Pseudovector meson with strangeness and closed charmTing-Wai Chiu¹ and Tung-Han Hsieh²

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We investigate the mass spectrum of 1^+ exotic mesons with quark content $(\mathbf{cs}\bar{\mathbf{c}}\bar{\mathbf{q}})/(\mathbf{cq}\bar{\mathbf{c}}\bar{\mathbf{s}})$, using molecular and diquark-antidiquark operators, in quenched lattice QCD with exact chiral symmetry. For the molecular operator $\{(\bar{\mathbf{q}}\gamma_i\mathbf{c})(\bar{\mathbf{c}}\gamma_5\mathbf{s}) - (\bar{\mathbf{c}}\gamma_i\mathbf{s})(\bar{\mathbf{q}}\gamma_5\mathbf{c})\}$ and the diquark-antidiquark operator $\{[\mathbf{q}^T C \gamma_i \mathbf{c}] \times [\bar{\mathbf{s}} C \gamma_5 \bar{\mathbf{c}}^T] - [\mathbf{q}^T C \gamma_5 \mathbf{c}][\bar{\mathbf{s}} C \gamma_i \bar{\mathbf{c}}^T]\}$, both detect a 1^+ resonance with mass around 4010 ± 50 MeV in the limit $m_q \rightarrow m_{u,d}$.

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I. INTRODUCTION

Since the discovery of $D_s(2317)$ [1] by *BABAR* in April 2003, a series of new heavy mesons¹ with open charm and closed charm have been observed by Belle, CDF, CLEO, *BABAR*, and BES. Among these new heavy mesons, the most intriguing ones are the charmoniumlike states, $X(3872)$ [3], $Y(3940)$ [4], $Y(4260)$ [5], $Z(3930)$ [6], and $X(3940)$ [7]. Evidently, one can hardly interpret all of them as orbital and/or radial excitations in the charmonium spectrum. Thus it is likely that some of them are exotic (non- $q\bar{q}$) mesons (e.g., molecule, diquark-antidiquark, and hybrid mesons). Theoretically, the central question is whether the spectrum of QCD possesses these resonances, with the correct quantum numbers, masses, and decay widths.

Recently, we have investigated the mass spectrum of closed-charm exotic mesons with $J^{PC} = 1^{--}$ [8], and 1^{++} [9], in lattice QCD with exact chiral symmetry [10–14]. By constructing molecular and diquark-antidiquark operators with quark content $(\mathbf{cq}\bar{\mathbf{c}}\bar{\mathbf{q}})$, we measured their time-correlation functions, and extracted the mass spectrum of the hadronic states overlapping with these exotic meson operators. Our results suggest that $Y(4260)$ and $X(3872)$ are in the spectrum of QCD, with $J^{PC} = 1^{--}$ and 1^{++} , respectively, and both with quark content $(\mathbf{cu}\bar{\mathbf{c}}\bar{\mathbf{u}})$. Note that we have been working in the isospin limit (with $m_u = m_d$), thus our results [8,9] also imply the existence of exotic mesons with quark content $(\mathbf{cd}\bar{\mathbf{c}}\bar{\mathbf{d}})$, even though we cannot determine their mass differences from those with $(\mathbf{cu}\bar{\mathbf{c}}\bar{\mathbf{u}})$. Moreover, we also observe heavier exotic mesons with quark contents $(\mathbf{cs}\bar{\mathbf{c}}\bar{\mathbf{s}})$ and $(\mathbf{cc}\bar{\mathbf{c}}\bar{\mathbf{c}})$, for $J^{PC} = 1^{++}$ [9], and 1^{--} [8].

Now, if the spectrum of QCD does possess exotic mesons with quark content $(\mathbf{cq}\bar{\mathbf{c}}\bar{\mathbf{q}})$, then it is likely that there are also exotic mesons with other quark contents, e.g.,

$(\mathbf{cq}\bar{\mathbf{c}}\bar{\mathbf{s}})$ and $(\mathbf{cs}\bar{\mathbf{c}}\bar{\mathbf{q}})$. However, in general, whether any combination of two quarks and two antiquarks can emerge as a hadronic state relies on the nonperturbative dynamics between these four quarks.

