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The correlation functions of $p\Xi^-$ and $\Lambda\Lambda$ pairs from pp and pA collisions are studied in the coupled-channel framework using the $N\Xi$-$\Lambda\Lambda$ coupled-channel baryon-baryon potentials obtained in the lattice QCD calculation at almost physical quark masses. The $p\Xi^-$ correlation function is calculated to be significantly enhanced from the pure Coulomb case, while the $\Lambda\Lambda$ correlation function is slightly enhanced from that of the pure fermion quantum statistics. These features reflect the large and small scattering lengths in the $p\Xi^-$ and $\Lambda\Lambda$ channels in magnitude, and agree with the observed data by the ALICE collaboration. The agreement confirms the $S = -2$ baryon-baryon potentials from lattice QCD.

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1. Introduction

The baryon-baryon interaction with $S = -2$ is important in exotic hadron and dense matter physics. The existence of the $H(uuddss)$ dibaryon state having $I = 0$, $S = -2$ and $J^\pi = 0^+$ has been one of the central issues in exotic hadron physics. The prediction of a deeply bound H from the $\Lambda\Lambda$ threshold [1] was ruled out by the discovery of the double Λ hypernucleus [2]: The double hypernucleus should decay strongly by emitting H via the H-$\Lambda\Lambda$ coupling if H is deeply bound, but until now several double hypernuclei have been found to decay weakly. The attraction in the H channel may still cause a $N\Xi$ bound state above the $\Lambda\Lambda$ threshold via the H-$\Lambda\Lambda$-$N\Xi$ coupling, while the $N\Xi$-$\Lambda\Lambda$ coupled-channel potential obtained from the lattice QCD calculation [3] does not predict a bound state of $\Lambda\Lambda$ and $N\Xi$. The $N\Xi$ and $\Lambda\Lambda$ interactions are also crucial for identifying the role of Λ and Ξ^- in neutron star matter: At several times the nuclear matter density, Λ and Ξ^- are expected to emerge in neutron star matter and soften the equation of state, which cannot support the two-solar-mass neutron stars (hyperon puzzle). We need precise knowledge on the two-body interactions in the strangeness sector at finite and zero densities to improve the theoretical predictions.

Femtoscopy is helpful to access the pairwise interaction as well as to deduce the existence of a bound state around the threshold. The momentum correlation function of two particles $C(q)$ is enhanced at low relative momenta q, when the interaction is attractive and the source is small. When the source size R is comparable with the absolute value of the scattering length, $R \sim |a_0|$, the correlation function is suppressed at small q if there is a bound state [4–6]. Together with the attractive Coulomb potential, the suppression at small q appears as a dip in the correlation function.

In this proceedings, we investigate the $p\Xi^-$ and $\Lambda\Lambda$ correlation functions using the $N\Xi$-$\Lambda\Lambda$ coupled-channel baryon-baryon potentials obtained from the lattice QCD calculation at almost physical quark masses [3]. We use the correlation function formula with the coupled-channel effects, the Koonin-Pratt-Lednicky-Lyuboshits-Lyuboshits (KPLLL) formula [6–9]. We also need to take care of the Coulomb potential and the threshold difference. The calculated correlation functions are compared with the recently obtained correlation function data of $p\Xi^-$ [10] and $\Lambda\Lambda$ [11] pairs. We assume the static Gaussian source function in the relative coordinate for simplicity. We find that the calculated results agree with the data well. Thus the $S = -2$ baryon-baryon potential from the lattice QCD is examined by the data. Details of the present work are given in Ref. [4].

2. $p\Xi^-$ and $\Lambda\Lambda$ correlation functions

The correlation function $C(\boldsymbol{q})$ in the single channel cases, referred to as the Koonin-Pratt formula [7], is extended to include the coupled-channel effects by Lednicky, Lyuboshits and Lyuboshits [8]. The extended version, the KPLLL formula, is revisited by Haidenbauer [9] and is applied to several correlation functions [4, 6, 9]. In the case of a non-identical particle pair and the static spherical source function, the KPLLL formula reads

$$C(q) = 1 + \int_0^\infty dr\, S_1(r) \left[|\psi_1^{(-)}(q;r)|^2 - |j_0(qr)|^2 \right] + \sum_{j>1} \int_0^\infty dr\, \omega_j S_j(r) |\psi_j^{(-)}(q_j;r)|^2, \quad (1)$$

where $S_j(r)$, ω_j, and q_j are the normalized source function, its weight, and the eigenmomentum in the jth channel, respectively. The measured channel is assigned as $j = 1$, and then $q = q_1$ shows

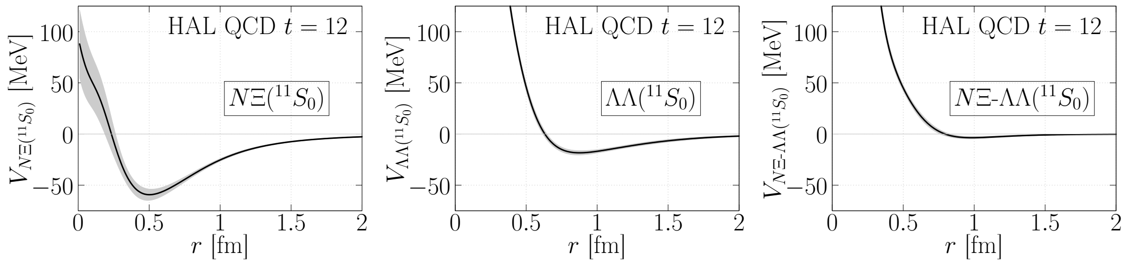

Figure 1: The s-wave coupled-channel $S = -2$ HAL QCD baryon-baryon potentials. The colored shadow denotes the statistical error of each potential.

