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# $\mathrm{D_0}$ Non-strange $0^+$ Heavy Mesons Have Molecular Structure in the Heavy Chiral Unitary Approach

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**Abstract** $\mathrm{D_0^*}(2308)$ and $\mathrm{B_0^*}$ resonances are discussed with the molecular state assumption in the heavy chiral unitary approach. By studying the heavy baryon-pseudoscalar meson interaction, some molecular states are found. It is shown that there exists a bound DK state with a mass of about $2.312\pm0.041$GeV in the strange sector, which can be identified as $\mathrm{D_{s0}^*}(2317)$. While in the non-strange sector, one wide-width state at about 2.1GeV and one narrow-width state at about 2.44GeV are found. These states should be associated with the $\mathrm{D_0^*}$ state. Therefore, $\mathrm{D_0^*}(2308)$ cannot be explained by the assumption of the molecular structure only. Moreover, $\mathrm{B_{s0}^*}$ and $\mathrm{B_0^*}$ states are also predicted. A $\mathrm{B\bar{K}}$ bound state with the mass of $5.725\pm0.039$GeV which can be assigned to the $\mathrm{B_{s0}^*}(5725)$ state and $\mathrm{B_0^*}(5536)$ and $\mathrm{B_0^*}(5819)$ should be considered as the corresponding states in the non-strange sector.

**Key words** $\mathrm{D_0}$, $\mathrm{B_0}$, heavy chiral unitary approach, dynamically generated states

In 2003, Babar observed a new state in the inclusive $\mathrm{D_s^+}\pi^0$ invariant mass distribution from $\mathrm{e^+e^-}$ annihilation[1]. The state was identified with the mass of $2318\pm0.3\pm0.9$MeV, the width less than 10MeV and $J^P=0^+$, and it was suggested as a candidate of $^3P_0$ $\mathrm{c\bar{s}}$ state($\mathrm{D_s}$). Later, that state was confirmed by CLEO in the same process and by Belle in the $\mathrm{B}\rightarrow\mathrm{\bar{D}D_{sJ}}$ process[2]. Because it has a very narrow intrinsic width and a mass smaller than that predicted by various theoretical models, the new observation regenerates the enthusiasm of physicists on the open charm spectrum study. Up to now, many physicists have conjectured that the observed state is a conventional $\mathrm{c\bar{s}}$ meson state[3]. But others believed that the new state might be an exotic meson state, for instance, various tetraquark state[4] or various molecular state[5] or even a mixture of a $\mathrm{c\bar{s}}$ state with a molecular state[6] or with a tetraquark state[7]. Nevertheless, the structure of the $0^+$ state in the strange sector is still in dispute.

In the following year, Belle Collaboration observed another new state $\mathrm{D_0^{*0}}$ with the mass of $2308\pm17\pm15\pm28$MeV and the width of $276\pm21\pm18\pm60$MeV[8]. But FOCUS Collaboration claimed that such a state should have a mass of $2407\pm21\pm35$MeV and a width of $240\pm55\pm59$MeV[9]. Theoretical investigations showed that this state could be a conventional $\mathrm{c\bar{n}}$ meson[10],or a tetraquark state[11], or a $\mathrm{c\bar{n}}$+tetraquark admixture[7]. Whether these two states are the same state and whether the state is the corresponding state of $\mathrm{D_{sJ}^*}(2317)$ in the non-strange sector are even challenging.

In this talk, we will present whether these states, especially the $\mathrm{D_0^{*0}}(2308)$ state, can be explained under the assumption of the meson-meson molecular structure only. A better framework for carrying out this in-

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vestigation is the so-called chiral unitary approach[12]. In this approach, the meson-meson interaction can be well described and many light scalar mesons, such as σ, $f_0(980)$, $a_0(980)$, $\kappa$, etc. can dynamically be generated through $S$ wave interactions between Goldstone bosons[13].

