Charged charmonium-like states as rescattering effects in $\bar{B} \to D_{sJ}^+ D^{(*)}$ decays

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Using purely phenomenological approach we show that the peaking structures observed in the $\psi(2S)\pi^+$ and $\chi_{c1}\pi^+$ mass spectra in $\bar{B} \to \psi(2S) (\chi_{c1})\pi^+K$ decays can be result of $(D\bar{D}^{(*)})^+ \to (c\bar{c})_{\text{res}} \pi^+$ rescattering in the decays $\bar{B} \to D_{sJ}^+ \to \bar{D}^{(*)}K D^{(*)}$. In particular, the position of the peak in the chain $\bar{B} \to D_s(2S)^- D^+ \to K^- D^{*0} D^+ \to K^- \psi(2S)\pi^+$ coincides well with the measured $Z(4430)^+$ mass, assuming the mass of $D_s(2S)^-$ (the first radial excitation of $D_s^-$) to be 2610 MeV/c$^2$. The widths of the $Z(4430)^+$ peak is also well reproduced in this approach independent on the width of $D_s(2S)^-$. Although the decay $\bar{B} \to \bar{D}_s(2S)^- D^+$ has not been observed so far and even $D_s(2S)^-$-meson is not discovered yet, this decay is expected to be large, and the mass of $D_s(2S)^-$ is predicted in the range $(2600-2650)$ MeV/c$^2$. The broad bump in $\chi_{c1}\pi^+$ spectrum can be attributed to the $\bar{B} \to D_{sJ}^+ D^+ \to K^- D^{*0} D^+$ decay observed with a large branching fraction followed by rescattering $D^{*0} D^+ \to \chi_{c1}\pi^+$.

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The charmonium-like charged $Z^+$ states, seen by Belle in $\bar{B} \to \psi(2S)\pi^+ K$ and $\bar{B} \to \chi_{c1}\pi^+ K$ decays remained puzzles for last few years. Belle [1] observed the first $Z(4430)^+$ state as a sharp peak in $\psi(2S)\pi^+$ mass spectrum near $M(\psi(2S)\pi^+) = 4430$ MeV/c$^2$ with statistical significance of more than 6$\sigma$. The main background around the peak region is due to $\bar{B} \to \psi(2S)K^*(892)$ and $\bar{B} \to \psi(2S)K_2^+(1430)$ decays. In the Belle analysis the two $K^{(*)}$ states were vetoed to suppress this background. It was noted that interference between different partial waves in the $\pi K$-system can produce peaks, that are reflections of the $K^{(*)}$ polarization. However, these effects should also produce additional sharp structures nearby in $M(\psi(2S)\pi^+)$, which are not observed by Belle. More detailed analysis was performed by Belle [2] a year latter to prove quantitatively the absence of fake peaks by the Dalitz fit over all signal events including $K^{(*)}$ regions. In this study Belle confirmed the $Z(4430)^+$ observation and found its parameters consistent with those measured in the first paper. Although BaBar [3] has reported no evidence of $Z(4430)^+$ in their $\bar{B} \to \psi(2S)\pi^+ K$ analysis, the non-uniform structures are presented in their spectrum as well, and both Belle and BaBar spectrum are consistent with each other.

Two broader peaks ($Z_1(4050)^+$ and $Z_2(4250)^+$) were found by Belle [4] in the $\chi_{c1}\pi^+$ mass spectrum in the analysis of $\bar{B} \to \chi_{c1}\pi^+K^0$ decay. A Dalitz fit with a single resonance in the $Z^+$ channel is favored over a fit with only $K^{(*)}$-resonances and no $Z^+$-fit by more than 10$\sigma$. Moreover, a fit with two $Z^+$ resonances is favored over the fit with only one resonance by 5.7$\sigma$.

If the observed $Z^+$ peaks are real states, they would necessarily be exotic (non-conventional $q\bar{q}$) mesons, as their minimal substructure consists of four quarks. Many attempts of explanation of $Z^+$’s follow these observations including molecular [5,6], tetraquark [7], hadrocharmonium states [8] or cusp effects [9]. In this Letter we demonstrate that the observed peaks can be explained by the effect of rescattering in the decay chain

$$\bar{B} \to D_{sJ}^- D^{(*)} \quad \text{followed by} \quad D_{sJ}^- \to \bar{D}^{(*)} K$$

(1)

of $\bar{D}^{(*)} D^{(*)}$-pair into charmonium+$\pi^+$, where one $D^{(*)}$ is directly produced in $\bar{B}$-decay, while $\bar{D}^{(*)}$ is from the intermediate $D_{sJ}^-$ resonance (Fig. 1).

