Charmonium and -like states from Belle

V. Bhardwaj (for the Belle Collaboration)
Physics Department, Nara Women's University,
Kitauoya Nishi-machi, Nara, Japan -630 8506.

Large data collected at e^+e^- asymmetric B-factories has resulted in addition of many new states in the charmonium spectrum. Few states agrees well with the prediction of the charmonium models (conventional $c\bar{c}$ states), while others are totally unexpected (candidates for tetraquark or molecular-interpretation). In this paper, we report the recent results from Belle Collaboration on the searches for isospin triplet partner of $X(3872)$ in $J/\psi\pi\pi$, $J/\psi\eta$ and $\chi_{c1}\gamma$. Along with this first evidence of ψ_2 candidate around 3820 MeV/c^2 is also presented.

1 Introduction

Belle detector is a general purpose detector build to test Standard Model mechanism for CP-violation in B decays to charmonium (golden channel) [1]. Parallel to this, Belle has also proven to be an ideal place to carry charmonium spectroscopy due to very clean environment. Many new $c\bar{c}$ and $c\bar{c}$-like states such as $\eta_c(2S)$, $X(3872)$, $X(3915)$, $Z(3930)$, $X(3940)$, $Z_1(4050)^+$, $Z_2(4250)^+$, $Y(4260)$, $Z(4430)^+$ and $Y(4660)$ have been found. Out of these states, $X(3872)$ is the most interesting state. It was first observed in $B^\pm \to (J/\psi\pi^+\pi^-)K^\pm$ at Belle [2]. Soon after it's discovery, it was confirmed by CDF, D0 and BaBar. Recently, it has also been observed in LHCb and CMS. The observation of $X(3872)$ in the same final states $(J/\psi\pi^+\pi^-)$ in the six different experiments, reflects the eminent status of the $X(3872)$. $X(3872)$ narrow width and the proximity of its mass, 3871.5 ± 0.2 MeV/c^2 to the $D^{*0}\bar{D}^0$ threshold makes it a good candidate for a $D\bar{D}^*$ molecule [3]. Other possibilities have also been proposed for the $X(3872)$ state, such as tetraquark[4], $c\bar{c}g$ hybrid meson [5] and vector glueball models [6].

Mass, width, J^{PC} and branching ratio ($\mathcal{B}$) plays an important role in identifying its nature. Using 772 Million $B\bar{B}$ pairs (full and final $\Upsilon(4S)$ data sample), Belle updated[7] these properties. We also carried search for the charged partner of $X(3872)$ ($X(3872)^+$). Radiative decays of $X(3872)$ provide us an opportunity to understand the nature of $X(3872)$. One such decay, $X(3872) \to J/\psi\gamma$ resulted in the confirmation of C-even ($C = +$) parity for $X(3872)$[8,9,10]. similar decay mode $X(3872) \to \psi'\gamma$, important as it can help in identifying $X(3872)$ as a charmonium, molecular or molecular with charmonium mixing[3,11,12], is under conflict due to Belle's no evidence of the signal (disagree with the BaBar's evidence) [9,10]. If $X(3872)$ is tetraquark than it has a C-odd parity ($C = -$) partner, which can dominantly decay into $X(3872) \to J/\psi\eta$ and $X(3872) \to \chi_{c1}\gamma$. Along with this search for a new narrow state is also carried out in these final states. In this search, we find first evidence of $X(3823) \to \chi_{c1}\gamma$, most probably the missing ψ_2 ($^3D_2$ $c\bar{c}$ state).

For update on the properties of $X(3872)$, B reconstruction is done using $(J/\psi\pi^+\pi^-)K$ decay mode, while in our search of the charged $X(3872)$, B is reconstructed using $(J/\psi\pi^+\pi^0)K^-$.

