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Meson mass decomposition from lattice QCD

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Hadron masses can be decomposed as a sum of quark and glue components that are defined through hadronic matrix elements of QCD operators. The components consist of the quark mass term, the glue energy term, the trace anomaly term, and the traceless part of the energy-momentum tensor. Each term in the total tensor does not. The trace term of the tensor is given by

$$T_{\mu\nu} = -m^2 \bar{\psi} \gamma_\mu \gamma_\nu \psi + \frac{\beta(g)}{2g} F^2, \quad (2)$$

in which the quantum trace anomaly (the term proportional to the anomalous dimension of the mass operator $\gamma_m$ plus the glue term) has been taken into account. In the above anomaly equation, the first term and the combined second and third terms are scale independent. The definition of the anomalous dimension of the mass operator is

$$\gamma_m = -\frac{\mu}{m} \frac{dm}{d\mu}. \quad (3)$$

In lowest order perturbation, the coefficient of the glue anomaly term [the third term in Eq. (2)] is $\beta(g) = -(11 - 2n_f/3)g^3/(4\pi)^2$ with $n_f$ being the number of flavors.

Combining the classical $T_{\mu\nu}$ from Eq. (1) and the quantum anomaly in Eq. (2), one can divide $T_{\mu\nu}$ into a traceless part $\bar{T}_{\mu\nu}$ and a trace part $\hat{T}_{\mu\nu}$, i.e. $T_{\mu\nu} = \bar{T}_{\mu\nu} + \hat{T}_{\mu\nu}$ [1]. From its matrix element of a single-meson state with momentum $P$, $\langle P | T_{\mu\nu} | P \rangle = 2P_{\mu}P_{\nu}$, and taking $\mu = \nu = 4$ in the rest frame, one has

I. INTRODUCTION

Hadrons are confined states of quarks and gluons. QCD is the theory describing the interaction of the quarks and gluons. Given the fact that masses of hadrons are well measured and successfully calculated with lattice QCD, an interesting, important, and yet unanswered question is how large the contributions are to the masses from the quark and glue constituents. The answer will be important for understanding the quark-glue structure of hadrons. It is clear that the question can only be answered by solving QCD non-perturbatively, and/or with information from experiments. The decomposition for the proton has been carried out with lattice QCD for the first time. The calculation is carried out with overlap fermion on domain-wall fermion gauge configurations. We confirm that the quark mass term and the glue energy term, and the trace anomaly term. We calculate these components for mesons hadronic matrix elements of QCD operators. The components consist of the quark mass term, the quark energy term which is consistent with the picture of the quark potential model.
\[ \mathcal{T}_{44} = \frac{\langle P| \int d^3x T_{44} (\tilde{x}) | P \rangle}{\langle P|P \rangle} = -M, \]
\[ \langle \mathcal{T}_{44} \rangle = -3/4M, \quad \langle \hat{\mathcal{T}}_{44} \rangle = -1/4M \]  
with \[
\hat{\mathcal{T}}_{44} = \frac{1}{4} \bar{\psi} \gamma_4 D_4 \psi - \frac{1}{16} \bar{\psi} \gamma_\mu D_\mu \psi + F_{4a} F_{4a} - \frac{1}{4} F^2
\]
\[ = \sum_{u,d,s} \left( \bar{\psi} \gamma_4 \tilde{D}_4 \psi + \frac{1}{4} m \bar{\psi} \psi \right) + \frac{1}{2} (E^2 - B^2), \]  
\[ \mathcal{T}_{44} = \frac{1}{4} T_{\mu \nu}
\]
\[ = \frac{1}{4} \left[ - (1 + \gamma_m) \sum_{u,d,s} \bar{m} \bar{\psi} \psi + \frac{\beta(g)}{g} (E^2 + B^2) \right], \]  
for the zero momentum case. The Hamiltonian of QCD can be decomposed as \[ H_{\text{QCD}} = - \int d^3x T_{44}(\tilde{x}) = H_q + H_g + H_g^a + H_m, \]  
\[ H_q = - \sum_{u,d,s, \ldots} \int d^3x \bar{\psi} (D_4^a \psi), \]
\[ H_g = \int d^3x \frac{1}{2} (B^2 - E^2), \]
\[ H_g^a = \int d^3x \frac{-\beta(g)}{4g} (E^2 + B^2), \]
\[ H_m = \sum_{u,d,s, \ldots} \int d^3x \frac{1}{4} \gamma_m \bar{m} \bar{\psi} \psi \]  
with \[ H_q, H_g, H_g^a, \text{ and } H_m \] denoting the total contributions from the quarks, the glue field energy, the QCD glue trace anomaly, and the quark mass anomaly, respectively. Note that the sum of the first two and the sum of the last two terms are separately scale and renormalization scheme independent, while each term separately is not. Using the equation of motion (EOM), \[ H_q \] can be further divided into quark energy and mass terms
\[ H_q = H_E + H_m, \]  
with
\[ H_E = \sum_{u,d,s, \ldots} \int d^3x \bar{\psi} (\tilde{D} \cdot \gamma) \psi, \]
\[ H_m = \sum_{u,d,s, \ldots} \int d^3x \bar{m} \bar{\psi} \psi. \]  
N.B.: the quark energy \[ H_E \] includes both kinetic and potential energies due to the covariant derivative. Given the above division, a hadron mass can be decomposed into the following matrix elements:
\[ M = - \langle T_{44} \rangle = \langle H_q \rangle + \langle H_g \rangle + \langle H_a \rangle, \]
\[ = \langle H_E \rangle + \langle H_m \rangle + \langle H_g \rangle, \]  
\[ \frac{1}{4} M = - \langle \hat{\mathcal{T}}_{44} \rangle = \frac{1}{4} \langle H_{m} \rangle + \langle H_a \rangle, \]  
with all the \[ \langle H \rangle \] defined by \[ \langle P|H|P \rangle / \langle P|P \rangle \] and
\[ \langle H_a \rangle = \langle H_m \rangle + \langle H_g \rangle \]  
as the total trace anomaly. Each matrix element can be calculated with lattice QCD. Since hadron masses can be obtained from the two-point correlators on the lattice, we calculate \[ \langle H_q \rangle \text{ (or } \langle H_E \rangle \text{) and } \langle H_m \rangle \text{ through the three-point correlators and extract } \langle H_g \rangle \text{ from Eqs. (11)–(12) in this work. We will directly calculate these glue matrix elements in the future.} \]

