

Title	$p$ Correlation in Relativistic Heavy Ion Collisions with Nucleon-Hyperon Interaction from Lattice QCD
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Citation	Nuclear Physics A (2017), 967: 856-859
Issue Date	2017-11
URL	<a href="http://hdl.handle.net/2433/233589">http://hdl.handle.net/2433/233589</a>
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Type	Journal Article
Textversion	publisher

# $p\Xi^-$ Correlation in Relativistic Heavy Ion Collisions with Nucleon-Hyperon Interaction from Lattice QCD

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## Abstract

On the basis of the  $p\Xi^-$  interaction extracted from (2+1)-flavor lattice QCD simulations at the physical point, the momentum correlation of  $p$  and  $\Xi^-$  produced in relativistic heavy ion collisions is evaluated.  $C_{\text{SL}}(Q)$  defined by a ratio of the momentum correlations between the systems with different source sizes is shown to be largely enhanced at low momentum due to the strong attraction between  $p$  and  $\Xi^-$  in the  $I = J = 0$  channel. Thus, measuring this ratio at RHIC and LHC and its comparison to the theoretical analysis will give a useful constraint on the  $p\Xi^-$  interaction.

*Keywords:* exotic dibaryon, hyperon-nucleon force, Lattice QCD

## 1. Introduction

The coupled-channel Nambu-Bethe-Salpeter (NBS) wave function measured in lattice QCD [1, 2] can now provide “theoretical” information of hyperon-nucleon and hyperon-hyperon interactions through the HAL QCD method [3, 4, 5, 6]. The energy-independent non-local potentials  $U(r, r')$  obtained by the method allow us to calculate the scattering phase shifts and binding energies of two baryons.

These potentials are also useful for analyzing the two-particle momentum correlations in relativistic heavy ion collisions [7]. It was recently studied in [8] that the possible spin-2  $p\Omega^-$  dibaryon state suggested by lattice QCD [9] can be probed by the  $p\Omega^-$  momentum correlation at RHIC and LHC. In particular, the ratio of correlation functions between small and large collision systems,  $C_{\text{SL}}(Q)$ , is shown to be a good measure to extract the strong interaction effect without much contamination from the Coulomb effect [8]. In the present paper, we extend the analysis to the  $p\Xi^-$  system in  $I = J = 0$  channel which was recently predicted to have large attraction by the lattice QCD simulations at physical quark masses [4].

## 2. Lattice QCD formulation

We start with the normalized four-point function  $R$  in channel  $\alpha$  defined by

$$R^\alpha(\vec{r}, t) \equiv \frac{\langle 0 | B_{\alpha_1}(\vec{x} + \vec{r}, t) B_{\alpha_2}(\vec{x}, t) \overline{\mathcal{F}}(0) | 0 \rangle}{\sqrt{Z_{\alpha_1} Z_{\alpha_2}} \exp[-(m_{\alpha_1} + m_{\alpha_2})t]}, \quad (1)$$

where  $B_{\alpha_1}(\vec{x}, t)$  and  $B_{\alpha_2}(\vec{x}, t)$  are the sink operators for octet baryons.  $\sqrt{Z_{\alpha_1}}$   $\sqrt{Z_{\alpha_2}}$  are the corresponding wave-function renormalization factors, and  $\mathcal{J}(0)$  is a source operator at zero initial-time to create two baryons. The coupled channel potential is obtained through the linear partial differential equation [2];

$$(D_t^\alpha - H_0^\alpha)R^\alpha(\vec{r}, t) = \int d^3r' U^{\alpha\beta}(\vec{r}, \vec{r}')\Delta^{\alpha\beta}R^\beta(\vec{r}', t), \quad (2)$$

with  $H_0^\alpha = -\frac{\nabla^2}{2\mu^\alpha}$  and  $\Delta^{\alpha\beta} = \exp[-(m_{\beta_1} + m_{\beta_2})t]/\exp[-(m_{\alpha_1} + m_{\alpha_2})t]$ .  $D_t^\alpha$  is a time-derivative operator whose leading-order term reads  $-\partial/\partial t$ . We introduce a derivative expansion to treat the non-local potential as

$$U^{\alpha\beta}(\vec{r}, \vec{r}') = (V_{\text{LO}}^{\alpha\beta}(\vec{r}) + V_{\text{NLO}}^{\alpha\beta}(\vec{r}) + \dots)\delta(\vec{r} - \vec{r}'). \quad (3)$$

In the following, we truncate the expansion at the leading order.