$B^{\pm} \to (J/\psi\eta(\to \gamma\gamma))K^{\pm}$ and $B^{\pm} \to (\chi_{c1}(\to J/\psi\gamma)\gamma)K^{\pm}$ decay modes are used in the search for C-odd partner of the $X(3872)$ and other new narrow resonances. In all the decay modes, J/ψ is reconstructed via $e^{+}e^{-}$ and $\mu^{+}\mu^{-}$. B candidates are identified using: energy difference $\Delta E \equiv E_{B}^{*} - E_{beam}^{*}$ and beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{(E_{beam}^{*})^{2} - (p_{B}^{cms})^{2}}$, where E_{B}^{*} is the cms beam energy, and E_{B}^{*} and p_{B}^{*} are the cms energy and momentum of the reconstructed particles. Invariant mass of the final state (of interest) is used to identify the resonance.

2 Update on the properties of $X(3872)$

To extract the signal yield 3-dimension unbinned maximum likelihood (UML) fit to ΔE, $M_{\rm bc}$ and $M_{J/\psi\pi\pi}$, is used. Table 1 summarizes the mass, $\mathcal{B}$ and the signal yield extracted by the fit.

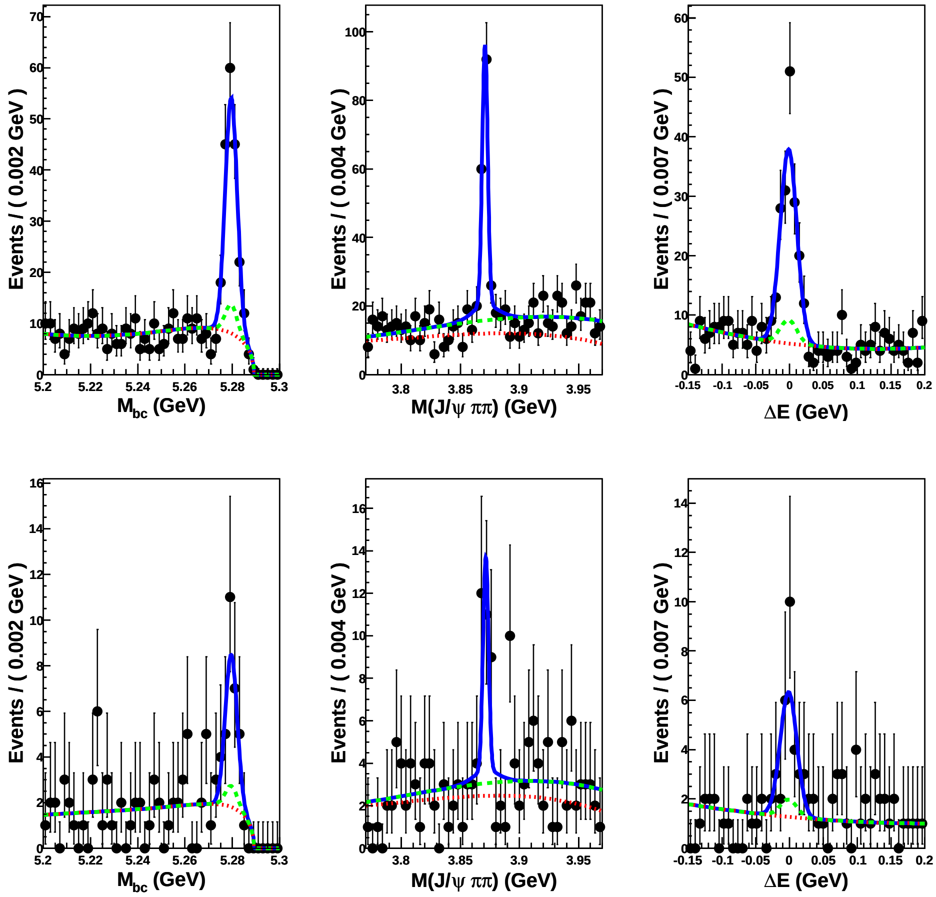

Figure 1: 3D UML fit to $M_{\rm bc}$ (left), $M_{J/\psi\pi\pi}$ (center) and ΔE (right) to extract signal yield for $B^{\pm} \to X(3872)K^{\pm}$ (top) and $B^{0} \to X(3872)K_{S}^{0}$ (bottom) within the signal regions of other two quantities. In the fit, combinatorial background is shown as red dotted line, combinatorial plus peaking background by green dashed line and the total fit (background plus signal is shown by blue solid line). Signal region is defined as $M_{\rm bc} > 5.27$ GeV/c^{2}, $-35 < \Delta E < 30$ MeV and $3.863 < M_{J/\psi\pi\pi} < 3.881$ GeV/c^{2}.