The structure of the rest of the paper is organized as follows. The numerical details of the simulation, including the fermion action and configurations used, and the systematic uncertainties, will be discussed in Sec. II. In Sec. III, the results such as the condensates in the mesons, the decomposition of the PS/V mesons, and their difference (the splitting) are provided. A short summary and outlook are presented in Sec. IV.

**II. NUMERICAL DETAILS**

In this work, we use the valence overlap fermion on 2 + 1 flavor domain-wall fermion (DWF) configurations [6] to carry out the calculation [7]. The effective quark propagator of the massive overlap fermion is the inverse of the operator \( D_c = m + m_0 \) [8,9], where \( D_c \) is chiral, i.e. \[ \langle D_c \rangle \gamma_5 \] is the renormalized masses \( m_R \) and \( m_R^a \) that correspond to the \( \rho \) and \( \gamma_5 \) entries in the 3 by 3 Dirac matrix. The 

\[ D_c = \frac{\rho D_{ov}}{1 - D_{ov}/2} \quad \text{with } D_{ov} = 1 + \gamma_5 (\gamma_5 D_w (\rho)), \]  
where \( \rho \) is the matrix sign function and \( D_w \) is the Wilson Dirac operator with a negative mass characterized by the parameter \( \rho = 4 - 1/2 \kappa \) for \( \kappa < \kappa < 0.25 \). We set \( \kappa = 0.2 \), which corresponds to \( \rho = 1.5 \).

