Results on conventional and exotic charmonium at \textit{BABAR}

Denis Bernard, on behalf of the \textit{BABAR} Collaboration

Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS/IN2P3, F-91128 Palaiseau, France

Presented at XXI International Workshop on Deep-Inelastic Scattering and Related Subject -DIS2013, 22-26 April 2013 Marseille, France

To appear in Proceedings of Science

The \textit{B} factories provide a unique playground for studying the properties of conventional and exotic charmonium states. We present recent results in initial state radiation and two-photon fusion, obtained using the full data set collected by the \textit{BABAR} experiment. Amongst \textit{BABAR} ’s harvest presented in this talk, the determination of the quantum numbers of the $X(3915)$ resonance, a body of concording evidence pointing to $J^{PC} = 1^{++}$ for the $X(3872)$, and updates on the family of the $Y$ resonance to the full integrated luminosity.

In this talk I have presented recent results obtained by the BaBar experiment on charmonium and charmonium-like resonances, using production mechanisms that select the quantum numbers. Angular momentum conservation, and for strong decays parity conservation and charge conjugation invariance then imply that these quantum numbers also apply to the final state. In the case of two-photon fusion, charge conjugation is positive, and for non-tagged events, for which the initial electron and positron are unobserved, the event selection performed during the analysis is such that the two intermediate photons are quasi-real: allowed $J^{PC}$ are $0^{±+}$, $2^{±+}$, $4^{±+}$ and $3^{++}$, $5^{++}$, $\ldots$. In the case of initial state radiation (ISR), for which a photon is emitted by either of the incoming leptons, $J^{PC} = 1^{--}$.

Results presented here are related to understanding the nature and the properties of “new” resonances $X(3872)$, $X(3915)$, and the $Y$ family.

1 Study of $X(3915)$ and search for $X(3872)$, decaying to $J/\psi \omega$ in two-photon collisions

Several charmonium-like states have been observed by the $B$ factories in the mass region above the $D\bar{D}$ threshold, with properties that disfavor their interpretation as conventional charmonium mesons \cite{1,2,3,4,5,6,7,8,9}.

\begin{thebibliography}{9}
\bibitem{1} [reference to be added]
\bibitem{2} [reference to be added]
\bibitem{3} [reference to be added]
\bibitem{4} [reference to be added]
\bibitem{5} [reference to be added]
\bibitem{6} [reference to be added]
\bibitem{7} [reference to be added]
\bibitem{8} [reference to be added]
\bibitem{9} [reference to be added]
\end{thebibliography}
The X(3915) resonance, decaying to the $J/\psi \omega$ final state, was first observed by the Belle Collaboration in two-photon collisions [10]. The $Z(3930)$ resonance was discovered in the $\gamma \gamma \rightarrow D \bar{D}$ process [6, 7]. Its interpretation as the $\chi_{c2}(2P)$, the first radial excitation of the $3P_2$ charmonium ground state, is commonly accepted [11]. Interpretation of the X(3915) as the $\chi_{c0}(2P)$ [12] or $\chi_{c2}(2P)$ state [13] has been suggested. The latter would imply that the X(3915) and Z(3930) are the same particle, observed in different decay modes.

Despite the many measurements available [11], the nature of the X(3872) state, which was first observed by Belle [14], is still unclear [15]. The observation of its decay into $\gamma J/\psi$ [16] ensures that this particle has positive $C$-parity. The spin analysis performed by CDF on the decay $X(3872) \rightarrow J/\psi \pi^+\pi^-$ concludes that only $J^P = 1^+$ and $J^P = 2^-$ are consistent with data [17]. If $J^P = 2^-$, the production of the X(3872) in two-photon collisions would be allowed, while for $J = 1$ if would be forbidden.

