Studies of radiative $X(3872)$ decays at Belle

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We present a study of the radiative decays of $X(3872)$ at Belle. In the $\chi_{c1}\gamma$ final state, we got the first evidence of a new particle at 3823 MeV/$c^2$.

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1 Introduction

The Belle detector is a general purpose spectrometer built to test the Standard Model mechanism for CP-violation in B decays to charmonium (golden channel) [1]. Parallel to this, Belle has proven to be an ideal place to carry out charmonium spectroscopy thanks to its very clean environment. Many new $c\bar{c}$ and $c\bar{c}$-like exotic candidates states such as $\eta_c(2S)$, $X(3872)$, $X(3915)$, $Z(3930)$, $X(3940)$, $Z_1(4050)^+$, $Z_2(4250)^+$, $Y(4260)$, $Z(4330)^+$ and $Y(4660)$ have been found. Among them $X(3872)$ is the most interesting state which was first observed in $B^\pm \rightarrow (J/\psi \pi^+ \pi^-) K^\pm$ at Belle [2]. Soon after its discovery, it was confirmed by the CDF [3], D0 [4] and BaBar [5] collaborations. Recently, it has also been observed at LHCb [6] and CMS [7]. The observation of $X(3872)$ in the same final states ($J/\psi \pi^+ \pi^-$) in six different experiments, reflects the eminent status of the $X(3872)$. $X(3872)$’s narrow width and the proximity of its mass, 3871.7 ± 0.2 MeV/c$^2$ to the $D^{*0}\bar{D}^{0}$ threshold makes it a good candidate for a $DD^*$ molecule [8]. Other possibilities have also been proposed for the $X(3872)$ state, such as tetraquark [9], $c\bar{c}g$ hybrid meson [10] and vector glueball models [11].

Radiative decays of $X(3872)$ provide a unique opportunity to understand the nature of $X(3872)$. For example, $X(3872) \rightarrow J/\psi \gamma$ resulted in the confirmation of $C$-even ($C = +$) parity for $X(3872)$ [12, 13, 14]. A similar decay mode $X(3872) \rightarrow \psi' \gamma$ can help to identify $X(3872)$ as a charmonium, molecular or mixture of those states [8, 15, 16]. Belle reported no significant signal [14] and it disagrees with the evidence at BaBar [13].

A recent search for the charged tetraquark partner of $X(3872)(\rightarrow J/\psi \pi^+ \pi^0)$ gave negative results [17]. But still it is hard to totally rule out $X(3872)$ as a tetraquark, as some tetraquark models predict $X(3872)^+$ to be broad, thus still difficult to observe at current statistics [18]. On the other hand, in both molecular and tetraquark hypothesis a $C$-odd parity ($C = -$) partner can exist and it may dominantly decay into $\chi_{c1}\gamma$ and $\chi_{c2}\gamma$ final states. Partner searches would be another approach to reveal $X(3872)$ structure. Along with this, undiscovered $^3D_2$ charmonium ($\psi_2$) is expected to have a significant branching fraction to $\chi_{c1}\gamma$ and $\chi_{c2}\gamma$ [19, 20]. In this report, we also describe the first evidence of $\psi_2 \rightarrow \chi_{c1}\gamma$ decay.

2 Reconstruction

$B$ mesons reconstructed using $B^\pm \rightarrow (\chi_{c1}(\rightarrow J/\psi \gamma) \gamma) K^\pm$ and $B^\pm \rightarrow (\chi_{c2}(\rightarrow J/\psi \gamma) \gamma) K^\pm$ decay modes are used in the search for $C$-odd partner of the $X(3872)$ and other new narrow resonances. The results presented here are obtained from a data sample of $772 \times 10^6 B\bar{B}$ events collected by the Belle detector [21] at the KEKB [22] energy-asymmetric $e^+e^-$ collider operating at the $\Upsilon(4S)$ resonance.