The lattice we use has a size \( 24^3 \times 64 \) with lattice spacing \( a^{-1} = 1.77(5) \) GeV set by Ref. [11]. The light sea \( u/d \) quark mass \( m_{1a} = 0.005 \) corresponds to \( m_u \sim 330 \text{MeV} \). We have calculated the PS and V meson masses and the corresponding \( \langle H_m \rangle \), \( \langle H_g \rangle \), and \( \langle H_E \rangle \) at 12 valence quark mass parameters that correspond to the renormalized masses \( m_R^q = m_R^{q_{MS}} \text{ (2 GeV)} \) ranging from 0.016 to 1.1 GeV after the nonperturbative renormalization procedure in Ref. [12]. The smallest one is slightly smaller than the sea quark mass and corresponds to a pion mass at 281 MeV, and the largest quark mass is close to that of the

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charm. In order to enhance the signal-to-noise ratio in the calculation of three-point functions, we set two smeared noise-grid sources at $t_s = 0/32$ [13] and four noise-grid point sources at positions $t_f$ that are ten time slices away from the sources on 101 configurations. To obtain a better signal in the light quark region ($<0.1$ GeV), the low-mode substitution technique [7] is applied to the contraction in those cases.

It would be ideal to use the conserved lattice stress tensor and there are attempts to construct the conserved stress tensor on the lattice perturbatively and nonperturbatively [4] and recently by Suzuki [14,15] with Wilson flow at finite lattice spacing. However, these approaches inevitably involve complicated sets of operators, which are difficult to compute in the lattice calculation. Our approach is to use the quark stress operators with lattice derivative (the point-split operators with gauge links [4]) for $\bar{\psi} \gamma_\mu D_\mu \psi$,

$$\frac{1}{2} \langle \bar{\psi}(x) \gamma_\mu (U_\nu(x) \psi(x + \hat{\nu}) - U_\nu^\dagger(x - \hat{\nu}) \psi(x - \hat{\nu})) + (\bar{\psi}(x + \hat{\nu}) U_\nu(x + \hat{\nu}) - \bar{\psi}(x + \hat{\nu}) U_\nu^\dagger(x)) \gamma_\mu \psi(x) \rangle = a \gamma_\mu \bar{\psi}(x) \psi(x) + O(a^3),$$

(15)

to carry out lattice calculation at a finite cutoff and then to extrapolate to the continuum limit as a next step.

The matrix elements for the operators $\bar{\psi} \gamma_\mu D_\mu \psi$, $\bar{\psi} \gamma_\mu D_\mu \bar{\psi}$, and $m \bar{\psi} \psi$ are extracted from the plateaus of the ratios of three-to-two point functions to obtain $\langle H_m \rangle$, $\langle H_\psi \rangle$, and $\langle H_E \rangle$ in the connected insertions for different quark masses. In the present work, we only consider the equal-mass case for the quark-antiquark pairs in the mesons.

We show in Fig. 1 the ratio of three-point functions to corresponding two-point functions for (a) PS mesons and (b) V mesons with light quark pairs, which corresponds to $m_q \sim 330$ MeV. We see that the plateaus for $\langle H_m \rangle$, $\langle H_\psi \rangle$, $\langle H_E \rangle$ from the ratio of three-to-two point functions are clearly visible. At the same time, the plateaus of the total mass $M$ from the effective mass of the two-point function with noise-smeared grid source are also long enough to obtain precise results. We also applied a curve fit including the contribution of excited states to extract the matrix elements and found that the results are consistent with the ones from the constant fit.

As observed in Fig. 1, the quark mass term $\langle H_m \rangle$ contributes about half of the light PS mass, while the quark energy term $\langle H_E \rangle$ is very small. This implies that the other half of the light PS mass comes mainly from the glue. For the light V mass, the combined glue components also contribute roughly one half, while $\langle H_E \rangle$ is dominant in the other half, and $\langle H_m \rangle$ is small.

