Possible $B^{(*)}\bar{K}$ hadronic molecule state

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In the present work, we estimate the decays of the $X(5568)$ and $X(5616)$ in a $B\bar{K}$ and a $B^*\bar{K}$ $S$-wave hadronic molecule scenarios, respectively, which may correspond to the structure observed by D0 Collaboration. Our estimation indicates both $B\bar{K}$ and $B^*\bar{K}$ hadronic molecule decay widths could explain the experimental data in a proper model parameter range.

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I. INTRODUCTION

Very recently, the D0 Collaboration observed a new narrow structure in the $B^0\pi^\pm$ invariant mass spectrum, named $X(5568)$, the mass and width of the structure are $5567.8 \pm 2.9$ (stat)$^{+0.9}_{-1.0}$ (syst) MeV and $21.9 \pm 6.4$ (stat)$^{+5.0}_{-7.7}$ (syst) MeV, respectively [1]. The observed channel indicates the isospin of the $X(5568)$ is 1. If the structure decays into $B^0\pi^\pm$ via a $S$-wave, the quantum numbers of the $X(5568)$ are $J^{PC}=0^{++}$. As indicated in Ref. [1], the observed structure may decay through the chain $B^{*0}\pi^0$, $B^{*}\pi^\pm \to B^0\gamma$, in which the soft photon may not be detected since the mass gap of $B_0^{*0}$ and $B^0$ is less than 50 MeV. In this case, this structure decays into $B_0^{*}\pi^\pm$, and the mass of the structure should be shifted by addition of the mass difference of $B^{*0}_0$ and $B^0$, which is about 5616 MeV, while the width remains unchanged. This structure would be named $X(5616)$ with the quantum number $J^{PC}=1^{++}$ if it couples to $B_0^{*}\pi^\pm$ via the lowest $S$-wave.

The quark components of the $B^{*0}_1$ and $\pi^\pm$ are $\bar{b}s$ and $ud/\bar{u}d$, respectively, thus $X(5568)$ is a kind of structures with four different flavors of quarks, which is observed for the first time. This peculiar property of the $X(5568)$ indicates that it could not be a conventional meson formed by a quark and an antiquark. For a system composed of two quarks and two antiquarks, the color factorization property of the system indicates a two-meson-deuteron-like hadronic molecule structure.

Newly observed hadron states have been extensively investigated in hadronic molecule scenario. For example, in Refs. [2–6], the properties of the $Y(4260)$ were studied, in which the $Y(4260)$ were assigned as a $DD_1(2420)$ molecule. Similarly, the masses and decay behaviors of the $Z_c(3900)/Z_c(4020)$ and $Z_b(10610)/Z_b(10650)$ were estimated in the $D^*D+h.c./D^*D^*$ and $B^*B+h.c./B^*B^*$ hadronic molecular pictures, respectively [7–14].

As for the discussed $X(5568)$ or $X(5616)$, we can find that this structure could be decomposed into a bottom-strange meson and a light meson or a bottom meson and a strange meson. For the former case, the bottom-strange meson and light meson could not interact by exchanging a conventional quark-antiquark meson and form a bound state. While for the latter case, the bottom and strange mesons could form a hadronic molecule state by exchanging a proper light meson. We notice that the thresholds of $B\bar{K}$ and $B^*\bar{K}$ are 5777 and 5822 MeV, respectively [15]. The observed masses of the $X(5568)$ and $X(5616)$ are about 200 MeV below the thresholds of $B\bar{K}$ and $B^*\bar{K}$, respectively. Thus, we can assign the $X(5568)$ and $X(5616)$ reported by the D0 Collaboration as a deeply bounded $B\bar{K}$ or $B^*\bar{K}$ hadronic molecule state with $I=1$, which is different with the one discussed in Ref. [16].

To further check the possibilities of the $X(5565)$ and $X(5616)$ as a $B\bar{K}$ and a $B^*\bar{K}$ hadronic molecule state, we study the strong decays of the $B\bar{K}$ and $B^*\bar{K}$ hadronic molecule states in present work. Due to the kinematic limit, the $X(5565)$ and $X(5616)$ can only strongly decay into $B\pi$ and $B^*\pi$, respectively, which is the observed channel of these states. The approach for describing and treating the deuteron-like hadronic molecule state has been proposed in Refs. [17, 18] and developed in Refs. [19–21]. This approach has been widely used to study the decay behaviors of the hadronic molecule [5, 12–14, 19–23].

This work is organized as follows: The molecule structure of the $X(5568)$ and $X(5616)$ and their decays are present in the following section. The numerical results and discussions for the decays are presented in Section III. and Section IV is dedicated to a short summary.

