New Charmonium-like States at B-Factories

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Since the discovery of the \(X(3872)\) in 2003 the B-factory experiments BaBar and Belle have been driving forces in the spectroscopy of new charmonium-like states. In this article the latest results on the decays \(X(3872) \rightarrow D^0\bar{D}^{*0}\) and \(X(3872) \rightarrow \psi\gamma\), where \(\psi\) stands for \(J/\psi\) or \(\psi(2S)\), are presented and analyses of \(Z(4430)\)\(^+\rightarrow \psi\pi^+\) and \(Z(4050/4250)\)\(^+\rightarrow \chi_{c1}\pi^+\) are discussed.

1 Introduction

Several new states have been discovered in the last few years\(^2\), most of them at B-factories. The B-factories provide a clean environment to search for and study these new particles either in \(B\) meson decays or in the production in \(e^+e^-\) reactions with initial state radiation. In this article the recent analyses of new states in \(B\) decays are presented. Both experiments, BaBar and Belle, together have now a total sample of 1.3 billion \(B\bar{B}\) pairs available.

The oldest member of the family of new charmonium-like states is the \(X(3872)\), discovered by Belle in 2003\(^3\). Despite several measurements of its properties at B-factories and at the Tevatron the nature of this particle is still unknown. It does not fit into the predicted spectrum of conventional chamonium states. Since its mass is very close to the \(D^0\bar{D}^{*0}\) threshold the hypothesis of a \(D^0\bar{D}^{*0}\) molecule is considered\(^4\). Another explanation is a bound state of a diquark and an anti-diquark\(^5\).

It is also possible, though unlikely, that the \(X(3872)\) is a \(c\bar{c}\) state and our theoretical models fail to describe it. Therefore the observation of the \(Z(4430)\)\(^+\) was received with great interest. As it is charged it can not be a conventional charmonium state.

2 \(X(3872) \rightarrow D^0\bar{D}^{*0}\)

The decay \(B^{+/0} \rightarrow X(3872)K^{+/0}\) with \(X(3872) \rightarrow D^0\bar{D}^{*0}\) was first observed by Belle in 2006 with a significance of 6.4 standard deviations\(^6\). This observation was confirmed by BaBar last year\(^7\). In \(B^{+/0}\bar{D}^{0}\bar{D}^{*0} \rightarrow K^{+/0}\) decays, where the \(\bar{D}^{*0}\) is reconstructed via \(\bar{D}^0\pi^0\) or \(\bar{D}^0\gamma\), BaBar sees an excess near threshold with a significance of 4.9\(\sigma\) (see Fig. 1 left). A template fit is performed that takes into account threshold effects. While the width of \(\Gamma = 3.0^{+1.1}_{-1.4}\)\text{stat.} \pm 0.9(syst.) MeV is consistent with other measurements, the mass of \(M = 3875.1^{+0.7}_{-0.5}\)\text{stat.} \pm 0.5(syst.) MeV does not agree with the mass of \(M = 3871.46\pm 0.19\) MeV that is obtained by averaging the measurements in the \(X(3872) \rightarrow J/\psi\pi^+\pi^-\) mode. This may raise the question whether the same particle is observed in both modes or whether there are additional threshold effects.

Belle updated their analysis now including \(D^{*0} \rightarrow D^0\gamma\)\(^8\). Combining both \(D^{*0}\) modes, a signal with a significance of 8.8\(\sigma\) is observed (see Fig. right). A fit with a relativistic Breit-Wigner function and mass-dependent resolution yields \(M = 3872.6^{+0.5}_{-0.4}\)\text{stat.} \pm 0.4(syst.) MeV, \(\Gamma = 3.9^{+2.5}_{-1.3}(\text{stat.})^{+0.8}_{-0.3}(\text{syst.})\) MeV, and \(B(B \rightarrow X(3872)K) \times B(X(3872) \rightarrow D^0\bar{D}^{*0}) = \) DIS 2009
(0.73 ± 0.17(stat.) ± 0.08(syst.)) \times 10^{-4}. While the mass is closer to the average value in the $J/\psi \pi^+ \pi^-$ mode, some uncertainty due to the line shape model remains. An alternative fit using a Flatté function which assumes a mass below threshold is able to describe the data, too.

