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Charmonium and charmonium-like results from BaBar

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Summary. — We present new results on charmonium and charmonium-like states from the BaBar experiment located at the PEP-II asymmetric energy e^+e^- collider at the SLAC National Accelerator Laboratory.

PACS 13.66.Bc – Hadron production in e^-e^+ interactions.
PACS 14.40.Lb – Charmed mesons.
PACS 14.40.Pq – Heavy quarkonia.
PACS 13.25.Gv – Decays of J/ψ, Υ, and other quarkonia.

1. – Charmonium spectroscopy

The charmonium spectrum consists of eight narrow states below the open charm threshold (3.73 GeV) and several tens of states above the threshold. Below the threshold almost all states are well established. On the other hand, very little is known above the threshold, there are several new "Charmonium-like" states that are very difficult to accommodate in the charmonium spectrum.

The B-factories are an ideal place to study charmonium since charmonium states are produced in four different processes:

- B decays, charmonium states of any quantum numbers can be produced
- Two photon production: in this process two virtual photons are emitted by the colliding e^+e^- pair ($e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-(c\bar{c})$), charmonium states with $J^{PC} = 0^{\pm+}, 2^{\pm+}, 4^{\pm+}, \ldots, 3^{++}, 5^{++} \ldots$ can be produced.
- Initial State Radiation (ISR): where a photon is emitted by the incoming electron or positron ($e^+e^- \to \gamma c\bar{c}$), only states with $J^{PC} = 1^{--}$ are formed
- Double charmonium production: in this process a J/ψ or a $\psi(2S)$ is produced together with another charmonium state.

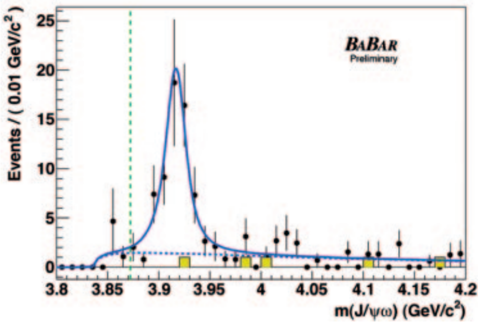

Fig. 1. – The efficiency-corrected invariant-mass distribution for the $J/\psi\omega$ final state. The vertical dashed line is at the X(3872) mass.

2. – Study of the process $\gamma\gamma \to J/\psi\omega$

The charmonium-like state Y(3940) was first seen by Belle [1] and then confirmed by BaBar [2] in the same B meson decay mode, but with lower mass and smaller width compared to the Belle results.

In a re-analysis [3] of the BaBar data which used the complete $\Upsilon(4S)$ data sample, the precision of the Y(3940) measurements was improved and evidence for the decay X(3872)$\to J/\psi\omega$ was reported. This confirmed an earlier unpublished Belle claim for the existence of this decay mode [4]. The latter was based on the behaviour of the invariant $\pi^+\pi^-\pi^0$ mass distribution near the X(3872), whereas the BaBar result is obtained directly from a fit the the $J/\psi\omega$ mass distribution.

A subsequent paper from Belle [5] reports the observation in $\gamma\gamma \to J/\psi\omega$ of a state, the X(3915), with mass and width values similar to those obtained for the Y(3940) in the BaBar analysis [2].

The BaBar analysis of the process $\gamma\gamma \to J/\psi\omega$ has been performed in order to search for the X(3915) and the X(3872) resonances via the decay to $J/\psi\omega$, using a data sample of $519\,\text{fb}^{-1}$. Figure 1 presents the reconstructed $J/\psi\omega$ invariant-mass distribution after all the selection criteria have been applied. We perform an extended maximum-likelihood fit to the efficiency-corrected spectrum. A large peak at near $3915\,\text{MeV}/c^2$ is observed with a significance of 7.6 σ. The measured resonance parameters are $m[X(3915)] = (3919.4 \pm 2.2 \pm 1.6)\,\text{MeV}/c^2$, $\Gamma[X(3915)] = (13 \pm 6 \pm 3)\,\text{MeV}$. The measured value of the two-photon width times the branching fraction, $\Gamma_{\gamma\gamma}[X(3915)] \times \mathcal{B}(X(3915) \to J/\psi\omega)$ is $(52 \pm 10 \pm 3)\,\text{eV}$ and $(10.5 \pm 1.9 \pm 0.6)\,\text{eV}$ for the spin hypotheses $J = 0$ and $J = 2$, respectively, where the first error is statistical and the second is systematic. In addition, a Bayesian upper limit (UL) at 90% confidence level (CL) is obtained for the X(3872), $\Gamma_{\gamma\gamma}[X(3872)] \times \mathcal{B}(X(3872) \to J/\psi\omega) < 1.7\,\text{eV}$, assuming $J = 2$.