II. HADRONIC MOLECULE STRUCTURE OF THE $X(5568)$ AND $X(5616)$ AND THEIR DECAYS

hadronic molecule structure.— In the present work, we consider the $X(5568)$ and $X(5616)$ as hadronic molecules with $I=1$, represented by a $B\bar{K}$ and $B^*\bar{K}$ $S$-wave bound state, respectively. The $J^{PC}$ quantum numbers of the $X(5568)$ and $X(5616)$ are $0^{++}$ and $1^{++}$, respectively. The interactions of the hadronic molecule states with their components could be
described by the effective Lagrangian, which are

\[ L_{X_{BK}} = g_{X_{BK}}X^+(x) \int dy\Phi_X(y^2)B^+(x + \omega_{KB}y) \times \bar{K}(x - \omega_{KB}y), \]

\[ L_{X_{B-K}} = g_{X_{B-K}}X^0(x) \int dy\Phi_X(y^2)B^0(x + \omega_{KB}y) \times \bar{K}(x - \omega_{KB}y), \]

where \( X \) and \( X' \) refer to \( X(5568) \) and \( X(5616) \), respectively. \( \omega_{ij} = m_i/(m_i + m_j) \) is the kinematic parameter. The correlation function \( \Phi(y) \) is employed to describe the distributions of the molecular components in the hadronic molecule and to render the Feynman diagrams ultraviolet finite as well. In the present calculations, a Gaussian form of the correlation function is adopted, which has been widely used to investigate the hadronic molecule decays [5, 12–14, 19–23]. The Fourier transform of the correlation function \( \Phi(P_E) \) is in the form,

\[ \Phi(P_E) = \exp(-P_E^2/\Lambda^2) \]

where \( P_E \) is the Jacobi momentum in the Euclidean space, and \( \Lambda \) is a model parameter which characterizes the distribution of the components in the hadronic molecule. The concrete value of the \( \Lambda \) should be of order 1 GeV and dependent on a different molecular system [5, 12–14, 19–23].

The coupling strength of a hadronic molecule to its components could be evaluated from the compositeness condition [17, 18], in which the renormalization constant of a composite particle wave function is zero. As for the discussed scalar hadronic molecule, \( X(5568) \), the renormalization constants is

\[ Z_X \equiv 1 - \Sigma_X(m_X^2) = 0, \]

where, \( \Sigma_X(m_X^2) \) is derivative of the mass operator of the \( X(5568) \), which is presented in Fig. 1-(a). The concrete form of the mass operator of the \( X(5568) \) is

\[ \Sigma_X(5568) = g^2_{X_{BK}} \int \frac{d^4q}{(2\pi)^4} \Phi_X^2[-(q - \omega_{BK}p)^2] \times \frac{1}{(p - q)^2 - m_K^2} \frac{1}{q^2 - m_B^2}. \]

As a pseudo-vector hadronic molecule, the mass operator of the \( X(5616) \) includes the transverse and longitudinal components, which is,

\[ \Sigma_X^\mu(p) = g^\mu_\perp \Sigma_X(p^2) + \frac{p^\mu p^\nu}{p^2} \Sigma_X(p^2), \]

with \( g^\mu_\perp = g^\mu_\nu - p^\mu p^\nu/p^2 \). The \( \Sigma_X(p^2) \) and \( \Sigma_X^\mu(p^2) \) are the conventional transverse and longitudinal components, respectively. As shown in Fig. 1-(b), the mass operator of \( X(5616) \) is

\[ \Sigma_X^\mu(5616) = g^\mu_{X_{BK}} \int \frac{d^4q}{(2\pi)^4} \Phi_X^2[-(q - \omega_{BK}p)^2] \times \frac{1}{(p - q)^2 - m_K^2} \frac{-g^\mu_\perp + q^\mu q^\nu/m_B^2}{q^2 - m_B^2}. \]

The compositeness condition of the \( X(5616) \) indicates

\[ Z_{X'} \equiv 1 - \Sigma_{X'}(m_{X'}^2) = 0. \]

Decays of the hadronic molecule.— We calculate the hadronic molecule decays in an effective Lagrangian approach. The Lagrangians related to the bottom mesons and the light mesons are [24–26],

\[ L_{B^{-}\to B^{-}\nu} = -i g_{BB\nu} B_i^\mu \bar{\nu}_j (\gamma^\mu B_i B_j), \]

\[ + i g_{BB\nu} B_i^\mu \bar{\nu}_j (\gamma^\mu B_i B_j), \]

\[ + 4 i g_{BB\nu} B_i^\mu \bar{\nu}_j (\gamma^\mu B_i B_j - \gamma^\mu B_i B_j), \]