We assume that the $\bar{B}$ decay dynamics can be factorized from the rescattering process. Under this assumption the mass of the charmonium+$\pi^+$ combination is equal to those of $\bar{D}^{(*)} D^{(*)}$. The mass spectrum of $(c\bar{c})_{\text{res}} \pi^+$ system produced via rescattering consists of peaking structure(s) reflecting the $D_{sJ}^-$ polarization in $\bar{B}$-decay or $\bar{D}^{(*)} D^{(*)}$ polarization in the formation of $(c\bar{c})_{\text{res}} \pi^+$. Here we denote the $\bar{D}^{(*)} D^{(*)}$ as $(c\bar{c})_{\text{res}} \pi^+$ as “$Z^*$” and calculate “$Z^*$” mass ignoring the subsequent decay “$Z^*$” $\to (c\bar{c})_{\text{res}} \pi^+$. However, angular momentum/parity conservation impose restrictions on “$Z^*$” production depending on the final $(c\bar{c})_{\text{res}} \pi^+$ state that should be taken into account. In particular, $\psi(2S)\pi^+$ and $\chi_{c1}\pi^+$ systems have different spin-parity, thus different decay chains of the type (1) should be proposed for the explanation of the peaks in their spectra. We also assume that rescattering of $\bar{D}^{(*)} D^{(*)}$ in $S$-wave dominates.

There are many decay chains [11] that can provide the required conditions; all of them should be considered taking into account interference between them. We are now limiting ourselves by searching for the dominant contribution that can roughly reproduce the features of the observed $(c\bar{c})_{\text{res}} \pi^+$ spectra. We note that orbital $D_{sJ}^-$ excitations are
hardly suitable for our explanation: j = 1/2 states are below D*(K) threshold, while B-decays into j = 3/2 states are strongly suppressed (B ≤ 10^{-4})]. Radial D_s^+ excitations could be better candidates: the decay \( B \rightarrow D_s(2700)^- D \) was observed by Belle with relatively large branching fraction \( B(B \rightarrow D_s(2700)^- D) \times B(D_s(2700)^- \rightarrow DK) \sim 10^{-3} \). The quantum numbers of the \( D_s(2700)^- \) have been measured to be \( J^P = 1^- \) and this state is likely to be a radial excitation of \( D_s^- \) (as expected mostly \( \lambda_s = 0 \). If this is really true, the pseudo scalar state, \( D_s(2S)^- \), have a mass of (2600 – 2650) GeV/c^2 (expected 2S^1 – 2S^3 splitting is (60 – 100) MeV/c^2), and should decay predominantly into \( D^+K \). It is also expected that two body \( B^- \)-decays into \( D_s(2S)^- \) are not suppressed.

We are first looking for an explanation of the Z(4430)^+ peak. The rescattering of \((D\bar{D})^+ \rightarrow \psi(2S)\pi^+\) is forbidden by parity/angular momentum conservation, while the diagram \((\bar{D}D^*)^+ \rightarrow \psi(2S)\pi^+\) is allowed for both initial and final systems in the S-wave. The two \( B \rightarrow D^+D^{0}\bar{K} \) and \( \rightarrow D^0D^{+}\bar{K} \) decay modes that include all intermediate states (as expected mostly \( D_{sJ}^- \)) has a relatively large branching fraction of \( \sim 10^{-2} \). \((D\bar{D}^*)^+ \) system should form a pseudo-state with the spin equal to one and positive parity \( (J^P = 1^+) \), thus the parity of the intermediate \( D_{sJ}^- D^* \) combination should be also positive. The decay chain \( \bar{B} \rightarrow D_s(2S)^- D^+ \) followed by \( \rightarrow D_s(2S)^- \rightarrow D^{*0}\bar{K} \) matches this parity constraint. Another allowed decay chain that can result in \( \psi(2S)\pi^+ \) is \( \bar{B} \rightarrow D_s(2S)^- \rightarrow (\rightarrow D^0\bar{K}) D^*+ \). We calculate the matrix elements of these decays in the helicity formalism

\[
\mathcal{M}(M_{(D\bar{D})^+}) \sim \left| \sum_{\lambda_{D^*}} a_{\lambda_{D^*}} A_{BW}(M_{D^*\bar{K}}) D_{D_{sJ}}(\theta, \lambda_{D^*}) D_{D^*}(\theta', \lambda_{D^*}) D_{Z}(\theta'') \right|^2 ,
\]

where \( A_{BW} \) is a Breit-Wigner function for a corresponding \( D_{sJ}^- \)-resonance; \( D(\theta, \lambda_{D^*}) \) is its angular part depending on the \( D_{sJ}^- \) decay angle, \( \theta \), and helicity of \( D^* \), \( \lambda_{D^*}. \) (In case of the second decay chain the angular term depends on the \( D_s(2S)^- \) helicity; however here we use equality \( \lambda_{D^*} = \lambda_{D^*} \).) The next term, \( D_{D^*}(\theta', \lambda_{D^*}) \), is responsible for the rotation of the \( D^* \) spin from the \( D_{sJ}^- \) (or \( \bar{B} \) in case of the second decay chain) to “Z” rest frame. We note that in the “Z” rest frame the \( D^* \) helicity is fixed to zero. Finally, \( D_{Z}(\theta'') \) provides formation of “Z” from helicity-0 \( D^* \) and \( \bar{D} \). We list explicitly angular contributions to the matrix elements in the upper lines of Table 1 for two considered decays: \( \bar{B} \rightarrow D_s(2S)^- D \) and \( B \rightarrow D_s(2S)^+ D^* \) in terms of (small) Wigner functions. In the later decay we assume that \( S \) (over \( D \) wave dominates.