After applying mass correction determined from $B^{+} \to \psi' K^{+}$ sample, mass of $X(3872)$ is estimated to be: $M_{X(3872)} = (3871.85 \pm 0.27 \pm 0.19)$ MeV. First uncertainty is due to statistics while second due to systematics. Width of $X(3872)$ is estimated using likelihood scan and after including systematics it comes out to be as $\Lambda_{X(3872)} < 1.2$ MeV. If $X(3872)$ is tetraquark then few model predicts the mass of $X(3872)$ in the charged B and neutral B to have measurable difference of ΔM $(M_{X(B^{+})} - M_{X(B^{0})})$ $= (8 \pm 3)$ MeV. We measure this difference and found

Table 1: $\mathcal{B}$ estimated from the 3D UML fits.

Channel	Yield	Mass (MeV)	$\mathcal{B}(B \to XK)\mathcal{B}(X \to J/\psi\pi\pi)$ (10^{-6})
$X(3872)K^+$	152 ± 15	3870.85 ± 0.28	$8.61 \pm 0.82 \pm 0.52$
$X(3872)K^0$	21.0 ± 5.7	3871.56 ± 0.92	$4.3 \pm 1.2 \pm 0.4$
Combined	173 ± 16	3870.92 ± 0.27	

it to be consistent with zero ($-0.69 \pm 0.97 \pm 0.19$) MeV. Also, tetraquark model predicts the existence of isospin triplet : $X(3872)^+$ (charged $X(3872)$) having large $\mathcal{B}$ such that $\mathcal{B}(B^\pm \to X(3872)^\pm K^0) = 2 \times \mathcal{B}(B^0 \to X(3872)K^0)$. We search for the charged $X(3872)^+$ using $J/\psi\pi^+\pi^0$ and found no signal in the 2D ($M_{\rm bc}$ and $M_{J/\psi\pi^+\pi^0}$) UML fit, as shown in Figure 2. We provide the world best U.L. (@ 90% C.L.) on the $\mathcal{B}$ of the production of $X(3872)^+$ in B decays as:

- $\mathcal{B}(\bar{B}^0 \to X(3872)^+K^-)\mathcal{B}(X(3872)^+ \to J/\psi\rho^+) < 4.2 \times 10^{-6}$
- $\mathcal{B}(\bar{B^+} \to X(3872)^+K^0)\mathcal{B}(X(3872)^+ \to J/\psi\rho^+) < 6.2 \times 10^{-6}$

