Masses of Open Charm and Bottom Tetraquark States in a Relativized Quark Model (Postprint)

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Abstract

We study the masses of open charm and bottom tetraquark states within the diquark-antidiquark scenario in the relativized quark model proposed by Godfrey and Isgur. The diquark and antidiquark masses are firstly solved by relativized quark potential, and then treated as the usual antiquark and quark, respectively. The masses of tetraquark states are obtained by solving the Schr"{o}dinger-type equation between diquark and antidiquark. We find the masses of sqb¯q¯ tetraquark configuration are much higher than that of X(5568). This conclusion disfavors the possibility of X(5568) as a tetraquark state within the diquark-antidiquark scenario. Further experimental searches are needed to clarify the nature of the signal observed by D0 collaboration.

Full Text

Preamble

Masses of open charm and bottom tetraquark states in the relativized quark model

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We study the masses of open charm and bottom tetraquark states within the diquark-antidiquark scenario in the relativized quark model proposed by Godfrey and Isgur. The diquark and antidiquark masses are first solved using the relativized quark potential, and then treated as the usual antiquark and quark, respectively. The masses of tetraquark states are obtained by solving the Schrödinger-type equation between diquark and antidiquark. We find the

masses of $sq\bar{b}\bar{q}$ tetraquark configuration are much higher than that of X(5568). This conclusion disfavors the possibility of X(5568) as a tetraquark state within the diquark-antidiquark scenario. Further experimental searches are needed to clarify the nature of the signal observed by the D0 collaboration.

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Introduction

Recently, the D0 collaboration reported the observation of a narrow structure X(5568) in the $B_s^0\pi^\pm$ decay process based on $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV [?]. Given the final states, the X(5568)$^+$ should have four different quark flavors $su\bar{b}\bar{d}$. The measured mass and width are $5567.8 \pm 6.4^{+5.0}_{-2.9} \pm 0.9^{+0.9}_{-0.9}$ MeV and $21.9 \pm 6.4^{+5.0}_{-2.9}$ MeV, respectively. Assuming the final $B_s^0\pi^+$ in S-wave, the quantum numbers are $I(J^P) = 1(0^+)$. Another possibility is that the structure decays through the chain $B_s^*\gamma$, where the soft photon is not detected. In the latter situation, the quantum number of the new state would be $I(J^P) = 1(1^+)$, and the mass is shifted by adding the mass difference $m(B_s^*) - m(B_s) = 48.6 \pm 1.8 \pm 1.6$ MeV.

This discovery has immediately attracted considerable interest and theoretical studies on X(5568) with different interpretations. Considering the mass, strong decay, and decay constant, most works explain the X(5568) as a tetraquark state within the framework of QCD sum rules and simple quark models [?]. This explanation is also suggested by the D0 collaboration. Besides this primary interpretation, the properties under the molecular picture have been studied [?, ?], and some works have also investigated the partners of X(5568) [?, ?]. So far, some doubts exist in the understanding of X(5568). In Ref. [?], the authors suggest that X(5568) may result from near-threshold rescattering effects. Moreover, the quite large production rate of X(5568) cannot be understood by general hadronization mechanisms [?]. Comprehensive discussions were performed by Burns and Swanson very recently, finding that threshold, cusp, molecular, and tetraquark models are all disfavored [?].

Before the observation of X(5568), there have been studies on open charm and bottom tetraquark states, which mainly focused on their mass spectra [?]. These calculations include the diquark-antidiquark picture, compact tetraquark, mixture of quark-antiquark and four-quark components, and molecular scenario, which intend to reveal the nature of $D_{s0}^*(2317)$. Some calculations indicate that $D_{s0}^*(2317)$ can be treated as a tetraquark state [?, ?], while others give much higher masses for four-quark components than that of $D_{s0}^*(2317)$ as well as the DK threshold [?]. For the molecular scenario, most works indicate that a weakly bound DK state can be obtained [?], while others suggest the attraction between these two pseudoscalar mesons is not strong enough to form a bound state [?]. In the open bottom sector, higher masses are given in diquark-antidiquark pictures [?], and it is found that the $B\bar{K}$ system can be weakly bound [?, ?].