We calculate the M(“Z”) spectra using Monte Carlo simulation. In this calculations we assume the mass of \( D_s(2S)^- \) to be 2610 MeV/c^2 and its widths to be 60 MeV; the \( D_s(2S)^+ \) parameters are fixed to PDG values [10]. The obtained spectra are presented for \( \bar{B} \rightarrow D_s(2S)^- D \) and \( B \rightarrow D_s(2S)^+ D^* \) decays in Fig. 2(a) and b), respectively. The solid lines show the \( Z(4430)^+ \) peak position; the dashed lines show ±\( \Gamma_{Z^+} \) window (as determined in Ref. 2). The main peak position and width in Fig. 2(a) are close to the experimentally measured values for Z(4430)^+ \( \). The contribution from \( B \rightarrow D_s(2S)^- D^* \) (Fig. 2(b) may be responsible for another broad excess of signal events over combinatorial background in the region above 4.1 GeV/c^2, that can be seen in both Belle and BaBar data. For comparison the experimental spectra seen at Belle and BaBar are shown in Fig. 2(c) and d), respectively. We note that the instrumental reconstruction efficiency in the region of (4.6 – 4.75) GeV/c^2 drops very sharply, as this mass

\[\text{TABLE I: The angular parts of the } B \rightarrow D_{sJ}^- D^{(*)} \rightarrow (D^{(*)} D^{(*)})K \rightarrow \text{“Z”} K \text{ chain matrix element.}\]

| \( B \) decay mode | \( \lambda_{D^*} \) | \( a_{\lambda_{D^*}} \) | \( \mathcal{M}(M_{D^*\bar{K}}) \) | \( D_{D_{sJ}}(\theta, \lambda_{D^*}) \) | \( D_{D^*}(\theta', \lambda_{D^*}) \) | \( D_{Z}(\theta'') \) |
|-------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( \psi(2S)\pi^+ \) | \( D_s(2S)^- D \) | 0 | 1 | 1 | \( d_{0,0} \) | \( d_{0,0} \) |
| \( \chi_{c1}\pi^+ \) | \( D_s(2S)^- D \) | \( \pi^+ \) | \( \sqrt{1/3} \) | \( d_{1,0} \) | \( d_{1,0} \) | \( d_{1,0} \) |
intermediate states (e.g. \(Y(4350)\) and \(Y(4660)\) states) may be related to the interference of \(\psi\)-resonances and many intermediate states (e.g. \(D_1D, D_2D, D_2D^*, \text{ etc.}\)) in their decays with different \(D^*\) helicities resulting in the \(DD^*\) final state. In particular, large \(e^+e^- \rightarrow \psi(4415) \rightarrow DD^*\) cross section can serve as a hint of the vicinity of the \(Y(4350)\) and \(Y(4660)\) states to the \(\psi(4415)\) resonance. However, the quantitative calculations are still beyond our capabilities mainly because of lack of experimental data.

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FIG. 3: a) The $M(\bar{D}D)$ spectrum in the decay $\bar{B} \to D_s(2S)^+D$. b) The $M(\chi_c\pi^+)$ spectrum in the Belle data.

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[1] S.K. Choi, et al. (Belle Collab.), Phys. Rev. Lett. 100, 142001 (2008).
[2] R. Mizuk, et al. (Belle Collab.), Phys. Rev. D 80, 031104 (2009).
[3] B. Aubert, et al. (BaBar Collab.), Phys. Rev. D 79, 112001 (2009).
[4] R. Mizuk, et al. (Belle Collab.), Phys. Rev. D 78, 072004 (2008).
[5] X. Liu, Y.-R. Liu, W.-Z. Deng, S.-L. Zhu, Phys. Rev. D 77, 034003 (2008).
[6] S.H. Lee, K. Morita, M. Nielsen, Nucl. Phys. A 815, 29 (2009).
[7] X.-H. Liu, Q. Zhao, F.E. Close, Phys. Rev. D 77, 094005 (2008).
[8] S. Dubynskiy, M.B. Voloshin, Phys. Lett. B 666, 344 (2008).
[9] D.V. Bugg, J. Phys. G 35, 075005 (2008).
[10] K. Nakamura, et al. (PDG group), J. Phys. G 37, 075021 (2010).
[11] J. Brodzicka, et al. (Belle Collab.), Phys. Rev. Lett. 100, 092001 (2008).
[12] W. Bardeen, E. Eichten, C. Hill, Phys. Rev. D 68, 054024 (2003); E. Swanson, Phys. Rept. 429, 243 (2006); A.M. Badalian, B.L.G. Bakker, arXiv:1104.1918 (2011).
[13] G. Pakhlova, et al. (Belle Collab.), Phys. Rev. D 80, 091101 (2009).
[14] G. Pakhlova, et al. (Belle Collab.), Phys. Rev. Lett. 100, 062001 (2008).