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A QCD sum rule calculation of the $X^{\pm}(5568) \to B_s^0 \pi^{\pm}$ decay width

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ABSTRACT

To understand the nature of the $X(5568)$, recently observed in the mass spectrum of the $B_s^0\pi^{\pm}$ system by the D0 Collaboration, we have investigated, in a previous work, a scalar tetraquark (diquak–antidiquark) structure for it, within the two-point QCD sum rules method. We found that it is possible to obtain a stable value of the mass compatible with the D0 result, although a rigorous QCD sum rule constrained analysis led to a higher value of mass. As a continuation of our investigation, we calculate the width of the tetraquark state with same quark content as $X(5568)$, to the channel $B_s^0\pi^{\pm}$, using the three-point QCD sum rule. We obtain a value of (20.4 ± 8.7) MeV for the mass ~ 5568 MeV, which is compatible with the experimental value of $21.9 \pm 6.4(\text{sta})^{+5.0}_{-2.5}(\text{syst})$ MeV/c^2. We find that the decay width to $B_s^0\pi^{\pm}$ does not alter much for a higher mass state.

The D0 Collaboration has recently reported the study of the $B_s^0\pi^{\pm}$ mass spectrum in the energy range 5.5–5.9 GeV, where a narrow enhancement of the experimental data is found and interpreted as a new state: $X(5568)$ [1]. The mass and width for this state have been found to be $m = 5567.8 \pm 2.9(\text{sta})^{+0.9}_{-1.9}(\text{syst})\,\text{MeV}/c^2$ and $\Gamma = 21.9 \pm 6.4(\text{sta})^{+5.0}_{-2.5}(\text{syst})$ MeV/c^2, respectively [1]. The isospin of $X(5568)$ is clearly one. Its spin-parity is not yet known although a scalar four quark interpretation has been suggested in Ref. [1].

The finding of this new state adds to the rigor with which the exotic hadrons with heavy quark flavor are being studied currently. Until just about a decade ago, the data related to the spectroscopy of hadrons with open or hidden charm/bottom structure were relatively scarce and of poor statistical quality. However, the scenario has changed rapidly during the last few years with the working of new experimental facilities like LHCb, BES, BELLE, etc., and good quality experimental data is being published continuously. With sufficient amount of data available, it has been possible to identify several new states, actually way too many to fit in the traditional quark–antiquark spectrum. Indeed, theoretical studies indicate that many of these hadrons must be exotic in nature. For example, the first such state discovered in the charm sector is the $X(3872)$ [2]. The mass as well as the narrow width of $X(3872)$, $\Gamma < 1.2$ MeV [2], in spite of having a large phase space for decay to some open channels, cannot be explained within the conventional quark model. A series of similar states have been found and their structure, quantum numbers, etc., are being debated continuously in the literature. Recently, even clearer evidence of the exotic nature has been brought forward with the finding of special mesons, which are heavy quarkonium-like but at the same time are electrically charged. Such states would at least require four valence quarks to get the nonzero charge. Some examples of such charged charmonium-like states are: $Z_c(3900)$, $Z_c(4025)$, $Z_c(4250)$, $Z_c(4430)$ in the charm sector [3–6] and $Z_b(10610)$, $Z_b(10650)$ [7] in the bottom sector. The $X(5568)$ is an addition to the list of undoubtedly exotic mesons, since its wave function consists of four different flavors: u, b, d and s quark.