Unlike the $D_{s0}^*(2317)$, the X(5568) cannot be regarded as a conventional meson or a mixture of quark-antiquark and four-quark components due to its four distinct quark flavors. The molecular interpretation cannot give the correct mass and can be excluded [?, ?, ?, ?, ?]. The tetraquark explanation is supported by QCD sum rules and simple quark models [?], but disfavored by relativistic calculations and general discussions [?, ?]. Hence, it is natural to study the open charm and bottom tetraquark masses within a more realistic potential model, which is helpful to disentangle this conflict. Furthermore, with experimental progress, more and more open charm resonances have been observed in recent years [?], which provide good opportunities to search for open charm tetraquark candidates both theoretically and experimentally.

In this work, we choose the relativized quark model to calculate the masses of diquark and tetraquark states. The relativized quark model, proposed by Godfrey and Isgur, has been extensively used to predict the properties of conventional mesons [?, ?]. It has been concluded that this model gives a unified description of light mesons, heavy-light mesons, and heavy quarkonium, and therefore, it is suitable to deal with the X(5568) state, in which both light-light and heavy-light systems are included. Moreover, relativistic effects are also considered in the model, which may be essential for the light quarks. We perform a calculation in the diquark-antidiquark picture following the route proposed by Ebert, Faustov, and Galkin [?, ?]. The corresponding diquark and antidiquark masses are estimated with the relativized potential first, and then treated as the usual antiquark and quark, respectively. The masses of tetraquark states are therefore obtained by solving the Schrödinger-type equation between diquark and antidiquark. We find that our results give much higher masses for the $sq\bar{b}\bar{q}$ tetraquark configuration. This disfavors the assumption of X(5568) as a tetraquark state. Moreover, possible candidates for open charm tetraquark states are also discussed in this work.

This paper is organized as follows. The relativized quark model is briefly introduced and the masses of diquarks are calculated in Sec. II. The masses of tetraquark states and discussions are presented in Sec. III. Finally, we give a short summary in the last section.

II. Masses of Diquarks

The Hamiltonian between quark and antiquark in the relativized quark model can be expressed as

$$\tilde{H} = H_0+\tilde{V}(p,r), \quad H_0 = (p^2+m_1^2)^{1/2}+(p^2+m_2^2)^{1/2}, \quad \tilde{V}(p,r) = \tilde{H}_{conf}+\tilde{H}_{cont}+\tilde{H}_{ten}+\tilde{H}_{so}$$

where $\tilde{H}_{conf}$ includes the spin-independent linear confinement and Coulomb-like interaction, $\tilde{H}_{cont}$ is the color contact term, $\tilde{H}_{ten}$ is the color tensor interaction, and $\tilde{H}_{so}$ denotes the spin-orbit term. $\tilde{H}$ represents an operator that has taken into account the relativistic effects according to the relativized scheme. The explicit forms of these interactions and the details of this relativization procedure can be found in Appendix A of Ref. [?]. For the quark-quark interaction in a diquark, the relation $\tilde{V}_{qq}(p,r) = \tilde{V}_{q\bar{q}}(p,r)/2$ is employed since we only consider the $\bar{3}$ type diquark in color. All model parameters used in our calculations are taken from Ref. [?].

For the diquark, the qq pair is in S-wave. The spin-parities of the diquark are $J^P = 0^+$ and $J^P = 1^+$, named scalar diquark and axial diquark, respectively. We use the Gaussian expansion method to solve the Hamiltonian (1) with $\tilde{V}_{qq}(p,r)$ potential [?]. The masses of these diquarks are listed in TABLE I.

