Meson-Meson and Meson-Baryon Interactions in Lattice QCD

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Abstract. We study the meson-meson and meson-baryon interactions in lattice QCD. The simulation is performed on $20^3 \times 24$ lattice at $\beta = 5.7$ using Wilson gauge action and Wilson fermion at the quenched level. By adopting one static quark for each hadron as “heavy-light meson” and “heavy-light-light baryon”, we define the distance $r$ of two hadrons and extract the inter-hadron potential from the energy difference of the two-particle state and its asymptotic state. We find that both of the meson-meson and meson-baryon potentials are nontrivially weak for the whole range of $0.2 \text{fm} < r < 0.8 \text{fm}$. The effect of including/excluding the quark-exchange diagrams is found to be marginal.

INTRODUCTION

One of the main goals in hadron physics is to understand the nature of the nuclear system and its interaction from the fundamental theory. Although nuclear potential models have been developed as semi-fundamental theories of nuclei, the relation between these potential models and the genuine fundamental theory, QCD, is not still revealed yet. In particular, the short-range part of the hadron-hadron interaction is of our interest, because the degrees of freedom of quarks and gluons in QCD are expected to be most relevant in this range, while the degrees of freedom of mesons and baryons are more relevant for the long-range interaction, as is well established in one-pion exchange in nuclear force. Although effective short-range interactions such as spin-spin interaction are proposed so far, it is desirable to analyze from nonperturbative first-principle QCD calculations, such as lattice QCD. It is also worth pointing out that recent experimental discoveries of tetra-, penta- and nona-quark candidates require the precise information about the interaction between meson-meson, meson-baryon and baryon-baryon. With these motivations, we study meson-meson, meson-baryon and baryon-baryon interactions in lattice QCD. The former two are presented in this paper, while the latter is presented elsewhere [1]. The analysis in static quark limit is also given in this proceedings [2].

THE FORMALISM AND LATTICE QCD RESULTS

We analyze the meson-meson and meson-baryon interactions using SU(3)$_c$ lattice QCD. By calculating the correlation function of hadron-hadron operators, we evaluate the en-
energy of the hadron-hadron system. The difference between the energy of the two-particle state and the sum of the energy of one-particle states corresponds to the interaction of the particles. In order to extract the potential as a function of the distance of two hadrons, we consider the system with (infinitely) heavy-light mesons and a heavy-light-light baryon. In fact, the center of mass of each hadron is defined by the location of the (heavy) static quark, and therefore we can define the distance \( r \) of two hadrons of concern. This is a more convenient way than performing the scattering state analysis using the Lüscher formula, which is very expensive. The same technique is also used in Ref. [3]. We evaluate the correlation function \( \Pi(\vec{x}, \vec{y}; t) = \langle J(\vec{x}, \vec{y}; t)\bar{J}(\vec{x}, \vec{y}; 0) \rangle \), where the operator \( J(\vec{x}, \vec{y}; t) \) is taken as \( J(\vec{x}, \vec{y}; t) = J_M(\vec{x}; t)J_M(\vec{y}; t) \) or \( J(\vec{x}, \vec{y}; t) = J_B(\vec{x}; t)J_M(\vec{y}; t) \) for a meson-meson or a meson-baryon system, respectively. Here, the inter-meson/meson-baryon distance can be expressed as \( r = |\vec{x} - \vec{y}| \). Using the rotational/translational symmetry, we pick up 2-4 spatial configurations for \((\vec{x}, \vec{y})\) on the lattice and average them at each gauge configuration, which leads to higher statistics. In this paper, we consider an open heavy-flavored pseudoscalar meson \( J_M(\vec{x}; t) \equiv \bar{q}(\vec{x}; t)i\gamma_5 q(\vec{x}; t) \), and a heavy-flavored \( \Lambda \) baryon \( J_B(\vec{x}; t) \equiv \epsilon_{abc}(q_a^T(\vec{x}; t)C\gamma_5 q_b(\vec{x}; t))Q_c(\vec{x}; t) \), where \( q \) denotes a light-quark and \( Q \) a static quark. Interactions with other meson/baryon systems are subjects for future work.

In the evaluation of the correlation function, we have two kinds of diagrams depending on the flavor assignment for light quarks in the hadrons. In fact, if the flavors of light-quarks in two hadrons of concern are different each other, only diagrams without quark exchange can contribute to the correlation function, as is shown in Fig. 1 (left). On the other hand, if the flavors in two hadrons are identical, not only non-exchange diagrams but also exchange diagrams contribute to the correlation function, as is shown in Fig. 1 (left+right). We analyze both of the two cases, in order to study the possible effect from the Pauli-blocking, direct quark exchange and/or effective meson exchange.

We perform the Monte Carlo simulations with the standard Wilson action for \( \beta = 5.7 \) \((a \approx 0.19 \text{ fm})\) at the quenched level and generate about 200 gauge configurations. In order to accommodate two hadrons in the lattice, we adopt the large lattice of \( 20^3 \times 24 \), which corresponds to \((3.8 \text{ fm})^3 \times 4.6 \text{ fm}\) in the physical scale. We employ Wilson fermion with the hopping parameter \( \kappa = 0.1600, 0.1625, 0.1650 \) for a light quark \( q \), which roughly corresponds to \( m_\pi \approx 500 - 700 \text{ MeV} \).

In Fig. 2 we plot the lattice results of the meson-meson potential and the meson-baryon potential for \( \kappa = 0.1600 \). We find that both of the interaction are rather weak.
FIGURE 2. The meson-meson potential (left) and the meson-baryon potential (right) in terms of the distance $r$ of two hadrons for $\kappa = 0.1600$. The triangle (circle) symbols denote the results without (with) quark exchange diagrams.

for the whole range of distance $0.2 \text{fm} \lesssim r \lesssim 0.8 \text{fm}$. This is quite nontrivial, considering that the short-range interaction in nuclear potential at least amounts to several hundred MeV. In Fig. 2 it is also shown that the inclusion/exclusion of quark exchange diagrams yields marginal effects on the potential.

As a physical reason why the potential is so weak, we examine the possibility that the spin-spin interaction is weakened in this lattice QCD simulation, because the adopted quark mass is larger than the physical light-quark mass. In fact, in the quark model, the spin-spin interaction is suppressed by the (constituent) quark mass. We, however, find that analyses with lighter quark mass ($\kappa = 0.1625, 0.1650$) also yield the similar nontrivially weak potential, which indicates that the above possibility is not a main scenario. Further studies are in progress, for example, from the viewpoint of specific choice of operators, to understand the physics of this nontrivial lattice result.

In summary, we have investigated the meson-meson and meson-baryon interactions in lattice QCD at the quenched level. By adopting one static quark for each hadron, we have defined the distance $r$ of two hadrons and have extracted the inter-hadron potentials. We have found that both of the meson-meson and meson-baryon potentials are nontrivially weak. The effect of including/excluding the quark-exchange diagrams has been found to be marginal.

The lattice QCD Monte Carlo simulations have been performed on NEC SX-5 at Osaka University and HITACHI SR8000 at KEK.

REFERENCES

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