3. – Study of the process $\gamma\gamma \to \eta_c\pi^+\pi^-$

This analysis has been studied for the first time and is performed to search for resonances decaying into $\eta_c\pi^+\pi^-$, using a data sample of $474\,\text{fb}^{-1}$. The η_c was reconstructed via its decay to $K^0_S K^+\pi^-$, with $K^0_S \to \pi^+\pi^-$. The signal yield for each X resonance is extracted from a two-dimensional fit to $m(K^0_S K^+\pi^-)$ and $m(K^0_S K^+\pi^-\pi^+\pi^-)$. Figure 2 presents the two-dimensional fits around each of the resonances. No significant signal is

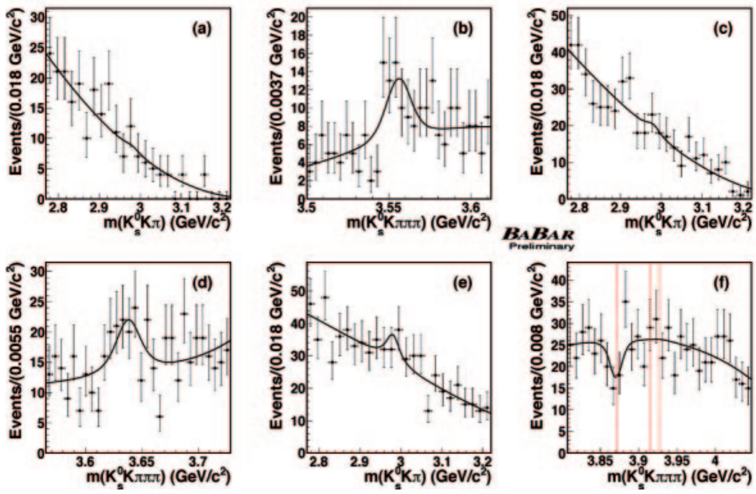

Fig. 2. – Distributions of (a,c,e) $m(K^0_S K^+\pi^-)$ and (b,d,f) $m(K^0_S K^+\pi^-\pi^+\pi^-)$ with the fit function overlaid for the fit regions of the (a,b) $\chi_{c2}(1P)$, (c,d) $\eta_c(2S)$, and (e,f) X(3872), X(3915) and $\chi_{c2}(2P)$. The vertical dashed lines in (f) indicate the peak mass positions of the X(3872), X(3915) and $\chi_{c2}(2P)$.

TABLE I. – *Results of the $\gamma\gamma \to \eta_c\pi^+\pi^-$ fits. For each resonance X, we show the peak mass and width used in the fit; the product of the two-photon partial width $\Gamma_{\gamma\gamma}$ and the $X \to \eta_c\pi\pi$ branching fraction, and the 90% CL upper limits on this product.*

Resonances	M_X (MeV/c^2)	Γ_X (MeV)	$\Gamma_{\gamma\gamma}\mathcal{B}$ (eV) Central Value	UL
$\chi_{c2}(1P)$	3556.20 ± 0.09	1.97 ± 0.11	$7.2^{+5.5}_{-4.4} \pm 2.9$	15.7
$\eta_c(2S)$	3638.5 ± 1.7	13.4 ± 5.6	$65^{+47}_{-44} \pm 18$	133
$X(3872)$	3871.57 ± 0.25	3.0 ± 2.1	$-4.5^{+7.7}_{-6.7} \pm 2.9$	11.1
$X(3915)$	3915.0 ± 3.6	17.0 ± 10.4	$-13^{+12}_{-12} \pm 8$	16
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	$-16^{+15}_{-14} \pm 6$	19

observed in any of the fits. Table I summarizes these results. ULs are obtained on the branching fractions $\mathcal{B}(\eta_c(2S) \to \eta_c\pi^+\pi^-) < 7.4\%$ and $\mathcal{B}(\chi_{c2}(1P) \to \eta_c\pi^+\pi^-) < 2.2\%$ at 90% CL.