BaBar searched for the X(3872) and the X(3915) resonances in the decay mode $J/\psi \omega$ and studied the quantum numbers of the X(3915) with angular analyses [18], in a sample of events corresponding to 519.2 fb$^{-1}$. Intermediate mesons are reconstructed in the modes $J/\psi \rightarrow \ell^+\ell^-$, ($\ell = e$ or $\mu$) and $\omega \rightarrow \pi^+\pi^-\pi^0$. Besides the usual event reconstruction and signal selection, several cuts are applied to reject specific backgrounds. Events with extra tracks with momentum greater than 0.1 GeV/c, or with a large energy non-associated with the event ($E_{\text{extra}} > 0.3$ GeV), events from ISR $J/\psi \pi^+\pi^-\pi^0$ production, and residual ISR $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ production are vetoed. The $\pi^0$ mass is constrained to its nominal value [11]. To improve the mass resolution, we define the $J/\psi \omega$ mass as $m(J/\psi \omega) = m(\ell^+\ell^-\pi^+\pi^-\pi^0) - m(\ell^+\ell^-) + m(J/\psi)_{PDG}$.

We observe a prominent peak near 3915 MeV/c$^2$ over a small background (Fig. 1), with 59±10 signal events, a mass of (3919.4±2.2±1.6) MeV/c$^2$ and a width of (13±6±3) MeV with a significance of 7.6σ, results which are compatible with those of Belle [10]. No structure is seen around 3872 MeV/c$^2$, with an upper limit of $\Gamma_{\gamma\gamma}[X(3872)] \times B(X(3872) \rightarrow J/\psi \omega) < 1.7$ eV at 90% CL, assuming $J = 2$. We first discriminate between $J^P = 0^\pm$
and $J^P = 2^+$ by using the Rosner \cite{19} predictions. The distribution of several angles that determine the final state are examined. In all cases the $J^P = 0^\pm$ hypothesis describes the data better than the $J^P = 2^+ \cite{18}$. For the distribution of the angle $\theta_n^*$ between the normal to the decay plane of the $\omega$ and the two-photon axis (Fig. 2 right) $\chi^2$ probabilities for $J^P = 0^\pm$ and $J^P = 2^+$ are respectively $64.7\%$ and $9.6 \times 10^{-9}\%$ respectively. We then discriminate between $J^P = 0^-$ and $J^P = 0^+$. In all cases the $J^P = 0^+$ hypothesis gives a smaller $\chi^2$ than the $J^P = 0^-$ hypothesis. For the distribution of the angle $\theta_n$ between the normal to the $\omega$ decay plane and the $\omega$ direction in the $J/\psi\omega$ rest frame (Fig. 2 left) $\chi^2$ probabilities for $J^P = 0^+$ and $J^P = 0^-$ are $6.1\%$ and $4.8 \times 10^{-11}\%$ respectively. We find that $J^P = 0^\pm$ is largely preferred over $J^P = 2^+$ and that $J^P = 0^+$ is largely preferred $J^P = 0^-$, which points to an interpretation of the $X(3915)$ resonance being the $\chi_{c0}(2P)$ charmonium meson.

2 Search for resonances decaying to $\eta_c \pi^+ \pi^-$ in two-photon interactions

An other final state that may be considered to test $X(3872)$ production in two-photon, still with the hope to discriminate $J^{PC} = 1^{++}$ from $J^{PC} = 2^{+-}$, is $\eta_c \pi^+ \pi^-$. Voloshin \cite{20} compared the $\eta'_c \rightarrow \eta_c$ and $\psi(2S) \rightarrow J/\psi$ dipion transitions in terms of QCD multipole expansion, and predicted $\mathcal{B}(\eta_c(2S) \rightarrow \eta_c \pi^+ \pi^-) / \mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-) = 2.9$, that is $\mathcal{B}(\eta_c(2S) \rightarrow \eta_c \pi^+ \pi^-) = (2.2^{+1.6}_{-0.6})\%$.

In the same spirit, with the possible assignment of the $X(3872)$ to the charmonium meson $\eta_{c2}$ ($1^1D_2$, with $J^{PC} = 2^{+-}$), the branching fraction of the isospin-conserving decay $X(3872) \rightarrow \eta_c \pi^+ \pi^-$ would be larger than that of the isospin-violating decay discovery channel $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ \cite{21}, which is larger than $2.6\% \cite{11}$. Two photon production would be allowed, and the event rate could be sizable.