In this paper, we investigate the masses of the lowest-lying states (with $J^P = 1^+$) of molecular and diquark-antidiquark operators with quark content $(\mathbf{cs}\bar{\mathbf{c}}\bar{\mathbf{q}})$ or $(\mathbf{cq}\bar{\mathbf{c}}\bar{\mathbf{s}})$. For two lattice volumes $24^3 \times 48$ and $20^3 \times 40$, each of 100 gauge configurations generated with single-plaquette action at $\beta = 6.1$, we compute point-to-point quark propagators for 30 quark masses in the range $0.03 \leq m_q a \leq 0.80$, and measure the time-correlation functions of these exotic meson operators. The inverse lattice spacing a^{-1} is determined with the experimental input of f_π . The strange quark bare mass $m_s a = 0.08$ and the charm quark bare mass $m_c a = 0.80$ are fixed such that the masses of the corresponding vector mesons are in good agreement with $\phi(1020)$ and $J/\psi(3097)$, respectively [15,16].

II. THE MOLECULAR OPERATOR

In general, one can construct many different molecular operators with quark content $(\mathbf{cq}\bar{\mathbf{c}}\bar{\mathbf{s}})$ or $(\mathbf{cs}\bar{\mathbf{c}}\bar{\mathbf{q}})$ such that the lowest-lying state of each operator has $J^P = 1^+$. However, not every one of them has good overlap with the lowest-lying hadronic state having the same quark content and quantum numbers. In the following we only present one of the good molecular operators.² Explicitly,

$$M = \frac{1}{\sqrt{2}} \{(\bar{\mathbf{q}}\gamma_i\mathbf{c})(\bar{\mathbf{c}}\gamma_5\mathbf{s}) - (\bar{\mathbf{c}}\gamma_i\mathbf{s})(\bar{\mathbf{q}}\gamma_5\mathbf{c})\}. \quad (1)$$

We measure the time-correlation function,

$$C(t) = \sum_{\vec{x}} \langle M(\vec{x}, t) M^\dagger(\vec{0}, 0) \rangle$$

¹For recent reviews of these new heavy mesons, see, for example, Ref. [2], and references therein.

²The operators we have investigated include $(\bar{\mathbf{q}}\gamma_i\mathbf{c})(\bar{\mathbf{c}}\gamma_5\mathbf{s})$, $(\bar{\mathbf{c}}\gamma_i\mathbf{s})(\bar{\mathbf{q}}\gamma_5\mathbf{c})$, and $[(\bar{\mathbf{q}}\gamma_i\mathbf{c})(\bar{\mathbf{c}}\gamma_5\mathbf{s}) \pm (\bar{\mathbf{c}}\gamma_i\mathbf{s})(\bar{\mathbf{q}}\gamma_5\mathbf{c})]$, and they all yield compatible masses for the lowest-lying meson.

where the $c\bar{c}$ annihilation diagrams are neglected such that $C(t)$ does not overlap with any conventional meson states. Also, $C(t)$ is averaged over C_i (with γ_i) for $i = 1, 2, 3$, where, in each case, the “forward-propagator” $C_i(t)$ and “backward-propagator” $C_i(T-t)$ are averaged to increase the statistics. The same strategy is applied to all time-correlation functions in this paper. Then the average of $C(t)$ over all gauge configurations is fitted to the usual formula

$$\frac{Z}{2ma} [e^{-mat} + e^{-ma(T-t)}]$$

to extract the mass ma of the lowest-lying state and its spectral weight

$$W = \frac{Z}{2ma}.$$

Theoretically, if this state is a genuine resonance, then its mass ma and spectral weight W should be almost constant for any lattices with the same lattice spacing. On the other hand, if it is a 2-particle scattering state, then its mass ma is sensitive to the lattice volume, and its spectral weight is inversely proportional to the spatial volume for lattices with the same lattice spacing. In the following, we shall use the ratio of the spectral weights on two spatial volumes 20^3 and 24^3 with the same lattice spacing ($\beta = 6.1$) to

FIG. 1 (color online). The ratio of spectral weights of the lowest-lying state of the molecular operator M , for $20^3 \times 40$ and $24^3 \times 48$ lattices at $\beta = 6.1$. The upper-horizontal line, $R = (24/20)^3 = 1.728$, is the signature of the 2-particle scattering state, while the lower-horizontal line, $R = 1.0$, is the signature of a resonance.

