Study of $B \rightarrow \chi_{cJ}X$ at Belle

V. Bhardwaj

Department of Physics and Astronomy
University of South Carolina, Columbia, SC 29208, USA

In spite of the fact that the two-body $B$ decays into $\chi_{c2}$ such as $B \rightarrow \chi_{c2}K^{(*)}$ are suppressed by the QCD factorization effect, the inclusive $B \rightarrow \chi_{c2}X$ branching fraction amounts to one third of the non-suppressed $B \rightarrow \chi_{c1}X$ decays because of the decay modes to the multi-body final states. Using a large statistics $\Upsilon(4S)$ data sample corresponding to 772 million $B$ meson pairs accumulated by the Belle detector at the KEKB $e^+e^-$ collider, precise measurements of inclusive $B \rightarrow \chi_{c1}$ and $\chi_{c2}$ branching fractions are carried out. The multi-body final states such as $\chi_{cJ}K\pi$, $\chi_{cJ}K\pi\pi$ and so on are also investigated to look for new charmonium-like resonance.

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1 Introduction

Inclusive production of $\chi_{c2}$ mesons in $B$ decays is relatively large \cite{1,2} in spite of the fact that two-body $B$ decays into $\chi_{c2}$ are highly suppressed \cite{3,4,5} (due to the angular momentum conservation). Differential branching fraction ($DB$) in bins of $\chi_{cJ}$ ($J = 1, 2$) \cite{6} suggests that $\chi_{c2}$ is found to be coming from three-body or higher multiplicity decays \cite{1,2}, which have not been studied in detail yet. More experimental input is needed to study these multi-body decay modes.

Study of more than three-body $B$ decay modes with $\chi_{c1}$ and $\chi_{c2}$ in final state not only help in understanding $B$ meson decays but also provide portal to search for charmonium/charmonium-like exotic states in one of the intermediate final states. For example, looking at the $\chi_{c1}\pi^+\pi^-$ invariant mass spectrum in $B \to \chi_{c1}\pi^+\pi^-K$ decays, one can search for $\chi_{c1}(2P)$ and/or $X(3872)$.

Using the $\chi_{cJ} \to J/\psi\gamma$ modes, we report on the inclusive branching fraction ($B$) of $B \to \chi_{cJ}X$ decays. To further understand $\chi_{c1}$ and $\chi_{c2}$ production in $B$ decays, we reconstruct the following exclusive $B$ decays: $B^0 \to \chi_{cJ}\pi^-K^+$, $B^+ \to \chi_{cJ}\pi^+K^0_S$, $B^+ \to \chi_{cJ}\pi^0K^+$, $B^+ \to \chi_{cJ}\pi^+\pi^-K^+$ and $B^0 \to \chi_{cJ}\pi^+\pi^-K^0_S$ \cite{7}.

2 Data sample and event selection

We use a data sample of $772 \times 10^6 B\overline{B}$ events collected with the Belle detector \cite{8} at the KEKB asymmetric-energy $e^+e^-$ collider \cite{9} operating at the $\Upsilon(4S)$ resonance. All results presented here are preliminary.

The $J/\psi$ meson is reconstructed via its decays to $\ell^+\ell^-$ ($\ell = e$ or $\mu$). To reduce the radiative tail in the $e^+e^-$ mode, the four-momenta of all photons within 50 mrad with respect to the original direction of the $e^+$ or $e^-$ tracks are included in the invariant mass calculation, hereinafter denoted as $M_{e^+e^-(\gamma)}$. The reconstructed invariant mass of the $J/\psi$ candidates is required to satisfy $2.95 \text{ GeV}/c^2 < M_{e^+e^-(\gamma)} < 3.13 \text{ GeV}/c^2$ or $3.03 \text{ GeV}/c^2 < M_{\mu^+\mu^-} < 3.13 \text{ GeV}/c^2$. For the selected $J/\psi$ candidates, a vertex-constrained fit is applied and then a mass-constrained fit is performed in order to improve the momentum resolution.