The observation of this new state has already motivated several theoretical investigations [8–16]. In Refs. [8–11] the calculations for the mass of $X(5568)$ have been done using the QCD sum rules (QCDSR) method, and results in excellent agreement with the experimental value have been found. In Refs. [8–10] $J^{PC} = 0^{++}$ was assumed while in Ref. [11] scalar as well as axial tetraquark currents were considered. In Ref. [12] a model using multiquark interactions has been used and a 150 MeV higher mass is found for $X(5568)$, although the systematic errors still allow their state to be related to $X(5568)$. Another multiquark model calculations using color-magnetic interaction has been presented in [13]. The possibility of explaining the enhancement in the data as near threshold rescattering effects has been studied in Ref. [14]. The $B\bar{K}$ and $B^*\bar{K}$ molecular interpretations have been suggested in Ref. [15]. A calculation of the width of $X(5568)$ has also been reported in Ref. [16]

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using sum rules based on light cone QCD, but with a Lagrangian that is not usual, with derivatives in the heavy particle fields and not in the pion field.

In Ref. [9] we investigated if the mass of $X(5568)$ can be reproduced in terms of a scalar diquark–antidiquark current (an isovector analog of the $D_{s0}^{\pm}(2317)$ description presented in Ref. [17]). We found that a stable value of mass can be obtained around 5568 MeV while ensuring the dominant contribution to come from the pole. However, further analysis showed that requiring a simultaneous convergence of the operator product expansion series on the QCD side leads to a higher value of the mass, $\sim$ 6390 MeV.

As a continuation of our investigation, we now calculate the decay width of the state found in Ref. [9] to $B_s^0\pi^{\pm}$, following the calculations of the analogous decay in the charm sector done in Ref. [18]. Before proceeding further, it is important to note that for a state with mass $\sim$ 5568 MeV, the decay channels $B\bar{K}$, $B^*\bar{K}^*$ and $B_s^{*0}\rho$ are closed. Moreover the 0^{++} spin-parity assignment would not allow the decay to the other possible open channel $B_s^{*0}\pi^{\pm}$. Even the radiative decay will be allowed only for the neutral member of the isospin triplet. In this case, the decay width to $B_s^0\pi^{\pm}$ should be comparable to the experimental total width [1]. However, for a higher mass, the decay to other channels may contribute to the total width. We calculate the width in both cases and present more discussions related to the results obtained. For the sake of convenience, we shall refer to our state as $X^{\pm}$ in the following discussions.

In Ref. [9] we considered a scalar diquark–antidiquark current in terms of the interpolating field:

$$j_X = \epsilon_{abc}\epsilon_{dec}(u_a^T C\gamma_5 s_b)(\bar{d}_d\gamma_5 C\bar{b}_e^T), \tag{1}$$

where a, b, c, ... are color indices, C is the charge conjugation matrix.

To calculate the vertex, $X^+ B_s^0\pi^+$, we use the three-point correlation function

$$\Gamma_\mu(p,p',q) = \int d^4x \int d^4y e^{ip'.x}e^{iq.y}\langle 0|T[j_{B_s^0}(x)j_{5\mu}^{\pi}(y)j_X^{\dagger}(0)]|0\rangle, \tag{2}$$

where $p = p' + q$ and the interpolating currents for the pion and B_s^0 mesons are given by:

$$j_{5\mu}^{\pi} = \bar{d}_a\gamma_\mu\gamma_5 u_a,$$
$$j_{B_s^0} = i\bar{b}_a\gamma_5 s_a. \tag{3}$$

As the standard procedure in the QCDSR calculations [19,20], we use the dual interpretation of the correlation function and assume that there is an interval over which Eq. (2) may be equivalently described at the quark as well as the hadron level. Following this assumption:

1. On the OPE side, the vertex function of Eq. (2) is calculated in terms of quark and gluon fields using the Wilson's operator product expansion (OPE).
2. On the phenomenological side, the same function is then calculated by treating the currents as the creation and annihilation operators of hadrons and as a result hadron properties, such as masses and coupling constants, are introduced in the process.
3. Finally, both results are equated to extract the value of the coupling constant required to obtain the width of the state.