The $\text{BaBar}$ experiment studied resonances decaying to $\eta_c \pi^+ \pi^-$ in two-photon interactions, using a data sample that corresponds to 473.9 fb$^{-1}$ \cite{22}. $\eta_c$ candidates were reconstructed in the $K_s^0 K^+ \pi^-$ decay mode. Background rejection is performed in a very sophisticated way. After an usual event reconstruction and a two-photon-like preselection
of the candidates, cuts are applied in the $\eta_c$ decay Dalitz plane to take advantage of the fact that $\eta_c \to K_s^0 K^+ \pi^-$ decays often proceed via intermediate $K_0^*(1430)$ states, while background events often contain a $K^*(892)$ meson. Finally a cut is applied on the output of a neural network whose inputs include general properties of the $\eta_c \pi^+ \pi^-$ candidate such as $p_T$ and $E_{extra}$, and particle identification information for the charged tracks.

Figure 3: Distributions of $m_{K_s^0 K^+ \pi^- \pi^-}$ in three mass ranges of interest, corresponding to the $\chi_{c2}(1P)$, to the $\eta_c(2S)$, and to the $X(3872)$, $X(3915)$ and $\chi_{c2}(2P)$ (the masses of which are indicated by the vertical lines) [22].

Two structures are found, for masses that are compatible with that of the $\chi_{c2}(1P)$ and of the $\eta_c(2S)$ meson, but no sign of any signal is detected for the $X(3872)$, $X(3915)$ and $\chi_{c2}(2P)$ (Fig. 3) which indicates again that the $2^{-+}$ assignment is disfavored for the $X(3872)$. We obtain an upper limit $B(\eta_c(2S) \to \eta_c \pi^+ \pi^-) < 7.4\%$ that is compatible with the prediction of 2.2%.

3 Study of ISR-produced resonances decaying to $\psi\pi^+\pi^-$

The $Y(4260)$ resonance discovered by $\text{BaBar}$ [1] in ISR production to $J/\psi \pi^+ \pi^-$ final state, has escaped firm interpretation to date. Most likely is it not a regular charmonium meson since all attempts to detect its decays to either $D\bar{D}$, $D\bar{D}^*$, $D^* \bar{D}^*$, $D_s^+ D_s^-$, $D_s^+ D_s^-$, $D_s^+ \bar{D}_s^-$ have failed. Most likely it is not a four-quark system since the most natural assignment would have it decay dominantly to $D_s^+ D_s^-$ [23], which are not seen. Searching for $Y(4260)$ decays to $\psi(2S)\pi^+ \pi^-$, $\text{BaBar}$ didn’t find any, but found instead a new similar resonance at an invariant mass of 4.32 GeV/$c^2$ [4], now named the the $Y(4330)$. Belle confirmed the existence of the $Y(4260)$ resonance, claimed a hint of an other object at a lower mass, close to 4 GeV/$c^2$, confirmed the existence of the $Y(4330)$ resonance, and discovered a new resonance, the $Y(4660)$, in the same channel $\psi(2S)\pi^+ \pi^-$ [5].

We report here a recent update by $\text{BaBar}$ of the $J/\psi \pi^+ \pi^-$ analysis to 454 fb$^{-1}$ [24], and the first $\text{BaBar}$ study of the $\psi(2S)\pi^+ \pi^-$ final state, using 520 fb$^{-1}$ [25]. $\text{BaBar}$ confirms [24, Fig. 4 left] its discovery of the ISR-produced $Y(4260) \to J/\psi \pi^+ \pi^-$ [1] and Belle’s observation of $Y(4360)$ and $Y(4660)$ to $\psi(2S)\pi^+ \pi^-$, but does not see any sign of an $Y(4008) \to J/\psi \pi^+ \pi^-$ [25, Fig. 4 right]. I agree with the Belle speaker [26] that this thing, which was presented without a significance, should be handled with quotes.
Figure 4: Mass distributions of the $J/\psi \pi^{+}\pi^{-}$ (left, [24]) and $\psi(2S)\pi^{+}\pi^{-}$ (right, [25]) final states.