\[ \frac{1}{2} g_{BB\nu} (\bar{B}_i \nu_j B^i B^j - \bar{B}_i \nu_j B^i B^j), \]

where \( B_i^\mu \equiv (B_i^{\mu-}, \bar{B}_i^{\mu-}, \bar{B}_i^{\mu0}) \) and \( \bar{B} \equiv \bar{B} \nu B = \bar{B} \nu B = \bar{B} A \). The \( V \) and \( P \) are the matrices of the vector nonet and the pseudoscalar nonet, respectively,

\[ V = \begin{pmatrix} (4^0 + \omega) & \rho^+ & K^{+0} & K^{+}\bar{\nu} \cr \rho^- & (4^0 - \omega) & K^{0} & \phi \cr K^{+} & K^{0} & (4^0 + \omega) & \phi \cr K^{-} & K^{0} & \bar{K}^{0} & (4^0 - \omega) \end{pmatrix}, \]

\[ P = \begin{pmatrix} \pi^+ & \pi^0 & K^+ & \bar{K}^0 \cr \pi^- & \pi^0 & K^- & \bar{K}^0 \cr K^{+0} & K^{+0} & \bar{K}^0 & \bar{K}^0 \cr K^{0} & K^{0} & \bar{K}^{0} & \bar{K}^{0} \end{pmatrix}. \]

The interaction between strange mesons and pion constructed by hidden local gauge symmetry is [27],

\[ L_{K^0 \bar{K}^0} = -i g_{K^0 \bar{K}^0} K^{+0} \bar{\nu} \gamma^\mu K^\mu, \]

where \( \bar{\nu} \) is the Pauli-Dirac matrix and \( \bar{\nu} \) is the pion isospin triplet. The \( K \) and \( K^* \) are the doublets of pseudoscalar and vector strange mesons, respectively.

As a \( B \bar{K} \) hadronic molecule, the \( X(5568) \) state can decay to \( B_\mu^0 \pi^\nu \) via S-wave. The amplitudes corresponding to the dia-
The coupling constants concerning to the bottom mesons and symmetry \[ \Sigma \text{ (5616)} \] could be evaluated by heavy quark limit and chiral gauge coupling constant where the overline indicates sum over polarizations of vector mesons.

The coupling constants of the bottom mesons to the light mesons are \[ \Sigma \text{ (5616)} \]. The corresponding amplitudes are

\[ M_1 = (i)^3 \int \frac{d^4q}{(2\pi)^4} [g_{B^*K^0}\Phi_X(-P_{12}^2)] \]
\[ \times [1 - i\sqrt{2}g_{K^*B}(ip_1^B + ip_2^B)] - ig_{BBV}(ip_2^B + ip_3^B) \]
\[ \times \frac{1}{p_1^2 - m_1^2} \frac{1}{p_2^2 - m_2^2} \frac{1}{q^2 - m_q^2} \] ,

\[ M_2 = (i)^3 \int \frac{d^4q}{(2\pi)^4} [g_{B^*K^0}\Phi_X(-P_{12}^2)] \]
\[ \times [ig_{BBV}(-ip_3^B)] - ig_{BBV}(ip_1^B + ip_2^B) \]
\[ \times \frac{1}{p_1^2 - m_1^2} \frac{1}{p_2^2 - m_2^2} \frac{1}{q^2 - m_q^2} \] .

where \( P_{12} = p_1\omega_{12} - p_2\omega_{12} \). The total amplitude of the process \( X(5616) \rightarrow B_s^0\pi^+ \) is

\[ |\mathcal{M}|^2 = M_1 + M_2, \]

and the decay width of \( X \rightarrow B_s^0\pi^+ \) is

\[ \Gamma(X(5616) \rightarrow B_s^0\pi^+) = \frac{1}{8\pi} \frac{1}{m_X^2} |\mathcal{M}|^2. \]

The \( X(5616) \) state can decay to \( B_s^0\pi^+ \) via the triangle diagrams presented in Fig. 3. The corresponding amplitudes are

\[ M_1 = (i)^3 \int \frac{d^4q}{(2\pi)^4} [g_{B^*K^0}\Phi_X(-P_{12}^2)] \]
\[ \times \frac{1}{p_1^2 - m_1^2} \frac{1}{p_2^2 - m_2^2} \frac{1}{q^2 - m_q^2} \]
\[ \times \frac{1}{p_1^2 - m_1^2} \frac{1}{p_2^2 - m_2^2} \frac{1}{q^2 - m_q^2} \]

where \( P_{12} = p_1\omega_{12} - p_2\omega_{12} \) and the total amplitude of process \( X(5616) \rightarrow B_s^0\pi^+ \) is

\[ |\mathcal{M}|^2 = M_1 + M_2 + M_3, \]

and the decay width of \( X(5616) \rightarrow B_s^0\pi^+ \)

\[ \Gamma(X(5616) \rightarrow B_s^0\pi^+) = \frac{1}{8\pi} \frac{1}{m_X^2} |\mathcal{M}|^2. \]

where the overline indicates sum over polarizations of vector mesons.