### A. Equation of motion and quark energy

Before presenting our results, we discuss the theoretical underpinning of the EOM in the context of lattice calculation of three-point functions. In the three-point function with the operator $D_c + m$ inserted at a time different from the meson source and sink, part of the correlator will involve the product of the operator and a quark propagator that has the relation

$$\sum_z (D_c + m)(x,z) \frac{1}{D_c(x) + m(x,z)} = \delta_{x,y},$$

(16)

where $x, y, z$ denote all the space-time, color, and Dirac indices. Since the inserted operator $D_c + m$ is at a different time from that of the source time, $x \neq y$. As a result, the matrix element of $D_c + m$ is zero. For the disconnected insertion (DI), the delta function leads to a constant for the quark loop. Since the uncorrelated part after gauge averaging is to be subtracted, this also gives a null result for $D_c + m$ in the DI. Therefore, the matrix element with the insertion of the $D_c + m$ operator is zero, which is just the equation of motion on the lattice for fermions with the quark mass as an additive constant in the fermion propagator. This does not hold straightforwardly for the Wilson fermion where there is an additive mass renormalization and mixing with lower dimensional operators that need to be taken into account.

Since $D_{xy}$ has eigenvalues on a unit circle centered at 1 on the real axis, the eigenvalues of $D_c$ are purely imaginary.
except for the zero modes [9]. This is the same as in the continuum. Thus, \( \bar{\psi}D_i \psi \) approaches \( \bar{\psi}D_i' \psi \) with an \( \mathcal{O}(a^2) \) error and we thus have \( \langle H_{q} \rangle = \langle H_{E} \rangle + \langle H_{m} \rangle + \mathcal{O}(a^2) \) as in the continuum in Eq. (9) modulo an \( \mathcal{O}(a^2) \) error.

One can estimate this \( \mathcal{O}(a^2) \) error by considering the ratio of \( \langle D_i \rangle \) to \( \langle H_{E} - H_{q} \rangle \). Both matrix elements approach the same matrix element of \( \bar{\psi} \gamma_\mu D_\mu \psi \) in the continuum. This is equivalent to considering the ratio

\[
R = \frac{\langle H_{m} \rangle + \langle H_{E} \rangle}{\langle H_{q} \rangle},
\]

which should be equal to \( 1 + \mathcal{O}(a^2) \). We plot \( R \) as a function of the quark mass in Fig. 2 for the PS and V mesons. Except for the region of very light quark masses, they are roughly the same for PS and V mesons. In the charm quark mass region, the ratio is close to unity, while for light quarks, the ratio for the PS can be as large as \( \sim 1.2 \) and it is close to unity for the V mesons. We take 20\% as a conservative estimate for the systematic errors of \( \langle H_{E} \rangle \) and \( \langle H_{q} \rangle \) for the light quark case due to the finite lattice spacing.

**B. Disconnected insertion**

The DI contribution to the quark mass and quark energy terms needs to be estimated stochastically, which is usually quite a bit noisier than that of the connected insertion (CI). It was found recently that the signal of the DI contribution for the quark loops with scalar density can be highly improved by the low-mode averaging in the loop and low-mode substitution for the nucleon propagator [13]. We use this approach and calculate the DI of the quark mass term for the PS and V mesons to gauge the DI contributions.

We show the \( H_{m} \) results for the DI in Fig. 3 for the cases where the quark loop mass equals that of the light sea (i.e. corresponding to \( m_s = 330 \) MeV), the valence quark mass in the meson, and the strange mass as a function of the valence quark mass of the meson. We see in the upper panel of Fig. 3 that in all cases, the DI contribution of \( H_{m} \) is of the order of a few MeV for all the PS mesons. For the case of the V mesons in the lower panel of Fig. 3, they are also small with the largest contribution being \( \sim 40 \) MeV due to the strange quark contribution in the light quark case. It is also about 40 MeV for the case where the loop and valence has the same quark mass for \( m_q > 0.2 \) GeV where the vector meson mass is greater than 1.5 GeV. Based on these estimates, we ignore the small and noisy DI contribution of \( H_{m} \) in this study.

In view of the fact the strange momentum fraction \( \langle x \rangle_s \) is only 2–4\% of the total nucleon momentum experimentally [16] and the ratio of \( \langle x \rangle_s \) to \( \langle x \rangle_{u/d} \) in the DI is 0.78(3) from the latest lattice calculation with overlap fermion on DWF configurations on the \( 24^3 \times 64 \) lattice [17], we expect that the DI contribution of the quark energy term is an order of magnitude smaller than that of the CI. Thus, we neglect them also in the present study.
C. The scale and renormalization scheme dependence of the decomposition

In the decomposition equation

\[ M = \langle H_a \rangle + \langle H_m \rangle + \langle H_g \rangle + \langle H_E \rangle, \]

each of the first two terms and the sum of the last two terms are separately scale and renormalization scheme independent, while each of the last two terms is not.

