Study of inclusive and exclusive multibody $B$ decays to $\chi_{c1}$ and $\chi_{c2}$ mesons

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In spite of the fact that the two-body $B$ decays into $\chi_{c2}$ such as $B \rightarrow \chi_{c2}K(\ast)$ 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 multibody 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 multibody final states such as $\chi_{c2}K\pi$, $\chi_{c1}\gamma K\pi$ and so on are also investigated to look for new charmonium-like resonances.

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1. Introduction

Inclusive production of $\chi_{c2}$ mesons in $B$ decays is relatively large [1, 2] in spite of the fact that two-body $B$ decays into $\chi_{c2}$ are highly suppressed [3] (as in the factorization hypothesis [4]). A study of the differential branching fraction ($D\beta$) in bins of $\chi_{cJ}$ ($J = 1, 2$) [5] suggests that $\chi_{c2}$ is found to be coming from three-body or higher multiplicity decays [1, 2], which have not yet been observed. More experimental studies are needed to search for these multibody decay modes if one wishes to understand the $B$ decays needed for precision studies. As inclusive production of $\chi_{c2}$ is large, one can naively expect that there can be some exotic intermediate states (charmonium or charmonium-like states) decaying into $\chi_{c2}$, as $B$ decays to $X\psi(2s)$ and then $X$ decays into $\chi_{c2}\pi$, $\chi_{c2}\pi\pi$ where $X$ is some unknown resonance.

Recently, Belle found a new charmonium state $X(3823)$ in the $B \to (\chi_{c1}\gamma)K$ final state, which is supposed to be the $\psi_{2D}$ ($1^3D_2$ $cc$) charmonium having $J^{PC}$ of $2^{--}$ [6]. In such case, one expects it to have a large branching fraction in the $B^0 \to X(3823)(\to \chi_{c1}\gamma)K^+(K^+\pi^-)$ [7] decay mode worth to be searched for.

2. Data sample and event selection

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

To suppress continuum backgrounds we require the ratio of the second to zeroth Fox-Wolfram moments to be less than 0.5 [10]. As charged tracks coming from $B$ decays originate from the interaction point (IP), the distance of closest approach to IP is required to be within 3.5 cm in the beam direction ($z$) and within 1.0 cm in the transverse plane ($xy$-plane). Photons are reconstructed from the energy deposition in the electromagnetic calorimeter by requiring no matching with any extrapolated charged track. The combined information from the central drift chamber, time-of-flight and aerogel threshold Cherenkov counters is used to identify charged kaons and pions on basis of the $K-\pi$ likelihood ratio, $R_{K(\pi)} = L_{K(\pi)}/(L_K + L_{\pi})$. A track is identified as a kaon (pion) if the likelihood ratio $L_{K(\pi)}$ is greater than 0.6.

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 [11]. 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 ($B^0 \to \chi_{c2}K^+\pi^-$, $B^+ \to \chi_{c2}K^+\pi^-\pi^+$ and $B^0 \to \chi_{c1}\gamma K^+\pi^-$). The reconstructed
invariant mass of the $\chi_{c1}$ ($\chi_{c2}$) is required to satisfy $3.467 \text{ GeV}/c^2 < M_{J/\psi\gamma} < 3.535 \text{ GeV}/c^2$ ($3.535 \text{ GeV}/c^2 < M_{J/\psi\gamma} < 3.611 \text{ GeV}/c^2$). A mass-constrained fit is applied to the selected $\chi_{c1}$ and $\chi_{c2}$ candidates.

3. Results

3.1 $B \to \chi_{cJ}X$ study

To identify the signal, we use $\Delta M \equiv M_{\ell\ell\gamma} - M_{\ell\ell}$, where $M_{\ell\ell\gamma}$ ($M_{\ell\ell}$) is the reconstructed mass of $J/\psi\gamma$ ($J/\psi$). We extract the signal yield using a one-dimensional binned maximum likelihood (1D BM) fit to the $\Delta M$ distribution. A double-sided Crystal Ball function is used to model the signal shapes of $B \to \chi_{c1}X$ and $B \to \chi_{c2}X$. Figure 2 (a) shows the fit to the $\Delta M$ distribution for $B \to \chi_{c1}X$ and $B \to \chi_{c2}X$ decays in the range of $[0.2,0.6] \text{ GeV}/c^2$.

We used a 89.45 fb$^{-1}$ continuum data sample to estimate the $\chi_{cJ}$ feed-down from continuum and possible $\chi_{cJ}$ production. The scaled $\chi_{c1}$ and $\chi_{c2}$ continuum yields are subtracted from the on-resonance yields. The reconstruction efficiency for full inclusive $B \to \chi_{c1}X$ and $B \to \chi_{c2}X$ is estimated to be 24.2% and 25.9%, respectively. Uncertainty on the efficiency is estimated to be 4.0%.

