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$X(3872)$ in lattice QCD with exact chiral symmetry

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Abstract

We investigate the mass spectrum of 1^{++} exotic mesons with quark content $(\mathbf{cq\bar{c}\bar{q}})$, using molecular and diquark–antidiquark operators, in quenched lattice QCD with exact chiral symmetry. For the molecular operator $\{(\bar{\mathbf{q}}\gamma_i\mathbf{c})(\bar{\mathbf{c}}\gamma_5\mathbf{q}) - (\bar{\mathbf{c}}\gamma_i\mathbf{q})(\bar{\mathbf{q}}\gamma_5\mathbf{c})\}$ and the diquark–antidiquark operator $\{(\mathbf{q}^T C\gamma_i\mathbf{c})(\bar{\mathbf{q}}C\gamma_5\bar{\mathbf{c}}^T) - (\bar{\mathbf{q}}C\gamma_i^T\bar{\mathbf{c}}^T)(\mathbf{q}^T C\gamma_5\mathbf{c})\}$, both detect a resonance with mass around 3890 ± 30 MeV in the limit $m_q \to m_u$, which is naturally identified with $X(3872)$. Further, heavier exotic meson resonances with $J^{PC} = 1^{++}$ are also detected, with quark content $(\mathbf{cs\bar{c}\bar{s}})$ around 4100 ± 50 MeV.

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Since the discovery of $D_s(2317)$ by BaBar in April 2003, a series of new heavy mesons[1] with open-charm and closed-charm have been observed by Belle, CDF, CLEO, BaBar, and BES. Among these new heavy mesons, the narrow charmonium-like state $X(3872)$ (with width < 2.3 MeV) first observed by Belle [3] in the exclusive decay $B^\pm \to K^\pm X \to K^\pm\pi^+\pi^- J/\psi$ seems to be the most remarkable. The evidence of $X(3872)$ has been confirmed by three experiments in three decay and two production channels [4–6]. Recently, the decay $X(3872) \to \gamma J/\psi$ has been observed by Belle [7], which implies that the charge conjugation of $X(3872)$ is positive. Further, $X(3872)$ is unlikely a vector 1^{--} state, since the bound $\Gamma(e^+e^-)Br(X \to \pi^+\pi^- J/\Psi) < 10$ eV at 90% C.L. has been obtained [8], with the data collected by BES at $\sqrt{s} = 4.03$ GeV. Now, the quantum numbers 0^{++} and 0^{-+} are ruled out based on the angular correlations in the $\pi^+\pi^- J/\psi$ system [9], also 2^{-+} and 1^{-+} are strongly disfavored according to the dipion mass distribution [9]. Thus it is likely that $X(3872)$ possesses $J^{PC} = 1^{++}$ [9], even though the assignment of $J^{PC} = 2^{-+}$ has not been ruled out [10].

Theoretically, one can hardly interpret $X(3872)$ as $2P$ or 1D states in the charmonium spectrum, in view of its extremely narrow width. Thus it is most likely an exotic (non-$q\bar{q}$) meson (e.g., molecule, diquark–antidiquark, and hybrid meson). Now the central question is whether the spectrum of QCD possesses a resonance around 3872 MeV with $J^{PC} = 1^{++}$.

In this Letter, we investigate the mass spectra of molecular and diquark–antidiquark interpolating operators whose lowest-lying states having $J^{PC} = 1^{++}$, in lattice QCD with exact chiral symmetry [11–15]. This study follows our recent investigation of the mass spectrum of closed-charm exotic mesons with $J^{PC} = 1^{--}$ [16], which suggests that $Y(4260)$ [17] is in the spectrum of QCD, with quark content $(\mathbf{cu\bar{c}\bar{u}})$. Here we follow the same procedures in our previous study [16], to extract the mass and spectral weight of the lowest-lying state of each operator, and also to use the same sets of gauge configurations, namely, for two lattice volumes $24^3 \times 48$

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[1] For recent reviews, see, for example, Refs. [1,2], and references therein.

