Quarkonium spectroscopy and search for new states at BaBar

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Abstract. The BaBar experiment at the PEP-II B-factory gives excellent opportunities for the quarkonium spectroscopy. Investigation of the properties of new states like the \( X(3872) \), \( Y(3940) \) and \( Y(4260) \) are performed aiming to understand their nature. Recent BaBar results will be presented in this paper.

1. Introduction

At the B-factories charmonium and charmonium-like states are copiously produced via several mechanisms: in \( B \) decay (color suppressed \( b \rightarrow c \) transition), double charmonium production (\( e^+e^- \rightarrow c\bar{c}+c\bar{c} \)), two photons production (\( \gamma^*\gamma^* \rightarrow c\bar{c} \), where the \( c\bar{c} \) state has positive C-parity) and in initial state radiation (ISR) when the \( e^\pm \) in its initial state emits a photon lowering the effective center of mass energy of the \( e^+e^- \) interaction (\( e^+e^- \rightarrow \gamma_{ISR}+c\bar{c} \), where the charmonium state has the quantum numbers \( J^{PC} = 1^{-+} \)).

Many new states have been recently discovered at the B-factories, BaBar and Belle, above the \( DD^* \) threshold in the charmonium energy region. While some of them appear to be consistent with conventional \( c\bar{c} \) states others do not fit with any expectation. Several interpretations for these states have been proposed: for some of them the mass values suggest that they could be conventional charmonia, but also other interpretations like \( D^0\bar{D}^{*0} \) molecule or diquark-antidiquark states among many other models have been advanced. Reviews can be found in Refs. [1][2]. In all cases the picture is not completely clear.

This situation could be remedied by a coherent search of the decay pattern to \( DD^* \), search for production in two-photon fusion and ISR, and of course improving the statistical precision upon the current measurements. The BaBar experiment at the PEP-II asymmetric collider, designed to perform precision measurement of CP violation in the \( B \) meson system, has an extensive quarkonium spectroscopy program. Recent BaBar outcomes on the \( X(3872) \) and \( Y(4260) \) and a new result on the \( Y(3940) \) are reported here.

2. The \( X(3872) \) state

The \( X(3872) \) is the first of the new charmonium-like states observed at the B factories starting a cascade of new discoveries which are reviving the spectroscopy. The \( X(3872) \) has been discovered by Belle [3] in \( B \) decays and confirmed by BaBar [4], and in hadronic production by CDF [5] and D0 [6]. It’s a narrow state (the width is below detector resolution), first observed in \( J/\psi \pi^+\pi^- \) final state with a mass of 3872 MeV (very close to the \( D^0\bar{D}^{*0} \) threshold).
The decays $B^- \to K^- J/\psi \pi^+ \pi^-$ and $B^0 \to K^0 J/\psi \pi^+ \pi^-$ have been studied by BaBar with a sample of 232 millions of $BB$ pairs (211 fb$^{-1}$) obtaining respectively 61 ± 15 and 8.3 ± 4.5 $X(3872)$ events with a variation of 6.1σ and 2.5σ [7]. The results include the 90% confidence interval $1.34 \times 10^{-6} < B(B^0 \to X(3872)K^0, X \to J/\psi \pi^+ \pi^-) < 10.3 \times 10^{-6}$ and the branching fraction $B(B^- \to X(3872)K^-, X \to J/\psi \pi^+ \pi^-) = (10.1 \pm 2.5 \pm 1.0) \times 10^{-6}$.

No signal at this mass was seen by BaBar in $B \to X^- K, X^- \to J/\psi \pi^0 \pi^-$ [8], which would have implied a charged partner of the $X(3872)$.

In a study of $B^+ \to J/\psi \gamma K^+$ decays, BaBar found evidence for the radiative decay $X(3872) \to J/\psi \gamma$ with a statistical significance of 3.4σ [9]. We measure the product of branching fractions $B(B^+ \to X(3872)K^+) \times B(X(3872) \to J/\psi \gamma) = (3.3 \pm 1.0 \pm 0.3) \times 10^{-6}$, where the uncertainties are statistical and systematic, respectively. This provides evidence of the radiative decay $X(3872) \to J/\psi \gamma$ and of charge parity $C = \pm$ for the $X(3872)$ state.