We employ (2 + 1)-flavor QCD configurations on the  $L^4 = 96^4$  lattice with the lattice spacing  $a \simeq 0.085\text{fm}$ . This corresponds to the physical size,  $La = 8.1\text{fm}$ , which guarantees that the finite volume effect on  $U^{\alpha\beta}(\vec{r}, \vec{r}')$  is negligible. The quark masses are chosen for the system to be almost at the physical point;  $m_\pi \simeq 146\text{ MeV}$  and  $m_K \simeq 525\text{ MeV}$  [4]. The total number of configurations is  $414 \times 4$  space-time rotations  $\times 48$  wall sources. The baryon masses measured in this setup are listed below.

baryon	$N$	$\Lambda$	$\Sigma$	$\Xi$
mass [MeV]	$953 \pm 7$	$1123 \pm 3$	$1204 \pm 2$	$1332 \pm 1$

### 3. $p\Xi^-$ potential in $I = 0$ channel

The  $S = -2$  baryon-baryon interactions including the  $I=0$   $\Lambda\Lambda - N\Xi - \Sigma\Sigma$  coupled-channel system have been recently reported in [4]. In particular, one of the diagonal components  $V_{N\Xi, N\Xi}(r)$  in the  $(I, J) = (0, 0)$  channel ( $^1S_0$ ) was shown to have large attractive well at intermediate distance and relatively weak repulsive core at short distance, while  $V_{N\Xi, N\Xi}(r)$  in the  $(I, J) = (0, 1)$  channel ( $^3S_1$ ) has weaker attractive well and stronger repulsive core. Also,  $V_{N\Xi, N\Xi}(r)$  in the  $I = 1$  channels do not have appreciable attraction. Motivated by these observations, we parametrize the lattice results of  $V_{N\Xi, N\Xi}(r)$  in the  $I = 0$  channels by a combination of the Gauss and Yukawa functions as shown in Fig.1. Curves with different  $t$  correspond to the potentials obtained from  $R(\vec{x}, t)$  for different  $t$ , so that the  $t$  dependence of  $V(r)$  reflects typical magnitude of the systematic error of the lattice data. We found that the strong QCD attraction in Fig.1(Left) together with the Coulomb attraction leads to the  $^1S_0$  system close to the unitary region where the inverse of the scattering length is close to zero. On the other hand, the  $^3S_1$  system described by Fig.1(Right) has strong repulsion even with the Coulomb attraction.

### 4. $p\Xi^-$ momentum correlation

The correlation function of non-identical pair such as  $p\Xi^-$  is given in terms of the two-particle distribution  $N_{p\Xi}(\mathbf{k}_p, \mathbf{k}_\Xi)$  normalized by a product of the single particle distributions,  $N_\Xi(\mathbf{k}_\Xi)N_p(\mathbf{k}_p)$ ,

$$C(\mathbf{Q}, \mathbf{K}) \equiv \frac{N_{p\Xi}(\mathbf{k}_p, \mathbf{k}_\Xi)}{N_p(\mathbf{k}_p)N_\Xi(\mathbf{k}_\Xi)} \simeq \frac{\int d^4x_p \int d^4x_\Xi S_p(x_p, \mathbf{k}_p)S_\Xi(x_\Xi, \mathbf{k}_\Xi) |\Psi_{p\Xi}(\mathbf{r}')|^2}{\int d^4x_p S_p(x_p, \mathbf{k}_p) \int d^4x_\Xi S_\Xi(x_\Xi, \mathbf{k}_\Xi)},$$