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and $20^3 \times 40$, each of 100 gauge configurations generated with single-plaquette action at $\beta = 6.1$. The inverse lattice spacing $a^{-1} = 2.237(76)$ GeV is determined from the spectral weight of the pion time-correlation function, with the experimental input of pion decay constant $f_\pi = 131$ MeV. 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 corresponding masses extracted from the vector meson correlation functions agree with $\phi(1020)$ and $J/\psi(3097)$ respectively [18].

Note that we have been working in the isospin limit ($m_u = m_d$), thus our results in Ref. [16] as well as in this Letter cannot exclude the possibility of the existence of exotic mesons with quark content ($\mathbf{c d \bar{c} \bar{d}}$), even though we cannot determine their mass differences from those with ($\mathbf{c u \bar{c} \bar{u}}$).

Next we construct the molecular and diquark–antidiquark interpolating operators[2] with quark fields ($\mathbf{c q \bar{c} \bar{q}}$) such that the lowest-lying state of each operator has $J^{PC} = 1^{++}$. Explicitly, they are:

$$M_1 = \frac{1}{\sqrt{2}}\left\{(\bar{\mathbf{q}}\gamma_i \mathbf{c})(\bar{\mathbf{c}}\gamma_5 \mathbf{q}) - (\bar{\mathbf{c}}\gamma_i \mathbf{q})(\bar{\mathbf{q}}\gamma_5 \mathbf{c})\right\} \tag{1}$$

and

$$X_4(x) = \frac{1}{\sqrt{2}}\left\{\left(\mathbf{q}^T C\gamma_i \mathbf{c}\right)_{xa}\left(\bar{\mathbf{q}} C\gamma_5 \bar{\mathbf{c}}^T\right)_{xa} - \left(\bar{\mathbf{q}} C\gamma_i^T \bar{\mathbf{c}}^T\right)_{xa}\left(\mathbf{q}^T C\gamma_5 \mathbf{c}\right)_{xa}\right\}, \tag{2}$$

where

$$(\bar{\mathbf{q}}\Gamma\mathbf{Q})_x = \bar{\mathbf{q}}_{a\alpha x}\Gamma_{\alpha\beta}\mathbf{Q}_{a\beta x}$$

denotes a meson operator with antiquark field $\bar{\mathbf{q}}$ coupling to quark field $\mathbf{Q}$ through the Dirac matrix Γ. Here x, $\{a, b, c\}$ and $\{\alpha, \beta\}$ denote the lattice site, color, and Dirac indices respectively. The diquark operator is denoted by

$$\left(\mathbf{q}^T \Gamma \mathbf{Q}\right)_{ax} = \epsilon_{abc}\mathbf{q}_{b\alpha x}\Gamma_{\alpha\beta}\mathbf{Q}_{c\beta x},$$

where ϵ_{abc} is the completely antisymmetric tensor, C is the charge conjugation operator satisfying $C\gamma_\mu C^{-1} = -\gamma_\mu^T$ and $(C\gamma_5)^T = -C\gamma_5$. Thus the diquark transforms like 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. 1, the ratio ($R = W_{20}/W_{24}$) of spectral weights of the lowest-lying state extracted from the time-correlation function of M_1 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 the quark fields $\mathbf{q}$ and $\bar{\mathbf{q}}$ are always taken to be different from $\mathbf{c}$ and $\bar{\mathbf{c}}$, even in the limit $m_q \to m_c$.) Evidently, $R \simeq 1.0$ for the entire range of quark masses, which implies that there exist $J^{PC} = 1^{++}$ resonances, with quark content ($\mathbf{c s \bar{c} \bar{s}}$) and ($\mathbf{c u \bar{c} \bar{u}}$) respectively.

