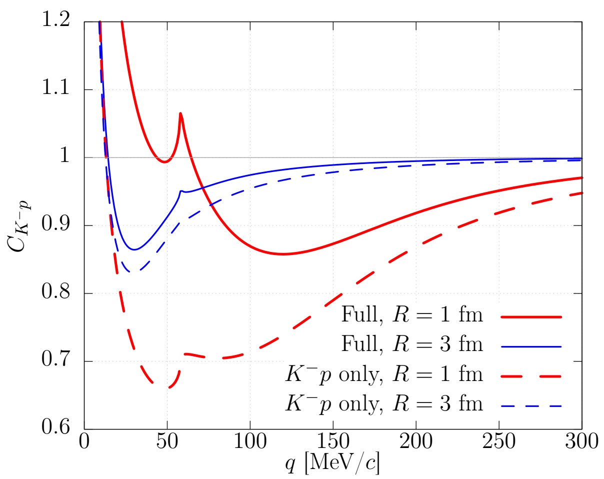

Figure 2. K^-p correlation function with $R = 1$ fm (thick lines) and $R = 3$ fm (thin lines). The long-dashed line denotes the result with K^-p component only. The solid lines show the full calculation result in which the contributions from all coupled-channel components are included.

We shall now calculate the K^-p correlation function using the coupled-channel wave function and the KPLLL formula. In Fig. 2, the results calculated with all the channel components of coupled-channel wave function (full calculation) and that calculated only with the K^-p component are shown for source sizes of $R = 1$ fm and 3 fm. For both source radii R, we see the strong enhancement due to the Coulomb attraction at small momenta and the cusp structure at the $\bar{K}^0n$ threshold at $q \simeq 58$ MeV/c. For the $R = 1$ fm case, the effect of the coupled-channel source, which is shown by the difference between the full calculation and the result with the K^-p component only, enhances the $C(q)$ in the low-momentum region and makes the cusp structure prominent. On the other hand, in the case of $R = 3$ fm, the coupled-channel source effect is moderate. This source size dependence of the coupled-channel source effect is due to the wave function components other than $K^- p$ taking significant values only at small distances as shown in Fig. 1. Thus, for the femtoscopy of the coupled-channel system, the correlation data from the small hadron sources is useful for the detailed study of the coupled-channel interaction while that from the large hadron sources is useful to directly see the interaction of the measured channel ($K^- p$).

4 DD^* and $D\bar{D}^*$ correlation function

Next we discuss the DD^* and $D\bar{D}^*$ correlation function for the study of T_{cc} and $X(3872)$. We assume that T_{cc} ($X(3872)$) state lies just below the D^0D^{*+} ($\{D^0\bar{D}^{*0}\} = (D^0\bar{D}^{*0} + \bar{D}^0D^{*0})/\sqrt{2}(C = +)$) threshold. This channel couples to the D^+D^{*0} (D^+D^{*-}) whose threshold energy is higher than that of D^0D^{*+} ($D^0\bar{D}^{*0}$). Since these channels lie close to each other, we take into account their coupled-channel effect. On the other hand, because the other channels that couple to these states are far from the energy region of interest, we do not include the coupled-channel source effect of these channels, however, the effect of the decay to the lower channels are partly included by using the complex optical potential for DD^* and $D\bar{D}^*$ interaction. We also assume that the $I = 0$ interaction, which is considered to generate the T_{cc} and $X(3872)$ states, gives the dominant contribution and we neglect the $I = 1$ interaction for simplicity.[1]

To calculate the wave function for the KPLLL formula, we use the Gaussian potential $V_{I=0}(r) = V_0 \exp(-m_\pi^2 r^2)$ with the pion mass m_π for DD^* and $D\bar{D}^*$ interaction. The complex interaction strength V_0 is determined so as to reproduce the empirically obtained scattering lengths. For the DD^* system, we use the scattering length $a_0^{D^0D^{*+}} = -7.16 + i1.85$ fm, which is determined in the experimental analysis in Ref. [11].[2] For the $D\bar{D}^*$ system, $a_0^{D^0\bar{D}^{*0}(C=+)} = -4.23 + i3.95$, which is determined by the eigenenergy $E_h = -0.04 - i0.60$ MeV in PDG [12] measured from the $D^0\bar{D}^{*0}$ threshold, is employed. We obtained $V_0 = -36.569 - i1.243$ MeV for the DD^* system and $V_0 = -43.265 - i6.091$ MeV for the $D\bar{D}^*$ system.

The D^0D^{*+} and $D^0\bar{D}^{*0}$ correlation functions are calculated with the determined potential as shown in Fig. 3. We see that both of the correlation functions show the strong source size dependence which is typical to the system with the near-threshold eigenstates. The cusp structure is found at the eigenmomentum corresponding to D^+D^{*0} (D^+D^{*-}) threshold energy in $C_{D^0D^{*+}}(q)$ ($C_{D^0\bar{D}^{*0}}(q)$) while it is moderate compared to that found in the $K^- p$ correlation function. On the other hand, we omit the results of correlation function of the higher channels (D^+D^{*0} and D^+D^{*-}) because these channels do not show such characteristic behavior. This is because the eigenenegies of T_{cc} and $X(3872)$ are much smaller than that of the deviation of threshold energies of isospin partners so that the only the wave functions of lower channels reflect the coupling to these states.