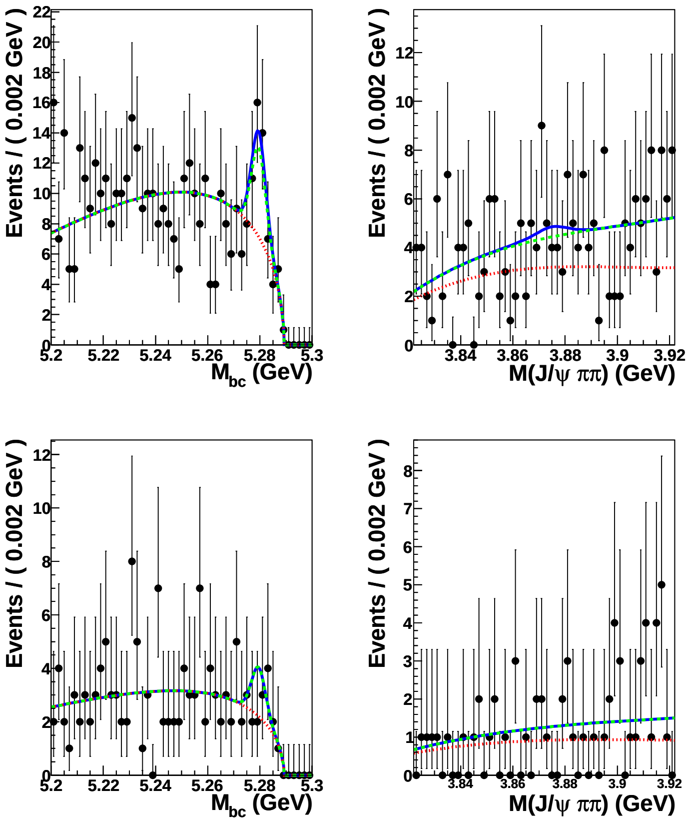

Figure 2: 2D UML fit to $M_{\rm bc}$ (left), $M_{J/\psi\pi^+\pi^0}$ (right) distributions for $B^0 \to X(3872)^+K^+$ (top) and $B^+ \to X(3872)^+K^0$ (bottom) within the signal regions of other quantity.

The angular study is carried out using $\cos\theta_X(J/\psi, K^\pm)$, $\cos\chi(\pi^+, K^\pm)$ and $\cos\theta_\ell(\ell, K^\pm)$, which suggests J^{PC} to be 1^{++} along with 2^{-+}. Fits to $M_{\pi^+\pi^-}$ distribution suggest J^{PC} to be 1^{++} without $\rho-\omega$ interference and when $\rho-\omega$ interference is taken into account, 2^{-+} also gives agreeable fit to $M_{\pi\pi}$ distribution. With current statistics, the most probable J^{PC} of $X(3872)$ is suggested to be either 1^{++} or 2^{-+} [7].

3 Search of C-odd partner of $X(3872)$ in $B^{\pm} \to J/\psi\eta K^{\pm}$

In the search of charged tetraquark partner of $X(3872)$, no signal is seen. Still it is hard to rule out $X(3872)$ as tetraquark, as some tetraquark model predicts $X(3872)^{+}$ to be broad resulting in non-observation at low statistics [13]. $X(3872)$'s C-odd partner can dominantly decay into J/ψ η and search for $X(3872)$'s $C-$odd partner in $J/\psi\eta$ can either result in the observation or much tighter constraint to the tetraquark interpretation of $X(3872)$. Previous study of $B \to J/\psi\eta K$ was carried out by BaBar [14].

We use ΔE to estimate the MC/data difference. We cut in the signal region defined as $M_{\rm bc} > 5.27$ GeV/c^2 and -35 MeV $< \Delta E <$ 30 MeV and look at the $M_{J/\psi\eta}$ for any resonance. Figure 3 shows the fit to $M_{J/\psi\eta}$. Difference between data and MC above 3.8 GeV/c^2 is found but once we include phase space component for $B^{\pm} \to J/\psi\eta K^{\pm}$, we are able to describe MC/data very well. No hint of a narrow resonance is evident from the current statistics. No $X(3872)$ signal is seen and U.L. (@ 90% CL) is provided using frequentist method. We also provide U.L. (@90% CL) at different masses using narrow width hypothesis, result shown in Figure 4. Table 2 summarizes the result from $B^{\pm} \to (J/\psi\eta)K^{\pm}$ study.

Table 2: Preliminary $\mathcal{B}$ for $B^{\pm} \to J/\psi\eta K^{\pm}$ analysis.

Channel	Yield	$\mathcal{B}(10^{-4})$
$B^{\pm} \to \psi'(\to J/\psi\eta)K^{\pm}$	52 ± 8.2	$5.81 \pm 0.92 \pm 0.44$
$B^{\pm} \to J/\psi\eta K^{\pm}$ (phase space)	395 ± 26	$1.17 \pm 0.07 \pm 0.11$
		$\mathcal{B}(B^{\pm} \to X(3872)K^{\pm})\mathcal{B}(X(3872) \to J/\psi\eta)(10^{-6})$
$B^{\pm} \to X(3872)(\to J/\psi\eta)K^{\pm}$	2.3 ± 5.2	< 3.8 (@ 90% CL)