In Fig. 2, the mass of the lowest-lying state extracted from the molecular operator M_1 is plotted versus $m_q a$. In the limit $m_q \to m_u \simeq 0.00265 a^{-1}$ (corresponding to $m_\pi = 135$ MeV),

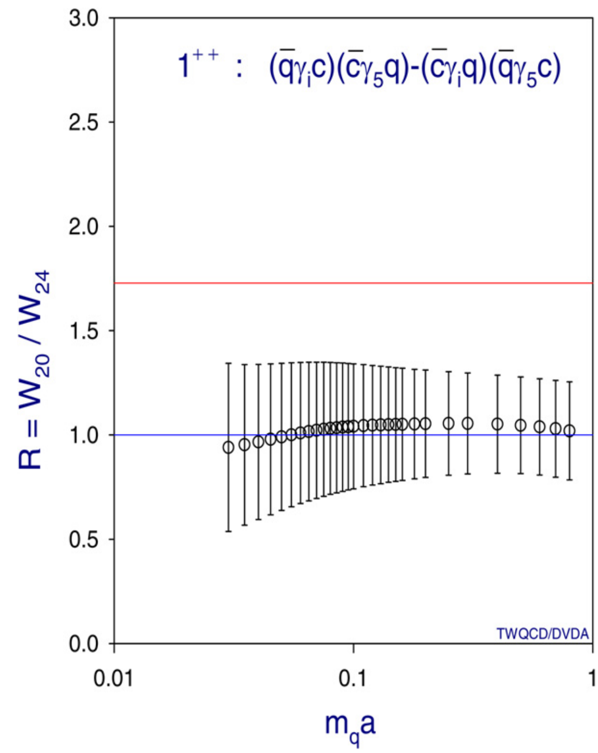


Fig. 1. The ratio of spectral weights of the lowest-lying state of the molecular operator M_1, for $20^3 \times 40$ and $24^3 \times 48$ lattices at $\beta = 6.1$. The upper-horizontal line $R = (24/20)^3 = 1.728$, is the signature of 2-particle scattering state, while the lower-horizontal line $R = 1.0$ is the signature of a resonance.

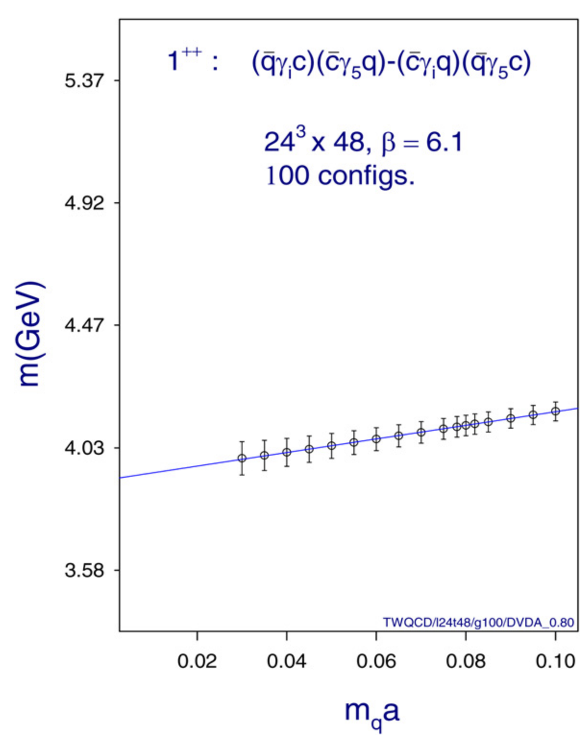
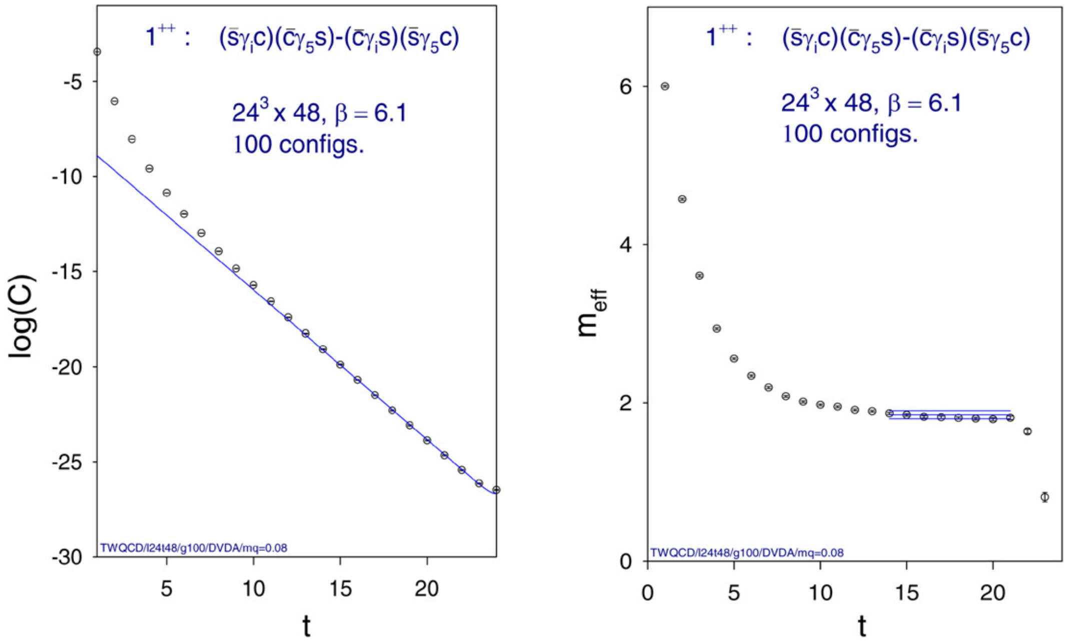