The $J/\psi$ meson is reconstructed in its decays to $\ell^+\ell^-$ ($\ell = e$ or $\mu$). In $e^+e^-$ decays,
the four-momenta of all photons within 50 mrad of each of the original $e^+$ or $e^-$ tracks are included in the invariant mass calculation [hereafter denoted as $M_{e^+e^-} (\gamma)$], in order to reduce the radiative tail. The reconstructed invariant mass of the $J/\psi$ candidates is required to satisfy $2.95 < M_{e^+e^-} (\gamma) < 3.13$ GeV/$c^2$ or $3.03 < M_{\mu^+\mu^-} < 3.13$ GeV/$c^2$. A mass- and vertex-constrained fit is applied to all the selected $J/\psi$ candidates in order to improve their momentum resolution. The reconstructed invariant mass of the $J/\psi$ candidates is required to satisfy $2.95 < M_{e^+e^-} (\gamma) < 3.13$ GeV/$c^2$ or $3.03 < M_{\mu^+\mu^-} < 3.13$ GeV/$c^2$. A mass- and vertex-constrained fit is again performed to all the selected $\chi_{c1,2}$ candidates in order to improve their momentum resolution. Charged tracks are identified as a kaon using information from the particle identification devices.

To reconstruct the $B$ candidates, each $\chi_{c1,2}$ is combined with a kaon candidate and an additional photon having energy ($E_\gamma$) greater than 200 MeV. The photons are reconstructed from the energy deposition in electromagnetic calorimeter. To reduce the background from $\pi^0 \rightarrow \gamma\gamma$, we calculate a likelihood function to distinguish an isolated photon from $\pi^0$ decays using the photon pair’s invariant mass, smaller photon’s laboratory energy and polar angle [23]. Then we reject a photon having the $\pi^0$ likelihood ratio greater than 0.7 by combining with any other photon. The reconstructed invariant mass of $\chi_{c1}$ and $\chi_{c2}$ is required to satisfy $3.467 < M_{J/\psi \gamma} < 3.535$ GeV/$c^2$ and $3.535 < M_{J/\psi \gamma} < 3.611$ GeV/$c^2$. A mass- and vertex-constrained fit is again performed to all the selected $\chi_{c1}$ and $\chi_{c2}$ candidates in order to improve their momentum resolution. Charged tracks are identified as a kaon using information from the particle identification devices.

To reconstruct the $B$ candidates, each $\chi_{c1,2}$ is combined with a kaon candidate and an additional photon having $E_\gamma > 100$ MeV. In this additional photon selection, we reject the photon which in combination with another photon in that event, gives mass in the region around $\pi^0$ mass defined as $117 < M_{\gamma\gamma} < 153$ MeV/$c^2$. In order to remove the reflection of photons coming from $\chi_{c1}$ and $\chi_{c2}$ decays, we reject the best $\chi_{c1}$ or $\chi_{c2}$ daughter photon from the additional photon list to form a $B$ candidate. To identify the $B$ candidate, two kinematic variables are used: energy difference $\Delta E \equiv E^*_B - E^*_{\text{beam}}$ and beam-energy constrained mass $M_{bc} \equiv \sqrt{(E^*_{\text{beam}})^2 - (p^*_{\text{beam}})^2}$, where $E^*_B$ is the center-of-mass frame (cms) beam energy, and $E_B$ and $p_B$ are the cms energy and momentum of the reconstructed particles. In case of multiple candidates, $\Delta E$ closest to 0 is selected as the best one. Invariant mass of the final state ($M_{\chi_{c1}\gamma}$ and $M_{\chi_{c2}\gamma}$) is used to identify the resonance. In order to improve the resolution of $M_{\chi_{c1}\gamma}$ [24], we scale the energy of $\gamma$ to make $\Delta E$ equal to zero.