To study heavy mesons, we adopt the lowest order Lagrangian in the heavy chiral perturbation theory[14]

$$\begin{aligned}\mathscr{L} = {} & \frac{1}{4f_\pi^2}(\partial^\mu P[\Phi,\partial_\mu\Phi]P^\dagger - P[\Phi,\partial_\mu\Phi]\partial^\mu P^\dagger) - \\ & \frac{1}{4f_\pi^2}(\partial^\mu P^{*\nu}[\Phi,\partial_\mu\Phi]P_\nu^{*\dagger} - \\ & P^{*\nu}[\Phi,\partial_\mu\Phi]\partial^\mu P_\nu^{*\dagger}),\end{aligned} \tag{1}$$

where $f_\pi = 92.4\text{MeV}$ is the pion decay constant, $P$ represents the charmed mesons ($c\bar{u}$, $c\bar{d}$, $c\bar{s}$), namely ($D^0$, $D^+$, $D_s^+$), and $\Phi$ denotes the octet pseudoscalar Goldstone bosons. Similarly, in the bottom sector, $P^*$ in Eq. (1) should be anti-bottom mesons ($b\bar{u}$, $b\bar{d}$, $b\bar{s}$), namely ($B^-$, $\bar{B}^0$, $\bar{B}_s$). From Eq. (1), one can immediately obtain the amplitude of the three diagrams in a specific channel

$$V_{ij}^I(s,t,u) = \frac{C_{ij}^I}{4f_\pi^2}(s-u), \tag{2}$$

where $i$ and $j$ represent the initial and the final states, respectively, $I$ denotes the isospin of the system, s, t, u are the usual Mandelstam variables and the coefficient $C_{ij}^I$ can be found in Ref. [15]. In the $I=0$ case, $i(j)$=1 and 2 represent the DK and $D_s\eta$ channels in the charmed sector, respectively, and $B\bar{K}$ and $B_s\eta$ channels in the bottom sector, respectively. These two channels are coupled through the non-diagonal term $V_{ij}^I$ with $i \neq j$. In the $I=\frac{1}{2}$ case, $i$ $(j)$=1, 2 and 3 denote the $D\pi$, $D\eta$ and $D_s\bar{K}$ channels in the charmed sector, respectively, and $B\pi$, $B\eta$ and $B_sK$ channels in the bottom sector, respectively. Again, the couplings between these channels are induced by the non-diagonal terms $V_{ij}^I$ with $i \neq j$.

Under the on-shell approximation, the full scattering amplitude can be written as an algebraic Bethe-Salpeter equation

$$T^I(s) = [1 - V^I(s)G(s)]^{-1}V^I(s)\ . \tag{3}$$

The propagator $G(s)$ can be calculated in the dispersion relation approach[15]. By setting the subtraction constant $a(\mu)$ in an appropriate region, where the corresponding cutoff momentum $q_{\max}$ picks up the value in the region of 0.6—1.0GeV, the artificial divergence of the propagator $G(s)$ can be removed.

The physical states are closely associated with the poles of the full amplitude of the coupled channel scattering on the appropriate Riemann sheets of the complex energy plane. In the $(I,S)=(0,1)$ channel, by examining the poles, we find $DK(D^*K)$ and $B\bar{K}(B^*\bar{K})$ bound states in the strange-charmed and strange-bottom sectors, respectively. The masses of these states are tabulated in Table 1.

Table 1. Masses of the states in the $(I,S)=(0,1)$ channel. $I$, $S$ and $J$ denote the isospin, spin and the total angular momentum of the system, respectively.

| $J$ | state | structure | mass/GeV | $J$ | state | structure | mass/GeV |
|---|---|---|---|---|---|---|---|
| 0 | $D_{s0}^*$ | DK | $2.312\pm0.041$ | 0 | $B_{s0}^*$ | $B\bar{K}$ | $5.725\pm0.039$ |
| 1 | $D_{s1}^*$ | $D^*K$ | $2.462\pm0.010$ | 1 | $B_{s1}^*$ | $B^*\bar{K}$ | $5.778\pm0.007$ |

From this table, one sees that the experimental data of the $D_{s0}^*$ and $D_{s1}^*$ states[1, 2] can simultaneously be well reproduced. This implies that the DK ($D^*K$) molecular structure is the dominate structure of the $D_{s0}^*$ ($D_{s1}^*$) state. Furthermore, in the strange-bottom sector, there should be a $B\bar{K}(B^*\bar{K})$ molecular state associated with $B_{s0}^*$ ($B_{s1}^*$), and one should find them at 5.725GeV (5.778GeV) in the experiment.

With the same assumption and Lagrangian, we examine the pole structure of the full amplitude in the $(I,S)=(1/2,0)$ channel. Two poles in each $J$ case are found. In the $J=0$ case, the lower pole, which associates with $D\pi$ ($B\pi$) resonance in the non-strange-charmed (non-strange-bottom) sector, is located on the second Riemann sheet. Since this resonance is easy to decay into $D+\pi$ ($B+\pi$), the width of the resonance is large. The higher pole, which associates with a metastable $D_s\bar{K}$ ($B_sK$) state in the non-strange-charmed (non-strange-bottom) sector due to its narrow width, is also located on the second Riemann sheet. We summarize the masses and widths of these states in Table 2.