Fig. 2. The mass of the lowest-lying state of M_1 versus the quark mass $m_q a$, on the $24^3 \times 48$ lattice at $\beta = 6.1$. The solid line is the linear fit.

[2] Here, we have omitted other operators which do not have good overlap with the hadronic state, as $m_q \to m_{u,d}$.



(a) (b)

Fig. 3. (a) The time-correlation function $C(t)$ of the lowest-lying state of M_1 for $m_q = m_s = 0.08a^{-1}$, on the $24^3 \times 48$ lattice at $\beta = 6.1$. The solid line is the hyperbolic-cosine fit for $t \in [14, 21]$. (b) The effective mass $M_{\text{eff}}(t) = \ln[C(t)/C(t+1)]$ of $C(t)$ (a).

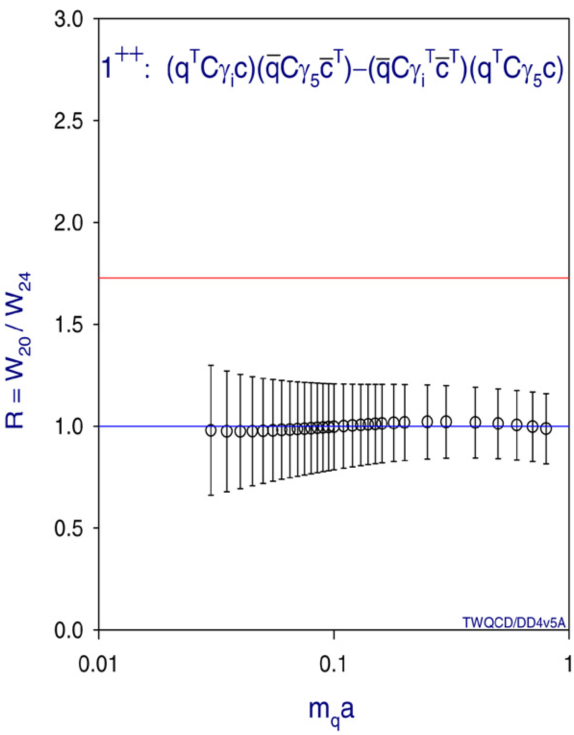


Fig. 4. The ratio of spectral weights of the lowest-lying state of diquark–antidiquark operator X_4, for $20^3 \times 40$ and $24^3 \times 48$ lattices at $\beta = 6.1$. The upper-horizontal line $R = (24/20)^3 = 1.728$, is the signature of 2-particle scattering state, while the lower-horizontal line $R = 1.0$ is the signature of a resonance.

