PROPERTIES OF SCALAR-QUARK SYSTEMS IN SU(3)$_c$ LATTICE QCD

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We perform the first study for the bound states of colored scalar particles $\phi$ (“scalar quarks”) in terms of mass generation with quenched SU(3)$_c$ lattice QCD. We investigate the bound states of $\phi$, $\phi^\dagger \phi$ and $\phi \phi^\dagger$ (“scalar-quark hadrons”), as well as the bound states of $\phi$ and quarks $\psi$, i.e., $\phi^\dagger \psi$, $\psi \psi \phi$ and $\phi \phi^\dagger \psi$ (“chimera hadrons”). All these new-type hadrons including $\phi$ have a large mass of several GeV due to large quantum corrections by gluons, even for zero bare scalar-quark mass $m_\phi = 0$ at $a^{-1} \sim 1$GeV. We find a similar $m_\phi$-dependence between $\phi^\dagger \psi$ and $\phi \phi^\dagger \psi$, which indicates their similar structure due to the large mass of $\phi$. From this study, we conjecture that all colored particles generally acquire a large effective mass due to dressed gluons.

Keywords: Dynamical mass generation; Lattice QCD; Scalar-quarks; Diquarks.

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1. Introduction

The origin of mass is one of the fundamental and fascinating subjects in physics. About 99% of mass of matter in the world originates from the strong interaction, which provides the large constituent quark mass $M_\psi = (300 - 400)$MeV. Such a dynamical fermion-mass generation in the strong interaction can be interpreted as spontaneous chiral-symmetry breaking ($\chi$SB)

In the strong interaction, however, there is other type of dynamical mass generation than $\chi$SB. For instance, gluons, which are massless in perturbation QCD, seem to have a large effective mass as $(0.5 - 1.0)$GeV due to non-perturbative effects. Actually, glueballs, which are ideally composed only by gluons, have a large mass, e.g., about 1.5GeV. The same holds for charm quarks. Whereas the current mass of charm quarks is about 1.2GeV at the renormalization point $\mu = 1$GeV,
the constituent charm-quark mass in the quark model is set to be about 1.6GeV. The about 400MeV difference between the current and the constituent charm-quark masses could be explained by dynamical mass generation without \( \chi_{\text{SB}} \), since there is no chiral symmetry for such heavy quarks. These examples imply mass generation without \( \chi_{\text{SB}} \) in the strong interaction. We therefore conjecture that large dynamical mass generation generally occurs even without \( \chi_{\text{SB}} \) in the strong-interaction world, i.e., all colored particles have a large effective mass generated by dressed gluon effects. In this study, we investigate the system of colored scalar particles, which do not have chiral symmetry.

### 2. Scalar-quark Hadrons and Chimera Hadrons in Lattice QCD

We consider light 3c-colored “scalar-quarks” \( \phi \). The light scalar-quarks can be also regarded as idealized point-like “diquarks” at the scale of \( a^{-1} \sim 1\text{GeV} \). We investigate “scalar-quark mesons” \( \phi^\dagger \phi \) and “scalar-quark baryons” \( \phi \phi \phi \) as the bound states of scalar quarks \( \phi \). We also investigate the bound states of scalar-quarks \( \phi \) and quarks \( \psi \), i.e., \( \phi^\dagger \psi \), \( \psi \psi \phi \) and \( \phi \phi \psi \), which we name “chimera hadrons.”

To include scalar-quarks \( \phi \) together with quarks \( \psi \) and gluons in QCD, we adopt the generalized QCD Lagrangian density,

\[
L = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \mathcal{L}_F + \mathcal{L}_{\text{SQ}}, \quad \mathcal{L}_{\text{SQ}} = \text{tr} \left( D_\mu \phi \right)^\dagger (D^\mu \phi) - m_\phi^2 \text{tr} \phi^\dagger \phi, \tag{1}
\]

where \( \mathcal{L}_F \) denotes the quark part and \( m_\phi \) the bare mass of scalar-quarks \( \phi \). In the actual calculation, we use a discretized Euclidean action on the \( 16^3 \times 32 \) lattice at \( \beta = 5 \) \( .7 \), i.e., lattice spacing \( a^{-1} \sim 1.1\text{GeV} \). The parameters employed in the analysis are summarized in Table 1.

The gauge-invariant local operators \( O(\mathbf{x}, t) \) of scalar-quark hadrons and chimera hadrons are summarized in Table 2. We introduce “scalar-quark flavor” denoted by \( i, j, k \) and investigate the scalar-quark flavor non-singlet mesons, which do not have disconnected diagrams in their correlators. Note that, without the “scalar-quark flavor” degrees of freedom, the baryonic local operators of \( \phi \phi \phi \) and \( \phi \phi \psi \) inevitably