The $\chi_{c1}$ and $\chi_{c2}$ candidates are reconstructed by combining $J/\psi$ candidates with a photon having energy ($E_{\gamma}$) larger than 100 MeV in the laboratory frame. To reduce the combinatorial background coming from $\pi^0 \to \gamma\gamma$, we use a likelihood function that distinguishes an isolated photon from $\pi^0$ decays using the photon pair invariant mass, photon laboratory energy and polar angle \cite{10}. We reject both $\gamma$'s in the pair if the $\pi^0$ likelihood probability is larger than 0.3 (0.8) for an inclusive study ($B \to \chi_{cJ}K\pi$, $B \to \chi_{cJ}K\pi\pi$ decay modes).
3 Inclusive $B$ decays to $\chi_{cJ}$

To identify the signal, we use the $J/\psi\gamma$ invariant mass $M_{J/\psi\gamma}$ distribution and extract the signal yield from a binned maximum likelihood fit. A double-sided Crystal Ball function is used to model the signal shapes of $B \rightarrow \chi_{c1}X$ and $B \rightarrow \chi_{c2}X$. Figure 1 (a) shows the fit to the $M_{J/\psi\gamma}$ distribution for $B \rightarrow \chi_{c1}X$ and $B \rightarrow \chi_{c2}X$ decays.

The reconstruction efficiencies for the inclusive $B \rightarrow \chi_{c1}X$ and $B \rightarrow \chi_{c2}X$ decays are estimated to be 24.2% and 25.9%, respectively. Uncertainty on the efficiency is estimated to be 4.0%.

Figure 1: (a) $M_{J/\psi\gamma}$ distribution of the $B \rightarrow \chi_{cJ}(\rightarrow J/\psi(\rightarrow \ell^+\ell^-)\gamma)X$ decays in data. The curves show the signal (cyan dash-dotted for $\chi_{c1}$ and red dashed for $\chi_{c2}$) and the background component (green dash-double-dotted for combinatorial) as well as the overall fit (blue solid). The lower plot shows the pull of the residuals with respect to the fit. (b) Plots showing $DB(B \rightarrow \chi_{c1}X)$ and $DB(B \rightarrow \chi_{c2}X)$ in each bin of $p^{*}_{\chi_{cJ}}$ for $B \rightarrow \chi_{cJ}(\rightarrow J/\psi\gamma)X$. These plots are without feed-down subtraction. The uncertainty shown in these plots are statistical only.

After subtracting the $\psi'$ feed-down contribution, we get the direct branching fractions $B(B \rightarrow \chi_{c1}X)$ and $B(B \rightarrow \chi_{c2}X)$ to be $(3.03 \pm 0.05 \pm 0.25) \times 10^{-3}$ and $(0.70 \pm 0.06 \pm 0.10) \times 10^{-3}$, respectively. First (second) error is statistical (systematic). Here, the systematic uncertainty dominates the measured branching fractions.

Figure 1 (b) shows the obtained distribution of the $DB$ in bins of $p^{*}_{\chi_{c1}}$. Suppression of two-body decay of $\chi_{c2}$ is visible in the $p^{*}_{\chi_{c1}}$ distribution. Most of the $\chi_{c2}$ production comes from decays of three-body or more.
4 Exclusive reconstruction

The reconstructed invariant mass of the $\chi_{c1}$ ($\chi_{c2}$) is required to satisfy $3.467 \text{ GeV}/c^2 < M_{J/\psi\gamma} < 3.535 \text{ GeV}/c^2$. A mass-constrained fit is applied to the selected $\chi_{c1}$ and $\chi_{c2}$ candidates.

$\chi_{cJ}$ candidates are combined with charged kaon and pion candidate tracks to reconstruct $B$ meson. To identify the $B$ meson, two kinematical variables are used: beam-constrained mass ($M_{bc}$) and energy difference ($\Delta E$). The $M_{bc}$ is defined as $\sqrt{E_{\text{beam}}^2 - (\sum_i \vec{p}_i)^2}$ and the $\Delta E$ is defined as $\sum_i E_i - E_{\text{beam}}$, where $E_{\text{beam}}$ is the beam energy in the CM frame and $p_i$ ($E_i$) is the momentum (energy) of the $i$-th daughter particle in the CM frame and the summation is over all final states used for reconstruction. We reject candidates having $M_{bc}$ less than 5.27 GeV/$c^2$ or $|\Delta E| > 120$ MeV.