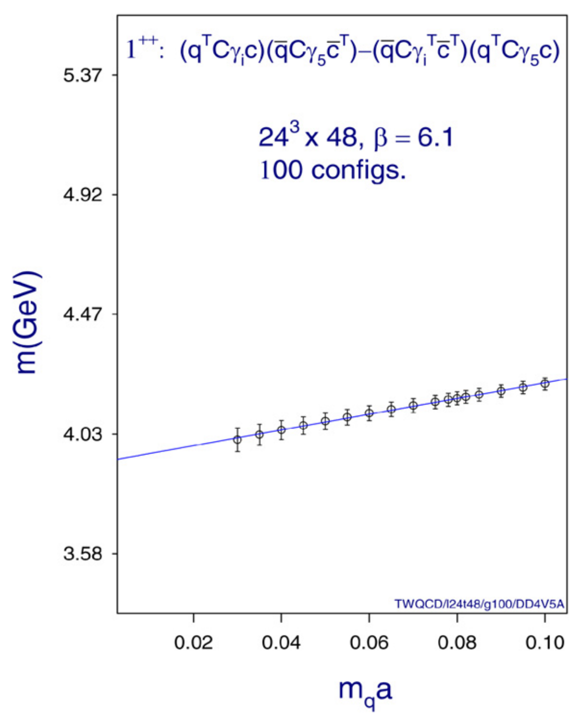
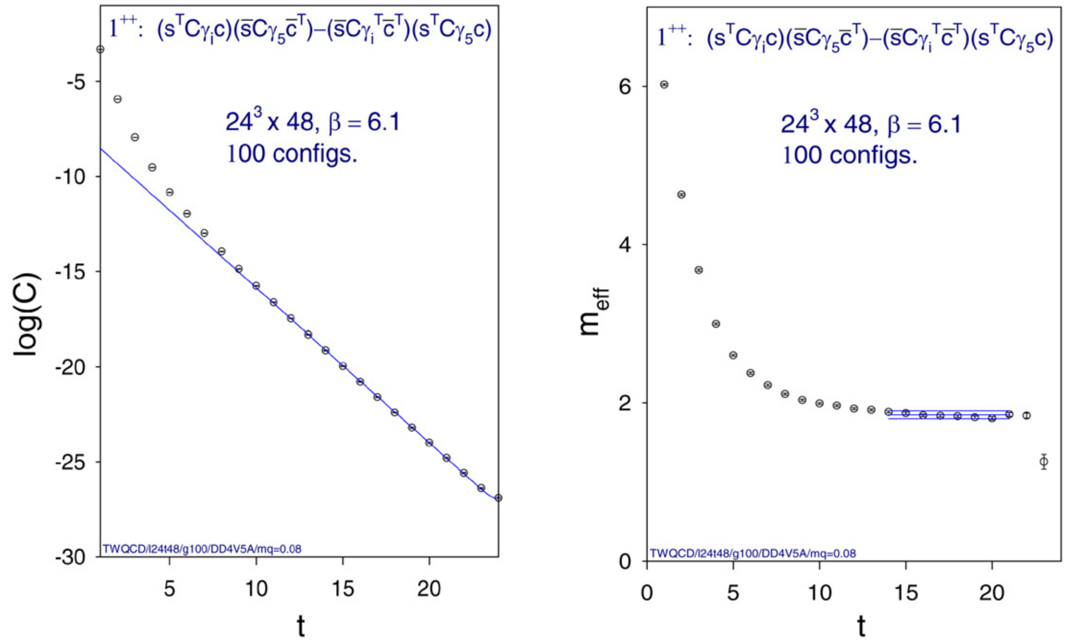


Fig. 5. The mass of the lowest-lying state of the diquark–antidiquark operator X_4 versus the quark mass $m_q a$, on the $24^3 \times 48$ lattice at $\beta = 6.1$. The solid line is the linear fit.