FIG. 2 (color online). The mass of the lowest-lying state of M versus the quark mass $m_q a$, on the $24^3 \times 48$ lattice at $\beta = 6.1$. The solid line is the linear fit.

discriminate whether any hadronic state under investigation is a resonance or not.

In Fig. 1, the ratio ($R = W_{20}/W_{24}$) of spectral weights of the lowest-lying state extracted from the time-correlation function of M on the $20^3 \times 40$ and $24^3 \times 48$ lattices is plotted versus the quark mass $m_q a \in [0.03, 0.80]$. [Here $\mathbf{q}$ ($\bar{\mathbf{q}}$) is always taken to be different from $\mathbf{c}$ ($\bar{\mathbf{c}}$) and $\mathbf{s}$ ($\bar{\mathbf{s}}$), even in the limit $m_q \rightarrow m_c$ or m_s]. Evidently, $R \approx 1.0$ for the entire range of quark masses, which implies that there exist $J^P = 1^+$ resonances, with quark contents $(\mathbf{c}\mathbf{s}\bar{\mathbf{c}}\bar{\mathbf{u}})$ and $(\mathbf{c}\mathbf{s}\bar{\mathbf{c}}\bar{\mathbf{d}})$, respectively.

In Fig. 2, the mass of the lowest-lying state extracted from the molecular operator M is plotted versus $m_q a$. In the limit $m_q \rightarrow m_{u,d} \approx 0.00265a^{-1}$ (corresponding to $m_\pi = 135$ MeV), it gives $m = 4007(34)$ MeV.

III. THE DIQUARK-ANTIDIQUARK OPERATOR

In general, one can construct many different diquark-antiquark operators with quark content $(\mathbf{c}\mathbf{q}\bar{\mathbf{c}}\bar{\mathbf{s}})$ or $(\mathbf{c}\mathbf{s}\bar{\mathbf{c}}\bar{\mathbf{q}})$ such that the lowest-lying state of each operator has $J^P = 1^+$. However, not every one of them has good overlap with the lowest-lying hadronic state having the same quark content and quantum numbers. In the following we only present one of the good diquark-antidiquark operators. Explicitly,

$$D_4(x) = \frac{1}{\sqrt{2}} \{ [\mathbf{q}^T C \gamma_i \mathbf{c}]_{xa} [\bar{\mathbf{s}} C \gamma_5 \bar{\mathbf{c}}^T]_{xa} - [\bar{\mathbf{s}} C \gamma_i^T \bar{\mathbf{c}}^T]_{xa} [\mathbf{q}^T C \gamma_5 \mathbf{c}]_{xa} \} \quad (2)$$

FIG. 3 (color online). The ratio of spectral weights of the lowest-lying state of the diquark-antidiquark operator D_4 , for $20^3 \times 40$ and $24^3 \times 48$ lattices at $\beta = 6.1$. The upper-horizontal line, $R = (24/20)^3 = 1.728$, is the signature of the 2-particle scattering state, while the lower-horizontal line, $R = 1.0$, is the signature of a resonance.

