

Study of charmoniumlike states by amplitude analyses at Belle

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Abstract. A review of charmoniumlike state studies at Belle which use amplitude analyses is presented, including the $Z_c(4430)^+$, $Z_c(4200)^+$ and $\chi_{c0}(3860)$.

1 Introduction

Recently, many new states containing a $c\bar{c}$ mesons have been observed; many of them do not match the expectations for the conventional quark-antiquark charmonium states [1]. Specifically, the charged charmoniumlike states have the minimal quark content $|c\bar{c}u\bar{d}\rangle$; thus, they are necessarily exotic. This review includes the studies of charmoniumlike states that were performed by the Belle Collaboration using amplitude analyses: the measurement of the $Z_c(4430)^+$ quantum numbers [2], the observation of the $Z_c(4200)^+$ [3], and the observation of the $\chi_{c0}(3860)$ [4]. The first two analyses study the charged charmoniumlike states, while the $\chi_{c0}(3860)$ is an alternative candidate for the conventional charmonium state $\chi_{c0}(2P)$.

2 Analyses

2.1 Measurement of the $Z_c(4430)^+$ quantum numbers

The $Z_c(4430)^+$ quantum numbers were measured by performing an amplitude analysis of the decays $\bar{B}^0 \rightarrow \psi(2S)\pi^+K^-$ [2] (inclusion of charge-conjugate modes is implied hereinafter). The Belle Collaboration previously observed the $Z_c(4430)^+$ in a one-dimensional analysis of the same decay [5] and later using a Dalitz analysis [6]. However, the previous Belle analyses either ignored the interference with the contribution of the K^* resonances completely or reduced the sensitivity by integrating over the angular variables; consequently, they were not sensitive to the $Z_c(4430)^+$ quantum numbers. Also, before the $Z_c(4430)^+$ quantum-number determination, a model-independent analysis had been performed by the BaBar Collaboration [7]; the $Z_c(4430)^+$ existence had not been confirmed, but the result had not contradicted the Belle observation because of a smaller data sample.

The default model included six K^* resonances ($K_0^*(800)$, $K^*(892)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, and $K^*(1680)$) and the $Z_c(4430)^+$. All possible quantum numbers of the $Z_c(4430)^+$ with $J \leq 2$ were considered: $0^-, 1^+, 1^-, 2^+, 2^-$. The preferred $Z_c(4430)^+$ spin-parity hypothesis was found to be 1^+ . Projections of the fit results onto $M_{\psi(2S)\pi^+}^2$ in the models without the $Z_c(4430)^+$ and with the $Z_c(4430)^+$ ($J^P = 1^+$) are shown in figure 1. The $Z_c(4430)^+$ parameters were measured to be $M = 4485_{-22}^{+22+28}$ MeV/ c^2 and $\Gamma = 200_{-46}^{+41+26}$ MeV.

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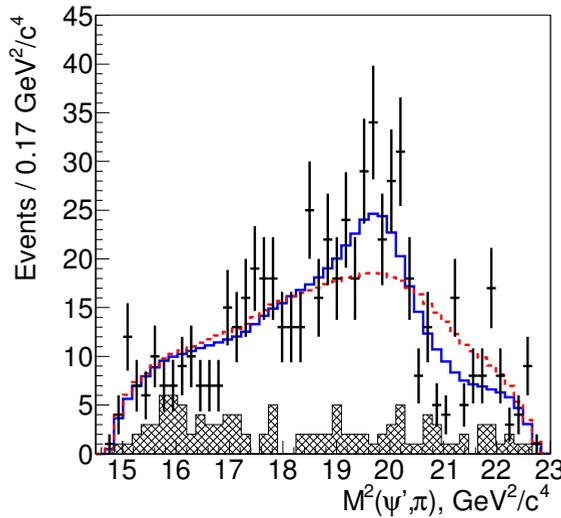


Figure 1. Projections of the $\bar{B}^0 \rightarrow \psi(2S)\pi^+K^-$ fit results onto $M^2_{\psi(2S)\pi^+}$. The points with error bars are the data, the hatched histogram is the background, the blue solid line is the fit with the $Z_c(4430)^+$, and the red dashed line is the fit without its contribution. The narrow K^* veto is applied: $|M_{K^-\pi^+} - m_{K^*(892)}| > 100$ MeV and $|M_{K^-\pi^+} - m_{K^*(1430)}| > 100$ MeV, where m_{K^*} are the nominal masses of the specified K^* resonances. Figure from reference [2].