Table 2. Masses and widths of the states with $J=0$ in the $(I,S)=(1/2,0)$ channel. $I$, $S$ and $J$ denote the isospin, spin and the total angular momentum of the system, respectively.

| $J$ | state | structure | mass/GeV | width/GeV |
|---|---|---|---|---|
| 0 | $D_0^*$ | $D\pi$ | $2.097\pm0.018$ | $0.213\pm0.080$ |
| | | $D_s\bar{K}$ | $2.443\pm0.046$ | $0.088\pm0.010$ |
| 0 | $B_0^*$ | $B\pi$ | $5.536\pm0.029$ | $0.234\pm0.086$ |
| | | $B_sK$ | $5.819\pm0.045$ | $0.046\pm0.008$ |

It is shown that the predicted $D_0^*$ states are consistent with those predicted in Ref. [16], although they all deviate from the experimental value of 2308MeV or 2407MeV[8, 9]. Because of the large uncertainty in the data analysis and the predicted higher narrow state just around the $D_2^*(2460)$ region, the molecular model cannot rudely be disregarded. If one believes that the $D_0^{*0}(2308)$ (or $D_0^{*0}(2407)$)and $D_{s0}^*(2317)$ are the corresponding states in the non-strange and strange sectors, respectively, there should be a pair of molecular states associated with $D_0^{*0}$. One of them is a wide-width resonant state at about 2.1GeV and the other is a narrow-width metastable state around 2.44GeV. Therefore, the resultant molecular state could give a contribution to the mass of $D_0^{*0}(2308)$ (or $D_0^{*0}(2407)$). One might surmise that the newly observed $D_0^{*0}(2308)$ (or $D_0^{*0}(2407)$) would have a mixed configuration, in which the molecular structure and other structures, such as the tetraquark, the conventional meson, etc., co-exist. Moreover, we predict possible $B_0^*(5536)$ and $B_0^*(5819)$ states in the non-strange sector as the corresponding state of $B_{s0}^*(5725)$ in the strange sector and tabulate their masses and widths in Table 2.

As a summary, within the molecular model, one can well describe the newly observed $D_{s0}^*(2317)$ and $D_{s1}^*(2460)$ states, simultaneously, but not the $D_0^{*0}(2308)$. If one believes that the $D_0^{*0}(2308)$ (or $D_0^{*0}(2407)$) and $D_{s0}^*(2317)$ are the corresponding states in the non-strange and strange sectors, respectively, there should be a pair of molecular states associated with $D_0^{*0}$. If more accurately determined mass of $D_0^{*0}$ in future experiments would not be the value of our prediction, the newly observed $D_0^{*0}(2308)$ (or $D_0^{*0}(2407)$) might have a mixed configuration, in which the molecular structure and other structures, such as the tetraquark, the conventional meson, etc., co-exist. More theoretical investigations on the structures of $D_0^{*0}$ are still needed.

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# 在手征么正模型中 $0^+$ 重介子是否存在分子态结构

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**摘要**　在分子态结构的假设下, 利用手征么正模型研究了 $D_0^*(2308)$ 和 $B_0^*$ 的可能结构. 通过研究重子–赝标介子相互作用, 找到了一些可能的分子态. 结果表明: 在带奇异数的系统中, 存在一个质量为 $2.312\pm0.041$GeV 的 DK 束缚态, 它可以被解释为实验上发现的 $D_{s0}^*(2317)$. 与此同时, 在非奇异系统中, 存在一个与之对应的、质量为 2.1GeV 的宽度较大的态和一个对应的、质量为 2.44GeV 的宽度较小的态. 这两个态应对应于 $D_0^*$. 因此, 分子态结构只能是 $D_0^*(2308)$ 一个分量. 计算结果还预言了一些 $B_{s0}^*$ 和 $B_0^*$ 态. 其中质量为 $5.725\pm0.039$GeV 的 $B\bar{K}$ 束缚态可以被解释为 $B_{s0}^*(5725)$, 而预言的 $B_0^*(5536)$ 和 $B_0^*(5819)$ 应为与 $B_{s0}^*(5725)$ 相对应的非奇异态.

**关键词**　$D_0$　$B_0$　重味手征么正模型　态的动力学产生

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