We extract the signal yield from an unbinned extended maximum likelihood (UML) fit to the $\Delta E$ variable. Fig. 2 and 3 shows the fit to the $\Delta E$ distribution for the decay modes of interest.

Figure 2: $\Delta E$ distribution for (a) $B^0 \rightarrow \chi_{c1} \pi^- K^+$, (b) $B^0 \rightarrow \chi_{c2} \pi^+ K^-$, (c) $B^+ \rightarrow \chi_{c1} \pi^- K^+$, (d) $B^+ \rightarrow \chi_{c2} \pi^+ K^-$, (e) $B^+ \rightarrow \chi_{c1} \pi^0 K^+$, and (f) $B^+ \rightarrow \chi_{c2} \pi^0 K^+$ decay modes. The curves show the signal (red dashed), peaking background (magenta dash-dotted) and the background component (green dotted for combinatorial) as well as the overall fit (blue solid).

To understand the production mechanism of intermediate states, we look at the background subtracted $M_{\chi_{cJ}\pi}$, $M_{K\pi}$, $M_{\chi_{c2}\pi\pi}$, $M_{K\pi\pi}$, and $M_{\pi\pi}$ distributions for the decay mode of interest. We perform a UML fit to the $\Delta E$ distribution and use the $s$Plot formalism to project signal events in the distribution of interest.
The $K^*(892)$ is found to be a major contribution in the $B \to \chi_{c1} \pi K$ decay modes as seen from Fig. 4 (a), (e) and (i), while in $B \to \chi_{c2} \pi K$ decays the $K^*(892)$ component is less prominent. Our study suggests that the $B \to \chi_{c2} K^*(892)$ mechanism does not dominate the $B \to \chi_{c2} \pi K$ decay, which is in marked contrast to the $\chi_{c1}$ case. From this study one can say that the production mechanism of the $\chi_{c2}$ from $B$ mesons is different in three-body decays for the $B \to \chi_{c1} \pi K$ case.

Background subtracted $\Delta E$ distributions for (a) $B^+ \to \chi_{c1} \pi^+ \pi^- K^+$, (b) $B^+ \to \chi_{c2} \pi^+ \pi^- K^+$, (c) $B^0 \to \chi_{c1} \pi^+ \pi^- K^0_S$, (d) $B^0 \to \chi_{c2} \pi^+ \pi^- K^0_S$, (e) $B^0 \to \chi_{c1}^0 \pi^- K^+$ and (f) $B^0 \to \chi_{c2}^0 \pi^- K^+$ decay modes. The curves show the signal (red dashed), peaking background (magenta dash-dotted) and background component (green dotted for combinatorial) as well as the overall fit (blue solid).

In our search for the $X(3872)$ and/or $\chi_{c1}(2P)$ decaying into $\chi_{c1} \pi^+ \pi^-$, we didn’t find any signal and provided upper limit (@ 90% C.L.) as:

- $\mathcal{B}(B^\pm \to X(3872)K^\pm) \times \mathcal{B}(X(3872) \to \chi_{c1} \pi^+ \pi^-) < 1.4 \times 10^{-6}$
- $\mathcal{B}(B^+ \to \chi_{c1}(2P)K^+) \times \mathcal{B}(\chi_{c1}(2P) \to \chi_{c1}(1P) \pi^+ \pi^-) < 1.1 \times 10^{-5}$

5 Summary

Belle presented the preliminary results at this conference. We measured the direct branching fractions $\mathcal{B}(B \to \chi_{c1} X)$ and $\mathcal{B}(B \to \chi_{c2} X)$ to be $(3.03 \pm 0.05 \pm 0.25) \times 10^{-3}$.
Figure 4: Background subtracted $s$-Plot $M_{K\pi}$ and $M_{\chi c\pi}$ distributions for (a and b) $B^0 \rightarrow \chi c_1^- K^+$, (c and d) $B^0 \rightarrow \chi c_2^- K^+$, (e and f) $B^- \rightarrow \chi c_1^- K^0_S$, (g and h) $B^- \rightarrow \chi c_2^- K^0_S$ and (i and j) $B^- \rightarrow \chi c_1^0 K^+$ decay modes.