Comparison of the quantum-number hypotheses was performed using Monte-Carlo (MC) pseudoexperiments generated in accordance with the fit results. It was performed for various amplitude models to take the systematic uncertainty into account. The resulting exclusion levels of the 0^- , 1^- , 2^- , and 2^+ hypotheses were found to be 3.4σ , 3.7σ , 4.7σ , and 5.1σ , respectively.

The observation of the $Z_c(4430)^+$ and the results of the measurement its quantum numbers were later confirmed by the LHCb Collaboration [8]. The LHCb Collaboration additionally observed the resonant character of the $Z_c(4430)^+$ by measuring the dependence of its amplitude on mass. The $Z_c(4430)^+$ existence was also confirmed by LHCb in a model-independent way [9].

2.2 Observation of the $Z_c(4200)^+$

The $Z_c(4200)^+$ was observed in the decays $\bar{B}^0 \rightarrow J/\psi\pi^+K^-$ [3]. The default model included 10 K^* resonances: $K_0^*(800)$, $K^*(892)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, $K^*(1680)$, $K_3^*(1780)$, $K_0^*(1950)$, $K_2^*(1980)$, $K_4^*(2045)$. The $Z_c(4430)^+$ was also included to the default model. Optionally, an additional Z_c^+ resonance was added. All possible quantum numbers of the new Z_c^+ state with $J \leq 2$ were considered. Its significance was calculated globally with the expected null-hypothesis distribution of $\Delta(-2 \ln L)$ determined from MC pseudoexperiments. A new charmoniumlike state $Z_c(4200)^+$ with $J^P = 1^+$ was found with a significance of 6.2σ . Its parameters were measured to be $M = 4196^{+31+17}_{-29-13}$ MeV/ c^2 and $\Gamma = 370^{+70}_{-70-132}$ MeV. Projections of the fit results onto $M_{J/\psi\pi^+}$ in the models with and without the $Z_c(4200)^+$ are shown in figure 2.

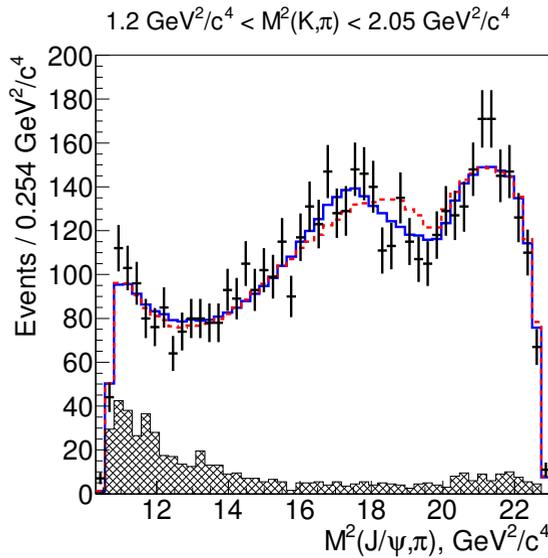


Figure 2. Projections of the $\bar{B}^0 \rightarrow J/\psi\pi^+K^-$ fit results onto $M_{J/\psi\pi^+}^2$. The points with error bars are the data, the hatched histogram is the background, the blue solid line is the fit with the $Z_c(4200)^+$, and the red dashed line is the fit without its contribution. The region with $1.2 < M_{K^-\pi^+}^2 < 2.05 \text{ GeV}^2/c^2$ is selected. Figure from reference [3].