4 Conclusion

We have presented studies of untagged production in two-photon fusion with the $J/\psi \omega$ and $\eta_c \pi^{+}\pi^{-}$ final states. Together with its two-photon production, angular analyses of $X(3915) \rightarrow J/\psi \omega$ determine the quantum numbers of the $X(3915)$ to be $J^{PC} = 0^{++}$, indicating the possible assignment to a $\chi_{c0}(2P)$ charmonium meson. The searches of $X(3872)$ in these two final states don’t show any significant signal, despite at least the branching fraction of $X(3872)$ to $\eta_c \pi^{+}\pi^{-}$ is expected to be sizable in the case of the $J^{PC} = 2^{-+}$. These two results, together with LHCb’s preliminary angular analysis of $X(3872) \rightarrow J/\psi \pi^{+}\pi^{-}$ [27] point to a $J^{PC} = 1^{++}$ assignment for the $X(3872)$. The proximity of its mass to the $D^{*0}\overline{D}^{0}$ threshold suggested it to be a $J^{PC} = 1^{++}$ hadronic molecule [28] or a a tetraquark [29]. The family of the $J^{PC} = 1^{--}$ $Y$ states produced in ISR with $\psi \pi^{+}\pi^{-}$ is now well established, with 3 confirmed states. We may be seeing the dawn of a hybrid charmonium spectroscopy [30].

References

[1] B. Aubert et al. [BaBar Collaboration], Observation of a broad structure in the $\pi^{+}\pi^{-}J/\psi$ mass spectrum around 4.26-GeV/$c^2$, Phys. Rev. Lett. 95 (2005) 142001 [hep-ex/0506081].

[2] T. E. Coan et al. [CLEO Collaboration], Charmonium decays of $Y(4260)$, psi(4160) and psi(4040), Phys. Rev. Lett. 96 (2006) 162003 [hep-ex/0602034].

[3] C. Z. Yuan et al. [Belle Collaboration], Measurement of $e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$ cross-section via initial state radiation at Belle, Phys. Rev. Lett. 99 (2007) 182004 [arXiv:0707.2541 [hep-ex]].

[4] B. Aubert et al. [BaBar Collaboration], Evidence of a broad structure at an invariant mass of 4.32- GeV/$c^2$ in the reaction $e^+e^- \rightarrow \pi^+\pi^-\psi_{2S}$ measured at BaBar, Phys. Rev. Lett. 98, 212001 (2007) [hep-ex/0610057].
[5] X. L. Wang et al. [Belle Collaboration], Observation of Two Resonant Structures in e+e- to pi+ pi- psi(2S) via Initial State Radiation at Belle, Phys. Rev. Lett. 99, 142002 (2007) arXiv:0707.3699 [hep-ex].

[6] S. Uehara et al. [Belle Collaboration], Observation of a chi-prime(c2) candidate in gamma gamma → D anti-D production at BELLE, Phys. Rev. Lett. 96 (2006) 082003 [hep-ex/0512035].

[7] B. Aubert et al. [BaBar Collaboration], Observation of the chi(2)(2P) meson in the reaction gamma gamma → D Dbar at BABAR, Phys. Rev. D 81 (2010) 092003 arXiv:1002.0281 [hep-ex].

[8] K. Abe et al. [Belle Collaboration], Observation of a near-threshold omega J/psi mass enhancement in exclusive B → K omega J/psi decays, Phys. Rev. Lett. 94 (2005) 182002 hep-ex/0408126.

[9] B. Aubert et al. [BaBar Collaboration], Observation of Y(3940) → J/psi omega in B → J/psi omega K at BABAR, Phys. Rev. Lett. 101 (2008) 082001 arXiv:0711.2047 [hep-ex].

[10] S. Uehara et al. [Belle Collaboration], Observation of a charmonium-like enhancement in the gamma gamma → omega J/psi process, Phys. Rev. Lett. 104 (2010) 092001 arXiv:0912.4451 [hep-ex].

[11] J. Beringer et al. [Particle Data Group Collaboration], Review of Particle Physics (RPP), Phys. Rev. D 86, 010001 (2012).

[12] X. Liu et al., X(3915) and X(4350) as new members in P-wave charmonium family, Phys. Rev. Lett. 104 (2010) 122001 arXiv:0911.3694 [hep-ph].

[13] T. Branz, R. Molina and E. Oset, Radiative decays of the Y(3940), Z(3930) and the X(4160) as dynamically generated resonances, Phys. Rev. D 83 (2011) 114015 arXiv:1010.5827 [hep-ph].