3 \textbf{X(3872) → $\psi\gamma$}

Evidence for the decay $B^{+/0} \rightarrow X(3872) K^{+/0}$ with $X(3872) \rightarrow J/\psi \gamma$ was first seen in 2005 by Belle with a significance of 4.0σ and one year later by BaBar with 3.4σ. Now BaBar presented an updated analysis adding $B^{+/0} \rightarrow X(3872) K^{+/0}$ events and considering also $X(3872) \rightarrow \psi(2S)\gamma$ decays.

Signals with a significance of 3.6σ and 3.5σ are seen in the $J/\psi \gamma$ and $\psi(2S)\gamma$ modes, respectively (see Fig. 3). For the $B$ decays to $\psi K^+$ branching ratios of $B(B^+ \rightarrow X(3872) K^+) \times B(X(3872) \rightarrow J/\psi \gamma) = (2.8 \pm 0.8(\text{stat.}) \pm 0.1(\text{syst.})) \times 10^{-6}$ and $B(B^+ \rightarrow X(3872) K^+) \times B(X(3872) \rightarrow \psi(2S)\gamma) = (9.5 \pm 2.7(\text{stat.}) \pm 0.6(\text{syst.})) \times 10^{-6}$ are measured. Limits for the other three $B$ decay modes where no significant signal is observed are quoted. The determined relative branching ratio of $B(X(3872) \rightarrow \psi(2S)\gamma)/B(X(3872) \rightarrow J/\psi \gamma) = 3.4 \pm 1.4$ is orders of magnitude higher than expected in $D^0 D^{*0}$ molecule models.

4 \textbf{Z(4430)^+ → $\psi\pi^+$}

In 2008 Belle published the observation of a resonance in the $\psi(2S)\pi^+$ invariant mass spectrum in $B^{+/0} \rightarrow \psi(2S)\pi^+ K^{0/\pm}$ decays with a significance of 6.5σ. In this analysis events with a $K\pi$ mass consistent with a $K^*(890)$ or $K^{*}(1430)$ were removed and the resulting $M(\psi(2S)\pi^+)$ distribution was fitted. From the fit the mass $M = 4433 \pm 4(\text{stat.}) \pm 2(\text{syst.})$ MeV, the width $\Gamma = 45^{+18}_{-13}(\text{stat.})^{+30}_{-13}(\text{syst.})$ MeV, and the branching ratio $B(B \rightarrow Z^+ K) \times B(Z^+ \rightarrow \psi(2S)\pi^+) = (4.1 \pm 1.0(\text{stat.}) \pm 1.4(\text{syst.})) \times 10^{-5}$ were extracted.
BaBar performed a detailed study of $B^{+/0} \rightarrow J/\psi \pi^+ K^{0/-}$ and $B^{+/0} \rightarrow \psi(2S)\pi^+ K^{0/-}$ decays [15]. As the most prominent features in the Dalitz plot are the $K^*(890)$ and $K^*(1430)$ resonances a good understanding of the $K\pi$ mass spectrum is important. BaBar is able to describe it well with $S$-, $P$-, and $D$-waves. This composition and the angular distributions of the components have a strong influence on the $\psi\pi^+$ mass spectrum. On the other hand they cannot create narrow peaks in the $M(\psi\pi^+)$ distribution.

BaBar looks at the $J/\psi\pi^+$ and $\psi(2S)\pi^+$ mass distributions for all events, events in the $K^*(890)$ and $K^*(1430)$ region, and events outside the $K^*$ regions and compares them to the projections of the $K\pi$ components (see Fig. 3 left). No signal is seen in the $M(\psi\pi^+)$ spectrum and no significant signal in the $M(\psi(2S)\pi^+)$ spectra. For the total sample there is an excess of 2.7$\sigma$ in the $\psi(2S)\pi^+$ mass distribution at $M = 4476 \pm 8$ (stat.) MeV with $\Gamma = 32 \pm 16$ (stat.) MeV. Using the values measured by Belle a 95% confidence level limit on the branching ratio of $B(B \rightarrow Z^+ K) \times B(Z^+ \rightarrow \psi(2S)\pi^+) < 3.1 \times 10^{-5}$ is set. A comparison of the background subtracted $M(\psi(2S)\pi^+)$ distribution with the one published by Belle shows good statistical agreement.

