Charged charmonium-like $Z^+(4430)$ from rescattering in conventional $B$ decays

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Abstract

We demonstrate that our hypothesis, proposed in the previous paper, that $\bar{D}^0D^+\rightarrow\psi'\pi^+$ rescattering in the decays $\bar{B}\rightarrow D_s^+D^+$, provides a feasible explanation of the $Z^+(4430)$ peak, observed by Belle and confirmed by LHCb. While according to our hypothesis the origin of the peaking structure is purely kinematical, reflecting the presence of a conventional resonance in the hidden intermediate state, the amplitude of the $Z^+(4430)$ peak carries a Breit-Wigner-like complex phase, arising from the intermediate $D_s^+$ resonance. Thus, our hypothesis is entirely consistent with the recent LHCb measurement of the resonant-like amplitude behaviour of the $Z^+(4430)$. We perform a toy fit to the LHCb data, which illustrates that our approach is also consistent with all the observed peaking structures. We suggest a critical test of our hypothesis that can be performed experimentally.

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Many $XYZ$ states above the open charm threshold, and decaying into charmonium and light hadron(s) have been observed in the past decade. Their conventional interpretations as charmonium states remain too controversial as their properties, especially their large decay rates into final states without open charm, do not easily match the levels of heretofore unobserved charmonia. Various exotic explanations, such as tetraquarks, molecular states, charmonium hybrids and hadrocharmonium are also not fully embraced by the physics community, as they can not describe the variety of observed states, and all their measured properties, within a single self-consistent approach.

The first charmonium-like state, the $Z(4430)^+$, which is fully inconsistent with the charmonium spectrum, was observed by Belle [1,2] in 2007 as a peak in the $\psi'/\pi^+$ mass near $M \sim 4430$ MeV in $B$ decays. Since this peak in being interpreted as a real resonance is charged and also contains a $c\bar{c}$ pair, its minimal quark content, $udcc$, is necessarily exotic. The existence of the $Z(4430)^+$ was cast into doubt by BaBar [3], but the recent $Z(4430)^+$ observation by LHCb [4] unambiguously (with the significance of $\sim 14\sigma$) supports Belle’s claim.

Among the exotic explanations of the $Z(4430)^+$ nature the most popular are the tetraquark [5], hadrocharmonium [6] and $DD^{(*)}$ molecules [7]. There are also non-resonant interpretations such as the “cusp effect” [8] and the initial single pion emission mechanism [9]. However, the latter two seem to be excluded by the recent LHCb analysis of a complex phase rotation in the $Z(4430)^+$ region: the extracted Argand diagram for the $Z(4430)^+$ amplitude is found to be consistent with resonance behavior. In our previous paper [10] we have suggested another possible explanation of the $Z(4430)^+$ peak resulting from $D^{(*)}D^+\rightarrow\psi'\pi^+$ rescattering in the decays $B\rightarrow D_s^+D^+$. If our $ad~hoc$ hypothesis is correct, the origin of the peaking structure is purely kinematical, reflecting the presence of a conventional resonance (the $D_s^+$ meson) in the hidden intermediate state. However, our explanation also implies a new interesting underlying phenomena: namely, a non-vanishing rescattering amplitude over a wide range of $M(D^{(*)}D^+)$. In this Letter, we demonstrate that our approach is fully consistent with all the experimental data,
including the recent $Z(4430)^+ \rightarrow J/\psi \pi^+$ phase study by LHCb, as the $Z(4430)^+$ phase would then arise from the Breit-Wigner $D^*_s$ amplitude. We show that other structures that are evident in the LHCb $\psi' \pi^+$ spectrum can be attributed to similar effects. We also suggest here a critical test of our hypothesis that can be performed by Belle, BaBar and LHCb.