III. Masses of Tetraquark States

With the diquarks listed in TABLE I, we can calculate the masses of tetraquarks regarded as bound states of diquark and antidiquark. When the diquark structure is considered, a form factor $F(r)$ emerges in the Coulomb-like one-gluon exchange term in the quark-antiquark potential. That is, the $1/r$ term in diquark-antidiquark interaction becomes $F_1(r)F_2(r)/r$. The $F(r)$, which stands for the internal structure of the diquark, can be approximated with high accuracy by the following expression [?]:

$$F(r) = 1 - \frac{\xi r^2}{1+\zeta r^3}$$

where ξ and ζ are nonnegative real numbers. It can be found that the form factor satisfies $0 \leq F(r) \leq 1$. In our present work, we calculate the tetraquark mass with $F(r) = 1$, and we will discuss the effects induced by this form factor qualitatively later on.

In the $F(r) = 1$ case, the screening effects due to the finite size of the diquark are totally neglected, namely, the diquark is treated as point-like or the distance between diquark and antidiquark is large enough [?, ?]. The predicted masses of open charm and bottom tetraquark states in 1S ground states are shown in TABLE II. For the $sq\bar{b}\bar{q}$ quark content, we also plot the mass spectrum in [Figure 1: see original paper]. We find that for a certain quark flavor, the lowest state is the $J^P = 0^+$ $A\bar{A}$ type diquark-antidiquark configuration. This ordering of the mass spectrum differs from the results of Ref. [?], in which the $J^P = 0^+$ $S\bar{S}$ type is the lowest one. The spin-spin interaction provides the fine splitting with coefficients of -2, -1, and 2 for the 0^+, 1^+, and 2^+ $A\bar{A}$ states, respectively, while no fine structure exists for the $S\bar{S}$ tetraquark. Although the mass of A type diquark is higher than that of S type, the larger fine splitting induced by the spin-spin interaction can reduce the $J^P = 0^+$ $A\bar{A}$ state to be the lowest one. The lowest mass of the $J^P = 0^+$ $sq\bar{b}\bar{q}$ state, in our calculation, is 6150 MeV, which is much larger than the mass of the X(5568) state. The lowest mass of the $J^P = 1^+$ $sq\bar{b}\bar{q}$ state is 6210 MeV, which is also larger than

$m_{X(5568)} + m(B_s^*) - m(B_s)$. Hence, our calculated results disfavor the possibility of X(5568) as a tetraquark state within the diquark-antidiquark scenario.

Different from our results, some works claim that they can describe the mass of X(5568) in the tetraquark picture. In those papers, the selected masses of diquarks are lower than ours, and they are not consistently obtained by solving the quark model potentials. For example, a set of parameters with $m_{bq} = 5.249$ GeV and $m_{sq} = 0.590$ GeV are used to calculate the masses of $sq\bar{b}q$ tetraquarks, in which the lowest $J^P = 0^+$ state is about 150 MeV higher than the X(5568) [**?**, **?**]. If we take those lighter diquark values as the masses of A type diquarks and solve the relativized Schrödinger-type equation, we can also obtain a rather low tetraquark mass of 5672 MeV.

[Figure 1: see original paper] The predicted mass spectrum of the $sq\bar{b}\bar{q}$ tetraquarks.

TABLE II: Masses of tetraquark states with diquark-antidiquark in ground 1S state. A dash denotes that this state does not exist.

Diquark content	Open charm (MeV)	Open bottom (MeV)
$cq\bar{q}\bar{q}$	...	...
$cq\bar{s}\bar{q}$	...	...
$cs\bar{s}\bar{q}$	...	...
$cs\bar{s}\bar{s}$	...	...
$qq\bar{b}\bar{q}$	...	...
$sq\bar{b}\bar{q}$	...	...
$sq\bar{b}\bar{s}$	...	...
$ss\bar{b}\bar{s}$	...	...

Another argument is that tetraquark masses can be roughly estimated by the spin-averaged mass of mesons. This situation occurs in studying the masses of XYZ states, where the tetraquark and molecular pictures can both give similar masses in most cases [**?**]. The spin-averaged mass of B^*, B, K^*, and K is 6107 MeV [**?**], which is well consistent with the 6150 MeV ($A\bar{A}$ case) in our present calculation.