To suppress continuum background, events having a ratio of the second to zeroth Fox-Wolfram moments $R_2 > 0.5$ are rejected. Large $B \rightarrow J/\psi X$ MC samples (corresponding to 100 times the data sample size used in this analysis) are used to study the background. The non-$J/\psi$ (non-$\chi_{cxy}$) background is studied using the $M_{ll}$ ($M_{J/\psi\gamma}$) sidebands in data. $B^\pm \rightarrow (\chi_{c1}\gamma)K^\pm$ and $B^\pm \rightarrow (\chi_{c2}\gamma)K^\pm$ yields are extracted from a 2D UML fit applied to the distribution in the $M_{\chi_{cxy}\gamma}$ - $M_{bc}$ space.
3 Results

In $B^\pm \rightarrow (\chi_{c1}\gamma)K^\pm$ decay, a clear peak of $\psi' \rightarrow \chi_{c1}\gamma$ is observed in the $\chi_{c1}\gamma$ invariant mass ($M_{\chi_{c1}\gamma}$) projection. In addition to this, we also find clear evidence of a narrow peak at 3823 MeV/$c^2$, denoted as $X(3820)$ hereafter. Since statistics are still limited, its width is poorly constrained to be 4±6 MeV even if it is floated in the fit. Therefore we set $X(3820)$ natural width to be 0 MeV for further discussion. We estimate the statistical significance of $X(3820) \rightarrow \chi_{c1}\gamma$ to be 4.2σ including systematic uncertainty. In our search for $X(3872) \rightarrow \chi_{c1}\gamma$, no signal is seen and 90% confidence level (C.L.)
### Table 1: Summary of the results.

| Channel | Yield          | $\mathcal{B}(10^{-4})$ |
|---------|----------------|-------------------------|
| $B^\pm \to \psi'(\to \chi_{c1}\gamma)K^\pm$ | $193.2^{+19.2}_{-18.6}^{+4.8}$ | $7.7^{+10.4+0.9}_{-0.7-0.8}$ |
| $B^\pm \to \psi'(\to \chi_{c2}\gamma)K^\pm$ | $59.1^{+8.0}_{-8.0}$ | $6.3 \pm 0.9 \pm 0.8$ |
| $B^\pm \to X(3820)(\to \chi_{c1}\gamma)K^\pm$ | $33.2^{+9.2}_{-8.5}$ | $9.7^{+2.8+1.1}_{-2.5-1.0}$ |
| $B^\pm \to X(3872)(\to \chi_{c1}\gamma)K^\pm$ | $-0.9 \pm 5.1$ | $< 2.0$ |
| $B^\pm \to X(3820)(\to \chi_{c2}\gamma)K^\pm$ | $0.3^{+3.9}_{-3.1}$ | $< 3.6$ |
| $B^\pm \to X(3872)(\to \chi_{c2}\gamma)K^\pm$ | $4.7^{+4.4}_{-3.6}$ | $< 6.7$ |

upper limit (U.L.) on $\mathcal{B}(B^\pm \to X(3872)K^\pm)\mathcal{B}(X(3872) \to \chi_{c1}\gamma)$ is estimated using a frequentist approach. In $B^\pm \to (\chi_{c2}\gamma)K^\pm$, we observe a clear peak of the $\psi' \to \chi_{c2}\gamma$. However, we do not see any hint of a narrow resonance with the current statistics. Figure 1 shows the projections of 2D UML fits to the $M$ states to be 3815-3840 MeV/$c^2$. Table 1 summarizes the results of $B^\pm \to (\chi_{c1}\gamma)K^\pm$ and $B^\pm \to (\chi_{c2}\gamma)K^\pm$ decays.

The mass of $X(3820)$ is near the potential model expectations for the center-of-gravity (cog) of $1^3D_J$ states: the Cornell [26] and the Buchmuller-Tye [27] potential, which gives $M_{\text{cog}} (1D) = 3810$ MeV/$c^2$. Some models predict the mass of $3D_2 (J^{PC} = 2^-)$ states to be 3815-3840 MeV/$c^2$ [28, 29]. $X(3820)$ mass agrees quite well within the expectation. The $X(3820)$ state is likely to be the missing $3D_2 \sigma (\psi_2)$ state.