Figure 5: Background subtracted $s$-Plot (a) $M_{\chi c_1^+ \pi^-}$, (b) $M_{\chi c_1^+ \pi^+}$, (c) $M_{\chi c_2^+ \pi^-}$ and (d) $M_{\chi c_2^+ \pi^0}$ distributions for $B^+ \rightarrow \chi cJ \pi^+ \pi^- K^+$ decay modes.
Table 1: Summary of the results. Signal yield \((Y)\) from the fit, significance \((S)\) with systematics included, corrected efficiency \((\epsilon)\) and measured \(B\). For \(B\), the first (second) error is statistical (systematic). Here, in the neutral \(B\) decay case, the \(K_S^0 \to \pi^+\pi^-\) branching fraction is included in the efficiency \((\epsilon)\) but the factor of 2 (for \(K_0^0 \to K_S^0\) or \(K_L^0\)) is taken into account separately. \(R_B\) is the ratio of \(B(B \to \chi_{cJ}X)\) to \(B(B \to \chi_{c1}X)\), where \(X\) is the same set of particles accompanying the \(\chi_{c1} (\chi_{c2})\) in the final states.

| Decay \(B^0 \to \chi_{cJ}\pi^-K^+\) | Yield \((Y)\) | \(S(\sigma)\) | \(\epsilon(\%)\) | \(B\) \((10^{-4})\) | \(R_B\) |
|---|---|---|---|---|---|
| \(\chi_{c1}\) | 2774 ± 66 | 66.7 | 17.9 | 4.97 ± 0.12 ± 0.28 | 0.14 ± 0.02 |
| \(\chi_{c2}\) | 206 ± 25 | 8.7 | 16.2 | 0.72 ± 0.09 ± 0.05 | 0.20 ± 0.04 |

| Decay \(\bar{B}^+ \to \chi_{cJ}\pi^+K^0\) | Yield \((Y)\) | \(S(\sigma)\) | \(\epsilon(\%)\) | \(B\) \((10^{-4})\) | \(R_B\) |
|---|---|---|---|---|---|
| \(\chi_{c1}\) | 770 ± 35 | 33.7 | 8.6 | 5.75 ± 0.26 ± 0.32 | < 0.21 |
| \(\chi_{c2}\) | 76.4 ± 14.7 | 4.6 | 7.5 | 1.16 ± 0.22 ± 0.12 | < 0.62 |

| Decay \(\bar{B}^+ \to \chi_{cJ}\pi^0K^+\) | Yield \((Y)\) | \(S(\sigma)\) | \(\epsilon(\%)\) | \(B\) \((10^{-4})\) | \(R_B\) |
|---|---|---|---|---|---|
| \(\chi_{c1}\) | 803 ± 70 | 15.6 | 7.8 | 3.29 ± 0.29 ± 0.19 | < 0.36 ± 0.05 |
| \(\chi_{c2}\) | 17.5 ± 28.4 | 0.4 | 7.0 | < 0.62 |

| Decay \(\bar{B}^+ \to \chi_{cJ}\pi^+\pi^-K^+\) | Yield \((Y)\) | \(S(\sigma)\) | \(\epsilon(\%)\) | \(B\) \((10^{-4})\) | \(R_B\) |
|---|---|---|---|---|---|
| \(\chi_{c1}\) | 1502 ± 70 | 19.2 | 12.8 | 3.74 ± 0.18 ± 0.24 | < 0.61 |
| \(\chi_{c2}\) | 269 ± 34 | 8.4 | 11.4 | 1.34 ± 0.17 ± 0.09 | < 1.70 |