Another way to decompose the first two terms is to absorb the quark mass anomaly term \( \langle H_m^a \rangle \) into the quark mass term \( \langle H_m \rangle \) (1 + \( \frac{1}{4} \gamma_m \)) (\( \langle H_m \rangle \)), leaving the QCD glue anomaly \( \langle H_g^a \rangle \) alone. Using Eqs. (46)–(49) of Ref. [18], we would get the four-loop result of \( \gamma_m \) in the \( \overline{\text{MS}} \) scheme at 2 GeV to be

\[ \gamma_M(2 \text{ GeV}) = 0.26(1), \]

with the uncertainty estimated by its fourth order contribution. The higher order corrections of \( \beta(\gamma) \) could also be found in Ref. [18], but this would be beyond the demand of this work since we do not calculate the glue contribution directly. Such a decomposition is not favored, however, as both the total quark mass term and the QCD glue anomaly term depend on both renormalization scheme and scale. It is worthwhile to note that, in the light quark case, the anomaly quark mass term is suppressed by both the quark mass and the factor \( \gamma_m/4 \) so that the two kinds of decompositions are not significantly different numerically.

For the quark/glue energy, the present calculation of the quark energy is its lattice value at the scale around the inverse of the lattice spacing \( a^{-1} = 1.77 \text{ GeV} \). Since the combined energy is scale and renormalization scheme independent, the glue energy is also at the same scale. In principle, to obtain the result at 2 GeV in the \( \overline{\text{MS}} \) scheme, we could calculate the renormalization of the quark energy in \( \text{RI/MOM} \) scheme with simulation and then convert it into \( \overline{\text{MS}} \) scheme perturbatively, or use lattice perturbation theory to calculate the renormalization of the quark energy in \( \overline{\text{MS}} \) with finite lattice spacing. Also, the mixing effect between the quark/glue components should be taken into account [3,19].

III. RESULTS

A. The scalar matrix element in the PS/V meson

The \( \text{CI} \) parts of the matrix element \( S_M \equiv \langle M | \int d^4x \bar{q} \gamma_m q | M \rangle / \langle M | M \rangle \) for PS and V are plotted in Fig. 4. Even though they are almost identical in the heavy quark region as expected, \( S_{PS,CI} \) increases with decreasing \( m_q^{R} \), while \( S_{V,CI} \) remains largely constant and is close to unity throughout the quark mass range below the charm quark mass. From the Feynman-Hellman theorem,

\[ S_{M,CI} = \frac{\partial M}{\partial m_q}, \]

one can easily deduce the \( 1/\sqrt{m_q^{R}} \) behavior of PS mesons with the Gell-Mann-Oakes-Renner relation \( m_{PS}^2 = -2m_q \langle \bar{q}q \rangle / f_{\pi}^2 \). We see later that Eq. (20) is also useful to understand the quark mass dependence of the V meson.

B. Pseudoscalar meson

Our lattice results of the difference between \( M \) and the quark mass term \( \langle H_m \rangle \), i.e. \( M - \langle H_m \rangle \), the quark kinetic and potential energy term \( \langle H_E \rangle \), the glue field energy \( \langle H_g \rangle \), and the anomaly \( \langle H_a \rangle \) for the PS meson as a function of the renormalized valence quark mass are presented in Fig. 5. It is interesting to observe that all these contributions are positive, which suggests that they all approach zero at the chiral limit when the pion mass approaches zero. We also note that the contributions from the glue energy and trace anomaly are stable in the region of \( m_q^{R} \) from 0.2 to 0.8 GeV and then the former one decreases for the heavier quark mass case.

We also plot the ratios of the quark and glue components with respect to \( M \) in Fig. 6. For the light PS mesons, the quark mass term is about 50% of the total mass. This can be derived from the Gell-Mann-Oakes-Renner relation

FIG. 4 (color online). Matrix elements \( S_{M,CI} \) for the PS and V mesons. \( S_{PS,CI} \) (red square) increases with decreasing \( m_q^{R} \) while \( S_{V,CI} \) (blue circle) remains constant and is close to unity throughout the quark mass range below the charm quark mass.

