Charged charmoniumlike states at Belle

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Abstract. Results on charged charmoniumlike states observed in B-meson decays at Belle are reviewed. The review also includes the results on these states from other experiments (BABAR and LHCb).

1. Introduction
Recently, a number of new states containing a $c\bar{c}$ quark pair have been observed. Among these states are charged charmoniumlike state candidates with a minimal quark content that is necessarily exotic: $|c\bar{c}u\bar{d}\rangle$. The results on charged charmoniumlike states observed in B-meson decays are reviewed below.

2. Charged charmoniumlike states
2.1. $Z_c(4430)^+$
The first observed charged charmoniumlike state was the $Z_c(4430)^+$ [1]. It was observed in 2007 by the Belle Collaboration in the decay mode $\bar{B} \to \psi(2S)\pi^+K$, where $\bar{B}$ is $\bar{B}^0$ or $B^+$ and $K$ is $K^-$ or $K_S^0$. A one-dimensional analysis was performed; the distribution of the invariant mass of the combination $(\psi(2S)\pi^+)$ was studied outside of the regions of the $K^*(892)$ and $K_S^*(1430)$. The distribution of the $\psi(2S)\pi^+$ invariant mass is shown in figure 1. A narrow peak with the parameters $M = 4433 \pm 4 \pm 2$ MeV/$c^2$, $\Gamma = 45^{+18}_{-13}^{+30}_{-13}$ MeV and the significance of $6.5\sigma$ was observed.

After that the BABAR Collaboration searched for the $Z_c(4430)^+$ in the decays $\bar{B} \to \psi(2S)\pi^+K$ and $\bar{B} \to J/\psi\pi^+K$ [2] using a different method. The data were divided into intervals in $K\pi^+$ invariant mass. The Legendre moments depending on the $K^*$ helicity angle were determined for each interval, and the expected distribution of $\psi(2S)\pi^+$ invariant mass was reconstructed. The distribution of $M_{\psi(2S)\pi^+}$ observed in data was fitted to a sum of the expected distribution and the $Z_c(4430)^+$ signal. No significant $Z_c(4430)^+$ signal was observed.

The methods of the first Belle analysis and the BABAR analysis did not take into account the interference of the amplitudes of the decays via the $Z_c(4430)^+$ and $K^*$. To confirm the existence of the $Z_c(4430)^+$ more reliably, the Belle Collaboration performed a Dalitz analysis of the decays $\bar{B} \to \psi(2S)\pi^+K$ using the same data [3]. The observation of the $Z_c(4430)^+$ in Belle data was confirmed with $6.4\sigma$ significance. The $Z_c(4430)^+$ parameters have changed: the new values of the mass and width were $M = 4443^{+15}_{-12}^{+19}_{-13}$ MeV/$c^2$ and $\Gamma = 107^{+86}_{-43}^{+74}_{-56}$ MeV, respectively. Projections of the fit results onto the $M_{\psi(2S)\pi^+}^2$ axis with and without the $Z_c(4430)^+$ are shown in figure 2.
However, a Dalitz analysis is not sensitive to the $Z_c(4430)^+$ quantum numbers because of information loss due to the integration over the angular variables. A full amplitude analysis of $\bar{B}^0 \to \psi(2S)K^-\pi^+$ decays, which has a better sensitivity to the $Z_c(4430)^+$ quantum numbers, has been performed by the Belle Collaboration in [4]. The default model included the contributions of the $K^*$ resonances and the $Z_c(4430)^+$ with quantum numbers $0^-, 1^-, 1^+, 2^-$ or $2^+$. The hypothesis $J^P = 1^+$ was preferred and the hypotheses $0^-, 1^-, 2^-$ and $2^+$ were excluded at the level $3.4\sigma$, $3.7\sigma$, $4.7\sigma$ and $5.1\sigma$, respectively. Comparison of the fit results without the $Z_c(4430)^+$ and with the $Z_c(4430)^+ (J^P = 1^+)$ is shown in figure 3. The resulting mass and width of the $Z_c(4430)^+$ were $M = 4485^{+22+28}_{-22-11}$ MeV/$c^2$ and $\Gamma = 200^{+41+26}_{-46-35}$ MeV, respectively.

This result was later confirmed by the LHCb Collaboration in [5]. In addition, the LHCb collaboration measured the $Z_c(4430)^+$ amplitude in six bins; the obtained Argand plot confirmed that the phase of the $Z_c(4430)^+$ amplitude rotates as expected for a resonance. The projection of the fit result onto $M^2_{\psi(2S)\pi^+}$ and the Argand plot are shown in figure 4b.