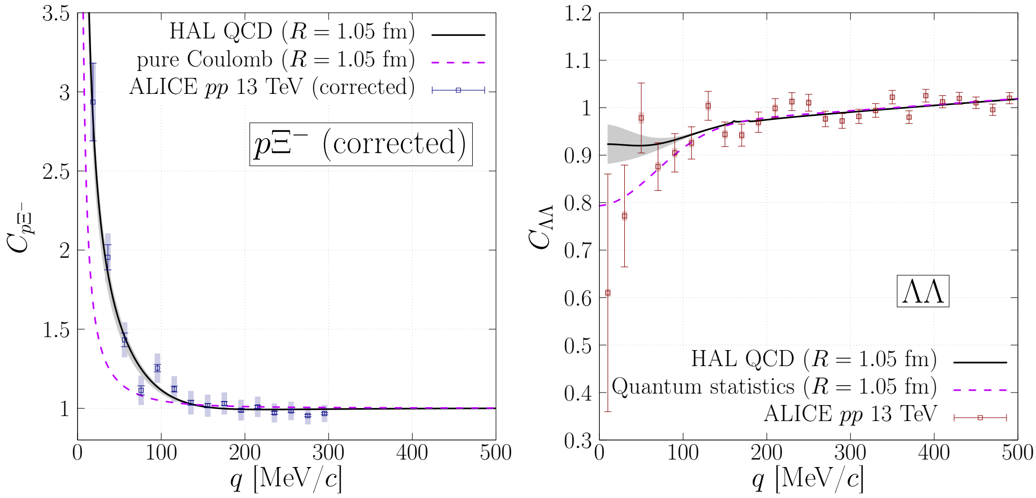

Figure 2: Comparison of calculated $p\Xi^-$ and $\Lambda\Lambda$ correlation function and experimental data. The left and right panels show the $p\Xi^-$ and $\Lambda\Lambda$ correlation functions fitted to 13 TeV pp collision data. The shaded area denotes the theoretical uncertainty of the correlation function. The ALICE data are taken from Refs. [10, 11].

the relative momentum in the measured channel. The first and second terms in Eq. (1) represent the single channel correlation function in the KP formula. We here ignore the Coulomb potential tentatively and assume that only the s-wave component is modified by the strong interaction. We need to impose the $\Psi^{(-)}$ boundary condition, where the outgoing wave component exists only in the measured channel ($j = 1$) in the correlation function. From Eq. (1), the correlation function is found to represent the average enhancement of the squared wave function within the source in the single channel case. By comparison, $C(q)$ is enhanced also by the wave functions in other channels in the coupled-channel case.

We use the $N\Xi$-$\Lambda\Lambda$ coupled-channel potentials from lattice QCD calculations at almost physical quark masses obtained by the HAL QCD collaboration [3]. Potentials in the isospin-singlet–spin-singlet ($^{11}S_0$) channel are shown in Fig. 1. We find significant attraction ($\simeq -50$ MeV) in the $N\Xi$ diagonal potential, but the $\Lambda\Lambda$ potential is weak. With these potentials, the scattering lengths in all the s-wave channels have negative real parts, and there is no bound state caused by the strong interaction in the $N\Xi$-$\Lambda\Lambda$ system.

In Fig. 2, we show the calculated $p\Xi^-$ and $\Lambda\Lambda$ correlation functions [4] in comparison with data from pp collisions at 13 TeV [10, 11]. Effects of the Coulomb potential, the coupled-channels, the threshold differences, and quantum statistics (for $\Lambda\Lambda$) are included. The source function is assumed to be a static Gaussian having a common size in $p\Xi^-$ and $\Lambda\Lambda$ channels, and its size is determined by fitting to the data. The obtained source size is $R = 1.05$ fm, which is consistent with the size obtained by the ALICE collaboration [10]. Details of the fitting procedure is found in Ref. [4]. The calculated and observed $p\Xi^-$ correlation functions show a strong enhancement over the pure Coulomb case at small q implying that the $N\Xi$ potential is significantly attractive. The $\Lambda\Lambda$ correlation function is enhanced slightly compared with the pure quantum statistical result both in the calculation and data. The small enhancement implies that the $\Lambda\Lambda$ potential is weakly attractive. The calculated results explains the data well.

3. Summary

We have investigated the $p\Xi^-$ and $\Lambda\Lambda$ correlation functions by using the $N\Xi$-$\Lambda\Lambda$ coupled-channel potentials from lattice QCD calculation at almost physical quark masses [3]. The calculated correlation functions in pp collisions agree with the data. This also applies to the correlation function from pPb collisions as discussed in Ref. [4]. Then we can conclude that the $N\Xi$-$\Lambda\Lambda$ potentials from lattice QCD in Ref. [3] are reasonable.

The strong enhancement of $p\Xi^-$ correlation function data at low momenta suggests that the $N\Xi$ potential is attractive, while the lattice QCD calculation does not predict a bound state of $N\Xi$. In order to confirm the non-existence of the $N\Xi$ bound state, the source size dependence of the correlation function needs to be studied. When there is a bound state of $N\Xi$ in the energy region between the $\Lambda\Lambda$ and $N\Xi$ thresholds, one expects a dip in the correlation function at a larger source size [4–6]. The preliminary STAR data [12] show enhancement in the $p\Xi^-$ correlation function from Au+Au collisions, and we do not find a dip. Thus, together with the ALICE data, it is plausible that there is no bound state in $N\Xi$ caused by the strong interaction.

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