FIG. 5 (color online). Different component contributions to the PS mass as functions of the renormalized valence quark mass. The contributions from the glue energy and trace anomaly are stable in the region from 0.2 to 0.8 GeV, while the former one decreases for heavier quark masses.
$m_π \propto \sqrt{m^a}$ and the Feynman-Hellman relation Eq. (20). This implies from Eq. (12) that the anomaly term $\langle H_a \rangle$ contributes $\sim 12\%$ of the mass. The remaining contributions from $\langle H_g \rangle$ and $\langle H_E \rangle$ are $\sim 30\%$ and $\sim 8\%$ respectively. They are consistent with an estimate based on the quark momentum fraction in the pion and the Gell-Mann-Oakes-Renner relation [2]. Since our present results are from the partially quenched calculation, it will be interesting to check them again in the future for configurations with physical light sea quark masses.

C. Vector meson

The same components in the $V$ mesons and their ratios to the total mass are plotted in Figs. 7–8. Close to the chiral limit, $\langle H_E \rangle$ constitutes $\sim 40\%$ of the $\rho$ meson mass, while the sum of the glue energy and anomaly terms contributes about $60\%$ and $\langle H_g \rangle$ vanishes like $O(m^g)$. For the heavier $V$ mesons, the behavior

$$M_V(m^R_q) \sim 2m^R_q C_0 + \text{const.}$$

with $C_0$ being a constant is observed in Fig. 9.

D. Hyperfine splitting

As seen in Figs. 5 and 7, when the valence quark mass increases, the quark energy contribution also increases while both the glue energy and trace anomaly decrease. To study the consequence of this behavior, we examine the hyperfine splitting of charmonium and we plot in Fig. 10 the difference of the quark and glue components between the $V$ and PS mesons as a function of the quark mass. For charmonium with $m^R_q$ at 1 GeV, $\Delta\langle H_m \rangle$ is consistent with zero. Therefore, as in Fig. 11, $\Delta\langle H_a \rangle$ gives $1/4$ of the hyperfine splitting from the quark mass dependence of the $V$ meson mass is linear in the current quark mass and comes mostly from $\langle H_m \rangle$; see their difference marked by the dark blue square.
trace anomaly equation Eq. (12). On the other hand, \( \Delta H_g \) turns negative in the charm mass region and largely cancels out the positive \( \Delta H_a \). As a result, the major part of the hyperfine splitting is due to the quark energy difference \( \Delta H_E \). This seems to be consistent with the potential model picture where the charmonium hyperfine splitting is attributable to the spin-spin interaction of the one glue-exchange potential. Higher precision calculation is needed to confirm this.

**IV. SUMMARY**

In summary, we have directly calculated the quark components of the pseudoscalar and vector meson masses with lattice QCD. The glue field energy and the anomaly components are extracted from the mass relations from the Hamilton and the trace anomaly. We have estimated the systematic errors due to the neglect of the disconnected insertions and the use of the equation of motion. From our exploratory study, we confirmed that there are significant contributions from the glue components in light mesons. Throughout the valence quark mass range below the charm, the quark mass dependence of the V meson mass comes almost entirely from \( H_m \), which is linear in the valence quark mass; whereas, \( \langle H_E \rangle, \langle H_a \rangle, \) and \( \langle H_g \rangle \) are almost constant. We also find that the hyperfine splitting between \( J/\Psi \) and \( \eta_c \) is dominated by the quark energy term.

In the decomposition equation Eq. (18), each of the first two terms and the sum of the last two terms are separately scale and renormalization scheme independent, while each of the last two terms is not. For reference, the scale independent combination of the quark and glue energy contributions to the PS/V meson mass is plotted in Fig. 12. We can see that the combined energy in the V meson is almost a constant (~650 MeV), and the one in the PS meson becomes close to that value only in the charm quark region.

For future studies, we will perform calculations with the physical sea quark masses and calculate the glue field energy and trace anomaly contributions directly.

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