Recently, Belle showed an excess of events in the $D^0 D^0 \pi^0$ invariant mass in the channel $B \to D^0 D^0 \pi^0 K$, with a mass of 3875.4 ± 0.7$^{+0.3}_{-1.6}$ ± 0.8 MeV/\(c^2\) [10]. The observed invariant mass is 2σ higher than the world average value of the $X(3872)$ resonance. We have searched for resonances in exclusive decays $B^0/B \to D^0 D^0 \pi^0 K$, with a mass above open-charm threshold [13]. Unconventional explanations for the $Y(3940)$ include hybrid charmonium-gluon bound states, $ccg$ [14], charmonium light quark molecules, $\psi(2S) u\bar{u}d\bar{d}$ [15], or multi-quark states [16].

We report here a new BaBar results of a study of the decays $B^+ \to J/\psi \omega K^+$ and $B^0 \to J/\psi \omega K_S^0$ using 383 millions $BB$ events. Fig. 1 shows the $J/\psi \omega$ mass distribution obtained for $B^+$ (a) and $B^0$ (b) decay. Our observation leads to a lower mass and a smaller width than reported in Belle’s analysis, we obtain: $M_{Y} = 3914.3^{+3.8}_{-3.4} (stat) \pm 1.6(syst)$ MeV/\(c^2\) and $\Gamma_{Y} = 33^{+12}_{-8} (stat) \pm 0.6(syst)$ MeV.

The $Y(3940)$, discovered by the Belle Collaboration [12] in the decay process $B \to K J/\psi \omega (\omega \to \pi^+ \pi^- \pi^0)$, with mass $3943 \pm 11 \pm 13$ MeV/\(c^2\) and a large width, $87 \pm 22 \pm 26$ MeV, appears to be a puzzle, unexpected and unexplained by $q\bar{q}$ quark models of mesons. The mass and widths suggest a radially excited $P$ wave $c\bar{c}$ state. However decay to $J/\psi \omega$ is not readily explained for mass above open-charm threshold [13]. Unconventional explanations for the $Y(3940)$ include hybrid charmonium-gluon bound states, $ccg$ [14], charmonium light quark molecules, $\psi(2S) u\bar{u}d\bar{d}$ [15], or multi-quark states [16].

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4. The ISR $J/\psi \pi \pi$

Among the new charmonium-like states, the $Y(4260)$ is probably the most intriguing. Its discovery was reported by BaBar in the $J/\psi \pi \pi$ subsystem in the radiative return reaction $e^+ e^- \to \gamma_{ISR} J/\psi \pi \pi$ [17]. Using 233 fb$^{-1}$ of data, a broad enhancement has been observed at 4260 MeV/\(c^2\), an unbinned fit with a Breit-Wigner signal function and a second order polynomial background yields $125 \pm 23 Y(4260) \to J/\psi \pi^+ \pi^-$ events, with a mass $M_{Y} = 4259 \pm 8(stat)^{+2}_{-0} (syst)$ MeV/\(c^2\) and a width $\Gamma_{Y} = 88 \pm 23(stat)^{+6}_{-4} (syst)$ MeV.

BaBar searched for the $Y(4260)$ in $e^+ e^- \to \gamma_{ISR} p\bar{p}$ events. No signal has been found so far, and its possible to set the upper limit $B(Y(4260) \to p\bar{p})/B(Y(4260) \to J/\psi \pi^+ \pi^-) < 13\%$ at 90% C.L. [18]. Looking for the $Y(4260)$ in the radiative return process $e^+ e^- \to \gamma_{ISR} \psi(2S) \pi^+ \pi^-$, where
Figure 1. The $J/\psi\omega$ mass distribution for (a) $B^+$ and (b) $B^0$ decay. The solid curves result from the fit. (c) The $B^0/B^+$ ratio; the dashed line corresponds to isospin conservation.

$p(2S) \rightarrow J/\psi\pi^+\pi^-$, BaBar observed a broad structure near 4.32 GeV, that is not consistent with the $\psi(4415) \rightarrow J/\psi\pi^+\pi^-$. A fit to the mass spectrum with a single resonance yields a mass of $4324 \pm 23$ MeV/$c^2$ and a width of $172 \pm 33$ MeV (where the errors are statistical only). This structure has a mass that differs somewhat from the reported for the $Y(4260)$, however, the possibility that it represents evidence for a new decay mode for the $Y(4260)$ cannot be ruled out at this time.

The $Y(4260)$ therefore represents an overpopulation of the expected $1^{--}$ states in the mass region above the $DD$ threshold. The absence of open charm production also argues against it being a conventional $cc$ state. The observation of other decay modes may help in understanding the nature of this state.

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