4. – Search for the $Z_1(4050)^+$ and $Z_2(4250)^+$

Belle reported the observation of two resonance-like structures, $Z_1(4050)^+$ and $Z_2(4250)^+$ in the study of $\bar{B}^0 \to \chi_{c1}K^-\pi^+$, both decaying to $\chi_{c1}\pi^+$ [6].

BaBar studied the same final states [7] to search for the $Z_1(4050)^+$ and $Z_2(4250)^+$ decay into $\chi_{c1}\pi^+$ in $\bar{B}^0 \to \chi_{c1}K^-\pi^+$ and $B^+ \to K^0_S\chi_{c1}\pi^+$ (this mode is analyzed for the first time) where $\chi_{c1} \to J/\psi\gamma$, using a data sample of 429 fb^{-1}. The $\chi_{c1}\pi^+$ mass distribution, background-subtracted and efficiency-corrected, was modeled using

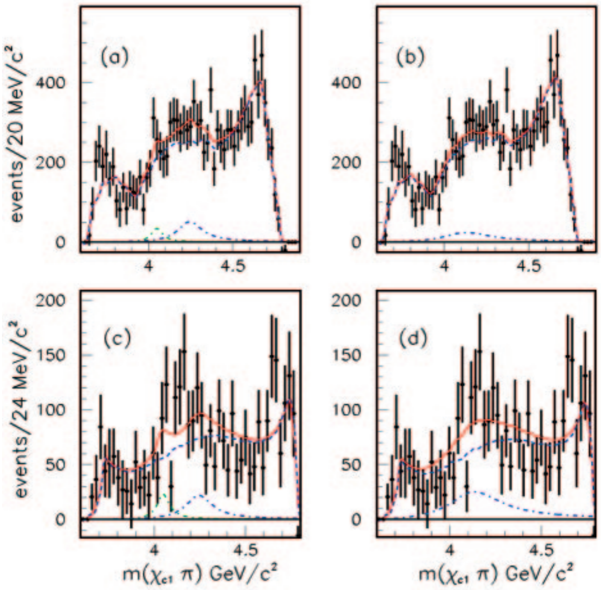

Fig. 3. – Fit to the background-subtracted and efficiency-corrected $\chi_{c1}\pi$ mass distributions. See text for more details.

the $K\pi$ mass distribution and the corresponding normalized $K\pi$ Legendre polynomial moments. Figure 3 shows the results of the fits to the $\chi_{c1}\pi^+$ mass spectrum. The fit shown in fig. 3(a) includes both $Z_1(4050)^+$ and $Z_2(4250)^+$ resonances and the fit shown in fig. 3(b) includes a single broad $Z(4150)^+$ resonance. Figures 3(c,d) show the $\chi_{c1}\pi$ mass spectrum fitted in the Dalitz plot region $1.0 \leq m^2(K\pi) < 1.75\,\text{GeV}^2/c^4$ in order to make a direct comparison to the Belle results [6] (this region is labeled as "window" in table II). The results of the fits are summarized in table II and in every case the yield significance does not exceed 2σ. The ULs on the 90% CL on the branching fractions are: $\mathcal{B}(\bar{B}^0 \to Z_1(4050)^+K^-) \times \mathcal{B}(Z_1(4050)^+ \to \chi_{c1}\pi^+) < 1.8 \times 10^{-5}$; $\mathcal{B}(\bar{B}^0 \to Z_2(4250)^+K^-) \times \mathcal{B}(Z_2(4250)^+ \to \chi_{c1}\pi^+) < 4.0 \times 10^{-5}$ and $\mathcal{B}(\bar{B}^0 \to Z^+K^-) \times \mathcal{B}(Z^+ \to \chi_{c1}\pi^+) < 4.7 \times 10^{-5}$.