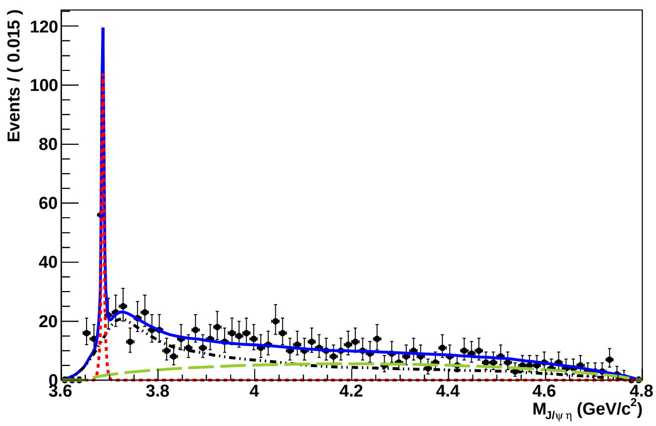

Figure 3: 1D UML fit to $M_{J/\psi\eta}$ distribution in order to extract the signal yield for the mode of interest. Red dashed (green long dashed) curve shows the signal for $B^{\pm} \to \psi'(\to J/\psi\eta)K^{\pm}$ (phase space component $B^{\pm} \to J/\psi\eta K^{\pm}$), while black dashed-dotted curve shows the background parameterized using $B \to J/\psi X$ MC sample.

4 First evidence of ψ_2 around 3823 MeV/c^2

Complimentary to $B^{\pm} \to (J/\psi\eta)K^{\pm}$ study, $X(3872)$'s C-odd partner search is also carried in $B^{\pm} \to (\chi_{c1}\gamma)K^{\pm}$ decay. Along with this search, we also look for any other narrow charmonium or charmonium-like candidate. Charmonium model predict that there should be a narrow state

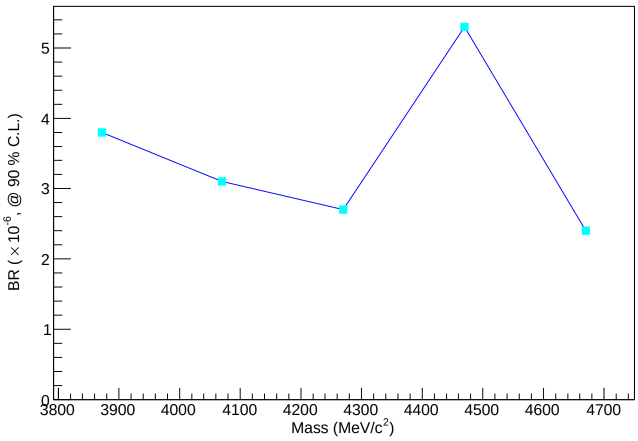

Figure 4: U.L. (@90% C.L.) on the $\mathcal{B}$ estimated at different masses using narrow width hypothesis for the $B^{\pm} \to (J/\psi\eta)K^{\pm}$ decay mode.

($^3D_2\ c\bar{c}$) which lies around 3810-3840 MeV [15]. In our search, we find a clear evidence for a narrow peak at 3823 MeV in $M_{\chi_{c1}\gamma}$ with a significance of 4.2 σ (syst. included). We extract the signal yield using 2D UML fit to $M_{\chi_{c1}\gamma}$ and $M_{\rm bc}$ distribution. While estimation of the width, we find data to be insensitive enough to provide a proper width estimation (4 ± 6 MeV) due to low statistics. The mass of the peak is estimated to be 3823.5 ± 2.1 MeV$/c^2$. Figure 5 shows the 2D UML fit to extract signal yield. Table 3 summarizes the result from $B^{\pm} \to (\chi_{c1}\gamma)K^{\pm}$ study.

Table 3: Preliminary $\mathcal{B}$ for $B^{\pm} \to \chi_{c1}\gamma K^{\pm}$ analysis.