where relative and total momenta are defined as  $\mathbf{Q} = (m_p\mathbf{k}_\Xi - m_\Xi\mathbf{k}_p)/M$  and  $\mathbf{K} = \mathbf{k}_p + \mathbf{k}_\Xi$ , respectively, with  $M \equiv m_p + m_\Xi$ . The source functions  $S_i(x_i, \mathbf{k}_i) \equiv E_i \frac{dN_i}{d^3\mathbf{k}_i d^4x_i}$  (with  $i = p, \Xi$  and  $E_i = \sqrt{\mathbf{k}_i^2 + m_i^2}$ ) correspond to the phase space distributions of  $p$  and  $\Xi$  at freeze-out. The final state interaction after the freeze-out is described by the two-particle wave function  $\Psi_{p\Xi}$  with a shifted relative coordinate  $\mathbf{r}' = \mathbf{x}_\Xi - \mathbf{x}_p - \mathbf{K}(t_p - t_\Xi)/M$ .

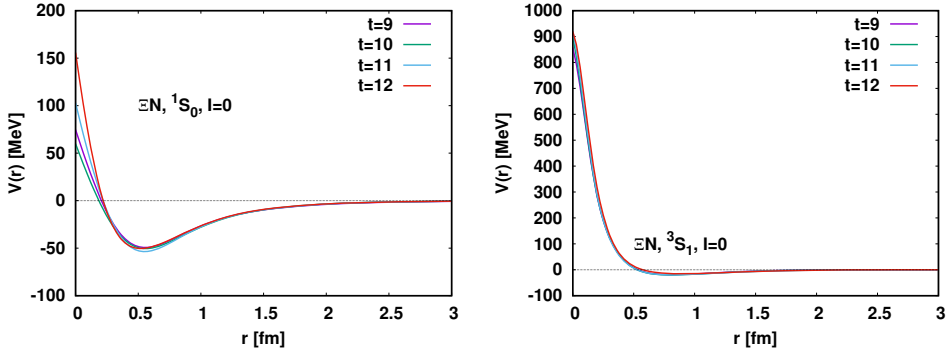


Fig. 1. The  $N\Xi$  potentials in the  $I = 0$  channel fitted to the (2+1)-flavor lattice QCD data at the physical point. Euclidean time used for extracting the lattice QCD potential is denoted by  $t$ . (Left) The potential in the  $(I, J) = (0, 0)$  channel ( $^1S_0$ ). (Right) The potential in the  $(I, J) = (0, 1)$  channel ( $^3S_1$ ).

Here we consider the static source function with spherical symmetry to extract the essential part of physics;

$$S_i(x_i, \mathbf{k}_i) \propto E_i e^{-\frac{x_i^2}{2R_i^2}} \delta(t - t_i), \quad (i = p, \Xi^-), \quad (4)$$

where  $R_i$  is a source size parameter. Assuming the equal-time emission  $t_p = t_\Xi$ , we obtain

$$C(Q) = \int [dr] \int \frac{d\Omega}{4\pi} |\psi^C(\mathbf{r})|^2 + \frac{1}{8} \int [dr] (|\chi_{sc}^{J=0}(r)|^2 - |\psi_0^C(r)|^2) + \frac{3}{8} \int [dr] (|\chi_{sc}^{J=1}(r)|^2 - |\psi_0^C(r)|^2), \quad (5)$$

where  $[dr] = \frac{1}{2\sqrt{\pi}R^3} dr r^2 e^{-\frac{r^2}{4R^2}}$  with  $R = \sqrt{(R_p^2 + R_\Xi^2)}/2$  being the effective size parameter.  $\int d\Omega$  is the integration over the solid angle between  $\mathbf{Q}$  and  $\mathbf{r}$ . Note that  $\psi^C(\mathbf{r})$  is the Coulomb wave function characterized by the reduced mass and the Bohr radius of the  $p\Xi^-$  system. Its S-wave component is denoted by  $\psi_0^C(r)$ . The scattering wave functions obtained by solving the Schrödinger equation with both strong interaction and Coulomb interaction are denoted by  $\chi_{sc}^{J=0}(r)$  and  $\chi_{sc}^{J=1}(r)$  for the  $^1S_0$  channel and  $^3S_1$  channel, respectively. We assume that the  $I = 1$  sector does not contribute substantially to  $C(Q)$ , which is supported by the fact that the  $I = 1$   $p\Xi^-$  potential has only short-range repulsion [4]. The factors  $1/8 = 1/2 \times 1/4$  and  $3/8 = 1/2 \times 3/4$  originate from the isospin and spin multiplicities. Also, we assume that the absorptive contribution by the coupling to the  $\Lambda\Lambda$  channel is negligible since it is reported to be weak due to its short range nature [4].