The comparison of the quantum numbers was performed by using $\Delta(-2 \ln L)$; it was checked using the pseudoexperiment method. The 0^- , 1^- , 2^- , and 2^+ hypothesis were found to be excluded at the levels of 6.1σ , 7.4σ , 4.4σ , and 7.0σ , respectively.

In addition, the mass dependence of the $Z_c(4200)^+$ amplitude was measured by performing an alternative fit with the $Z_c(4200)^+$ contribution represented by complex constants in six mass bins. The resulting Argand plot for the H_1 amplitude shows a resonant dependence; it is presented in figure 3. The H_0 amplitudes have much larger relative errors and it is not possible to determine whether they also change resonantly.

The significance of the $Z_c(4430)^+$ was measured to be 4.0σ . Thus, evidence for $Z_c(4430)^+ \rightarrow J/\psi\pi^+$ was found. The $Z_c(4430)^+$ interferes destructively with the K^* resonances.

The presence of exotic $J/\psi\pi^+$ contribution in the decays $\bar{B}^0 \rightarrow J/\psi\pi^+K^-$ was recently confirmed by the LHCb Collaboration [10]. The observed distribution of the $J/\psi\pi^+$ invariant mass suggests the existence of two resonances with masses of two resonances with $M_{J/\psi\pi^+} \approx 4200 \text{ MeV}/c^2$ and $M_{J/\psi\pi^+} \approx 4600 \text{ MeV}/c^2$. The analysis performed by LHCb is model-independent and it consequently does not measure the masses, widths, and quantum numbers of the $J/\psi\pi^+$ resonances. In addition, the $Z_c(4200)^+$ state may be the same as the $Z_c(4240)^+$ (or $R_{c0}(4240)^+$) state found by LHCb in the decays $\bar{B}^0 \rightarrow \psi(2S)\pi^+K^-$ [8] if the $Z_c(4240)^+$ quantum numbers are $J^P = 1^+$ (the preferred hypothesis is 0^- , but it is preferred over 1^+ at 1σ level only).

2.3 Observation of an alternative $\chi_{c0}(2P)$ candidate

The $\chi_{c0}(3860)$ was observed in the process $e^+e^- \rightarrow J/\psi D\bar{D}$ [4], where D means either D^0 or D^+ . The analysis was motivated by the inconsistency of the observed properties

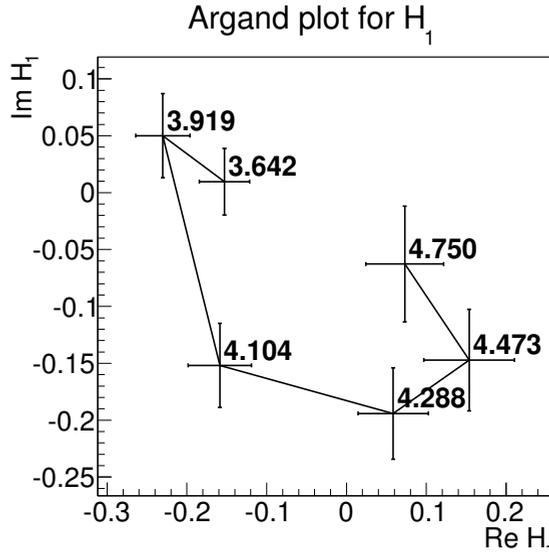


Figure 3. Argand plot for the $Z_c(4200)^+$ helicity amplitude H_1 . The bin central mass values (in GeV/c^2) are shown near the points. Figure from reference [3].

of the $X(3915)$ and those expected for the $\chi_{c0}(2P)$ state [11, 12]. The Belle Collaboration had previously observed new charmoniumlike states $X(3940)$ and $X(4160)$ in the processes $e^+e^- \rightarrow J/\psi D^{(*)}\bar{D}^{(*)}$ [13]; the process $e^+e^- \rightarrow J/\psi\chi_{c0}(1P)$ had also been observed by Belle [14, 15] before the $\chi_{c0}(2P)$ search.