5 Summary

In this proceedings, we have discussed how the exotic states can be studied with the momentum correlation function obtained from the high-energy collision experiments. With the result of the $K^- p$ correlation function, we find that the coupled-channel source effect gives significant additional enhancement on the $K^- p$ correlation function especially for the small source case. On the other hand, the correlation function from the large source is not affected by this coupled-channel effect so much. Thus, with the careful comparison of the femtoscopic data

[1] The discussion with the different assumptions on the $X(3872)$ and $D\bar{D}^*$ interaction can be found in Ref. [4].

[2] Here we use the the high-energy physics convention for the scattering length where the positive (negative) real value corresponds to the weakly attractive (repulsive or strongly attractive) interaction.

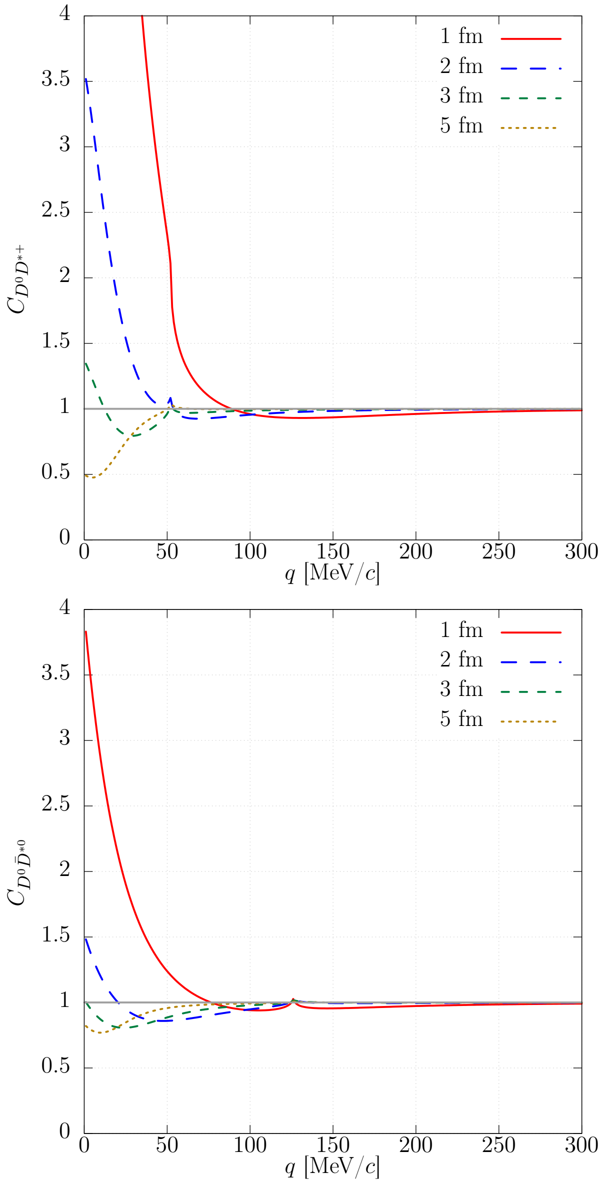

Figure 3. The D^0D^{*+} (upper panel) and $D^0\bar{D}^{*0}$ (lower panel) correlation function for several source sizes.

from the different source sizes and the theoretical models, the detailed $\bar{K}N$ interaction in the low-energy region can be determined.

In Ref. [4], it is found that the SU(3) chiral model works well to describe the ALICE K^-p correlation data from high-energy pp collisions [13] with the reasonable femtoscopic parameters. On the other hand, in the latest detailed analysis using both of the ALICE pp collisions and pPb collisions data [14], it is found that the theoretical chiral SU(3) model with the carefully determined source function cannot fully reproduce the data with the different source sizes. This deviation indicates that there is a possibility to further constrain the $\bar{K}N$ interaction to elucidate the nature of $\Lambda(1405)$.

Finally, we applied the KPLLL formula to the DD^* and $D\bar{D}^*$ correlation functions to elucidate the nature of the T_{cc} and $X(3872)$ states. We have found that both of the D^0D^{*+} and $D^0\bar{D}^{*0}$ correlation functions show the strong source size dependence due to the near-threshold states. According to Ref. [15], with the ALICE 3 upgrade with the large acceptance and the high luminosity, the DD^* and $D\bar{D}^*$ correlation data from both different colliding systems (pp and PbPb) can be measured with the great resolution, which is enough to see the characteristic behavior. Thus, by investigating the source size dependence of the DD^* and $D\bar{D}^*$ correlation function in the future experiments, the origin of the T_{cc} and $X(3872)$ can be distinguished.

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