Channel	Yield	$\mathcal{B}(10^{-4})$
$B^{\pm} \to \psi'(\to \chi_{c1}\gamma)K^{\pm}$	193 ± 19	$7.74^{+0.77+0.87}_{-0.74-0.83}$
		$\mathcal{B}(B^{\pm} \to XK^{\pm}) \times \mathcal{B}(X \to \chi_{c1}\gamma)(10^{-6})$
$B^{\pm} \to X(3823)(\to \chi_{c1}\gamma)K^{\pm}$	33.2 ± 9.1	$9.70^{+2.84+1.06}_{-2.52-1.03}$
$B^{\pm} \to X(3872)(\to \chi_{c1}\gamma)K^{\pm}$	-0.9 ± 5.1	< 2.0 (@ 90% CL)

5 Summary

Belle updated the mass, width and $\mathcal{B}$ of the $X(3872)$ using the full data sample. In search for charged partner of the $X(3872)$, no signal is seen. Also, in the search of C-odd partner, no signal is seen for $B^{\pm} \to (J/\psi\eta)K^{\pm}$ and $B^{\pm} \to (\chi_{c1}\gamma)K^{\pm}$ decays and provided much tighter constraint to the tetraquark interpretation of $X(3872)$. Along with this, Belle also provided the first evidence for a narrow state having mass of 3823.5 ± 2.1 MeV$/c^2$. This narrow state seems to be the missing ψ_2 of the charmonium spectrum.

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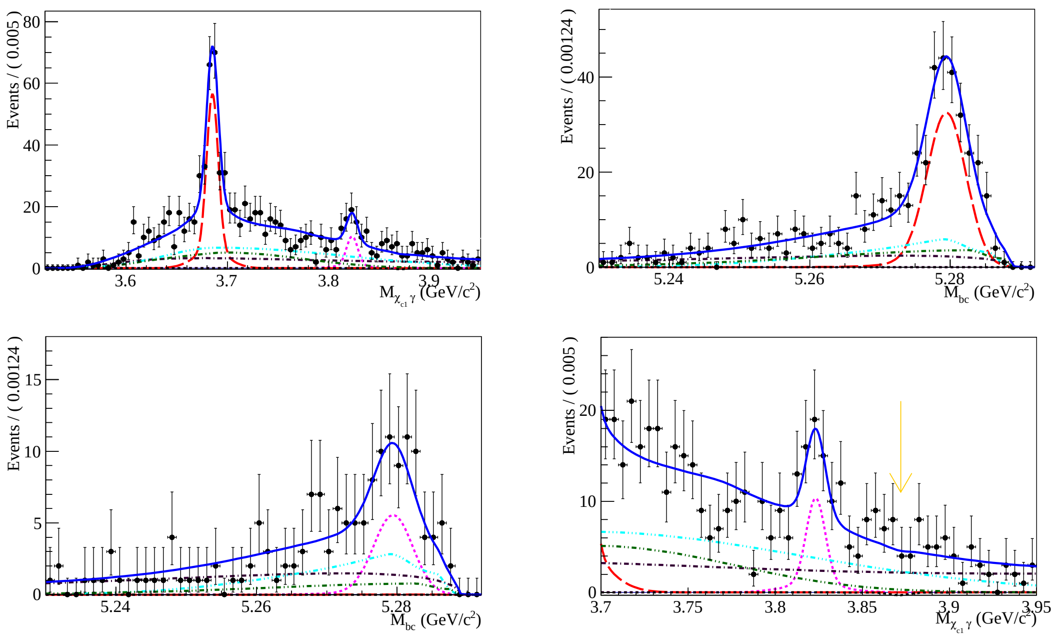

Figure 5: 2D UML fit projections of $M_{\chi_{c1}\gamma}$ (top left), $M_{\rm bc}$ (top right), $M_{\rm bc}$ (bottom left) and $M_{\chi_{c1}\gamma}$ (bottom right) for the signal region $M_{\rm bc} > 5.27$ GeV/c^2, $3.66 < M_{\chi_{c1}\gamma} < 3.708$ GeV/c^2 (ψ' signal region), $3.805 < M_{\chi_{c1}\gamma} < 3.845$ GeV/c^2 ($X(3823)$ signal region) and $M_{\rm bc} > 5.27$ GeV/c^2 [yellow arrows shows the $X(3872)$ position]. The curves shows the signal [red large-dashed for ψ' and pink dashed for ψ_2] and the background component [black dotted-dashed for combinatorial, dark green two dottted-dashed for $B^\pm \to \psi'$(other than $\chi_{c1}\gamma)K^\pm$ and cyan three dotted-dashed for peaking component] as well as the overall fit [blue solid].

MNiSW (Poland); MES and RFAAE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE and NSF (USA).

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