We use the Particle Data Group [12] values for secondary daughter branching fractions. After subtracting the $\psi'$ feed-down contribution, we get the direct branching fractions $\mathcal{B}(B \to \chi_{c1}X)$ and $\mathcal{B}(B \to \chi_{c2}X)$ to be $(3.00 \pm 0.04 \pm 0.24) \times 10^{-3}$ and $(0.70 \pm 0.05 \pm 0.08) \times 10^{-3}$, respectively, where the first (second) error is statistical (systematic). The branching fractions are summarized in Table 1.

![Figure 1:](image1.png) (a) $\Delta M$ distribution (in GeV/$c^2$) (b) $p_{\chi_{c1}}^*$ distribution (in GeV/$c$)

Figure 1: (a) BML fit to the $\Delta M$ distribution of the $B \to \chi_{cJ}(\to J/\psi\gamma)X$ decays in the data. The curves show the signal (magenta dot-dashed for $\chi_{c1}$ and red dashed for $\chi_{c2}$) and the background component (green double-dotted dashed 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 $D\mathcal{B}(B \to \chi_{c1}X)$ [magenta circle •] and $D\mathcal{B}(B \to \chi_{c2}X)$ [red triangle ▼] in bins of $p_{\chi_{c1}}^*$.

Figure 2 (b) shows the obtained distribution of the $D\mathcal{B}$ in bins of $p_{\chi_{c1}}^*$. It seems that $\chi_{c2}$ is mostly coming from multibody $B$ decays.
Table 1: Yields and branching fractions. Errors are statistical only.

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<td>subtracted</td>
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<td>$\psi' \rightarrow \chi_{c1}\gamma$ feed down subtracted</td>
<td>—</td>
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<td></td>
<td>—</td>
<td>0.70 ± 0.05</td>
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3.2 $B^0 \rightarrow \chi_{c2}K^+\pi^-$ and $B^+ \rightarrow \chi_{c2}K^+\pi^-\pi^+$ decay modes

Figure 3a (3b) shows the unbinned maximum likelihood (UML) fit to the $\Delta E$ distribution of the $B^0 \rightarrow \chi_{c2}K^+\pi^-$ ($B^+ \rightarrow \chi_{c2}K^+\pi^-\pi^+$) decay mode. We observe the $B^0 \rightarrow \chi_{c2}K^+\pi^-$ ($B^+ \rightarrow \chi_{c2}K^+\pi^-\pi^+$) decay with 206 ± 25 (269 ± 34) signal events, having a statistical significance of 9.7σ (8.7σ), for the first time. We also look at the $M_{\chi_{c2}\pi^+}$ and $M_{\chi_{c2}\pi^+\pi^-}$ distribution in order to search for any new resonance and find ourselves limited by the statistics.

![Figure 2: 1D UML fit to the $\Delta E$ distribution of the (a) $B^0 \rightarrow \chi_{c2}K^+\pi^-$ and (b) $B^+ \rightarrow \chi_{c2}K^+\pi^-\pi^+$ decay modes. The curves shows the signal [red dashed for $B^0 \rightarrow \chi_{c2}K^+\pi^-$ in (a) and $B^+ \rightarrow \chi_{c2}K^+\pi^-\pi^-$ in (b)], peaking background [magenta dotted-dashed for $B^0 \rightarrow \chi_{c1}K^+\pi^-$ in (a) and $B^+ \rightarrow \chi_{c1}K^+\pi^-\pi^-$ in (b)] and the background component (green dotted for combinatorial) as well as the overall fit (blue solid).](image)

3.3 $B^0 \rightarrow (\chi_{c1}\gamma)K^+\pi^-$ decay mode

In our search for $B^0 \rightarrow X(3823)K^+\pi^-$, we find a strong hint of a narrow peak at 3823 MeV in $M_{\chi_{c1}\gamma}$ with a significance of 2.5σ (systematics included). Figure 4 shows the UML fit to the $M_{\chi_{c1}\gamma}$ distribution for the $B^0 \rightarrow (\chi_{c1}\gamma)K^+\pi^-$ decay mode. Using the central value of the measured branching fraction, we get $\frac{\mathcal{B}(B^0 \rightarrow X(3823)K^+\pi^-)}{\mathcal{B}(B^0 \rightarrow X(3823)K^+)} = 2.5 \pm 1.0$(stat. only).

4. Summary

Belle presented first preliminary results at this conference. $\mathcal{B}(B \rightarrow \chi_{c1}X)$ measured by Belle is consistent with the previous results. $D\mathcal{B}(B \rightarrow \chi_{c1}X)$ measured in bins of $p_T$, shows a suppression of $\chi_{c2}$ production in higher momentum bins. Belle observed the $B^0 \rightarrow \chi_{c2}K^+\pi^-$ and
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$B^+ \rightarrow \chi_{c1} K^+ \pi^+$ decay modes for the first time, while no narrow resonance is found in the $M_{\chi_{c1}}$ distributions. 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. A hint of $X(3823)$ in $B^0 \rightarrow X(3823) K^+ \pi^-$ is seen with a significance of 2.5σ (syst. included) and the large $B(B^0 \rightarrow X(3823) K^+ \pi^-)$ suggests its $J$ to be 2. This further supports $X(3823)$ to be identified as the $\psi_{2D}(1^{3}D_{2} c\bar{c})$ state.

References

[5] 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.