When the finite size of the diquark is considered, the one-gluon exchange interaction between diquark and antidiquark becomes weaker, as does the spin-spin interaction. The masses of tetraquarks will increase, while the fine splitting becomes smaller. This situation is the same as the case adopted by Ebert, Faustov, and Galkin, where the mass of the $J^P = 0^+$ $S\bar{S}$ type tetraquark is the lowest and the fine splitting is small [**?**]. In the $F(r) = 0$ limit, only the linear confining interaction remains, and the three $A\bar{A}$ type tetraquark states become degenerate. Of course, the X(5568) cannot be described as a tetraquark state even when the finite size and form factor of the diquark are introduced.

Finally, for the open charm resonances observed by LHCb and BaBar collaborations in recent years [?], extensive theoretical works have been performed in conventional $c\bar{q}$ and $c\bar{s}$ pictures within the quark pair creation model [?], chiral quark model [?], and heavy quark symmetry [?, ?]. From the masses, spin-parities, decay modes, and numerous theoretical analyses in the literature, the $D^*(2600)$, $D_1^*(2760)$, $D_{s1}^*(2760)$, and $D_{s1}^*(2860)$ are believed to have spin-parity 1^-, the $D(2750)/D_J(2740)$ has spin-parity 2^-, and $D_3^*(2760)$ and $D_{s3}^*(2860)$ have spin-parity 3^-. Those states have lower masses and opposite parities to S-wave tetraquark states, which can hardly be described in tetraquark pictures. The $D_J(3000)$ and $D_{sJ}(3040)$ are two unnatural states, while the $D_J^*(3000)$ has natural spin-parity. The masses of these three states are all around 3 GeV. Various theoretical interpretations of these three resonances are not in agreement with each other. The properties of $D_J(3000)$, $D_{sJ}(3040)$, and $D_J^*(3000)$ and the possible tetraquark configurations in the Godfrey-Isgur potential are shown in TABLE III. We expect that more experimental information is needed to reveal the natures of these resonances.

TABLE III: Possible tetraquark configurations of $D_J(3000)$, $D_{sJ}(3040)$, and $D_J^*(3000)$. N and UN stand for natural spin-parity and unnatural spin-parity, respectively.

State	Spin-parity	Mass (MeV)	Tetraquark
$D_J(3000)$	···	···	$1^+ A\bar{A}\ cs\bar{s}\bar{q}$
$D_{sJ}(3040)$	···	···	$1^+ A\bar{A}\ cs\bar{s}\bar{s}$
$D_J^*(3000)$	···	···	$0^+ S\bar{S}\ cs\bar{s}\bar{q}$

However, our present consistent calculations for both diquarks and tetraquarks in the realistic potential do not support the X(5568) as a tetraquark state. Moreover, we know that the masses of bsu flavor baryons Ξ_b and Ξ_b^* are 5794 and 5945 MeV, respectively. It is natural to believe that the $sq\bar{b}\bar{q}$ tetraquarks, containing an additional valence quark, should be above or at least around these two masses.

IV. Summary

In this work, we study the masses of open charm and bottom tetraquark states in the diquark-antidiquark picture using the relativized quark model proposed by Godfrey and Isgur. The diquark and antidiquark masses are obtained with the relativized potential, which is half of the $q\bar{q}$ interaction. Then, the diquark and antidiquark are regarded as the usual antiquark and quark, respectively. The form factor, simulating the diquark (antiquark) internal structure, is neglected in our calculations. This assumption means the diquark is treated as point-like or the distance between diquark and antidiquark is large enough.

The masses of tetraquark states are obtained by solving the Schrödinger-type equation between diquark and antidiquark. We find the masses of $sq\bar{b}\bar{q}$

tetraquark configuration are much higher than that of X(5568), which disfavors the possibility of X(5568) as a tetraquark state. The effects induced by the form factor and finite size of the diquark are qualitatively discussed, and other possible candidates for open charm tetraquark states are also investigated. We expect that further experimental information is needed to reveal the nature of the signal observed by the D0 collaboration.

It should be stressed that very recent discussions based on chiral symmetry and heavy quark symmetry support our conclusion [**?**]. Moreover, new results from the LHCb collaboration observed no peak at X(5568) in *pp* collisions [**?**].

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Note: Figure translations are in progress. See original paper for figures.