| Decay \(\bar{B}^0 \to \chi_{cJ}\pi^+\pi^-K^0\) | Yield \((Y)\) | \(S(\sigma)\) | \(\epsilon(\%)\) | \(B\) \((10^{-4})\) | \(R_B\) |
|---|---|---|---|---|---|
| \(\chi_{c1}\) | 268 ± 30 | 7.1 | 5.4 | 3.16 ± 0.35 ± 0.32 | < 0.61 |
| \(\chi_{c2}\) | 37.8 ± 14.2 | 1.8 | 4.8 | < 1.70 |

| Decay \(\bar{B}^0 \to \chi_{cJ}\pi^0\pi^-K^+\) | Yield \((Y)\) | \(S(\sigma)\) | \(\epsilon(\%)\) | \(B\) \((10^{-4})\) | \(R_B\) |
|---|---|---|---|---|---|
| \(\chi_{c1}\) | 545 ± 81 | 6.5 | 5.0 | 3.52 ± 0.52 ± 0.24 | < 0.25 |
| \(\chi_{c2}\) | -76.7 ± 42.0 | - | 4.3 | < 0.74 |
is compatible with the interpretation of $X$ as an U.L. on the product of branching fractions. The negative result for our searches on $\chi_{c2}\pi^+\pi^-K^+$ decays has a significance of 4.6$\sigma$. In four-body decays, we observe the $B^+ \rightarrow \chi_{c1}\pi^+\pi^-K^+$, $B^0 \rightarrow \chi_{c1}\pi^+\pi^-K_0^0$, and $B^0 \rightarrow \chi_{c1}\pi^0\pi^-K^+$ decay modes for the first time and report on measurements of their branching fractions. We find that $\chi_{c2}$ production in comparison with $\chi_{c1}$ increases with a higher number of multi-body $B$ decays. We observe that the $\chi_{c2}$ is more often accompanied by higher $K^*$ resonances as opposed the $\chi_{c1}$ which is dominantly produced with lower $K^*$ resonance. Inclusive and exclusive study of $B$ decays having $\chi_{c2}$ in the final state suggests suppression of two-body $B$ decay due to suppression of a tensor, while multi-body $B$ decays into $\chi_{c2}$ are allowed. In our search for $X(3872) \rightarrow \chi_{c1}\pi^+\pi^-$ and $\chi_{c1}(2P)$, we determine an U.L. on the product of branching fractions. The negative result for our searches is compatible with the interpretation of $X(3872)$ as an admixture state of a $D^0\bar{D}^{*0}$ molecule and a $\chi_{c1}(2P)$ charmonium state.

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References

[1] K. Abe et al. (Belle Collaboration), Phys. Rev. Lett. 89, 011803 (2002).

[2] B. Aubert et al. (BaBar Collaboration), Phys. Rev. D 67, 032002 (2003).

[3] N. Soni et al. (Belle Collaboration), Phys. Lett. B 634, 155 (2006).

[4] B. Aubert et al. (Babar Collaboration), Phys. Rev. Lett. 102, 132001 (2009).

[5] V. Bhardwaj et al. (Belle Collaboration), Phys. Rev. Lett. 107, 091803 (2011).

[6] Hereinafter, $\chi_{cJ}$ refers to either $\chi_{c1}$ or $\chi_{c2}$, depending on which is reconstructed.

[7] Charge-conjugate and neutral modes are included throughout the paper unless stated otherwise.

[8] A. Abashian et al. (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 479, 117 (2002); also see detector section in J. Brodzicka et al., Prog. Theor. Exp. Phys. (2012) 04D001.

[9] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A 499, 1 (2003), and other papers included in this Volume; T. Abe et al., Prog. Theor. Exp. Phys. (2013) 03A001 and following articles up to 03A011.

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

[11] M. Pivk and F.R. Le Diberder, Nucl. Instrum. Methods Phys. Res., Sect. A 555, 356 (2005).