![Figure 1](image1.png)

**Figure 1.** Results of the fit to the invariant mass of the system $\psi(2S)\pi^+$ (from [1] by the Belle Collaboration).

![Figure 2](image2.png)

**Figure 2.** Projection of the Dalitz plot fit results without (dashed line) and with (solid line) the $Z_c(4430)^+$ onto the $M^2_{\psi(2S)\pi^+}$ axis (from [3] by the Belle Collaboration).
2.2. \( Z_c(4050)^+ \) and \( Z_c(4250)^+ \)

Two charged charmoniumlike states, the \( Z_c(4050)^+ \) and \( Z_c(4250)^+ \), were observed by the Belle Collaboration in the decays \( \bar{B}^0 \rightarrow \chi_{c1} K^-\pi^+ \) in [6]. A Dalitz analysis similar to [3] has been performed. Two new states with masses and widths \( M = 4051 \pm 14^{+20}_{-41} \) MeV/\( c^2 \), \( \Gamma = 82^{+21+47}_{-17-22} \) MeV and \( M = 4248^{+14+180}_{-29-35} \) MeV/\( c^2 \), \( \Gamma = 177^{+54+316}_{-39-61} \) MeV, respectively, were observed. The significance of the \( Z_c(4250)^+ \) was 6.2\( \sigma \) and the significance of the \( Z_c(4050)^+ \) was 5.0\( \sigma \). The projections of the fit results with and without new resonances onto \( M_{\chi_{c1}\pi^+} \) with the condition \( 1.0 \text{ GeV}^2/\text{c}^4 < M_{K^-\pi^+}^2 < 1.75 \text{ GeV}^2/\text{c}^4 \) are shown in figure 5.

The BABAR Collaboration searched for the \( Z_c(4050)^+ \) and \( Z_c(4250)^+ \) in [7]. A method similar to [2] was used. No significant signal was observed.

2.3. \( Z_c(4200)^+ \)

The Belle Collaboration performed an amplitude analysis of the decays \( \bar{B}^0 \rightarrow J/\psi K^-\pi^+ \) in [8]. A new charmoniumlike state \( Z_c(4200)^+ \) with quantum numbers \( J^P = 1^+ \) was observed.
Figure 5. Projection of the Dalitz plot fit results without (dashed line) and with (solid line) the $Z_c(4050)^+$ and $Z_c(4250)^+$ onto the $M_{\chi_{c1}\pi^+}^2$ axis and the $Z_c(4050)^+$ and $Z_c(4250)^+$ contributions (from [6] by the Belle Collaboration).

Figure 6. (a) Projection of the four-dimensional fit results without (dashed line) and with (solid line) the $Z_c(4200)^+$ onto $M_{J/\psi\pi^+}^2$ and the $Z_c(4200)^+$. (b) Argand plot for the helicity amplitude $H_1$ by the Belle Collaboration [8].

Its mass and width were measured to be $M = 4196^{+31+17}_{-29-13}$ MeV/c$^2$ and $\Gamma = 370^{+70+70}_{-70-132}$ MeV, respectively. The significance of the $Z_c(4200)^+$ was 7.9$\sigma$ for the default model and 6.2$\sigma$ including the systematic error. Comparison of the fit results for the models without the $Z_c(4200)^+$ and with the $Z_c(4200)^+$ ($J^P = 1^+$) is shown in figure 6. Other $Z_c(4200)^+$ quantum number hypotheses: $0^-$, $1^-$, $2^-$ and $2^+$ were excluded at the levels of 6.1$\sigma$, 7.4$\sigma$, 4.4$\sigma$ and 7.0$\sigma$, respectively. Also, evidence for the decay $Z_c(4430)^+ \rightarrow J/\psi\pi^+$ was found.

Similarly to LHCb analysis in [5], the helicity amplitudes of the $Z_c(4200)^+$ were measured in six bins. The absolute value and phase of the helicity amplitude $H_1$ change in accordance with the expectations for a resonance, while it is not possible to draw any conclusions for the helicity amplitude $H_0$ due to large relative errors. The Argand plot for the helicity amplitude $H_1$ is shown in figure 6b.
3. Conclusions
Though the first charged charmoniumlike state, the $Z_c(4430)^+$, is now confirmed, the available experimental information for these states is incomplete. Further measurements of the properties of charged charmoniumlike states and searches for their decays into different final states are required for their theoretical interpretation.

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