### 4 Summary

In the study of $B^\pm \to (\chi_{c1}\gamma)K^\pm$ and $B^\pm \to (\chi_{c2}\gamma)K^\pm$ decays, Belle observe the $\psi'$ peak in both decay modes and other peak is found to be consistent with expectation. In $B^\pm \to (\chi_{c1}\gamma)K^\pm$, Belle find the first evidence of a narrow state having mass of $3823.5 \pm 2.5$ MeV/$c^2$. This narrow state is likely to be the missing $\psi_2 (3D_2 \sigma$ state) because the observed mass totally agrees with a theoretical expectation and $\chi_{c1}\gamma$ is one of the dominant decay modes. While in the search of $C$-odd partner of $X(3872)$, no signal is found at the current statistics and U.L. in 90% C.L. are provided.

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References

[1] I. Adachi et al. (Belle Collaboration), Phys. Rev. Lett. 108, 171802 (2012).
[2] S.-K. Choi et al. (Belle Collaboration), Phys. Rev. Lett. 91, 262001 (2003).
[3] D. Acosta et al. (CDF Collaboration), Phys. Rev. Lett. 93, 072001 (2004).
[4] V.M. Abazov et al. (DO Collaboration), Phys. Rev. Lett. 93, 162002 (2004).
[5] B. Aubert et al. (BaBar Collaboration), Phys. Rev. D 71, 071103 (2005).
[6] R. Aaij et al. (LHCb Collaboration), Eur Phys. J.C 72, 1972 (2012).
[7] V. Chiochia et al. (CMS Collaboration), arXiv:hep-ex/1201.6677.
[8] E.S. Swanson, Phys. Lett. B 598, 197 (2004); E.S. Swanson, Phys. Rep. 429, 243 (2006).
[9] L. Maiani et al., Phys. Rev. D 71, 014028 (2005).
[10] B.A. Li, Phys. Lett. B 605, 306 (2005).
[11] K.K. Seth, Phys. Lett. B 612, 1 (2005).
[12] K. Abe et al. (Belle Collaboration), arXiv:hep-ex/0408116.
[13] B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett. 102, 132001 (2009).
[14] V. Bhardwaj et al. (Belle Collaboration), Phys. Rev. Lett. 107, 091803 (2011).
[15] T. Mehen and R. Springer, Phys. Rev. D 83, 094009 (2011).
[16] T.H. Wang, G.L. Wang, Phys. Lett. B 697, 3 (2011).
[17] S.-K. Choi et al. (Belle Collaboration), Phys. Rev. D 84, 052004 (2011).
[18] K. Terasaki, Prog. Theor. Phys. 127, 577-582 (2012).
[19] E.J. Eichten, K. Lane and C. Quigg, Phys. Rev. Lett. 89, 162002 (2002).
[20] P. Cho and M. B. Wise, Phys. Rev. D 51, 3352 (1995).
[21] A. Abashian et al. (Belle Collaboration), Nucl. Instrum. and Meth. A 479, 117 (2002).

[22] S. Kurokawa and E. Kikutani, Nucl. Instrum. and Meth. A 499, 1 (2003) and other papers included in this volume.

[23] P. Koppenburg et al. (Belle Collaboration), Phys. Rev. Lett. 93, 061803 (2004).

[24] Hereafter, $\chi_{c\chi}$ refers to $\chi_{c1}$ or $\chi_{c2}$ unless stated otherwise.

[25] G. Fox and S. Wolfram, Phys. Rev. Lett. 41, 1581 (1978).

[26] E. Eichten et al., Phys. Rev. D 17, 3090 (1978), E. Eichten et al., Phys. Rev. D 21, 203 (1980).

[27] W. Buchmüller and S.-H.H. Tye, Phys. Rev. D 24, 132 (1981).

[28] S. Godfrey and N. Isgur, Phys. Rev. D 32, 189 (1985).

[29] E. Eichten, K. Lane and C. Quigg, Phys. Rev. D 69, 094019 (2004).