Belle reanalyzed their data with a fit to the Dalitz plot taking into account all known $K\pi$ resonances [16]. The fit with $Z^+$ resonance included (solid line in Fig. 3 right) describes the data significantly better than without (dotted line) by 6.4$\sigma$. Systematic variation of the fit model yield a significance of 5.4$\sigma$. The updated measurements of the $Z^+$(4430) properties are $M = 4443_{-12}^{+15}$(stat.)$^{+19}_{-13}$(syst.) MeV, $\Gamma = 107_{-43}^{+86}$(stat.)$^{+74}_{-56}$(syst.) MeV, and $B(B \rightarrow Z^+ K) \times B(Z^+ \rightarrow \psi(2S)\pi^+) = (3.2_{-0.9}^{+1.8}$(stat.)$^{+5.3}_{-1.6}$(syst.)) $\times 10^{-5}$.

5 $Z(4050/4250)^+ \rightarrow \chi_{c1}\pi^+$

As the first candidate for a charged exotic state was observed as a $\psi(2S)\pi^+$ resonance, this suggests to search for similar charged states in combinations of other charmonia with pions. In a Dalitz plot analysis of $B^0 \rightarrow \chi_{c1}\pi^+ K^-$ events including all known $K\pi$ resonances Belle

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observes two new states, called $Z(4050)^+$ and $Z(4250)^+$ \(\text{(see Fig. 4)}\). From the change in the fit likelihood value a significance of the two-$Z^+$-state versus the no-$Z^+$-state hypothesis of 13.2σ is determined. Taking into account systematic variations of the fit model the significance is at least 8.1σ. Compared to the one-$Z^+$-state hypothesis the two states are favored by 5.7σ, or 5.0σ including systematics. The masses, widths and branching ratios of the two new states are measured to be $M(Z(4050)^+) = 4051 \pm 14\text{(stat.)}^{+20}_{-21}\text{(syst.)}\text{ MeV}$, $M(Z(4250)^+) = 4248^{+46}_{-25}\text{(stat.)}^{+180}_{-35}\text{(syst.)}\text{ MeV}$, $\Gamma(Z(4050)^+) = 82^{+21}_{-17}\text{(stat.)}^{+47}_{-22}\text{(syst.) MeV}$, $\Gamma(Z(4250)^+) = 177^{+54}_{-39}\text{(stat.)}^{+316}_{-61}\text{(syst.)}\text{ MeV}$, $B(B^0 \rightarrow Z(4050)^+K^-) \times B(Z(4050)^+ \rightarrow \chi_{c1}\pi^+) = (3.0^{+1.8}_{-0.8}\text{(stat.)}^{+3.7}_{-1.6}\text{(syst.)}) \times 10^{-5}$, and $B(B^0 \rightarrow Z(4250)^+K^-) \times B(Z(4250)^+ \rightarrow \chi_{c1}\pi^+) = (4.0^{+2.3}_{-0.9}\text{(stat.)}^{+19.7}_{-12.3}\text{(syst.)}) \times 10^{-5}$.

6 Conclusions and outlook

The study of the decay $X(3872) \rightarrow D^0\bar{D}^{*0}$ is an interesting topic because it is very close to threshold. While the $X(3872)$ mass measured by BaBar is significantly higher than the average mass measured in the $J/\psi\pi^+\pi^-$ mode, the latest Belle measurement agrees with it within 2σ. A detailed study of the exact line shape may reveal important information about the nature of the $X(3872)$, but requires a much larger data sample. The first observation of the decay $X(3872) \rightarrow \psi(2S)\gamma$ and the measured high branching ratio with respect to the $J/\psi\gamma$ mode disfavor the hypothesis of a $D^0\bar{D}^{*0}$ molecule.

The first observation of a charged charmonium-like state, the $Z(4430)^+$, was confirmed in a Dalitz plot analysis by Belle. But so far this particle is not confirmed by any other experiment. BaBar does not see a significant signal in the $J/\psi\pi^+$ and $\psi(2S)\pi^+$ mass spectra. Although statistical agreement with the Belle data is established, the conclusions of both experiments differ. Two further charged states with even higher significance have
been observed as $\chi_{c1}\pi^+$ resonances by Belle. A clear picture of the $Z^+$ states with precise measurements of their properties may only arise at upgraded B-factories.

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