The phenomenological side is calculated by inserting intermediate states for B_s^0, π^+ and X^+ in Eq. (2), and by using the definitions:

$$\langle 0|j_{5\mu}^{\pi^0}|\pi(q)\rangle = iq_\mu F_\pi, \tag{4}$$

$$\langle 0|j_{B_s^0}|B_s^0(p')\rangle = \frac{m_{B_s^0}^2 f_{B_s^0}}{m_b + m_s}, \tag{5}$$

$$\langle 0|j_X|X(p)\rangle = \lambda_X, \tag{6}$$

we obtain the following relation:

$$\Gamma_\mu^{phen}(p,p',q) = \frac{\lambda_X m_{B_s^0}^2 f_{B_s^0} F_\pi\, g_{XB_s^0\pi}\, q_\mu}{(m_b+m_s)(p^2-m_X^2)(p'^2-m_{B_s^0}^2)(q^2-m_\pi^2)} + \text{continuum contribution}, \tag{7}$$

where the coupling constant $g_{XB_s^0\pi}$ is defined by the on-mass-shell matrix element,

$$\langle B_s^0\pi|X\rangle = g_{XB_s^0\pi}. \tag{8}$$

The second term on the right-hand side in Eq. (7) contains the contributions of all possible excited states.

We follow Refs. [18,21] and work at the pion pole, as suggested in [22] for the pion–nucleon coupling constant. We do this because the matrix element in Eq. (8) defines the coupling constant only at the pion pole. For $q^2 \neq 0$ one would have to replace de coupling constant $g_{XB_s^0\pi}$, in Eq. (8), by the form factor $g_{XB_s^0\pi}(q^2)$ and, therefore, one would have to deal with the complications associated with the extrapolation of the form factor [23,24]. The pion pole method consists in neglecting the pion mass in the denominator of Eq. (7) and working at $q^2 = 0$. On the OPE side one singles out the leading terms in the operator product expansion of Eq. (2) that match the $1/q^2$ term. On the other hand, from phenomenological side, we get the following expression for the q_μ/q^2 structure,

$$\Gamma^{phen}(p^2,p'^2) = \frac{\lambda_X m_{B_{s0}}^2 f_{B_{s0}} F_\pi\, g_{XB_{s0}\pi}}{(m_b+m_s)(p^2-m_X^2)(p'^2-m_{B_s^0}^2)} + \int_{m_b^2}^{\infty} \frac{\rho_{cont}(p^2,u)}{u-p'^2}\, du. \tag{9}$$

In Eq. (9), $\rho_{cont}(p^2,u)$, gives the continuum contributions, which can be parametrized as $\rho_{cont}(p^2,u) = \frac{b(u)}{s_0-p^2}\Theta(u-u_0)$ [25], with s_0 and u_0 being the continuum thresholds for X^+ and B_s^0, respectively. Since we are working at $q^2 = 0$, we take the limit $p^2 = p'^2$ and we apply the Borel transformation to $p^2 \to M^2$ and get:

$$\Gamma^{phen}(M^2) = \frac{\lambda_X m_{B_s^0}^2 f_{B_s^0} F_\pi\, g_{XB_{s0}\pi}}{(m_b+m_s)(m_X^2-m_{B_s^0}^2)}\left(e^{-\frac{m_{B_s^0}^2}{M^2}} - e^{-\frac{m_X^2}{M^2}}\right) + A\, e^{-\frac{s_0}{M^2}} + \int_{u_0}^{\infty} \rho_{cc}(u)\, e^{-u/M^2} du, \tag{10}$$

where A is a parameter introduced to take into account pole-continuum transitions, which are not suppressed when only a single Borel transformation is done in a three-point function sum rule [25,26]. For simplicity, one assumes that the pure continuum contribution to the spectral density, $\rho_{cc}(u)$, is related to the spectral density obtained on the OPE side, $\rho_{OPE}(u)$, through the ansatz: $\rho_{cc}(u) = \rho_{OPE}(u)\Theta(u-u_0)$.

As discussed in Refs. [21,27], large partial decay widths are expected when the coupling constant is obtained from QCDSR in the case of multiquark states, that contains the same valence quarks