it gives $m = 3895(27)$ MeV, in good agreement with the mass of $X(3872)$. (Here one has to take into account of the errors due to finite lattice spacing, small statistics, and chiral extrapolations.) This seems to suggest that $X(3872)$ is a molecule of $D^* \bar{D}$. However, M_1 can also overlap with $D^* \bar{D}^*$, which is rather close to $D^* \bar{D}$. To disentangle these two molecular states, one can construct a set of operators $\{\mathcal{O}_i\}$ with $J^{PC} = 1^{++}$, and compute their correlation matrix

$$C_{ij}(t) = \sum_{\vec{x}} \langle \mathcal{O}_i(\vec{x}, t) \mathcal{O}_j^\dagger(\vec{0}, 0) \rangle.$$



(a) (b)

Fig. 6. (a) The time-correlation function $C(t)$ of the lowest-lying state of X_4 for $m_q = m_s = 0.08a^{-1}$, on the $24^3 \times 48$ lattice at $\beta = 6.1$. The solid line is the hyperbolic-cosine fit for $t \in [14, 21]$. (b) The effective mass $M_{\mathrm{eff}}(t) = \ln[C(t)/C(t+1)]$ of $C(t)$ in (a).

Table 1
Mass spectra of the molecular operator M_1 and the diquark–antidiquark operator X_4 with $J^{PC} = 1^{++}$. The column R/S denotes resonance (R) or scattering (S) states

Operator	Mass (MeV)	R/S	Candidate
$\frac{1}{\sqrt{2}}[(\bar{\mathbf{u}}\gamma_i\mathbf{c})(\bar{\mathbf{c}}\gamma_5\mathbf{u}) - (\bar{\mathbf{c}}\gamma_i\mathbf{u})(\bar{\mathbf{u}}\gamma_5\mathbf{c})]$	3895(27)(35)	R	X(3872)
$\frac{1}{\sqrt{2}}[(\bar{\mathbf{s}}\gamma_i\mathbf{c})(\bar{\mathbf{c}}\gamma_5\mathbf{s}) - (\bar{\mathbf{c}}\gamma_i\mathbf{s})(\bar{\mathbf{s}}\gamma_5\mathbf{c})]$	4109(21)(32)	R	
$\frac{1}{\sqrt{2}}\{(\mathbf{u}^T C\gamma_i\mathbf{c})(\bar{\mathbf{u}}C\gamma_5\bar{\mathbf{c}}^T) - (\mathbf{u}^T C\gamma_5\mathbf{c})(\bar{\mathbf{u}}C\gamma_i^T\bar{\mathbf{c}}^T)\}$	3891(17)(21)	R	X(3872)
$\frac{1}{\sqrt{2}}\{(\mathbf{s}^T C\gamma_i\mathbf{c})(\bar{\mathbf{s}}C\gamma_5\bar{\mathbf{c}}^T) - (\mathbf{s}^T C\gamma_5\mathbf{c})(\bar{\mathbf{s}}C\gamma_i^T\bar{\mathbf{c}}^T)\}$	4134(19)(25)	R	

Then diagonalize the correlation matrix $\{C_{ij}\}$, and use the eigenvalues $\{\lambda_k(t)\}$ to extract the masses of the lowest-lying state as well as the excited states. Now, since we have only extracted the mass of the lowest-lying state from one operator M_1, its value may be elevated due to the nearby first excited state. However, the mass turns out to be compatible with X(3872), taking into account of the errors due to finite lattice spacing, small statistics, and chiral extrapolations. Thus, we suspect that M_1 does not have large overlap with $D^*\bar{D}^*$, unlike the molecular operator

$$\frac{1}{\sqrt{2}}\big\{(\bar{\mathbf{q}}\gamma_i\mathbf{c})(\bar{\mathbf{c}}\gamma_j\mathbf{q}) + (\bar{\mathbf{c}}\gamma_i\mathbf{q})(\bar{\mathbf{q}}\gamma_j\mathbf{c})\big\}.$$