### III. NUMERICAL RESULTS AND DISCUSSIONS

The coupling constants of the bottom mesons to the light mesons could be evaluated by heavy quark limit and chiral symmetry \([24]\). The coupling constant \( g_{B^0\pi B^+} \) is related to a gauge coupling constant \( g \) by

\[ g_{B^0\pi B^+} = \frac{2g \sqrt{m_B}}{f_\pi}, \quad g_{BBV} = \frac{2g}{f_\pi} \sqrt{m_B m_{B^0}}, \]

where \( f_\pi = 132 \text{ MeV} \) is the pion decay constant and \( g = 0.44 \pm 0.03 \pm 0.00 \) is determined by the lattice QCD calculation[28]. The coupling constants concerning to the bottom mesons and the light vector mesons are \([29, 30]\),

\[ g_{BBB} = \beta g_\pi / \sqrt{2}, \quad g_{BBV} = \beta g_\pi / \sqrt{2}, \quad f_{BBV} = \lambda m_B g_\pi / \sqrt{2}, \]

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where the gauge couplings $\beta = 0.9$, $\lambda = 0.56 \text{GeV}^{-1}$, and $g_V = m_{\nu}/f_s$. We use the same $g_{K'K\pi}$ strong coupling constants as used in Ref. [27],

$$g_{K'K\pi} = 3.21.$$  \hspace{1cm} (20)

FIG. 4: The $\Lambda$ dependences of $g_{XB,K}$ (left column) and $g_{X'K,K}$ (right column).

Besides the coupling constants listed above, we estimated the coupling of $g_{XB,K}$ and $g_{X'K,K}$ via compositeness condition presented in Eqs. (3) and (7). The $\Lambda$ dependences of the coupling constants $g_{XB,K}$ and $g_{X'K,K}$ are presented in Fig. 4. Both $g_{XB,K}$ and $g_{X'K,K}$ decline with the increase of $\Lambda$ in our considered $\Lambda$ range, which is $0.2 \sim 0.6$ GeV for the $X(5568)$ and $0.6 \sim 1.8$ GeV for the $X(5616)$.

The partial width of $X(5568)^+ \to B_s^0\pi^+$ is presented in Fig. 5. It varies from 5.2 to 46.7 MeV with the variation of $\Lambda$ from 0.2 to 0.6 GeV. The blue band is the total width of the $X(5568)$ [1]. The overlapped $\Lambda$ range is 0.31 GeV $\sim$ 0.46 GeV. We present the partial decay width of $X(5616) \to B_s^0\pi^+$ in Fig. 6. It varies from 7.9 to 39.0 MeV with the increasing of $\Lambda$ from 0.6 to 1.8 GeV. The constrained $\Lambda$ range is 0.89 $\sim$ 1.43 GeV. As shown in Figs. 5 and 6, the partial widths of $X(5568) \to B_s^0\pi^+$ and $X(5616) \to B_s^{0}\pi^+$ depend on the model parameter $\Lambda$. Our calculations indicate that both constrained $\Lambda$ ranges are of order 1.0 GeV, which are in acceptable range.

There is another possibility that the experimental $X(5568)$ structure contains two states, i.e., the $X(5568)$ and $X(5616)$, which would overlap in the $B_s\pi$ invariant mass spectra. In this case, the present experimental measurement could not distinguish this two states [1]. However, the $X(5616)$ state can radiatively transit into $B_s^\ast$ and $B_s$, while the $X(5568)$ can only decay to $B_s^\ast\gamma$. The future experimental measurements of the radiative decays of the neutral $X(5568)$ and $X(5616)$ could provide us more information about the structure observed by the D0 Collaboration [1].

IV. SUMMARY

To summarize, we interpret the newly observed structure $X(5568)$ and $X(5616)$ as $S$–wave deeply bound state of $BK$ and $B^*K$, respectively. With an effective Lagrangian approach, we estimate the partial decay widths $X(5568) \to B_s^0\pi^+$ and $X(5616) \to B_s^{0}\pi^+$. Our results indicate both explanations could be acceptable since the constrained model parameter $\Lambda$ are of order 1.0 MeV. Since both $BK$ and $B^*K$ hadronic molecule could exist in the structure observed by D0 collaboration [1], we propose to study these states by radiative decay experimentally, which would help us to further understand the observed structure in the $B_s\pi$ invariant mass spectrum by the D0 Collaboration [1].

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