In [8], the ‘‘SL (small-to-large) ratio’’ was introduced: It is defined as a ratio of  $C(Q)$  between the systems with different source sizes,

$$C_{SL}(Q) \equiv C_{R_{p,\Xi}=2.5\text{fm}}(Q)/C_{R_{p,\Xi}=5\text{fm}}(Q), \quad (6)$$

which has good sensitivity to the strong interaction without much contamination from the Coulomb interaction [8]. Shown in Fig.2 is  $C_{SL}(Q)$  of the  $p\Xi^-$  system with the Coulomb interaction under the assumption of the static source given in Eq.(4).

The large enhancement of this ratio at small  $Q$  originates from the fact that the  $p\Xi^-$  system in the  $^1S_0$  channel is close to the unitary region. The result has rather weak dependence on  $t$ , which indicates that the systematic errors of the lattice data do not affect the final results significantly. We have also checked that taking the expanding source as discussed in [8] does not change the present result.

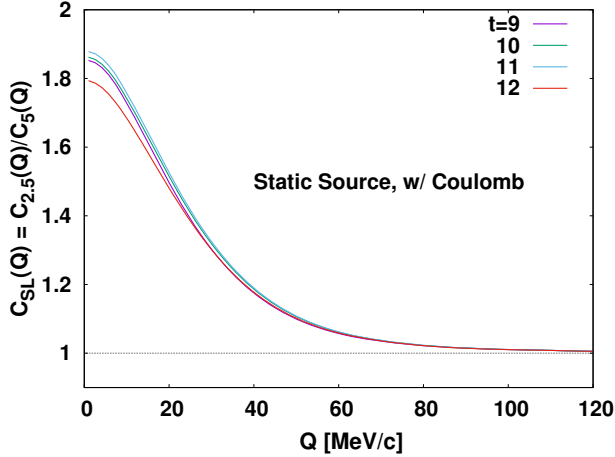


Fig. 2. SL (small-to-large) ratio  $C_{SL}(Q)$  for the momentum correlation of  $p\Xi^-$  system as a function of the relative momentum  $Q$  in the case of the static source. Both the strong and Coulomb interactions are taken into account for the  $p\Xi^-$  interaction. Different curves correspond to different potentials shown in Fig. 1.

## 5. Summary

The momentum correlation of the  $p\Xi^-$  system was presented by employing the  $p\Xi^-$  potential extracted from the coupled channel analysis of the (2+1)-flavor lattice QCD data at the physical point. So-called the SL-ratio of the momentum correlation ( $C_{SL}(Q)$ ) was calculated and was shown to have large enhancement at small  $Q$  due to the strong attraction between  $p$  and  $\Xi^-$  in the  $^1S_0$  channel. Measuring this ratio at RHIC and LHC and its comparison to the present theoretical analysis will give useful constraint on the  $p\Xi^-$  interaction. Such information is particularly important not only for the nature of the possible  $H$ -dibaryon coupled to  $p\Xi^-$  [4] but also for the properties of  $\Xi$ -hypernuclei [10] and for  $\Xi^-$  in the central core of the neutron star [11].

## Acknowledgments

This work is supported in part by MEXT Grant-in-Aid for Scientific Research (JP15K17667, 24105008), SPIRE (Strategic Program for Innovative REsearch) Field 5 project and "Priority Issue on Post-K computer" (Elucidation of the Fundamental Laws and Evolution of the Universe). K.M. was supported by JSPS Grant 16K05349, and National Science Center, Poland under grants: Maestro DEC-2013/10/A/ST2/00106. T.H. was partially supported by RIKEN iTHES Project and iTHEMS Program. The authors thank HAL QCD Collaboration for proving us with the data for  $p\Xi^-$  interactions and for stimulating discussions.

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