Next we turn to M_1 with $m_q = m_s = 0.08a^{-1}$. The time-correlation function and effective mass are plotted in Figs. 3(a) and 3(b) respectively. With single exponential fit, it gives the mass of the lowest-lying state, $m = 4109(21)$ MeV, with $J^{PC} = 1^{++}$ and quark content $(\bar{\mathbf{s}}\mathbf{c}\mathbf{s}\bar{\mathbf{c}})$. Again, we expect that its mass will become smaller in the continuum limit. This seems to suggest that there exists a molecular state like $D_s^*\bar{D}_s$. (The discussion of its overlap with $D_s^*\bar{D}_s^*$ is analogous to the case of M_1 with $m_q = m_u$.) It is interesting to see whether such a state will be observed by high energy experiments.

Now we turn to the diquark–antidiquark operator X_4. In Fig. 4, the ratio ($R = W_{20}/W_{24}$) of the spectral weights of the lowest-lying state extracted from the time-correlation function of X_4 on the $20^3 \times 40$ and $24^3 \times 48$ lattices is plotted versus the quark mass $m_q a$. Evidently, $R \simeq 1.0$ for the entire range of quark masses, which implies that there exist $J^{PC} = 1^{++}$ resonances, with quark content $(\mathbf{c}\mathbf{s}\bar{\mathbf{c}}\bar{\mathbf{s}})$, and $(\mathbf{c}\mathbf{u}\bar{\mathbf{c}}\bar{\mathbf{u}})$ respectively.

In Fig. 5, the mass of the lowest-lying state of the diquark–antidiquark operator X_4 is plotted versus $m_q a$. In the limit $m_q \to m_u$, it gives $m = 3891(17)$ MeV, which is in good agreement with the mass of $X(3872)$.

For $m_q = m_s = 0.08a^{-1}$, the time-correlation function and effective mass of the diquark–antidiquark operator are plotted in Fig. 6. The mass of the lowest-lying state is 4134(15) MeV, with $J^{PC} = 1^{++}$ and quark content $(\bar{\mathbf{s}}\mathbf{c}\mathbf{s}\bar{\mathbf{c}})$.

To summarize, we have investigated the mass spectra of the molecular operators M_1 and the diquark–antidiquark operator X_4 with $J^{PC} = 1^{++}$, in quenched lattice QCD with exact chiral symmetry. Our results are summarized in Table 1, where in each case, the first error is statistical, and the second one is our estimate of combined systematic uncertainty.

Evidently, both the molecular operator M_1 and the diquark–antidiquark operator X_4 detect a 1^{++} resonance around 3890 ± 30 MeV in the limit $m_q \to m_u$, which is naturally identified with $X(3872)$. This suggests that $X(3872)$ is indeed in the spectrum of QCD, with quark content ($\mathbf{c u \bar{c} \bar{u}}$), and $J^{PC} = 1^{++}$.

Further, our results suggest that $X(3872)$ has good overlap with the molecular operator M_1 as well as the diquark–antidiquark operator X_4. This is in contrast to the case of $Y(4260)$ in our recent study [16], in which $Y(4260)$ seems to have better overlap with the molecular operator $\{(\bar{\mathbf{q}}\gamma_5\gamma_i\mathbf{c}) \times (\bar{\mathbf{c}}\gamma_5\mathbf{q}) - (\bar{\mathbf{c}}\gamma_5\gamma_i\mathbf{q})(\bar{\mathbf{q}}\gamma_5\mathbf{c})\}$ than any diquark–antidiquark operators. This suggests that $X(3872)$ is more tightly bound than $Y(4260)$. It would be interesting to see whether this picture persists even for unquenched QCD.

Finally, for $m_q = m_s$, heavier exotic meson resonances with $J^{PC} = 1^{++}$ are also detected, with quark content ($\mathbf{c s \bar{c} \bar{s}}$) around 4100 ± 50 MeV. This serves as a prediction from lattice QCD.

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