TABLE II. – *Results of the $\chi_{c1}\pi$ fits. N_σ and Fraction give, for each fit, the significance and the fractional contribution of the Z resonances.*

Data	Resonances	N_σ	Fraction (%)	χ^2/NDF
a) Total	$Z_1(4050)^+$	1.1	1.6 ± 1.4	57/57
	$Z_2(4250)^+$	2.0	4.8 ± 2.4	
b) Total	$Z(4150)^+$	1.1	4.0 ± 3.8	61/58
a) Window	$Z_1(4050)^+$	1.2	3.5 ± 3.0	53/46
	$Z_2(4250)^+$	1.3	6.7 ± 5.1	
b) Window	$Z(4150)^+$	1.7	1.37 ± 8.0	53/47

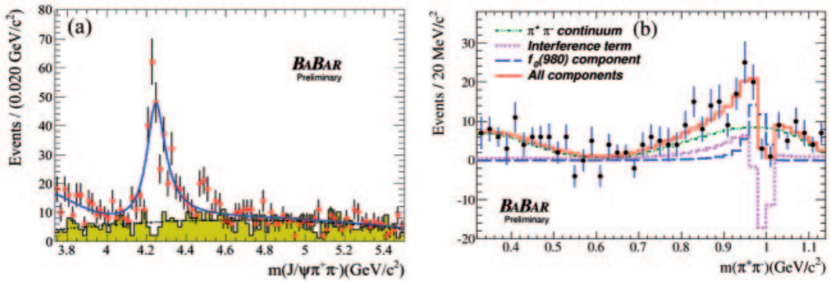

Fig. 4. – (a) The fit to the $J/\psi\pi^+\pi^-$ invariant-mass distribution. (b) The fit to the dipion invariant-mass distribution from the Y(4260) signal region.

5. – Study of the $J/\psi\pi^+\pi^-$ system via initial state radiation (ISR)

The Y(4260) charmonium-like resonance was discovered by BaBar [8] in ISR production of $J/\psi\pi^+\pi^-$. A subsequent Belle analysis [9] of the same final state suggested also the existence of an additional resonance around $4.1\,\mathrm{GeV}/c^2$ that they dubbed the Y(4008).

The BaBar analysis of the $J/\psi\pi^+\pi^-$ system produced in ISR has been repeated using a data sample of $454\,\mathrm{fb}^{-1}$ [10].

The $J/\psi\pi^+\pi^-$ mass region below $\sim 4\,\mathrm{GeV}/c^2$ is investigated for the first time. In that region an excess of events has been observed and the conclusion, after a detailed study of the $\psi(2S)$ lineshape (to estimate the $\psi(2S)$ tail contribution to that region), is that it is not possible to discount the possibility of a contribution from a $J/\psi\pi^+\pi^-$ continuum cross section in this region. From this study we obtain the cross section value 14.05 ± 0.26 (stat) pb for radiative return to the $\psi(2S)$ and a measurement of the width $\Gamma(\psi(2S) \to e^+e^-) = 2.31 \pm 0.05(\mathrm{stat})\,\mathrm{keV}$. Figure 4(a) shows the fit to the $J/\psi\pi^+\pi^-$ distribution. A clear signal of the Y(4260) is observed for which the values obtained are $m[Y(4260)] = 4244 \pm 5 \pm 4\,\mathrm{MeV}/c^2$, $\Gamma[Y(4260)] = 114^{+16}_{-15} \pm 7\,\mathrm{MeV}$ and $\Gamma_{ee} \times \mathcal{B}(J/\psi\pi^+\pi^-) = 9.2 \pm 0.8(\mathrm{stat}) \pm 0.7(\mathrm{syst})\,\mathrm{eV}$. No evidence for the state at $\sim 4\,\mathrm{GeV}/c^2$ reported by Belle [9] was seen. A study of the $\pi^+\pi^-$ system from the $Y(4260)$ decay to $J/\psi\pi^+\pi^-$ has been performed. The dipion system is in a predominantly S-wave state. The mass distribution exhibits an $f_0(980)$ signal, for which a simple model indicates a branching ratio with respect to $J/\psi\pi^+\pi^-$ of $0.17 \pm 0.13(\mathrm{stat})$. The fit to the dipion invariant-mass distribution is shown in fig. 4(b).

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