Since the signal yield in the processes $e^+e^- \rightarrow J/\psi D^{(*)}\bar{D}^{(*)}$ is known to be rather low even with a partial reconstruction, which includes only the J/ψ and one of the $D^{(*)}$ mesons, the event selection was optimized to improve the sensitivity. A multivariate analysis was performed for each D decay channel. After that, a global optimization of the selection requirements has been performed, which included the channel-specific definitions of the signal region and the neural-network output requirements.

The default model of the process $e^+e^- \rightarrow J/\psi D\bar{D}$ included the nonresonant amplitude (with three different parameterizations) and an additional resonance X^* decaying to $D\bar{D}$. The X^* produced in this process has even spin and positive parity; the C -parity should also be positive. Thus, two quantum-number hypotheses were considered: $J^{PC} = 0^{++}$ and 2^{++} . A new charmoniumlike state $X^*(3860)$ was observed with a significance of 6.5σ . The preferred quantum-number hypothesis is $J^{PC} = 0^{++}$ (thus, the new state can be denoted alternatively as the $\chi_{c0}(3860)$ [16]), however, the 2^{++} hypothesis was not excluded: the 0^{++} hypothesis is preferred at 2.5σ level. The $\chi_{c0}(3860)$ parameters were measured to be $M = 3862^{+26+40}_{-32-13} \text{ MeV}/c^2$ and $\Gamma = 201^{+154+88}_{-67-82} \text{ MeV}$. Projections of the fit results onto $M_{D\bar{D}}$ in the models with and without the $\chi_{c0}(3860)$ are shown in figure 2.

The new $\chi_{c0}(3860)$ resonance seems to be a better candidate for the $\chi_{c0}(2P)$ charmonium state than the $X(3915)$, because its properties are well matched to expectations for the $\chi_{c0}(2P)$ resonance. Such properties include the mass, the mass difference with the $\chi_{c2}(2P)$, the large-width $D\bar{D}$ observation decay mode, the production that is consistent with pure S -wave as is the case for the process $e^+e^- \rightarrow J/\psi\chi_{c0}(1P)$. In addition, the $\chi_{c0}(3860)$ mass and width

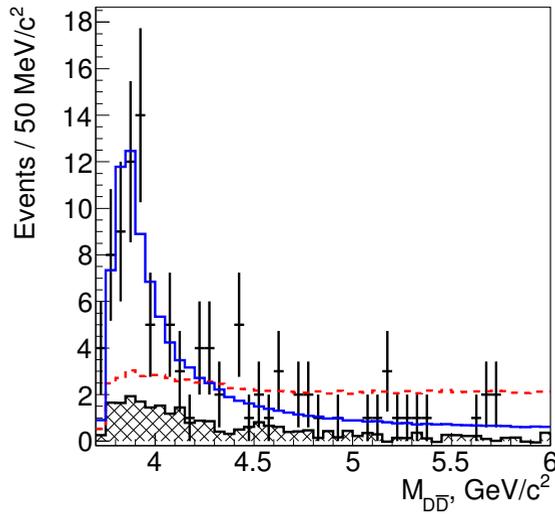


Figure 4. Projections of the $e^+e^- \rightarrow J/\psi D^{(*)}\bar{D}^{(*)}$ fit results onto $M_{D\bar{D}}$. The points with error bars are the data, the hatched histogram is the background, the blue solid line is the fit with the X^* resonance ($J^{PC} = 0^{++}$), and the red dashed line is the fit with nonresonant amplitude only. Figure from reference [4].

agree with the $\chi_{c0}(2P)$ parameters determined from an alternative fit to the Belle and BaBar $\gamma\gamma \rightarrow D\bar{D}$ data [11].

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