FIG. 4 (color online). The mass of the lowest-lying state of the diquark-antidiquark operator D_4 versus the quark mass $m_q a$, on the $24^3 \times 48$ lattice at $\beta = 6.1$. The solid line is the linear fit.

where C is the charge conjugation operator satisfying $C\gamma_\mu C^{-1} = -\gamma_\mu^T$ and $(C\gamma_5)^T = -C\gamma_5$. Here the diquark operator $[\mathbf{q}^T \Gamma \mathbf{Q}]_{xa}$ for any Dirac matrix Γ is defined as

$$[\mathbf{q}^T \Gamma \mathbf{Q}]_{xa} \equiv \epsilon_{abc} (\mathbf{q}_{xab} \Gamma_{\alpha\beta} \mathbf{Q}_{x\beta c} - \mathbf{Q}_{xab} \Gamma_{\alpha\beta} \mathbf{q}_{x\beta c}) \quad (3)$$

where x , $\{a, b, c\}$, and $\{\alpha, \beta\}$ denote the lattice site, color, and Dirac indices, respectively, and ϵ_{abc} is the completely antisymmetric tensor. Thus the diquark (3) transforms like a color antitriplet. For $\Gamma = C\gamma_5$, it transforms like $J^P = 0^+$, while for $\Gamma = C\gamma_i$ ($i = 1, 2, 3$), it transforms like 1^+ .

In Fig. 3, the ratio ($R = W_{20}/W_{24}$) of spectral weights of the lowest-lying state extracted from the time-correlation function of D_4 on the $20^3 \times 40$ and $24^3 \times 48$ lattices is plotted versus the quark mass $m_q a \in [0.03, 0.8]$. Evidently, $R \simeq 1.0$ for the entire range of quark masses, which implies that there exist $J^P = 1^+$ resonances, with quark contents $(\mathbf{cd}\bar{\mathbf{c}}\bar{\mathbf{s}})$ and $(\mathbf{cu}\bar{\mathbf{c}}\bar{\mathbf{s}})$, respectively.

In Fig. 4, the mass of the lowest-lying state of the diquark-antidiquark operator D_4 is plotted versus $m_q a$. In the limit $m_q \rightarrow m_{u,d}$, it gives $m = 4015(25)$ MeV.

IV. SUMMARY AND DISCUSSIONS

In this paper, we have investigated the mass spectra of the molecular operator M and the diquark-antidiquark operator D_4 , in quenched lattice QCD with exact chiral symmetry. Our results for M and D_4 are summarized in Table I, where, in each case, the first error is statistical, and the second one is our crude estimate of combined systematic uncertainty.

Evidently, both the molecular operator M and the diquark-antidiquark operator D_4 detect a 1^+ resonance around 4010 ± 50 MeV in the limit $m_q \rightarrow m_{u,d}$. Since its mass is just slightly above $Y(3940)$, high energy experiments should be able to see whether such a resonance, say, X_s , exists in some decay channels, e.g., $X_s \rightarrow K\pi J/\Psi$, in the near future.

Note that, in our calculations, we have omitted all internal quark loops generated by vacuum fluctuations (i.e., the quenched approximation). However, we expect that the quenched approximation only results in a few percent systematic error in the mass spectrum, especially for charmed mesons [16]. If it turns out that high energy experiments do not find any charmoniumlike resonances

TABLE I. Masses of the lowest-lying states ($J^P = 1^+$) of the molecular operator M and the diquark-antidiquark operator D_4 . The last column R/S denotes the resonance (R) or scattering (S) state.

Operator	Mass (MeV)	R/S
$\frac{1}{\sqrt{2}} [(\bar{\mathbf{u}}\gamma_i \mathbf{c})(\bar{\mathbf{c}}\gamma_5 \mathbf{s}) - (\bar{\mathbf{c}}\gamma_i \mathbf{s})(\bar{\mathbf{u}}\gamma_5 \mathbf{c})]$	4007(34)(31)	R
$\frac{1}{\sqrt{2}} \{ [\mathbf{u}^T C \gamma_i \mathbf{c}][\bar{\mathbf{s}} C \gamma_5 \bar{\mathbf{c}}^T] - [\mathbf{u}^T C \gamma_5 \mathbf{c}][\bar{\mathbf{s}} C \gamma_i \bar{\mathbf{c}}^T] \}$	4015(25)(27)	R

around 3960–4060 MeV, in particular, in the $K\pi J/\Psi$ channel, then it might imply that quenched QCD could be dramatically different from the unquenched QCD, even for the mass spectrum.

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