First, we note that in our previous paper [10] we have predicted the quantum numbers of the $Z(4430)^+$ to be $J^P = 1^+$ based on the simple argument that the $\bar{D}^{*0} D^* \rightarrow \psi' \pi^+$ rescattering should be dominated by $S$-waves in both the colliding $\bar{D}^{*0} D^*$ and also the produced $\psi' \pi^*$ systems. This prediction was confirmed by subsequent Belle [11] and LHCb [4] measurements. We also predicted the presence of other structures in the $\psi' \pi^+$ spectrum, in particular near $M \sim 4200$ MeV, that arises from another $\bar{B} \rightarrow D^*_{s0} D^*$ decay chain. Such a broad peak at $M = 4239$ MeV is, indeed, observed in the LHCb data, which has been interpreted as another $Z^*$ resonance.

We recall that our explanation of the peaking structures in $\psi' \pi^+$ spectrum proposed in [10] is based on the following form in the helicity formalism:

\[ \mathcal{A}(M_D \equiv M_{\bar{D}D}) = \sum_J \int \mathcal{A}_{BW}(M_{D_J^{*(s)})}) \]

\[ D_{1,0}^J(\theta_{\text{dec}}) D_{1,0}^J(\theta_{\text{rot}}) D_{1,0}^J(\theta_{\text{form}}) dM_{D_J^{*(s)}} \]

where $J$ is the $D_J^{*(s)}$ spin; $\theta_{\text{dec}}$ is the decay angle of the $D_J^{*(s)}$ (the angle between the $\bar{B}$ and $\bar{D}^{*0}$ in the $D_J^{*(s)}$ rest frame); $\theta_{\text{rot}}$ is the rotation angle of the $\bar{D}^{*0}$ spin from the $D_J^{*(s)}$ frame for the reaction (1) or the $B$ frame for the reaction (2) to the $Z^*$ frame; $\theta_{\text{form}}$ is the formation angle of $Z^*$, i.e. the angle between the $\bar{B}$ and $D^*$ in the $Z^*$ rest frame. The first Wigner $D$-function is responsible for the proper angular distribution of the $D_J^{*(s)}$ decay (in the case only the zero helicity projection is operative). The second function, $D_{1,0}^J(\theta_{\text{rot}})$, describes the $D^*$ spin rotation from the frame, where it is produced, to the frame where it is absorbed. Finally, the $D_{1,0}^J(\theta_{\text{form}})$ corresponds to the proper formation of the spin-1 $Z^*$ pseudostate from the vector ($D^*$) and the pseudoscalar ($D$). Two variables, $M_{D_J^{*(s)}}$ and $\theta_{\text{dec}}$, fully describe the three-body kinematics, thus $M_{D_J^{*(s)}}$, $\theta_{\text{rot}}$ and $\theta_{\text{form}}$ are functions of these two variables.

We have performed calculation of equation (3) numerically using Monte Carlo simulation: we generate
the $B \to D_{s}^{(*)} D^{(*)}$ decay kinematics and then sum over (complex) amplitudes resulting in the same $M_{DD^*}$ bin. The mass and width of the $D^{(*)}_{s}$ are fixed to the PDG values ($M = 2.709$ MeV, $\Gamma = 0.112$ MeV [14]); the $D^{(*)}_{s}$ parameters are fixed to $M = 2610$ MeV and $\Gamma = 100$ MeV as in our previous paper [10] (the expected $2S^1 - 2S^3$ splitting is $(60-100)$ MeV [13]). The resulting $Z^*$ shape for all four chains are shown in Fig. 1; we plot separately the contributions of different $D^*$ helicities in the case of decay into the $D_{s}^{(*)}$ resonance. In particular, the decay (2b) (Pseudo-scalar to Vector Vector) is described by three independent amplitudes.

The phase of the $Z^*$ amplitude, $\text{arg}(A_{Z^*})$, from the reaction (1b), which is responsible for the most prominent peak of the $Z(4430)^*$ is presented in Fig. 2. In the region around the $Z(4430)^*$ the phase turns out to have an inverse behavior compared to the conventional Breit-Wigner definition: it tends to rotate counterclockwise in the Argand diagram. However, experimentally the direction of amplitude rotation can not be determined as there is a two-fold ambiguity ($A \leftrightarrow \bar{A}$) in the extraction of the $Z^*$ amplitude from the measured $|A_{Z^*} + A_{\text{non}-Z^*}|^2$. Thus, our hypothesis is fully consistent with the LHCb Argand diagram.