| Names                  | Lorentz properties | Local operators                                                                 |
|------------------------|--------------------|-------------------------------------------------------------------------------|
| Scalar-quark meson     | Scalar             | \( M_i(x) = \Gamma^{ij}_M \phi_i^\dagger(x) \phi_j(x) \)                     |
| Scalar-quark baryon    | Scalar             | \( B_i(x) = \Gamma^{ijk}_B \epsilon_{abc} \phi_i^\dagger(x) \phi_j(x) \phi_k(x) \) |
| Chimera meson          | Spinor             | \( C^a_M(x) = \phi_a(x) \psi(x) \)                                           |
| Chimera baryon         | Scalar             | \( C_B(x) = \epsilon_{abc} (\psi_a^\dagger(x) C_{75} \psi_b(x)) \phi_c(x) \) |
| Chimera baryon         | Spinor             | \( C_B^a(x) = \Gamma^{ijk}_B \epsilon_{abc} \phi_i^\dagger(x) \phi_j(x) \psi_c(x) \) |
vanish due to the anti-symmetric tensor $\epsilon_{abc}$. We calculate the temporal correlator $G(t) = \overline{\psi} \sum_{\vec{x}} \langle O(\vec{x}, t)O(\vec{0}, 0) \rangle$, where the total momentum is projected to be zero. The mass $M$ of these hadrons is obtained as $M \approx -\frac{1}{T} \ln G(T)$ for large $T$.

Here, we show the lattice results for the masses of new-type hadrons. Figure 1 shows the squared scalar-quark-meson mass $M_{\phi^+\phi}^2$ and the squared scalar-quark-baryon mass squared $M_{\phi\phi\phi}^2$, plotted against the bare scalar-quark mass squared $m_{\phi}^2$ at $a^{-1} \approx 1.1$GeV. Even for zero bare scalar-quark mass, scalar-quark hadrons have a large mass as $M_{\phi^+\phi} \approx 3$GeV and $M_{\phi\phi\phi} \approx 4.7$GeV. We find the “constituent scalar-quark picture”, i.e., $M_{\phi^+\phi} \approx 2M_{\phi}$ and $M_{\phi\phi\phi} \approx 3M_{\phi}$, where $M_{\phi} \approx (1.5 - 1.6)$GeV is the constituent scalar-quark mass. The calculation can be performed even in the region $m_{\phi}^2 < 0$ due to large quantum corrections on $\phi$. We also find the relations, $M_{\phi^+\phi}^2 \approx 4m_{\phi}^2 + \text{const.}$ and $M_{\phi\phi\phi}^2 \approx 9m_{\phi}^2 + \text{const.}$ from the figure. Together with the “constituent scalar-quark picture”, we reach the relation $M_{\phi}^2 \approx m_{\phi}^2 + \Sigma_{\phi}$, where $\Sigma_{\phi}$ is the self-energy of $\phi$ and is expected to be insensitive to $m_{\phi}$. This is a natural relation between the renormalized mass and the bare mass for scalar particles.

Chimera hadrons also have a large mass even at $m_{\phi} = m_{\psi} = 0$, i.e., $M_{\phi^+\phi} \approx 1.9$GeV for chimera mesons $\phi^+\psi$, and $M_{\psi\psi\phi} \approx 2.2$GeV, $M_{\phi\psi\psi} \approx 3.6$GeV for chimera baryons $(\psi\phi, \phi\phi\psi)$. We find a “constituent scalar-quark/quark picture”, i.e., an approximate relation as $M_{m_{\phi} + n_{\psi}} \approx m_{\phi} + n_{\psi}$ with the constituent quark mass $M_{\phi} \approx 0.4$GeV, and the large constituent scalar-quark mass $M_{\phi} \approx (1.5 - 1.6)$GeV.
From the $m_\psi$-dependence of chimera hadron masses, we conjecture a similar structure between chimera mesons $\phi^\dagger \psi$ and chimera baryons $\phi \phi \psi$.\(^9\) The wave-function of $\psi$ in a chimera meson $\phi^\dagger \psi$ is distributed around the heavy scalar-quark $\phi^\dagger$ due to the large mass of $\phi$, and, similarly, the wave-function of $\psi$ in a chimera baryon $\phi \phi \psi$ is distributed around the point-like “di-scalar-quark” $\phi \phi$. (See Fig. 2.)

3. Summary and Conclusion

We have performed the first study of light “scalar-quarks” $\phi$ (colored scalar particles or idealized diquarks) and their color-singlet hadronic states in quenched SU(3)\(_c\) lattice QCD in terms of dynamical mass generation. We have investigated the mass of “scalar-quark mesons” $\phi^\dagger \phi$, “scalar-quark baryons” $\phi \phi \phi$ and “chimera hadrons” ($\phi^\dagger \psi$, $\psi \psi \phi$, $\phi \phi \psi$), which are composed of quarks $\psi$ and scalar-quarks $\phi$. We have observed the large dynamical mass generation of scalar-quarks $\phi$ about 1.5GeV at $a^{-1} \simeq 1.1\text{GeV}$ due to large quantum corrections by gluons, even at the zero bare scalar-quark mass $m_\phi = 0$. This lattice result also indicates that plausible diquarks used in effective hadron models cannot be described as the point-like particles and should have a much larger size than $a \simeq 0.2\text{fm}$\(^9\)\(^10\).

This study indicates that, even without $\chi_{\text{SB}}$, large dynamical mass generation in the strong interaction occurs for the scalar-quark systems. Together with the large glueball mass and the large difference between the current and the constituent charm-quark masses, this type of mass generation would generally occur in the strong interaction, and therefore we conjecture that all colored particles generally acquire a large effective mass due to dressed gluon effects\(^9\)\(^10\) as shown in Fig. 3.

![Fig. 3. Schematic figure for dynamical mass generation of colored particles. Even without chiral symmetry breaking, colored particles generally acquire a large effective mass due to dressed gluons.](image)

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