[14] S. K. Choi et al. [Belle Collaboration], Observation of a narrow charmonium - like state in exclusive B+ → K+ pi+ pi- J / psi decays, Phys. Rev. Lett. 91 (2003) 262001 hep-ex/0309032.

[15] N. Brambilla et al., Heavy quarkonium: progress, puzzles, and opportunities, Eur. Phys. J. C 71 (2011) 1534 arXiv:1010.5827 [hep-ph].

[16] B. Aubert et al. [BaBar Collaboration], Evidence for X(3872) → psi_2gamma in B^± → X_{3872} K^± decays, and a study of B → cc gamma K, Phys. Rev. Lett. 102 (2009) 132001 arXiv:0809.0042 [hep-ex].

V. Bhardwaj et al. [Belle Collaboration], Observation of X(3872) → J/psi gamma and search for X(3872) → psi' gamma in B decays, Phys. Rev. Lett. 107 (2011) 091803 arXiv:1105.0177 [hep-ex].

[17] A. Abulencia et al. [CDF Collaboration], Analysis of the quantum numbers J^PC of the X(3872), Phys. Rev. Lett. 98 (2007) 132002 [hep-ex/0612053].

[18] J. P. Lees et al. [BaBar Collaboration], Study of X(3915) → J/psi in two-photon collisions, Phys. Rev. D 86 (2012) 072002 arXiv:1207.2651 [hep-ex].

[19] J. L. Rosner, Angular distributions in J/psi(rh0, omega) states near threshold, Phys. Rev. D 70 (2004) 094023 hep-ph/0408334.
[20] M. B. Voloshin, The Decay \( \eta\prime(c) \to \eta(c) \pi \pi \), Mod. Phys. Lett. A 17, 1533 (2002) [hep-ph/0206240].

[21] S. L. Olsen [Belle Collaboration], Search for a charmonium assignment for the \( X(3872) \), Int. J. Mod. Phys. A 20, 240 (2005) [hep-ex/0407033].

[22] J. P. Lees et al. [BaBar Collaboration], Search for resonances decaying to \( \eta_c\pi^+\pi^- \) in two-photon interactions, Phys. Rev. D 86, 092005 (2012) [arXiv:1206.2008 [hep-ex]].

[23] L. Maiani, V. Riquer, F. Piccinini and A. D. Polosa, Four quark interpretation of \( Y(4260) \), Phys. Rev. D 72 (2005) 031502 [hep-ph/0507062].

[24] J. P. Lees et al. [BaBar Collaboration], Study of the reaction \( e^+e^- \to J/\psi\pi^+\pi^- \) via initial-state radiation at BaBar, Phys. Rev. D 86, 051102 (2012) [arXiv:1204.2158 [hep-ex]].

[25] J. P. Lees et al. [BaBar Collaboration], Study of the reaction \( e^+e^- \to \psi(2S)\pi^-\pi^- \) via initial state radiation at BaBar, [arXiv:1211.6271 [hep-ex]].

[26] Daniel Santel, Recent results on quarkonium spectroscopy and exotic quarkonium-like resonances at Belle, this conference.

[27] R. Aaij et al. [LHCb Collaboration], Determination of the \( X(3872) \) meson quantum numbers, [arXiv:1302.6269 [hep-ex]].

[28] N. A. Tornqvist, Isospin breaking of the narrow charmonium state of Belle at 3872-MeV as a deuson, Phys. Lett. B 590, 209 (2004) [hep-ph/0402237].

[29] L. Maiani, F. Piccinini, A. D. Polosa and V. Riquer, Diquark-antidiquarks with hidden or open charm and the nature of \( X(3872) \), Phys. Rev. D 71, 014028 (2005) [hep-ph/0412098].

[30] S. -L. Zhu, The Possible interpretations of \( Y(4260) \), Phys. Lett. B 625, 212 (2005) [hep-ph/0507025].

E. Kou and O. Pene, Suppressed decay into open charm for the \( Y(4260) \) being an hybrid, Phys. Lett. B 631, 164 (2005) [hep-ph/0507119].

F. E. Close and P. R. Page, Gluonic charmonium resonances at BaBar and BELLE?, Phys. Lett. B 628, 215 (2005) [hep-ph/0507199].