To illustrate that our hypothesis is plausible we use the LHCb $\psi'\pi^+$ mass spectrum with vetoed $K^+$ and $K^*_0(1430)$ resonances (Fig. 4 from [4]) and perform a toy fit to this spectrum ignoring interference between major $B \to \psi' K^{(*)}$ and rescattering contributions. This is not a fully correct procedure, we thus use it for illustration only. We first estimate the remaining contributions of

![Figure 1: The $M_{\psi'\pi^+}$ spectrum in the decay $B \to D_{s}^{(*)} D^{(*)}$, followed by rescattering $(\bar{D}D^*) \to \psi'\pi^+$, calculated according to Equation (3). a), b), c), and d) correspond to the chains (1a), (1b), (2a), and (2b). The black and red curves correspond to the lineshapes for $\lambda_{D^*} = 0$ and $\lambda_{D^*} = \pm 1$, respectively.](image1)

![Figure 2: The phase of $\text{arg}(A_{Z^*})$ in the decay $B \to D_{s}^{(*)} (\to D^{(*)} K^-) D^{(*)}$, followed by rescattering $D^{(*)} D^{(*)} \to \psi'\pi^+$, calculated according to the equation (4). The dashed curve represents the process lineshape.](image2)
RES IN DICITIONARY OF K+K−, D0K−, D0D−+K− can describe all possible contributions as well as the yet-undetermined parameters of the D∗ resonance. It is important to fix these amplitudes using a study of B → D0D−+K− and B → D0D−+K−, which is possible at B-factories or LHCb. However, there is an easier way to check our hypothesis experimentally. The Z∗-like structures should appear in the distributions of M(D∗,D∗)×cos2(θform) in either B → D0D−+K− or B → D0D−+K−, or in both. The M(D∗,D∗)×cos2(θform) is the (D∗,D∗) combination mass spectrum corrected in each bin for the fraction of the D∗ transverse component in the (D∗,D∗) rest frame, and also the 1′ formation factor D∗(θform) = cos2(θform).

In summary, we show that D0D∗ → ψ′π− rescattering in the decay chain B → D∗K− is the (D∗,D∗) + π− mass spectrum in B → ψ′π−K− decays around M = 4430 MeV and also correctly describes the quantum numbers and amplitude resonance-like behavior. This approach also to describe another peak around M ~ 4.2 GeV that is observed in LHCb data and has been interpreted as another exotic resonance, as well as a high mass structure at the upper bound of the mass spectrum, which remains still undersaturated by the LHCb fit (with many K∗+ and two Z(4430)+s included).

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Figure 3: a) Distribution of M2(D∗,D∗) in the LHCb data for 1.0 < M2(D∗,D∗) < 1.8 GeV2 interval, using Figs. 3 a) and b) from [16]. The LHCb data points with these three contributions superimposed (the histogram colors correspond to the LHCb notations) are shown in Fig. 3a. The spectrum in Fig. 3b is obtained after a bin-by-bin subtraction of K∗+ and non-resonance three body decays. This remaining spectrum we attribute to the rescattering contribution and perform the fit to this spectrum with a sum of contributions from the reactions (1a) and (1b) only, thus with five free parameters. We note that all intermediate B decay channels with various D∗(ψ′) states contribute to Z∗ production coherently with the same universal amplitude of rescattering. The fit results are plotted in Fig. 3b with the black solid line, and nicely describe all the features observed in data.

A real test of our hypothesis can be achieved with a 4D-fit performed by Belle, BaBar and LHCb for B → ψ′π−K− decays using amplitudes (3) instead of resonance-like Z∗+s. Obviously the fitting model with rescattering comprises too many free parameters: at least 7 complex amplitudes to describe all possible contributions as well as the yet-undetermined parameters of the D∗ resonance.